Desalination and Water Treatment
www.deswater.com

26 (2011) 172–177
February

doi: 10/5004/dwt.2011.2127

Cost analysis of large scale membrane treatment systems for potable water treatment

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Received 12 November 2009; Accepted 1 January 2010

ABSTRACT

Along with the increasing world population, the water sources are faced with considerably serious problems in terms of quantity, quality and all other sector-specific usages. Today, brackish water, surface water, seawater and even wastewater can be treated to supply drinking water. Reverse osmosis, nanofiltration, ultrafiltration and microfiltration are the most widely used membrane processes for the treatment of these water sources. It is necessary to calculate the total cost, including both capital expenses and operation and maintenance expenses such as energy labor, membrane replacement, chemicals and concentrate disposal to determine the most economical design. In this study, the costs of large scale membrane systems for the treatment of brackish, surface and seawater to obtain drinking water were investigated for Turkey. The effects of the Total Dissolved Solids (TDS) concentration, turbidity and salinity values on the treatment costs of brackish water, surface water and seawater were investigated, respectively taking into consideration also the variations in capacity and flux values.

Keywords: Cost analysis; Desalination; Membrane systems; Surface water; Brackish water; Seawater

1. Introduction

Brackish water, highly polluted surface waters, seawater and even wastewater are potential sources to obtain drinking water. One of the most effective methods used for this purpose is membrane treatment technology. Reverse osmosis, nanofiltration, ultrafiltration and microfiltration are the most widely used membrane processes.

Over the history, developments in membrane technology have resulted in a variety of advancements. These advancements included the enhancements in salt rejection capabilities, chemical stability and, perhaps most importantly, pressure requirements. Cost of each membrane separation systems varies depending on the production capacity, type of treatment, design criteria, climate condition, characteristics of land and building, etc. [1]. It is necessary to calculate the total cost, including both capital expenses and operation and maintenance expenses such as energy labor, membrane replacement, chemicals and concentrate disposal to determine the most economical design [2]. The cost of membrane treatment has decreased each year as shown in Fig. 1. That's why, it is necessary to obtain updated costs for each application. Additionally, Akgul et al. [3] studied about the cost analysis of seawater desalination with reverse osmosis systems up to a capacity of 10,000 m^3/d in Turkey. However, with the increasing demand of water throughout the world, there is no detailed cost analysis study for large scale membrane systems [3].

In this study, the costs of large scale membrane systems for the treatment of brackish water, surface water and seawater to obtain drinking water were investigated. Within this concept, unit costs of each system were obtained and compared with each other.

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Presented at the International workshop on urbanisation, land use, land degradation and environment (ULE 2009), 28 September – 1 October 2009, Denizli, Turkey

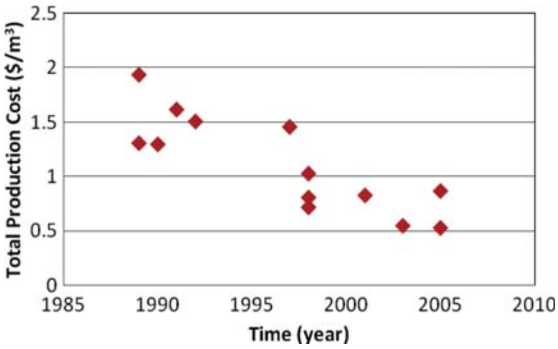

Fig. 1. Total production cost versus time for seawater treatment by reverse osmosis systems.

2. Materials and methods

Different designs were done for each water sources including brackish water, surface water and seawater. The computer program called IMS design (Hydranautics) was used in the design calculations. The effect of feed water quality, treatment system, flux and capacity were evaluated in the designs. Designed systems were evaluated regarding both capital and operating costs.

Five different production capacities of 1000, 5000, 10,000, 100,000, 300,000 m^3/d were investigated for the designs. Additionally, the effect of TDS concentrations (1000, 2000, 5000 and 10,000 ppm) for brackish water and the effect of turbidity values (5, 10 and 15 NTU) for surface water on the treatment costs were investigated. Besides, comparison of two alternative treatment systems (reverse osmosis, nanofiltration) for the treatment of surface water were also performed. Sand filtration and ultrafiltration were applied as pre-treatment methods for brackish water and surface water, respectively. Additionally, different membrane designs were performed for the Mediterranean Sea using five different capacities and three fluxes (15.6, 13.3 and 11.7 $L/m^2/h$) to investigate the effect of flux and capacity on the treatment costs. Three seawater samples (Mediterranean Sea, Marmara Sea and Black Sea) with different qualities and recoveries (40%, 45% and 48% for the Mediterranean Sea, the Marmara Sea and the Black Sea, respectively) were compared at a constant flux of 15.6 $L/m^2/h$ to evaluate the effect of feed water quality on the unit treatment costs. Recovery rates were selected according to the maximum treatment performance obtained for seawater. In seawater reverse osmosis systems, energy recovery units for the type of hydraulic load converter with piston were used. Sand filtration was applied as a pre-treatment for all desalination systems. Specifications of the membranes used in the design were provided in the Table 1.

Cost calculations were performed as capital costs and operating costs. Land, construction and water cost were not taken into consideration during cost analysis for every design. Operating costs included the costs of energy, membrane replacement, chemicals and cartridge filters.

3. Results and discussion

3.1. *The cost analysis of brackish water treatment for different salinity values*

The investment, operating and total production costs were shown in Fig. 2 as a function of feed capacity and salinity values for brackish water treatment with reverse osmosis system. As shown in Fig. 2, unit costs decreased

Table 1
Membranes that are used in the design and their specifications

Parameter	Specifications				
	ESPA4	CPA2	SWC5	ESNA-1 LF2	HYDRACAP 60
Process type	Reverse osmosis (surface water; brackish water: 1000–2000 ppm TDS)	Reverse osmosis (brackish water: 5000–10,000 ppm TDS)	Reverse osmosis (seawater)	Nanofiltration	Ultrafiltration
Total surface area (m^2)	37.1	36.5	37.1	37.1	46
Material	Composite polyamide	Composite polyamide	Composite polyamide	Composite polyamide	Hydrophilic polyethersulfone
Configuration	Spiral wound	Spiral wound	Spiral wound	Spiral wound	Capilar ultra-filtration module
Maximum operating pressure (bar)	41.6	41.6	82.7	41.6	5

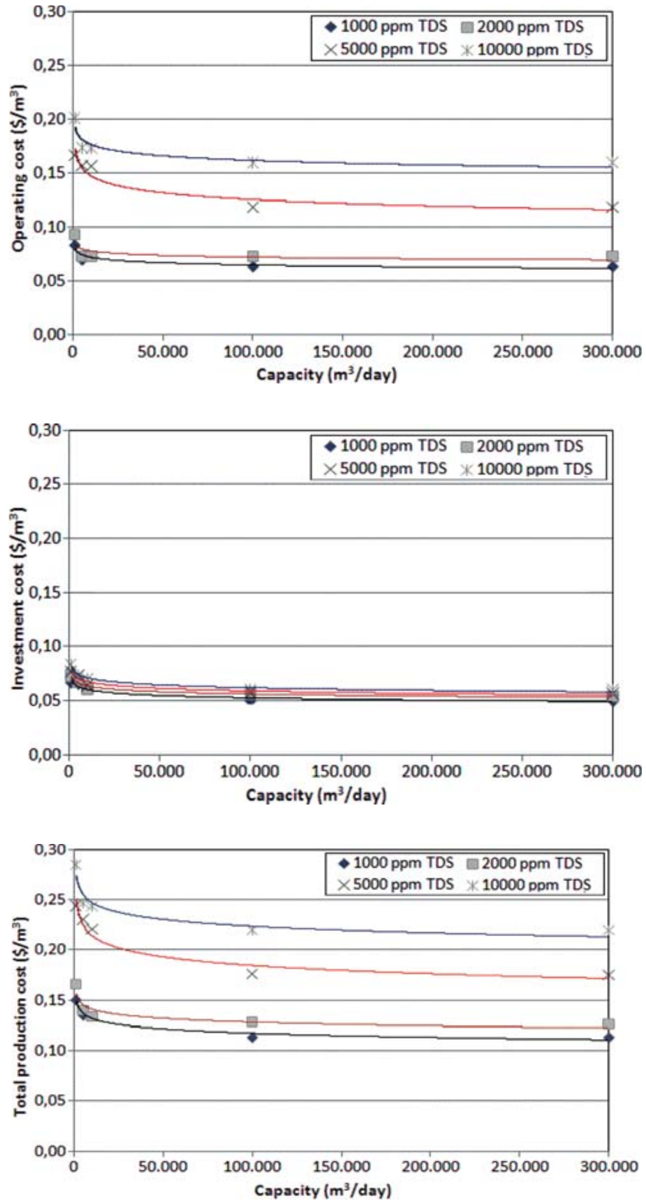

Fig. 2. Effect of system capacity and TDS concentration on operating, investment and total production costs of drinking water production from brackish waters by reverse osmosis.

with increasing capacity and were independent of the capacity after 10,000 m^3/d. This shows that with increasing capacity there is other factors affecting the unit production costs. The operating cost of the reverse osmosis system for brackish water with a 1000 ppm TDS concentration was 0.083 $/$m^3$ for a capacity of 1000 m^3/d, whereas it was obtained as 0.063 $/$m^3$ for a capacity of 300,000 m^3/d. An increase of capacity after 100,000 m^3/d did not lead to significant benefits in terms of treatment costs due to the limiting conditions related with the capacity of high pressure pumps.

There was a direct relation between TDS concentrations and treatment costs. The calculations showed that the increase in the treatment costs of brackish water from 1000 ppm to 2000 ppm TDS concentrations was about 10%, whereas it was about 20% from 5000 to 10,000 ppm TDS concentrations for a capacity of 1000 m^3/d. The maximum cost was observed for the treatment of a water with 10,000 ppm TDS at a capacity of 1000 m^3/d while the lowest cost was obtained at the treatment of water with a 1000 ppm TDS at a capacity of 300,000 m^3/d.

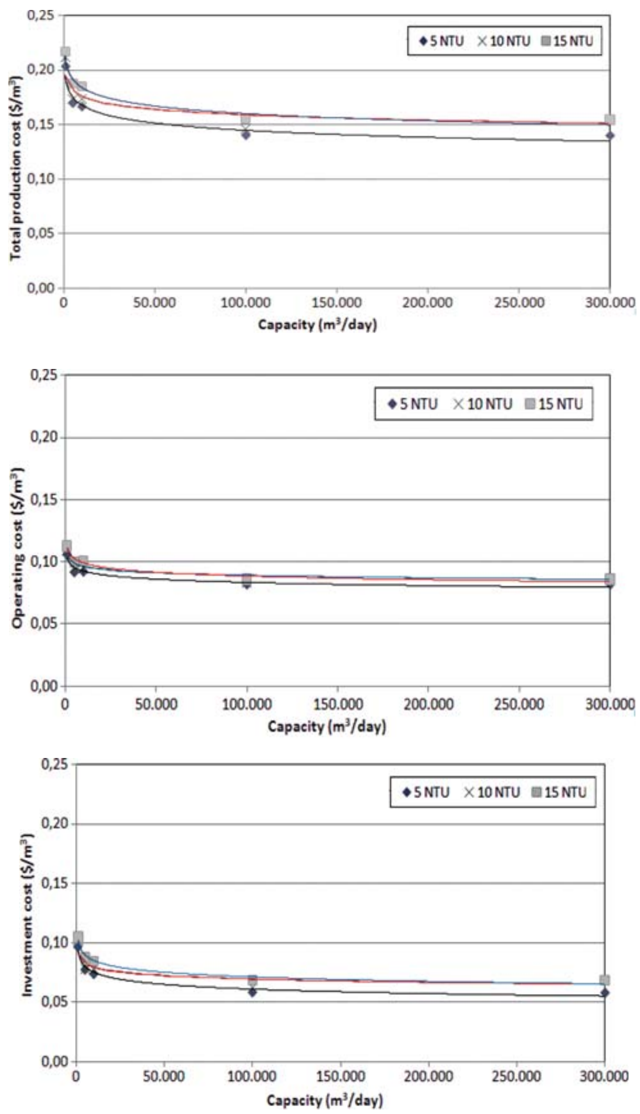

Fig. 3. Effect of system capacity and turbidity values on operating, investment and total production costs of drinking water production from surface waters by ultrafiltration and reverse osmosis.

3.2. The cost analysis of surface water treatment for different turbidity values

Fig. 3 illustrated the effect of increasing turbidity values of surface water on treatment costs. As shown in Fig. 3, the operating cost of ultrafiltration membranes increased with increasing turbidity values of surface water as a consequence of the linear relationship between the frequency of backwashing and chemical cleaning. The operating cost was about 0.106 $/m^3 for the turbidity value of 5 NTU at a capacity of 1000 m^3/d, whereas it was obtained as 0.112 $/m^3 for the turbidity value of 15 NTU.

As the capacity increased, the effect of increasing turbidity on the operating costs decreased. At a capacity of 5000 m^3/d, the increase in the operating costs of surface water treatment from 5 to 15 NTU turbidity value was about 8%. However, this value corresponded to 4% at the capacity of 300,000 m^3/d. The unit investment costs for a turbidity value of 10 NTU were 0.096, 0.077, 0.074, 0.058 $/m^3 for the capacities of 1000, 5000, 10,000 and 100,000 m^3/d, respectively. The investment cost of the membrane systems decreased at a rate of around 65% when the capacity increased from 1000 to 100,000 m^3/d.

The comparison of reverse osmosis and nanofiltration membranes for the treatment of surface water after ultrafiltration pretreatment was shown in Fig. 4. The operating costs of the two systems were almost the same while the investment cost of the nanofiltration membranes was higher due to the higher cost of nanofiltration membranes compared to low pressure reverse osmosis membranes. The increase in the total production costs from reverse osmosis to nanofiltration varied between 2% to 5%. This slight increase was observed as the feed capacity increased. According to Fig. 4, total production cost of reverse osmosis system decreased from 0.169 $/m^3 to 0.139 $/m^3 if the capacity increased from 5000 m^3/d to 300,000 m^3/d. In comparison to reverse osmosis systems, total production cost of nanofiltration membranes changed from 0.173 $/m^3 to 0.144 $/m^3 for the capacity of 300,000 m^3/d to 5000 m^3/d.

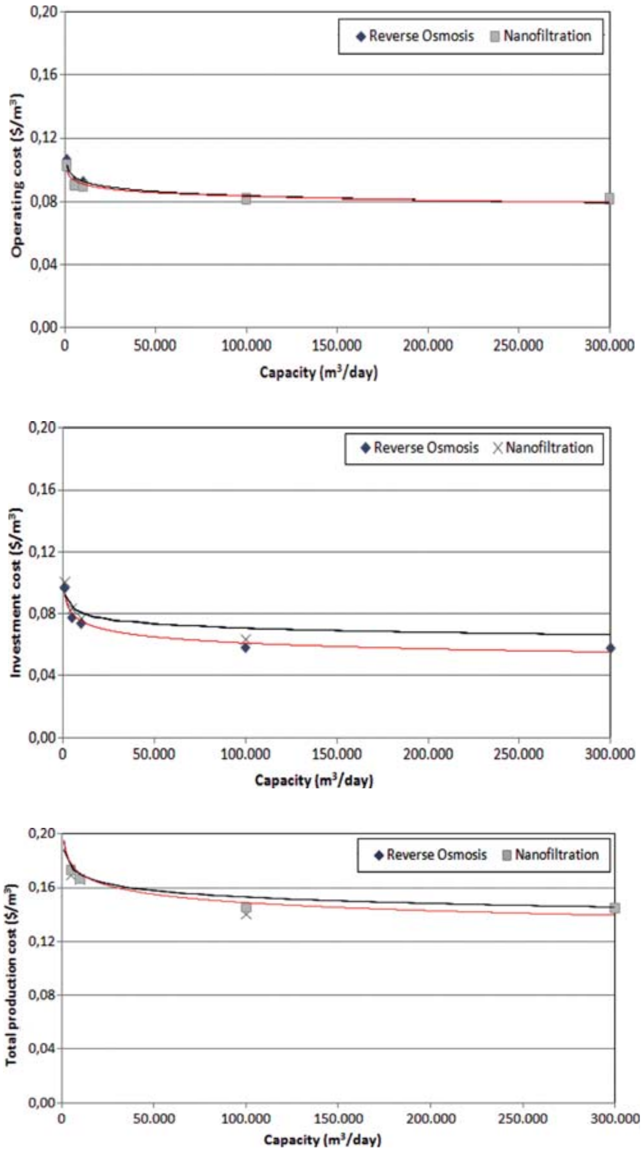

Fig. 4. Comparison of nanofiltration and reverse osmosis membranes for the treatment of surface water after ultrafiltration pretreatment for a turbidity of 5 NTU.

3.3. The cost analysis of seawater treatment at different flux values

Seawater desalination cost with reverse osmosis mainly depends on the flux and salinity values. For this reason, different flux values were used during cost analysis of Mediterranean Sea. The design values were as follows: recovery rate of 40%, 36,000 ppm of salinity and flux values of 15.6, 13.3 and 11.7 L/m^2/h. The capital, operating and total production costs were given in Fig. 5 for the desalination of Mediterranean Sea by reverse osmosis.

Increasing flux values resulted in a decrease in the number of membrane unit and, therefore, the capital cost. On the other hand, a higher flux required more energy input which in turn increased the operating cost. As it can be seen from Fig. 5 that operating cost of the treatment system at a flow rate of 5000 m^3/d was 5% lower than the system with a capacity of 1000 m^3/d. The reason of a slight decrease of the operating costs with increasing capacity could be related to the difficulty in finding a pump that was appropriate for systems at capacities higher than 5000 m^3/d. This situation resulted a requirement of 20 separate pumps with a capacity of 5000 m^3/d to reach a capacity of 100,000 m^3/d. Considering all the conditions, the minimum production cost obtained was 0.502 $/m^3 for the flux value of

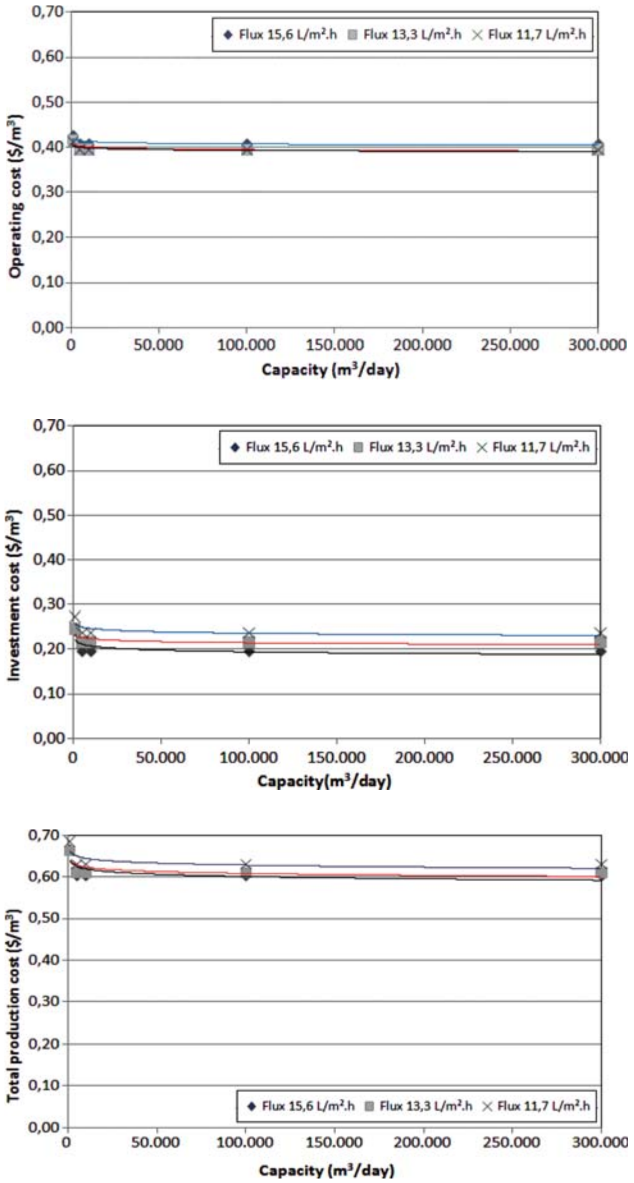

Fig. 5. Effect of system capacity and flux values on operating, investment and total production costs of drinking water production from Mediterranean Sea by reverse osmosis.

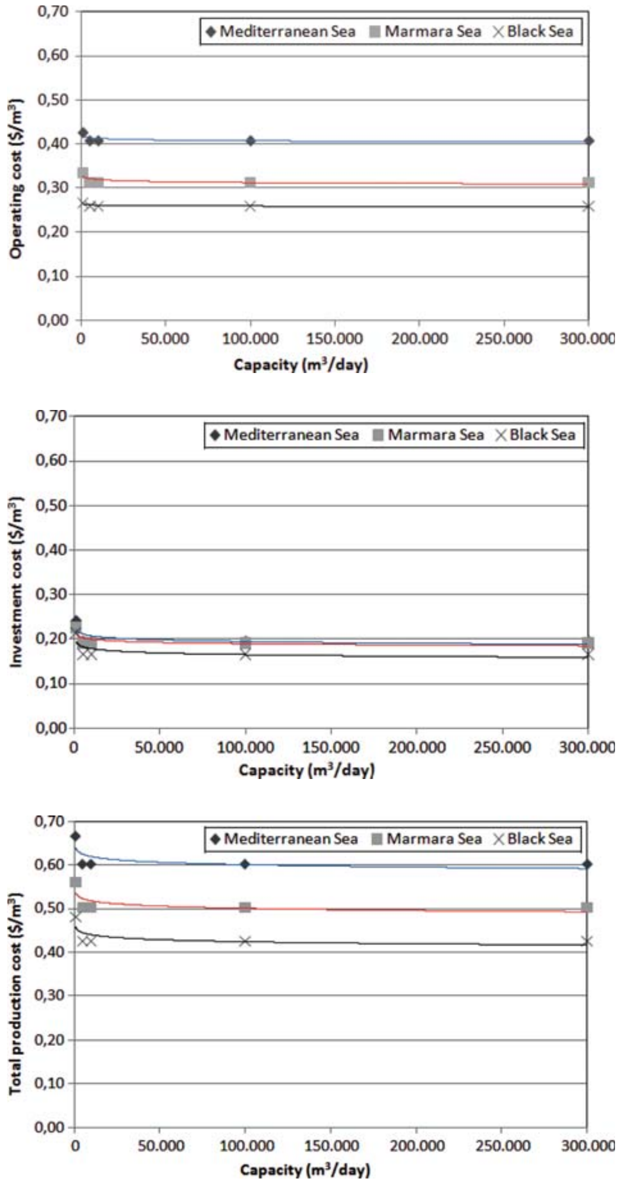

Fig. 6. Effect of different salinities on operating, investment and total production costs of drinking water production from seawater by reverse osmosis at constant flux of 15.6 l/m^2/h.

15.6 L/m^2/h at the capacity of 300,000 m^3/d and the maximum production cost was 0.685 \$/m^3 for the flux value of 11.7 L/m^2/h at the capacity of 1000 m^3/d. The difference between maximum and minimum costs was about 35%. The reason for a high treatment cost at a flux value of 11.7 L/m^2/h was due to the higher investment costs obtained at this flux.

The comparison of the cost analysis for different seawaters (Mediterranean Sea, the Marmara Sea and the Black Sea) at a constant flux of 15.6 L/m^2/h was provided in Fig. 6. The operating cost, investment cost and total production cost increased with increasing salinity. The highest cost was obtained for the Mediterranean Sea and unit costs decreased with increasing capacity. The total production cost for the Mediterranean Sea were 18% and 38% higher than the total production cost for the Marmara Sea and the Black Sea, respectively. The applied pressure has a big effect on the operating costs as seen from Fig. 6.

3.4. Comparison of operating and investment costs for the treatment of different water sources

Operating cost includes energy, chemical, membrane replacement and cartridge costs. Distribution of

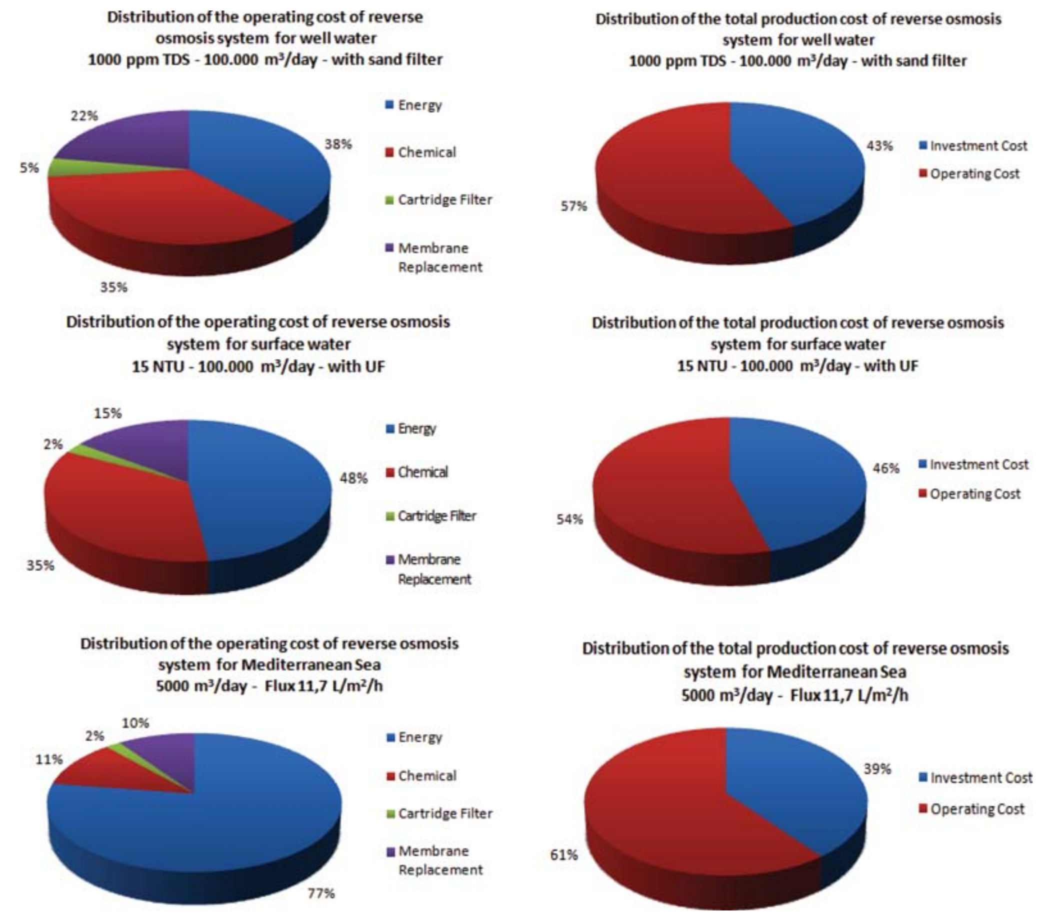

Fig. 7. Cost components of reverse osmosis system for different water sources.

operating and total production costs for the treatment of three different water sources were provided in Fig. 7. As shown in Fig. 7, energy comprised the largest ratio of the operation cost for each condition. Energy cost was followed by membrane replacement and cartridge filter. Membrane replacement and chemical costs were nearly the same for seawater treatment, whereas chemical costs were higher than membrane replacement and cartridge filter costs for brackish water treatment. The portion of energy cost increased for high salinity waters such as seawater and brackish water.

4. Conclusion

In this study, cost components of different membrane systems for obtaining drinking water from different water sources were evaluated. It was found that the minimum total production cost of reverse osmosis system for brackish water treatment was obtained at maximum capacities and minimum TDS concentration. Sand filtration decreased the unit costs as compared to ultrafiltration pretreatment. Additionally, total production costs increased almost 2.5–3 times if the capacity increased from 1000 m^3/d to 300,000 m^3/d. It was also determined that the operating costs of reverse osmosis system were nearly same with the nanofiltration system at all turbidity values for surface waters. The maximum total production cost of reverse osmosis system was obtained for Mediterranean Sea which has highest salinity values. The capacity of high pressure pumps was the limiting factor for all seawater treatment systems. Total production cost of reverse osmosis system for brackish water treatment with the minimum TDS concentration (1000 ppm) was 5.5 times lower than for desalination of Mediterranean Sea. Besides, energy cost constituted the largest part of the operation cost for each condition. The portion of energy cost increased with increasing feed salinities.

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