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The role of membrane distillation/crystallization technologies in the integrated membrane system for seawater desalination

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ABSTRACT

Membrane desalination technology has emerged in recent years as the most viable solution to water shortage. However, despite the enormous improvement in membrane desalination technology, some critical developments are still necessary in order to accomplish possible improvements in the process efficiency (increase recovery), operational stability (reduce fouling and scaling problems), environmental impact (reduce brine disposal), water quality (remove harmful substances) and costs. In particular, cost effective and environmentally sensitive concentrate management is today recognized as a significant obstacle to extensive implementation of desalination technologies. As a result of the significant impact of desalination plants on the environment, the requirements for concentrate management tight up: brine disposal minimization and zero liquid discharge (ZLD) are the demanding targets for several applications. In this concept, conventional pressure-driven membranes such as MF, NF and RO were integrated with the innovative units of membrane contactors such as Membrane Distillation/Crystallization (MD/MC). The integration of different membrane units represents an interesting way for achieving the ZLD goal due to the possibility of overcoming the limits of the single units and, thus, to improve the performance of the overall operation. The present research study is focusing on the evaluation of the integrated membrane system which merges the membrane contactor technology with the conventional pressure-driven membrane operations for seawater desalination. Sensitivity studies were performed for several configurations of the integrated system to obtain the most sensitive parameter in the total water cost and the optimal design of the system. The results revealed that the pressure-driven membrane operations were very sensitive to the feed concentration and the cost of electricity consumption. On the other hand, MD processes were not sensitive to the variation on the feed concentration or the electricity costs. The most sensitive parameter in the total water cost of the MD plant was the cost of steam which contributed to values as high as high as 11.4% in the case of MD without heat recovery system. The best tolerance to the variation of these parameters was obtained when using the integrated membrane system of pressure-driven membranes and MC processes.

Keywords: Membrane distillation; Integrated membrane system; Sensitivity analysis

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1. Introduction

Water shortage problem is now becoming more and more evident worldwide due to the limited water resources and increased population growth. Rational utilization and sustainable water resources management in combination with waste water treatment and developing high efficiency desalination technologies are the only solutions to face water shortage problem. Desalination is no longer a marginal water resource for municipal and industrial use as in some countries like as Qatar, Saudi Arabia and Kuwait. Two-third of the world's desalination plants are located in Gulf Cooperation Council (GCC) countries: Saudi Arabia, Kuwait, Qatar, Bahrain, UAE, and Oman [1,2]

Among different technologies available, multi-stage flash (MSF) distillation and reverse osmosis (RO) dominate the existing plants. Other technologies include multi-effect distillation (MED), vapor compression (VC), and electrodialysis (ED) [3].

Membrane distillation (MD) is a process that has a great potential to substitute the conventional desalination processes since it is a concentration process carried out at low temperature and is not affected by concentration polarization phenomenon like in RO. MD requires lower operating temperatures and smaller vapor space than the MSF and MED processes [4]. Recently, the interest of using MD process for desalination is increasing world-wide due to these attractive features, especially when coupled with solar energy or utilizing low-grade heat source [5].

Although desalination has offered a key solution for the water shortage problems, one of the main obstacles still open is the management of concentrated brines (wastes). Considering a typical RO desalination plant with water recovery factor of 45–60% (seawater) or 75–85% (brackish water), this would result in a significant excess of high concentrated solutions to be disposed-off. At present, the most frequent disposal practice for brines is a direct discharge into lakes, lagoons, rivers, ocean and sanitary drains. However, the requirements of more and more rigid environmental protection regulations will stop this low-cost brine disposal in the near future.

In the last years, several process engineering strategies have been implemented in order to accomplish the concept of the zero-liquid discharge (ZLD) in seawater desalination [6]. In this context, the combination of the conventional pressure-driven membrane operations such as MF, NF and RO with the membrane contactors technology such as membrane distillation/crystallization (MD/MC) is expected to offer alternative design-pathways for brine management. The integration of different membrane units represents an interesting way for achieving the ZLD goal due to the possibility of overcoming the limits of the single units and, thus, to improve the performance of the overall operation [7].

The purpose of this work is to perform a sensitivity analysis for different combination of the pressure-driven membrane operations with the membrane contactor technologies thus realizing the role of MD/MC technologies in the integrated membrane system for seawater desalination to approach the ZLD requirements.

2. Scheme and techniques

Four configurations of desalination plants were considered in this study. More details of these plants are given in the following lines:

2.1. MF-RO

The first system considered in the study was the commonly used MF-RO desalination plant [8,9]. The microfiltartion (MF) membranes are used as a pretreatment for the reverses osmosis (RO) desalination plant instead of the conventional pretreatment methods like sand and multi-media filtration. A schematic diagram of such plant is presented in Fig. 1.

The overall water recovery of the plant in the case was 47.5% assuming 95% and 50% water recovery rates of the MF and the RO, respectively [10].

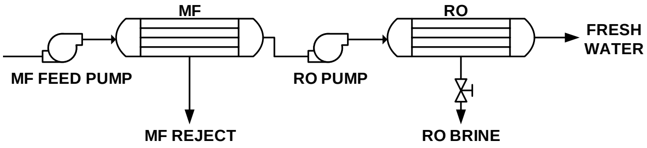

Fig. 1. Pressure-driven membrane operations (MF-RO).

2.2. MF-NF-RO

In this case a nanofiltration (NF) unit was installed between the MF and the RO as shown in Fig. 2.

The water recoveries were 95%, 70% and 60% for the MF, NF and RO, respectively. The overall plant recovery was 39.9% [10].

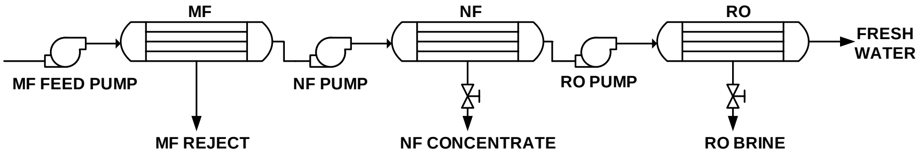

Fig. 2. Pressure-driven membrane operations (MF-NF-RO).

2.3. MD alone

Here the MD plant was operated as a stand-alone plant. The water recovery was 80% and the MD units were operated under the conditions of 30 degrees temperature difference and producing a flux of 8.2 kg/m^{2}h in the case of MD and a flux of 6.8 kg/m^{2}h in the case of MC as obtained from the MD simulation program using MATLAB studied earlier [11]. A schematic diagram of the MD plant is illustrated in Fig. 3.

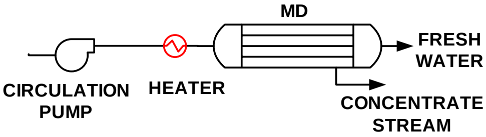

Fig. 3. Schematic diagram of the MD plant.

2.4. MF-NF-RO-MC_NF-MD_RO plants

In this case, the desalination plant was consisting of the pressure-driven membranes (MF-NF-RO) in combination with membrane crystallization (MC) units operated in the rejected stream of the NF units and membrane distillation units operated in the brine stream of the RO units as shown in Fig. 4. The overall fresh water recovery of the whole integrated system in this configuration was 89% assuming the same recoveries of MF, NF, RO and MD as above; and the water recovery of the MC units was assumed as 97.6% [12].

3. Results and discussion

At the beginning, the reference water cost of each plant configuration was calculated based on the data and the assumptions shown in Table 1. The calculated reference water cost for each scheme is shown in Table 2.

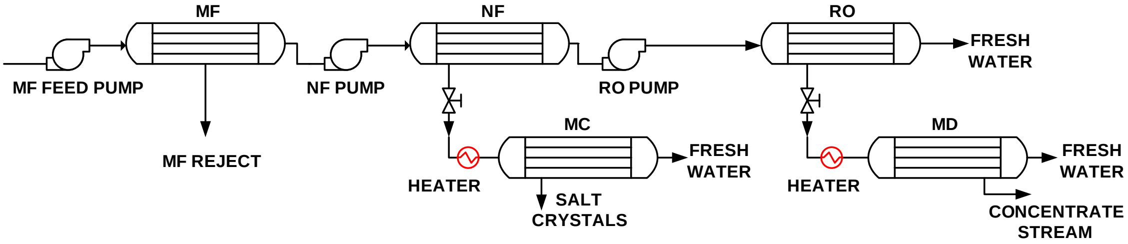

Fig. 4. Schematic representation of the integrated membrane system.

Table 1
Data and assumption used to calculate the reference water cost

Plant availability, *f*	90%	Direct capital cost, DCC		
Plant capacity, Q_P	1,000 m^3/h	Intake =658 (Q_P/η) 0.8		[13]
Plant annual capacity	8,760,000	Civil work = 1945 (Q_P/η) 0.8		[14]
Plant life, *n*	20 years	MF membrane cost =90 \$/m^2		[13]
		RO membrane cost =30 \$/m^2		[14]
Interest rate, *i*	5%	Steam heat exchanger cost = 2000 \$/m^2		[15]
Amortization factor: $a = \frac{i(1+i)^n}{(1+i)^n - 1}$		Heat recovery exchanger cost = 1540 \$/m^2		[15]
Fluxes		Indirect capital cost = 10% DCC		
UF flux = 90 L/m^2 h		Annual fixed charges = a×DCC/f×Q		
NF flux = 28 L/m^2 h				
RO flux = 15 L/m^2 h				
MD flux = 8.2 L/m^2 h		O&M specific costs		
MC flux = 6.8 L/m^2 h		Electricity cost	0.03 \$/kWh	[13]
		Membrane replacement	15%/y	[16]
		Steam cost	7 \$/ton	[16]
Efficiencies		Spares cost	0.033 \$/m^3	[13]
Pumps-motor combined efficiency = 0.75		Labor cost	0.03-0.05 \$/m^3	[14]
Pressure exchanger efficiency = 0.95		Chemical cost	0.018 \$/m^3	[16]
Heat exchanger efficiency = 0.8		Brine disposal	0.0015 \$/m^3	[16]

Table 2
Calculated reference water cost

Plant configuration	Calculated reference water cost ($/m^3)
MF-RO	0.51
MF-NF-RO	0.62
MD alone	1.13
MF-NF-RO-MC_NF-MD_RO	1.28

The sensitivity of changing different variables of the desalination process on the product water cost was studied in order to identify the most sensitive parameters on water cost and to establish optimal conditions for minimizing the total water cost. The water production capacity of 24,000 m^3/d was assumed in all cases.

The estimated water cost of desalination plants obtained by this study was comparable to the costs of water produced by conventional process around 0.5 $/m^3 for RO [7], 1.00 $/m^3 for MED and 1.40 $/m^3 for MSF [5].

3.1. Water recovery (yield)

The effects of changing the water recovery on the total water cost for the MF-RO, MF-NF-RO and MD plants was considered and the results are discussed below.

3.1.1. RO recovery in MF-RO plants

The first system considered in the study was the commonly used MF-RO desalination plant. The effect of changing the RO water recovery on the total water cost was investigated and the results are shown in Fig. 5. The results showed that when increasing the RO recovery from 40% to 60%, the total water cost decreased from 0.58 to 0.46 $/m^3 in the case of using the energy recovery system and from 0.64 to 0.50 $/m^3 in the case not using the energy recovery system. Since an RO recovery of 50% typically used, it has been taken as a reference value. An increment of 20% in this value will contribute to an average reduction of 10% in the total water cost for both cases with and without energy recovery system as obtained from the slope of the water cost variations graph in Fig. 5.

3.1.2. RO recovery in MF-NF-RO plants

In this case, higher RO recovery values can be achieved at lower osmotic pressure since most of the bivalent ions were removed by the NF membranes. As shown in Fig. 6, The RO recovery was changed within the range 48–72% and the results showed that the total water cost decreased from 0.71 to 0.56 $/m^3 and decreased from 0.75 to 0.59 $/m^3 for systems with and without energy recovery devices, respectively. Considering a recovery value of 60% as a reference, the total water cost was reduced by an average value of 10% as the RO recovery was increased by 20% for both cases with and without energy recovery systems as deduced from the slope of the water cost variations graph in Fig. 6.

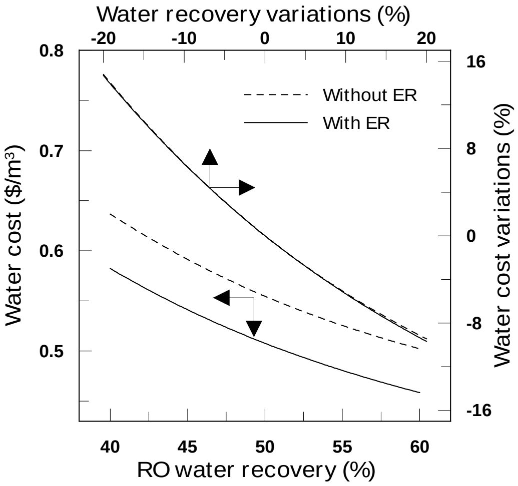

Fig. 5. Effects of the RO water recovery on the total water cost of MF-RO plants.

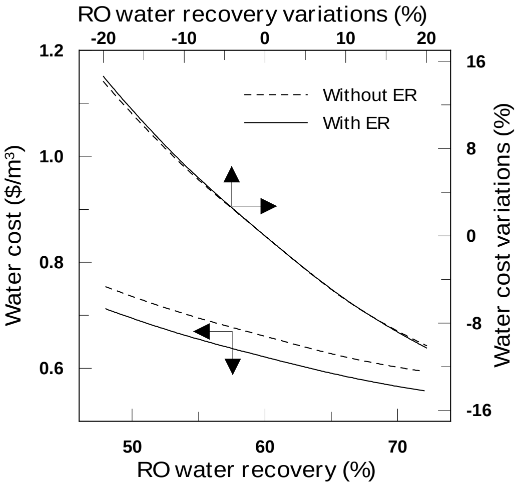

Fig. 6. Effects of the RO water recovery on the total water cost of MF-NF-RO plants.

3.1.3. NF recovery in MF-NF-RO plants

The NF recovery was varied from 56% to 84% and the results showed that total water cost was reduced from 0.69 to 0.57 $/m^3 in the case of the plant with the energy recovery system; and reduced from 0.73 to 0.61 $/m^3 in the case of the plant without energy recovery system as shown in Fig. 7. Taking a reference recovery value of 70%, an increase of 20% in this value will result in an average reduction of 8% and 7.8% in the total water cost

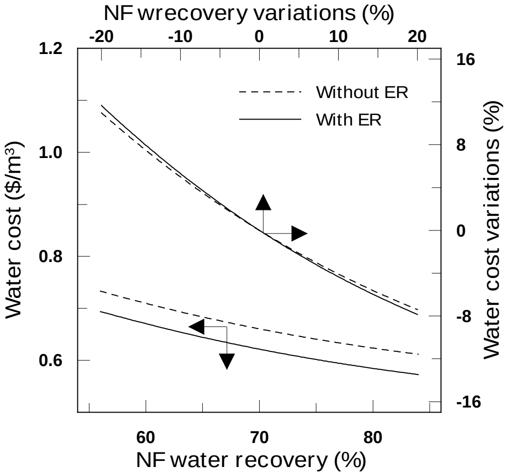

Fig. 7. Effects of the NF water recovery on the total water cost of MF-NF-RO plants.

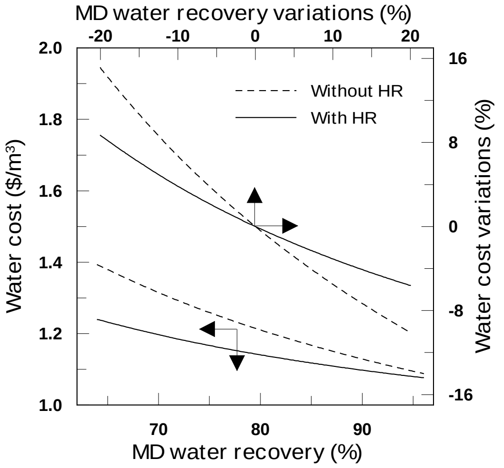

Fig. 8. Effects of the MD water recovery on the total water cost of MD plants.

for the plants with and without energy recovery system, respectively as given from the slope of the water cost variations graph in Fig. 7.

3.1.4. MD recovery in MD plants

High MD recovery values can be achieved since the MD plant is a thermal process and not limited by the osmotic pressure. The MD recovery was increased from 64% to 96% and the total water cost was reduced from 1.24 to 1.08 $/m^3 and from 1.39 to 1.09 $/m^3 for both cases with and without heat recovery systems, respectively as illustrated in Fig. 8. The difference in the water cost between MD with and without heat recovery was high (12%) when operating MD at low recovery values. However, at high water recovery values, the water cost of MD without heat recovery system became very close to the one of MD with heat recovery with difference of about 1% only. This was due to the fact that as the recovery was increased, the amount of hot brine was reduced and hence the amount of heat that can be recovered using the heat recovery system was reduced too. Increasing the MD recovery value by 20%, based on a reference recovery value of 80%, will lead to a reduction of 6.2% and 10.3% in the total water cost for cases with and without heat recovery systems, respectively as taken from the slope of the water cost variations graph in Fig. 8.

Generally, the total water cost decreased as the water recovery was increased in all cases. This was due to the fact that smaller intake/discharge facilities and lower membrane surface area were required since higher flux values were obtained at higher recoveries. The pressure-driven membrane desalination plants showed similar sensitivity to the changes in the water recovery values for both cases with and without energy recovery systems. However, in the case of MD, the sensitivity of the MD plant without heat recovery system was higher than the one with heat recovery system especially at low recovery values. This was due the dependency of the amount of heat to be recovered by the heat recovery system on the amount of the rejected brine which was varying with the recovery value.

3.2. Feed water concentration

The desalination plants were evaluated at situations where the feed concentration might vary. The total water cost was considered when the feed concentration changed between 10–25 g/L for brackish water and between 30–50 g/L for seawater.

3.2.1. MF-RO plants

The results showed that when the concentration was increased from 10 to 25 g/L in the case of brackish water, the water cost increased from 0.34 to 0.39 $/m^3 for plants with energy recovery system and increased from 0.35 to 0.41 $/m^3 for plants without energy recovery system as shown in Fig. 9. In the case of seawater plants, the concentration was increased from 30 to 50 g/L and accordingly the water cost increased from 0.47 to 0.53 $/m^3 and from 0.51 to 0.58 $/m^3 in the case of plants with and without energy recovery systems, respectively as shown in Fig. 9.

3.2.2. MF-NF-RO plants

In this case, the results showed that when increasing the concentration from 10 to 25 g/L for brackish water plants, the water cost increased from 0.34 to 0.41 $/m^3 for plants with energy recovery system and increased from 0.35 to 0.42 $/m^3 for plants without energy recovery system as shown in Fig. 10. The water cost increased from

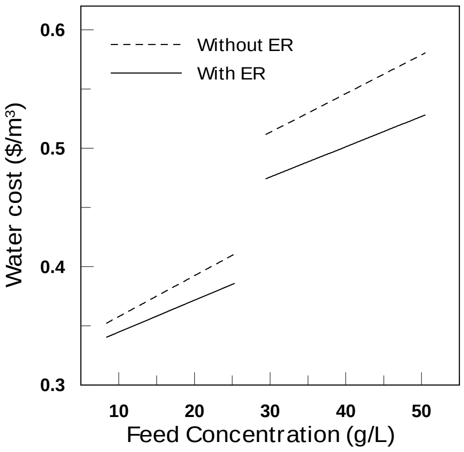

Fig. 9. Effects of the feed concentration on the total water cost of MF-RO plants.

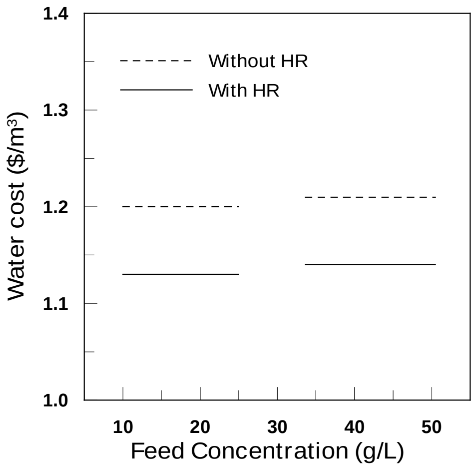

Fig. 11. Effects of the feed concentration on the total water cost of MD plants.

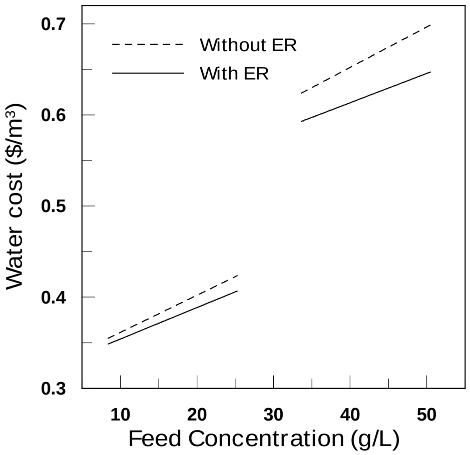

Fig. 10. Effects of the feed concentration on the total water cost of MF-NF-RO plants.

0.59 to 0.65 \$/m^3 and increased from 0.62 to 0.70 \$/m^3 for seawater plants with and without energy recovery systems, respectively as shown in Fig. 10.

3.2.3. MD plants

In the case of thermal processes, the total water cost was not affected by the change in the feed concentration for brackish and seawater plants as shown in Fig. 11. The water cost was 1.13 \$/m^3 and 1.20 \$/m^3 for brackish water plants with and without heat recovery system, respectively. For seawater plants, the water cost was 1.14 \$/m^3 and 1.21 \$/m^3 for plants with and without heat recovery system, respectively.

3.2.3. MF-NF-RO-MC_NF-MD_RO plants

These plants consisted of the integrated system which includes a membrane crystallization unit operated in the rejected stream of the NF unit and a membrane distillation unit operated in the brine stream of the RO unit. In this case, the results showed that when increasing the concentration from 10 to 25 g/L for brackish water plants, the water cost increased gradually from 1.09 to 1.13 \$/m^3 for plants with energy recovery system and increased steadily from 1.38 to 1.42 \$/m^3 for plants without energy recovery system as shown in Fig. 12. The water cost increased slowly from 1.26 to 1.29 \$/m^3 and increased from 1.50 to 1.53 \$/m^3 for seawater plants with and without energy recovery systems, respectively as shown in Fig. 12.

As shown above, the total water cost was increasing when the feed concentration increased in the case of pressure-driven membranes. This raise in the total water cost was related to the additional requirement of membrane surface area due to the flux reduction as well as the additional power requirement due to higher pres-

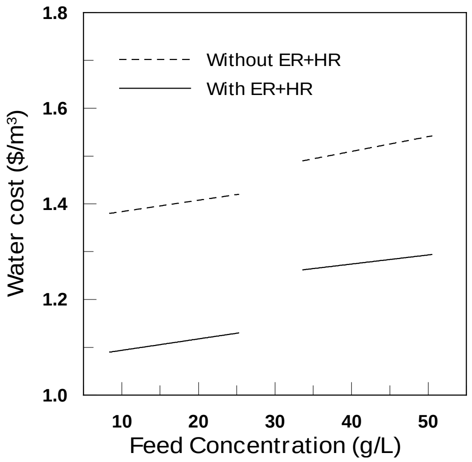

Fig. 12. Effects of the feed concentration on the total water cost of MF-NF-RO-MC_NF-MD_RO plants.

sure operations to overcome the additional resistance of osmotic pressure at higher concentration. On the other hand, MD plants were not greatly affected by the feed concentration. This was expected due to the fact that MD plants are thermal processes and they are not limited by osmotic pressure or concentration polarization phenomena. In the case of integrated plants which contain pressure-driven membrane operations and membrane contactors (MD and MC), the total water cost was less sensitive to the changes in the feed concentration than the other cases.

3.3. Membrane cost

The sensitivity of changing the membrane cost on the total water cost of desalination plants was studied. The reference values of the membrane cost was taken as 90 $/m^2 for MF membranes [13] and 30 $/m^2 for NF and RO membranes [14]. For study purposes, the membrane cost was changed by a factor of ±20% of these reference values in all cases.

3.3.1. MF-RO plants

An increase of 20% in the membrane cost contributed to an increase of 4.8% and 4.4% in the total water cost for plants with and without energy recovery system as shown in Fig. 13.

3.3.2. MF-NF-RO plants

In this case, the results showed that the total water cost was increased by 4.8% for plants with energy recovery system and increased by 5.6% for plants without energy recovery system when the membrane cost was increased by 20% as shown in Fig. 14.

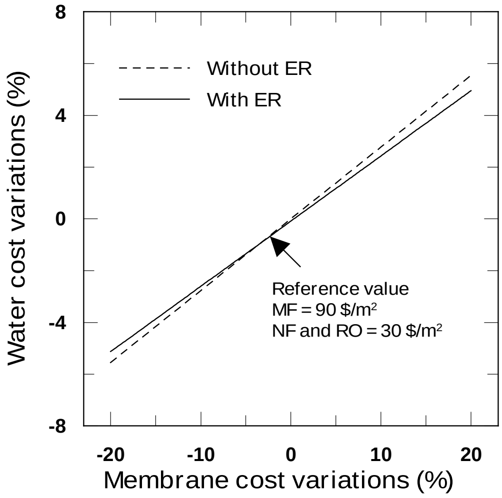

Fig. 14. Effects of the membrane cost on the total water cost of MF-NF-RO plants.

3.3.3. MD plants

In the case of MD processes, the total water cost was increased by 5.6% and 5.4% for plants with and without heat recovery system, respectively when the MD membrane cost was increased by 20% as shown in Fig. 15.

3.3.4. MF-NF-RO-MC_NF-MD_RO plants

In the case of the integrated system, the changes in the total water cost were less evident than the other cases. The total water cost was increased only by 1.5% and 1.6% for plants with and without energy and heat recovery systems, respectively when the membrane cost was increased by 20% as shown in Fig. 16.

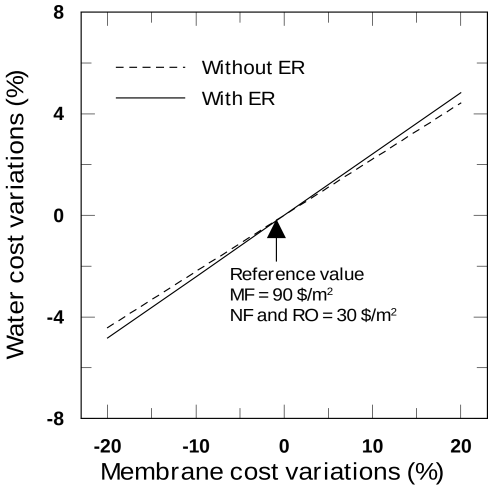

Fig. 13. Effects of the membrane cost on the total water cost of MF-RO plants.

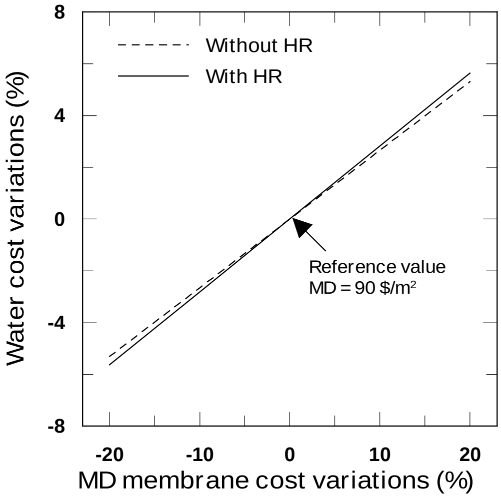

Fig. 15. Effects of the membrane cost on the total water cost of MD plants.

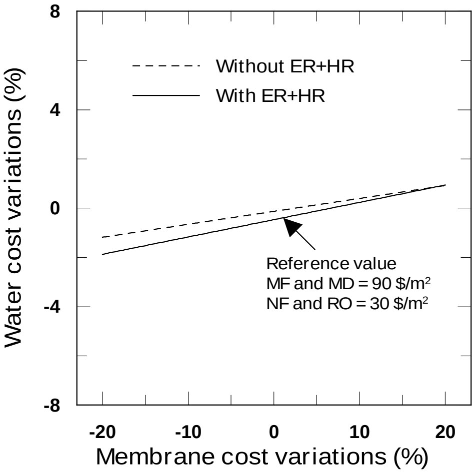

Fig. 16. Effects of the membrane cost on the total water cost of MF-NF-RO-MC_NF-MD_RO plants.

The results showed that when increasing the membrane cost per unit area by 20%, the total water cost was increased within the range 4.4–5.6% in all cases except the plant with the integrated systems. The plants with integrated systems showed better cost stability for the changes in the total water cost.

3.4. Electricity cost

The effects of the variations in the electricity cost were studied. The reference value was taken as 0.03 $/kWh [13]. The electricity cost was varied by a factor of ±20% of this reference value in all cases.

3.4.1. MF-RO plants

The total water cost was increased by 3.4% and 5.6% for plants with and without energy recovery system, respectively when the electricity cost was increased by 20% as shown in Fig. 17.

3.4.2. MF-NF-RO plants

An increase of 20% in the electricity cost will result in increasing the total water costs by 3.6% and 5.2% for plants with and without energy recovery systems as shown in Fig. 18.

3.4.3. MD plants

In the case of MD processes, the total water cost was not affected by the change in the electricity costs since the electricity power was used only as an auxiliary power supply for running the circulation pumps. The main energy input was the thermal energy provided as hot steam for heating the feed water. The total water cost was constant at 1.14 and 1.21 $/m^3 for plants with and without heat recovery systems, respectively.

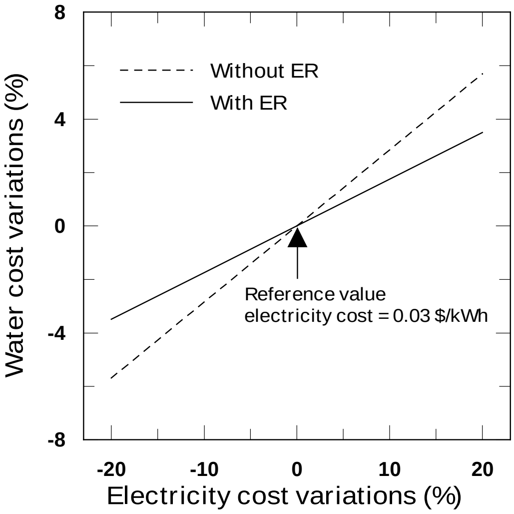

Fig. 17. Effects of the electricity cost on the total water cost of MF-RO plants.

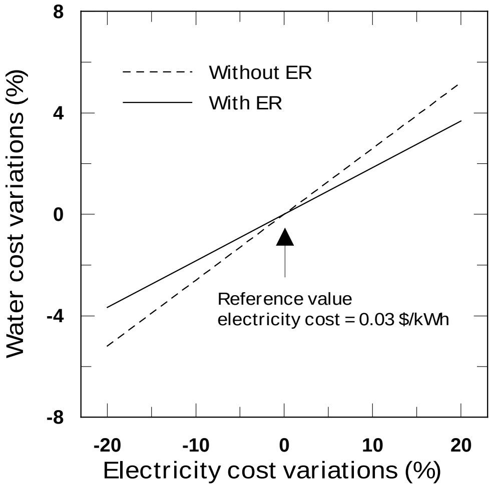

Fig. 18. Effects of the electricity cost on the total water cost of MF-NF-RO plants.

3.4.4. MF-NF-RO-MC_NF-MD_RO plants

In the case of the integrated system, the total water cost was increased only by 2.0% and 2.4% for plants with and without energy and heat recovery systems, respectively when the membrane cost was increased by 20% as shown in Fig. 19.

The results showed that the plants with energy recovery systems showed less sensitivity to the changes in the electricity cost than the ones without energy recovery systems in the case of pressure-driven membrane operations. This means that the energy recovery system was useful in making the plants less sensitive to the changes in the electricity cost. The thermal process (MD) showed

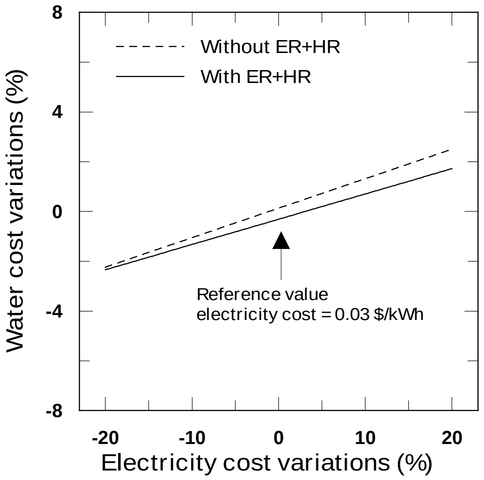

Fig. 19. Effects of the electricity cost on the total water cost of MF-NF-RO-MC_NF-MD_RO plants.

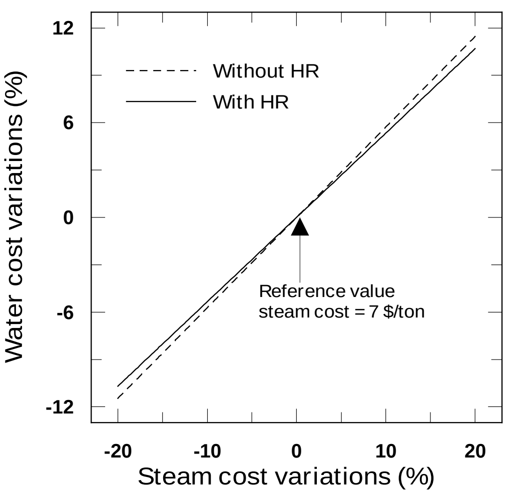

Fig. 20. Effects of the steam cost on the total water cost of MD plants.

constant water costs against the changes in the electricity costs since the electrical power was used only to operate auxiliary pumps and systems. Again, the integrated membrane system showed better stability to the changes in the electricity cost than the pressure-driven membrane operations alone.

3.5. Steam cost

The cost of energy has a very wide variation among different countries and it might be even different in the same country depending on the location of the plant. In Thermal plants the main energy input is heat in the form of steam. This is applicable only for the cases where the steam was used as the heat energy input like in MD plants and the integrated system when using MD and MC processes. The reference value of the steam was taken as 7 $/ton [16]. The steam cost was varied by a factor of ±20% of this reference value in all cases.

3.5.1. MD plants

In the case of operating MD process as a stand alone desalination plant, the total water cost increased by 10.6% for plants with heat recovery system and 11.4% for plants without heat recovery system when the steam cost was increased by 20% as shown in Fig. 20.

3.5.2. MF-NF-RO-MC_NF-MD_RO plants

The integrated system showed less sensitivity to the changes in the steam cost. The total water cost increased by 4.7% for plants with energy and heat recovery systems and by 4.1% for plants without energy and heat recovery systems when the steam cost was increased by 20% as shown in Fig. 21.

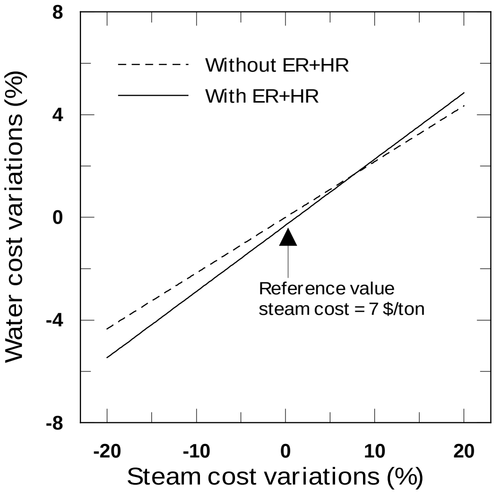

Fig. 21. Effects of the steam cost on the total water cost of MF-NF-RO-MC_NF-MD_RO plants.

The results showed that the MD process was very sensitive to any changes in the steam costs when operated as a stand alone desalination plant. However, when integrating MD and MC plants with the pressure-driven membrane operations, the system confirmed better stability against the changes in the steam costs.

3.6. Membrane life

The operating life time of the membrane is a very important factor on the total water cost of desalination plants. In this study, the shortest life time was considered as 2 years and the longest life time was 8 years. The total water cost was evaluated when changing the lie time of the membrane between these values for all cases. The results showed that the pressure-driven membranes

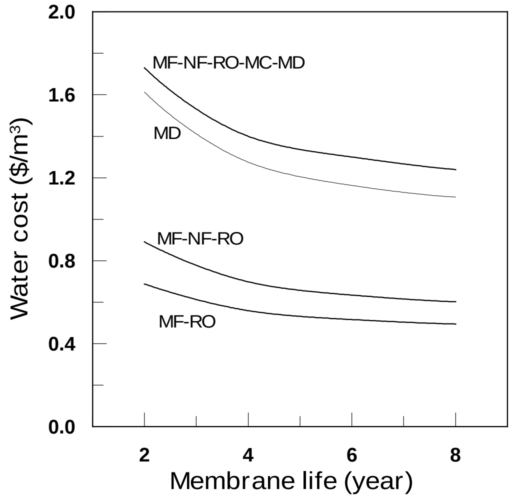

Fig. 22. Effects of membrane life time on the total water cost of desalination plants.

had lower dependency on the membrane life than the thermal and integrated processes. The total water cost was reduced from average values of about 0.8 $/m^3 at membrane life of 2 years to reach average values of about 0.5 $/m^3 at membrane life of 8 years for pressure-driven membrane operations as shown in Fig. 22. The MD plants showed similar dependency on the membrane life as the integrated system. In this case, the total water cost decreased from 1.75 to 1.15 0.5 $/m^3 at membrane life time of 2 and 8 years, respectively. The total water cost showed higher sensitivity for the change in the membrane life time for values less than 4 years and the sensitivity started to be lower at membrane life time more than 4 years as shown in Fig. 22.

4. Conclusions

The sensitivity analysis showed that the pressure-driven membrane operations were very sensitive to the changes in the feed concentration and the cost of electricity per 1 kWh. On the other hand, MD processes were not sensitive to the variation in the feed concentration or the electricity costs. The most sensitive parameter in the total water cost of the MD plant was the cost of steam which contributed to values as high as high as 11.4% in the case of MD without heat recovery system. The best tolerance to the variation of these parameters was obtained when using the integrated membrane system of pressure-driven membranes and MC processes.

Concerning the membrane life time, the results showed that the pressure-driven membranes had lower dependency on the membrane life than the thermal and the integrated processes. In addition, the total water cost showed higher sensitivity for the change in the membrane life time for values less than 4 years and the sensitivity started to be lower at membrane life time more than 4 years.

Accordingly, it was demonstrated that combining several membrane processes in an integrated membrane system will offer essential improvements in efficiency, water cost and environmental impact which maintain the process sustainability and growth; meeting the process intensification targets. In addition, the integrated membrane system has great potentials to achieve the zero-liquid discharge goal since the amount of the rejected brine was very limited.

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