Performance evaluation of a medium-scale industrial reverse osmosis brackish water desalination plant with different brands of membranes. A simulation study

Alanood A. Alsarayreh [1], Mudhar A. Al-Obaidi [2], Shekhah K. Farag [1], Raj Patel [1], and Iqbal M. Mujtaba [1,*]

[1] Department of Chemical Engineering, Faculty of Engineering and Informatics. University of Bradford. Bradford, West Yorkshire, BD7 1DP, UK
[2] Middle Technical University, Technical Institute of Baquba, Dayala – Iraq
***Corresponding author, Tel.: +44 0 1274 233645**
E-mail address: I.M.Mujtaba@bradford.ac.uk

Abstract

Brackish water can be considered an important source of fresh water, via desalination, especially for arid districts. Reverse Osmosis (RO) process has been successfully used to produce fresh water from brackish water sources. However, there is still the challenge of improving the performance of multistage RO desalination plants. From the selection of the RO configurations to the selection of the appropriate type of membranes and the operating conditions at the end determines the performance of RO process in terms of recovery, salt rejection, energy consumptions and ultimately the cost of production of freshwater. Using model-based simulation, this work attempts to investigate the most suitable types of membranes for an industrial scale RO plant from a set of different membrane brands that would attain the highest-performance at lowest specific energy consumption (SEC). As a case study, we considered a multistage multi-pass medium-scale RO plant (1200 m³/day) of Arab Potash Company (APC, Jordan) which produces high quality water for the boilers after pre-treatment stage. The simulation results confirmed that employment of the Filmtec BW30LE-440 would increase water recovery by about 22% besides reducing the product salinity and SEC by about 15% and 10 %, respectively compared to the existing membrane.

Keywords: Brackish water desalination; Reverse osmosis; Membrane brand; Water recovery and salinity; Specific energy consumption (SEC).

1. Introduction

The Reverse Osmosis (RO) process was first used in the 1950's and counted about 80% of the total desalination plant used worldwide [1]. RO has been designed to desalinate seawater and brackish water using an asymmetric cellulose acetate membrane, although many other functional materials have recently been suggested [2]. Membrane processes are considered to be more successful water desalination techniques compared to thermal ones. This is due to producing high-quality water at competitive low capital and operating costs [3,4]. This also explains the popularity of membrane desalination plants around the world and especially in the Gulf countries that suffer from the lack of freshwater resources [5,6]. RO membranes are non-porous and semi-permeable and therefore exclude many particles of low-molecular weight such as salt ions and organic pollutants [7,8]. Moreover, the low- specific energy consumption (SEC) is a major advantage of RO technology due to the absence of an evaporation step [9]. However, low productivity (compared to thermal desalination processes), concentration polarisation, and fouling are demonstrated as the main drawbacks of RO processes [10,4]. For instance, the concentration polarisation phenomena causes solute buildup on the membrane surface and thus blocking the pores. Moreover, the membrane scaling is another concern of the RO membrane. This leads to a decrease in the filtration performance with time as it retards water permeation [3]. On top of this, the membrane fouling causes gel-layer formation and solute adhesion at the membrane surface which requires periodic cleaning or replacing of the membranes [11,12,13]. Therefore, several researchers strived to improve the performance of RO process by developing efficient and effective water desalination at low concentration polarisation and fouling propensities. Moreover, purified water standards issued by health organizations became more stringent, which forced scientists to continually improve the design of water desalination plants [8]. The enhancement of RO systems has been made in several aspects including membrane synthesis, structure, material and configurations of RO systems to obtain higher productivity and improved quality of freshwater besides attaining low-SEC and freshwater production cost at low fouling propensity. Therefore, several researchers focused on synthesizing new brands of membranes of high durability by using different polymers and liquids, polymeric structure, surface chemistry, bulk texture, morphology, and spacer's design [14,15,16]. A wide variety of membranes were therefore developed with variable morphology, surface chemistry and production techniques. RO membranes are basically made from either cellulose acetate or polysulfone coated with aromatic polyamides [8]. In this aspect, the manufactured membranes were sorted out based on the type of liquid to be treated, i.e., seawater, brackish water, and wastewater [17,18]. Recently, many polyamide RO membranes have been intensively used due to their high selectivity and good durability [19,20,21]. On the other hand, the adaptation of an enhanced configuration of RO process and optimisation of membrane modules have mainly contributed to reduce the SEC [22,23,24]. Due to the aforementioned advancements, the RO process has become more economical, adaptable and environmental friendly. This has made it a more attractive water desalination technology compared to the intensive-energy thermal technologies [8].

Although, the SEC has greatly improved from as much as 20 kWh/m^3 to nearly 2 kWh/m^3 at 50% recovery of seawater desalination [25], the interest of lowering the wasted energy due to the existence of intensive energy units such as pumps, is one of the most projected aims of recent research. This is due to a positive relationship between SEC and freshwater production cost; lower SEC means lowering freshwater production cost [26]. Several successful studies can be found in the literature that provided a reliable RO system based on water desalination at low SEC.

Fethi [27] upgraded the performance of brackish water at the Kerkennah Islands desalination plant by replacing the cellulosic acetate membranes with polyamide membranes stuffed in spiral wound modules. Improved productivity of freshwater at a high efficiency was obtained. The new brand of polyamide membrane required only 15 atm of pressure to generate the same production rate as that of acetate membranes operating at 29 atm. Therefore, a substantial energy saving of about 46% was obtained when using polyamide membranes compared to the original ones.

Pearce and Kumar [5] utilised two new generation of brackish water RO membranes; ESPA 4 (Hydranautics, Inc, Oceanside, CA) and 4040 BL (Saehan Industries, South Korea) and their performances were compared against the old membranes of ESPA 2. The new membranes were more efficient due to improved rejection and water flux at the same operating pressure. The SEC was sufficiently reduced besides a substantial reduction in production cost.

Stover [28] succeeded to reduce the SEC of a large-scale desalination plant located in Singapore. They tested the Toray 8-inch TM820C of TFC spiral wound RO membrane and showed that the permeate flux, the salt rejection and the SEC were improved by 1.8%, 0.15%, and 1.7%, respectively.

The performance indicators of two large-scale seawater desalination plants with two different membrane types of SWC4+ 8-inch (Hydranautics) located in Spain and SW30HRLE 8-inch (DOW FILMTEC™) located in Australia were compared by Laine [29]. The results showed that the permeate flux, salt rejection and SEC of Hydranautics were 24.6 m^3/day, 99.7-99.8 %, and 4.17 KWh/m^3, respectively. However, 28 m^3/day, 99.6-99.75 %, and 3.40 KWh/m^3 were recorded when using the DOW FILMTEC™ membrane. The DOW FILMTEC™ membrane thus reduces the SEC by 18.5%.

Al-Obaidi et al. [30] assessed the possibility of lowering SEC of two configurations of RO systems (with and without energy recovery device, ERD) through altering the membrane dimensions. They tested the influence of membrane length, width, and feed channel height on the SEC for the elimination of chlorophenol from wastewater. Their results showed up to 60% and 54% energy savings for the two configurations with and without ERD, respectively.

This research intends to improve the performance of multistage multi-pass RO system of the Arab Potash Company (APC) located in Jordan. The plan is to test several brands of spiral-wound commercial membranes in the original RO plant and evaluating the performance indicators including water recovery, solute rejection, freshwater concentration and most importantly the SEC. The type of membrane currently used in the plant is TMG20D-400, Toray Membrane USA Inc. The performance results of the new membranes will be compared against the actual membrane used in the RO system.

To gain fair results, the simulation based the new membranes will be carried out at fixed and same operating conditions of RO plant of APC including the brackish water salinity, flow rate and temperature using gPROMS suite software. The characteristic of the tested membranes will be collected from literature. In other words, this research will explore the appropriate membrane type that could be used in the RO system of APC to attain the upgraded performance at the lowest SEC.

2. Description of BWRO desalination plant of APC

The brackish water RO desalination plant of the Arab Potash Company was designed with a capacity of 1200 m^3/h of potable water of around 2 ppm salinity. It supplies this water into a polishing unit and then pumps it to be used in the boilers as distilled water. The brackish water is collected from wells of 1100 ppm salinity and pumped directly into the RO system. Table 1 presents the composition analysis of the feed water. Fig. 1 is a schematic diagram of the multistage multi pass RO system of APC, which consists of 20 pressure vessels that are designed to hold 120 membranes (Type: TMG20D-400, Toray Membrane USA Inc.) with each pressure vessel holding 6 membranes connected in series. The membranes are distributed over two passes with parallel stages in arrangements of 4:2 and 2:1:1 for the first and second pass, respectively. The first pass is characterised by retentate reprocessing of brackish water in two stages connected in series as shown in Fig. 1. The second pass reprocesses the product stream (permeate) of the first pass in three stages connected in series. The brackish water treatment is started by feeding the water into the first pass using high pressure pumps. The retentate of the second pass is blended with the feed stream to form the feed stream of the first pass. Fig. 1 also shows the disposing of retentate stream (high salinity) of the 1st into the sea. Simultaneously, the permeate of the first pass is treated in the second pass after elevating its pressure to the original plant pressure using centrifugal pumps. The two streams of the last stage of the second pass constitute the product stream (collected in a product tank) and retentate stream that is recycled back to the first pass and combines with the feed stream. The design of RO system of two passes enables the production of very low salinity water that sufficiently fits the requirements of industry.

Table 1. Feed water composition analysis

Conductivity µs/cm	pH	Turbidity (NTU)	Alkalinity (HCO_3^-) (ppm)	Na^+ (ppm)	Cl^- (ppm)	SiO_2 (ppm)	Total hardness (ppm)	TDS (ppm)
1983.06	7.59	1	61	144.71	346.26	23.6	1367.17	1098.62

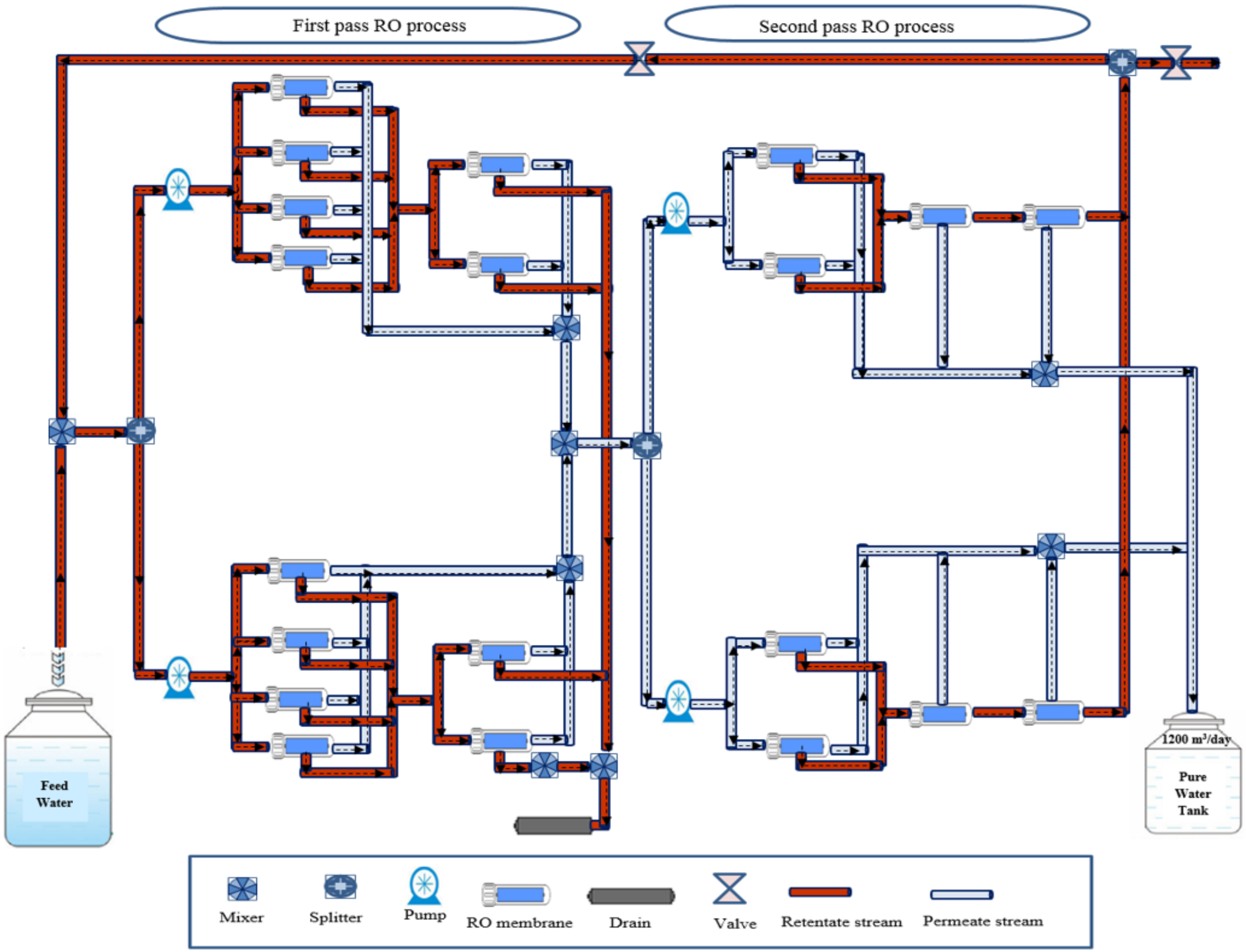


Fig. 1. Layout of BWRO desalination plant of APC (Adapted from Al-Obaidi et al. [31])

3. Modelling and simulation of RO system of APC

Al-Obaidi et al. [31] developed a comprehensive steady state model to characterise the performance of multistage multi pass RO process of APC. The model developed was used to specify the variation of concentration, pressure and flowrate profiles throughout the stages, pressure vessels and membranes. However, the temperature was assumed constant (isothermal process). This in turn aided to study and analyse the fluctuation of performance indicators such as solute rejection, water recovery, and product salinity against the expected change of inlet parameters as fully described by Al-Obaidi et al. [31]. The full details of model equations are given in Table A.1 of Appendix. A. The complete model has been coded and solved within the gPROMS software suite. To quantify the robustness of the model developed, the model predictions were compared against the actual data of RO system (collected from the plant) and the results confirmed a high consistency [31]. After attaining this, a comprehensive simulation study was carried out based on the model developed to test the process behavior against the inlet parameters' variations. In this regard, the simulation used the characteristics of the membrane (type Toray Membrane USA Inc, TMG20D-400, spiral wound) and the water and solute transport parameters provided in Table 2 and the actual inlet parameters of the RO system given in Table 3 as the base case. Thus, the simulation results at any variable feed flowrate, pressure, salinity, and temperature could predict the behaviors of solute rejection, water recovery, product salinity, retentate salinity [31] and SEC [32] and highlighted the best operating conditions of the process. The sensitivity analysis confirms that both operating pressure and feed flow rate have the most positive contributions on the product salinity. Moreover, the simulation results regarding the SEC show that decreasing the operating pressure and feed flow rate and increasing temperature are important to mitigate the SEC of the RO system.

Table 2. Characteristics of the membrane used in the RO system of APC and transport parameters

Membrane brand		**Transport parameters at 25 °C**	
Parameter	Value	Parameter	Value
Membrane supplier	Toray Membrane USA Inc.	Water $A_{w\,(T_o)}$(m/atm s)	9.6203x10^{-7}
Membrane type and configuration	TMG20D-400, Ultra low pressure BWRO, spiral wound, polyamide thin-film Composite	Solute $B_{s(T_o)}$	1.61277x10^{-7}
Dimensions		**Characteristics of spacer**	
Parameter	Value	Parameter	Value
Membrane area A (m²)	37.2	Spacer type	NALTEX-129
Membrane length L (m)	1	length of filament in the spacer mesh L_f (m)	2.77x10^{-3}
Membrane width W (m)	37.2	Feed and permeate spacer thickness t_f, t_p (m)	8.6x10^{-4} (34 mils), 5.5x10^{-4}
Limits of operating conditions		$A^{'}$ (dimensionless)	7.38
Max. feed pressure (atm)	40.464	n (dimensionless)	0.34
Max. pressure drop per membrane (atm)	0.987	ε (dimensionless)	0.9058
Max. feed temperature (°C)	45	k_{dc} (-)	1.501
Max. feed flowrate (m^3/h)	18		

Table 3. Input operating conditions of RO system of APC

Parameter	Operating feed flowrate (m³/h)	Operating temperature (°C)	Operating pressure (atm)	Inter-pass pump pressure (atm)	Salinity of brackish water (ppm)
Value	74	25	9.22	9.22	1098.62

4. Evaluation of different membrane brands on the performance of RO system of APC

Here, the evaluation of applying different brands of spiral wound membrane on the performance of RO system of APC is carried out with comparison against the simulation results of the original membrane. To fairly assess this change, a set of operating conditions of the RO system was used as shown in Table 3. The proposal here, is that different spiral wound membranes will have differing water and solute transport parameters that directly influence the water and solute fluxes via the membrane's pores and therefore controlling the performance indicators of the process including solute rejection, water recovery, product and retentate salinities, product and retentate capacities and more importantly the SEC. Consequently, this study would specify the best brand of membrane that integrates both performance metrics and lowest SEC. The specifications of each proposed membrane are collected from different articles found in the open literature. However, membrane costs are difficult to obtain and is beyond the scope of this research. Therefore, this research will not focus on the total freshwater production cost of the proposed design using different brands of membranes.

4.1 Results and discussion

The simulation results of employing different brands of membranes on the first and second passes of the RO system are shown in Table 4. In this regard, the simulation results of the original membrane type (base case) are also listed in Table 4 for comparison purposes. It can be seen that the Filmtec BW30LE-440 membrane shows the most promising results of the main performance indicators including the total water recovery and the SEC. Overall, this membrane also can remove salts from brackish water at very plausible product concentration.

Table 4. Simulation results of different brands of spiral wound membrane in the RO system of APC with characterizing the performance indicators

No.	Membrane Types	Water permeability constant, Aw (m/atm s)	Salt permeability constant, Bs (m/s)	Rej_plant (%)	Rec_plant (%)	Cp_plant (ppm)	Qp_plant (m^3/h)	Specific energy consumption, SEC (KWh/m^3)	Reference
1	Toray Membrane TMG20D-400	9.6203×10^{-7}	1.6127×10^{-7}	99.798	56.442	1.9879	48.133	0.8401	Al-Obaidi et al. [31]
2	SW30XLE-400	3.5463×10^{-7}	3.2×10^{-8}	99.964	25.379	0.3823	19.612	1.4107	Du et al. [14], Lu et al. [33]
3	SW30HR-380	2.7357×10^{-7}	3.2×10^{-8}	99.945	19.924	0.5788	15.237	1.6967	
4	SW30HR-320	3.141×10^{-7}	2.2×10^{-8}	99.979	22.725	0.2209	17.460	1.5344	
5	BW30-400	7.599×10^{-7}	6.2×10^{-8}	99.963	20.514	0.2806	15.453	1.4126	
6	Filmtec8I" SWC3	5.07×10^{-7}	5.6×10^{-9}	98.891	31.833	0.0508	15.762	1.9767	Avlonitis et al. [34]
7	FilmTec spiral wound from DOW	3.434×10^{-7}	5.65×10^{-8}	99.882	24.537	1.2509	18.955	1.4435	Du et al. [14], Sassi and Mujtaba [35]
8	4" ROGA 4160-HRa	2.112×10^{-7}	1.444×10^{-7}	98.499	15.258	16.271	11.629	2.0687	Boudinar et al. [36]
9	FT 30 SW 2.5" FilmTec	4.391×10^{-7}	3.506×10^{-8}	99.966	20.730	0.2694	15.460	1.4239	Avlonitis et al. [37,38]
10	ROGA-4000	1.985×10^{-7}	2.3×10^{-7}	96.406	14.222	39.169	10.846	2.1696	Marriott and Sørensen [39]
11	FilmTec SW30HR-380	2.360×10^{-7}	2.21×10^{-8}	99.968	17.349	0.3473	13.200	1.8966	Geraldes et al. [40]
12	Spiral wound Qatar SWRO plant	7.092×10^{-5}	1×10^{-5}	99.872	13.788	1.3158	15.179	1.0425	Majali et al. [41]
13	FILMTEC SW30HR-380	3.039×10^{-7}	1.7×10^{-8}	99.987	22.058	0.1333	16.922	1.5706	Kaghazchi et al. [42]
14	Filmtec, SW30-4040	9.058×10^{-8}	2.11×10^{-8}	99.824	6.803	1.9171	5.089	4.2494	Dimitriou et al. [43]
15	SW30-HR380	2.533×10^{-7}	2.5×10^{-8}	99.963	18.548	0.4002	14.144	1.7969	Vince et al. [44]
16	**Filmtec BW30LE-440**	$\mathbf{1.215 \times 10^{-6}}$	$\mathbf{15 \times 10^{-8}}$	**99.829**	**68.998**	**1.6896**	**58.836**	**0.7593**	
17	TORAY SU 820	1.136×10^{-6}	2.264×10^{-7}	99.651	63.041	3.4136	54.931	0.7943	Djebedjian et al. [45]
18	Filmtec8"RE 8040SN	5.88×10^{-7}	1.7×10^{-8}	98.919	28.567	0.0774	15.685	1.8197	Avlonitis et al. [34]
19	Filmtec8I"SW30HR380	4.56×10^{-7}	6.8×10^{-9}	98.823	31.101	0.0556	15.745	1.9419	

Table 4. Simulation results of different brands of spiral wound membrane in the RO system of APC with characterizing the performance indicators

Membrane Types	Kw (m/atm s)	Ks (m/s)	Plant rejection (%)	Plant Recovery (%)	Water quality (ppm)	Freshwater production (m^3/h)	SEC (KWh/m^3)
Toray Membrane TMG20D-400	$9.6203x10^{-7}$	$1.6127x10^{-7}$	99.798	56.442	1.9879	48.133	0.8401
SW30XLE-400	$3.5463\ x10^{-7}$	$3.2x10^{-8}$	99.964	25.379	0.3823	19.612	1.4107
SW30HR-380	$2.7357\ x10^{-7}$	$3.2x10^{-8}$	99.945	19.924	0.5788	15.237	1.6967
SW30HR-320	$3.141\ x10^{-7}$	$2.2x10^{-8}$	99.979	22.725	0.2209	17.460	1.5344
BW30-400	$7.599\ x10^{-7}$	$6.2x10^{-8}$	99.963	20.514	0.2806	15.453	1.4126
Filmtec8I" SWC3	5.07×10^{-7}	$5.6\ x\ 10^{-9}$	98.891	31.833	0.0508	15.762	1.9767
FilmTec spiral wound from DOW	$3.434\ x10^{-7}$	5.65×10^{-8}	99.882	24.537	1.2509	18.955	1.4435
4” ROGA 4160-HRa	$2.112\ x10^{-7}$	1.444×10^{-7}	98.499	15.258	16.271	11.629	2.0687
FT 30 SW 2.5” FilmTec	$4.391\ x10^{-7}$	$3.506\ \times10^{-8}$	99.966	20.730	0.2694	15.460	1.4239
ROGA-4000	$1.985x10^{-7}$	$2.3\ \times10^{-7}$	96.406	14.222	39.169	10.846	2.1696
FilmTec SW30HR-380	$2.360\ \times10^{-7}$	$2.21\ \times10^{-8}$	99.968	17.349	0.3473	13.200	1.8966
Spiral wound Qatar SWRO plant	$7.092\ \times10^{-5}$	$1\ \times10^{-5}$	99.872	13.788	1.3158	15.179	1.0425
FILMTEC SW30HR-380	$3.039\ \times10^{-7}$	1.7×10^{-8}	99.987	22.058	0.1333	16.922	1.5706
Filmtec, SW30-4040	$9.058\ \times10^{-8}$	$2.11\times\ 10^{-8}$	99.824	6.803	1.9171	5.089	4.2494
SW30-HR380	$2.533\ \times10^{-7}$	$2.5\times\ 10^{-8}$	99.963	18.548	0.4002	14.144	1.7969
Filmtec BW30LE-440	$\mathbf{1.215\ \times10^{-6}}$	$\mathbf{15\times\ 10^{-8}}$	**99.829**	**68.998**	**1.6896**	**58.836**	**0.7593**
TORAY SU 820	$1.136\ \times10^{-6}$	$2.264\ x\ 10^{-7}$	99.651	63.041	3.4136	54.931	0.7943
Filmtec8"RE 8040SN	5.88×10^{-7}	$1.7\ x\ 10^{-8}$	98.919	28.567	0.0774	15.685	1.8197
Filmtec8I"SW30HR380	4.56×10^{-7}	$6.8\ x\ 10^{-9}$	98.823	31.101	0.0556	15.745	1.9419

To systematically drive the discussion and analyse the results of Table 4, the authors decided to formalise the results in separate figures that would show the influence of using different membrane brands on each individual performance indicator with a thorough discussion. Fig. 2 shows the variation of total plant rejection for the different membranes. The simulation results of Table 4 indicate that almost all the membrane brands have succeeded to give high values of rejections except 4" ROGA 4160-HRa and ROGA-4000 (no. 8 and 10, respectively) (Fig.2). In this regard, the brackish water membrane, Filmtec BW30LE-440, shows the most improvement of solute rejection. The Filmtec BW30LE-440 membrane (line 16 in Table 4 and Fig. 2) shows very promising solute rejection of 99.83% that exceeds the rejection of base case membrane (Toray TMG20D-400) which rejects solutes with efficiency of 99.8%. Therefore, the deployment of this membrane brand will positively influence the rejection parameter of the RO system of APC. However, the optimum solute rejection can be achieved using the seawater membrane FILMTEC SW30HR-380 (lines 13 in Table 4 and Fig. 2) that results in an efficiency of 99.987%.

The growth of solute rejection of these membranes is attributed to their high values of water permeability coefficient compared to the base case membrane. For instance, the water permeability coefficient of Filmtec BW30LE-440 is 1.215 $\times 10^{-6}$ (m/atm s) compared to the Toray Membrane TMG20D-400 (base case) of 9.6203 $\times 10^{-7}$ (m/atm s). Increasing the water permeability coefficient means an increased propensity of water permeation through the membrane pores that would definitely reduce the salt concentration in the permeate channel and result in high rejection. It is also important to note that the solute transport parameter is related to solute flux through the membrane pores and therefore affects the solute rejection. For instance, the FILMTEC SW30HR-380 membrane obtains the optimum rejection due to its solute transport parameter of 1.7×10^{-8} (m/s), which is less than that of the Filmtec BW30LE-440 membrane of 15×10^{-8} (m/s). Moreover, the membrane ROGA-4000 has the lowest solute rejection due to its low water transport parameter of 1.985x10^{-7} (m/s atm) and high solute transport parameter of 2.3 $\times 10^{-7}$ (m/s) that triggers the propensity of solute passage. However, the membrane brand Spiral wound Qatar SWRO has the highest solute transport parameter and gained high solute rejection due to its 7.092 $\times 10^{-5}$ (m/s atm) water transport parameter that represents the highest value of the membranes.

From an engineering view, it can be said that the solute rejection of any membrane is affected by the combination of both water and solute transport parameters. Furthermore, the solute rejection is predominantly reliant on the membrane pore size, structure and their intensity that would directly control the solute passage through the membrane pores. However, this study has not covered the membrane texture and pore design (beyond scope of this research) and therefore the results are interpreted based on the characteristics of water and solute transport parameters.

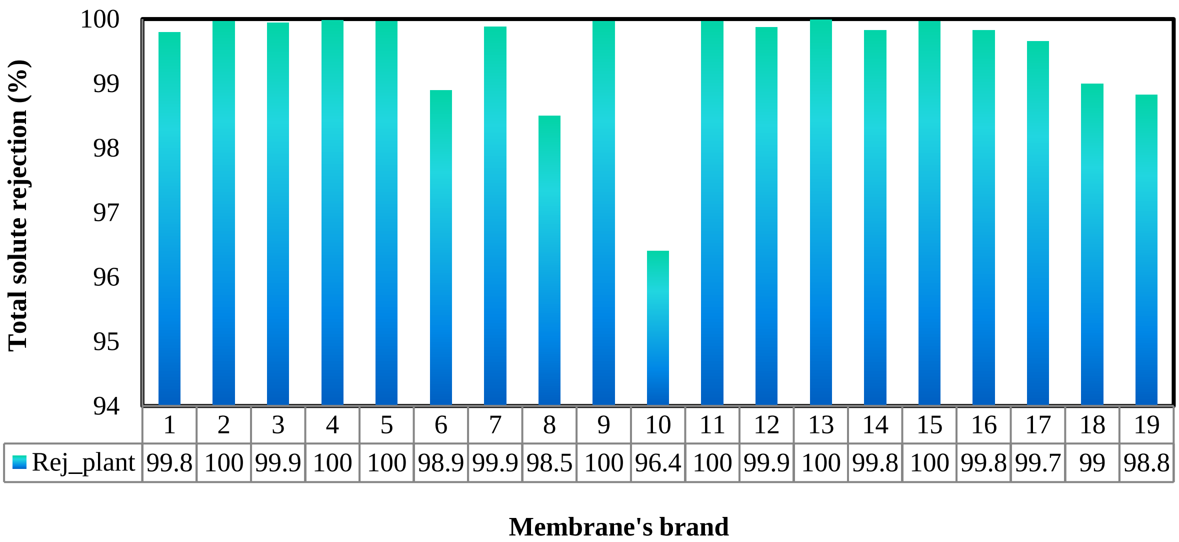
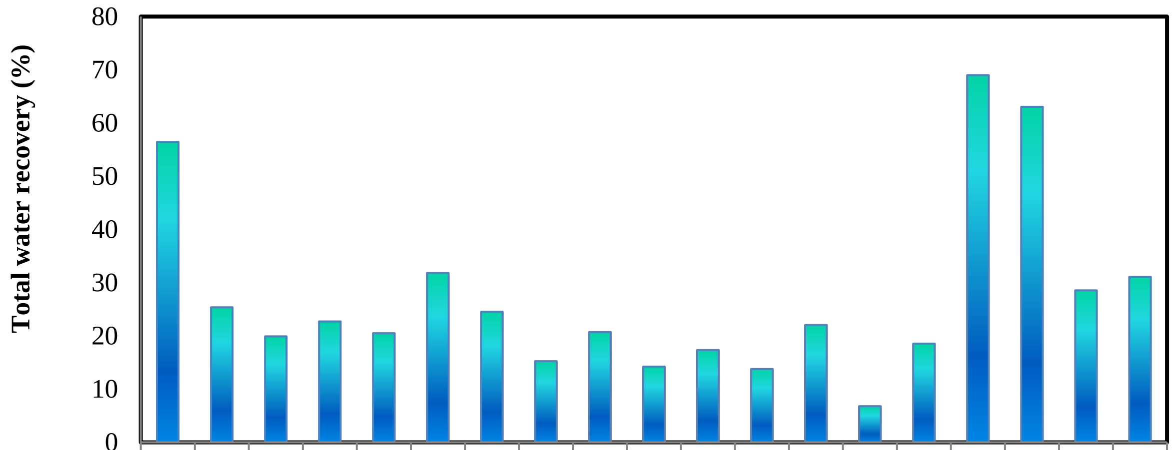


Fig. 2. Impact of membrane brands on total solute rejection of RO system

Fig. 3 and Table 4 show the total water recovery of the RO system for different brands of spiral wound membrane. In terms of water recovery, the results in Fig. 3 show that the best brand of membrane is Filmtec BW30LE-440 which has an optimal water recovery of 68.998 % followed by the TORAY SU 820 membrane (no. 17 in Table 4) achieved a recovery of 63.041%. Statistically, the improvement of water recovery made by the Filmtec BW30LE-440 membrane is larger than the water recovery of base case (56.442%) by around 22.2%. Again, the water flux is progressively increased with the Filmtec BW30LE-440 membrane due to its high-water transport parameter compared to the original membrane brand.

Fig. 3 confirms a considerable variation of water recovery for the tested membrane brands compared to the results of solute rejection (Fig. 2). This in turn explains the importance of water flux through the membrane and associated water recovery of the RO system.

It is important to note that the simulation of the different membrane brands was carried out at the same operating conditions. Therefore, the trend of water recovery results would similarly reflect the results of total water productivity as illustrated in Fig. 4. In this regard, the maximum and minimum productivities obtained with the Filmtec BW30LE-440 and the Filmtec, SW30-4040 were 58.84 m^3/hr, and 5.09 m^3/hr, respectively. Furthermore, the productivity of the original membrane brand used in the RO of APC plant is 48.13 m^3/h whereas the Filmtec BW30LE-440 membrane shows a productivity of 58.84 m^3/hr i.e. an improvement in productivity of 22.2%.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Rec_plant	56.4	25.4	19.9	22.7	20.5	31.8	24.5	15.3	20.7	14.2	17.3	13.8	22.1	6.8	18.5	69	63	28.6	31.1

Fig. 3. Impact of membrane brands on total water recovery of RO system

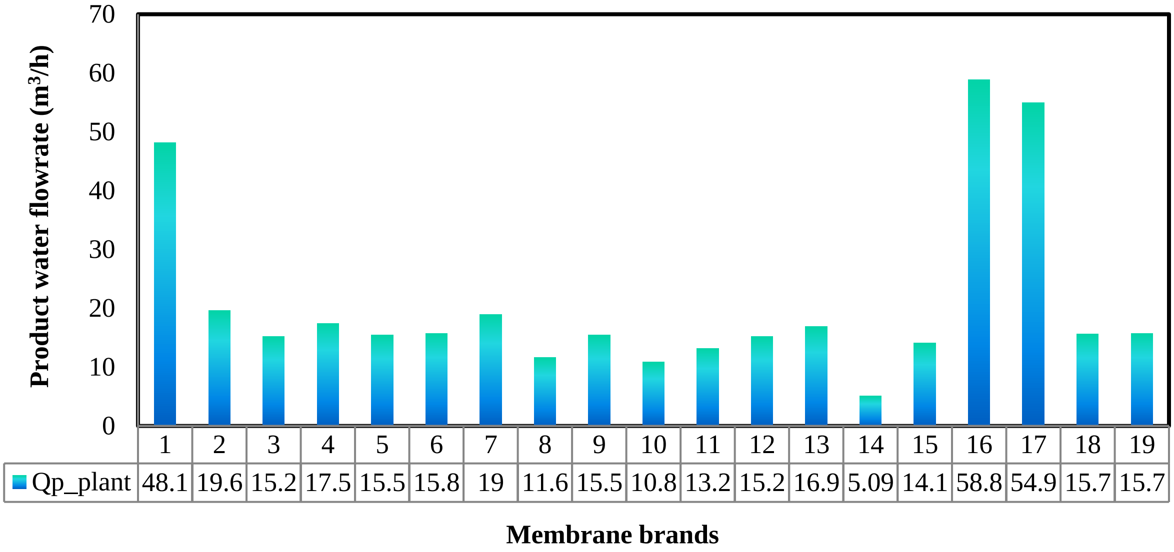


Fig. 4. Impact of membrane brands on total product flow rate of RO system

The product salinity is a paramount indicator of the performance of a RO process. Based on the results shown in Fig. 2, the product salinity varies with the membrane brand as demonstrated in Fig. 5. The data shows that the Filmtec BW30LE-440 membrane can generate product water with the lowest salinity compared to the original base case membrane brand. Statistically, the improved membrane brand attains high quality water of around 1.69 ppm, compared to 1.98 ppm of the original membrane brand. The improvement percentage of product salinity of 15% beyond the base case membrane is ascribed to an improved water flux of the new membrane that retards the product salinity. Interestingly, the result of product salinity comes with the tendency of reducing the product salinity that fits the required of distilled water to be used in the boilers. The Filmtec8I"SW30HR380 and 4" ROGA 4160-HRa membranes have constituted the best and worse product salinities of around 0.05 ppm and 16.27 ppm, respectively, compared to other membrane brands. These results are derived due to the solute transport parameters that hit the maximum and minimum values of Filmtec8I"SW30HR380 and 4" ROGA 4160-HRa, respectively.

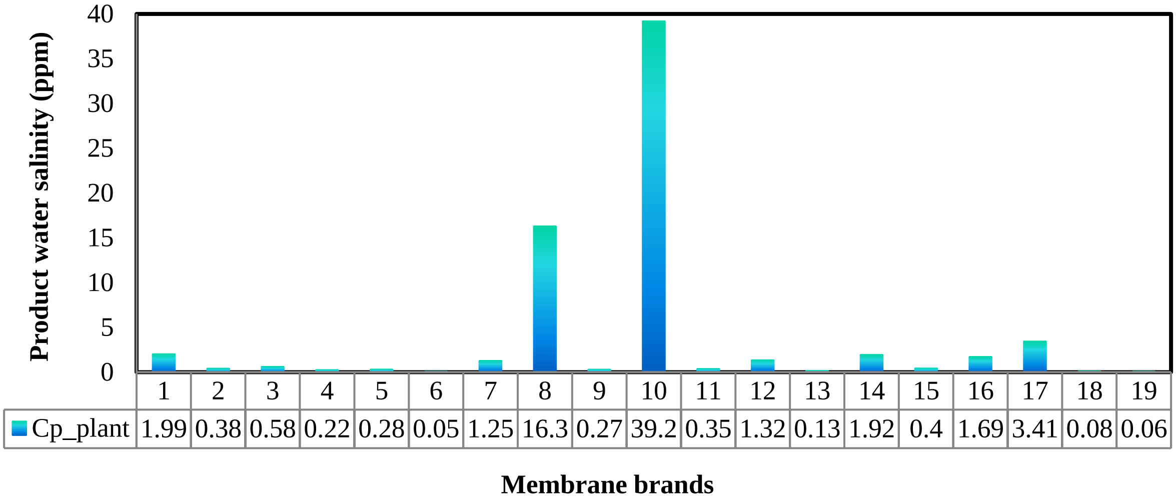


Fig. 5. Impact of membrane brands on product salinity of RO system

One of the most important performance indicators of any industrial process is the SEC, which needs to be limited as much as possible since it relates the total production cost and gases emissions. Fig. 6 shows the SEC profile of different membrane brands deployed in the RO system of APC.

It is clear from Table 4 and Fig. 6 that the Filmtec BW30LE-440 is the optimum membrane that can perform efficient filtration at the lowest SEC of 0.759 kWh/m^3 compared to the original membrane's (Toray Membrane TMG20D-400) consumption of 0.840 kWh/m^3. This new membrane would reduce the SEC by 9.62%. This is due to the improvement of water flux that reduces the SEC as represented in Eq. 25 in Table A.1 of Appendix A. Ettouney et al. [46] confirmed the relationship between the feed salinity and total energy requirements of the RO system. The lower the water salinity, the higher the product purity, which permits the operation to be carried out at a lower specific power level. Furthermore, the Filmtec, SW30-4040 membrane is the worst one due to attaining the highest SEC of more than 4 kWh/m^3.

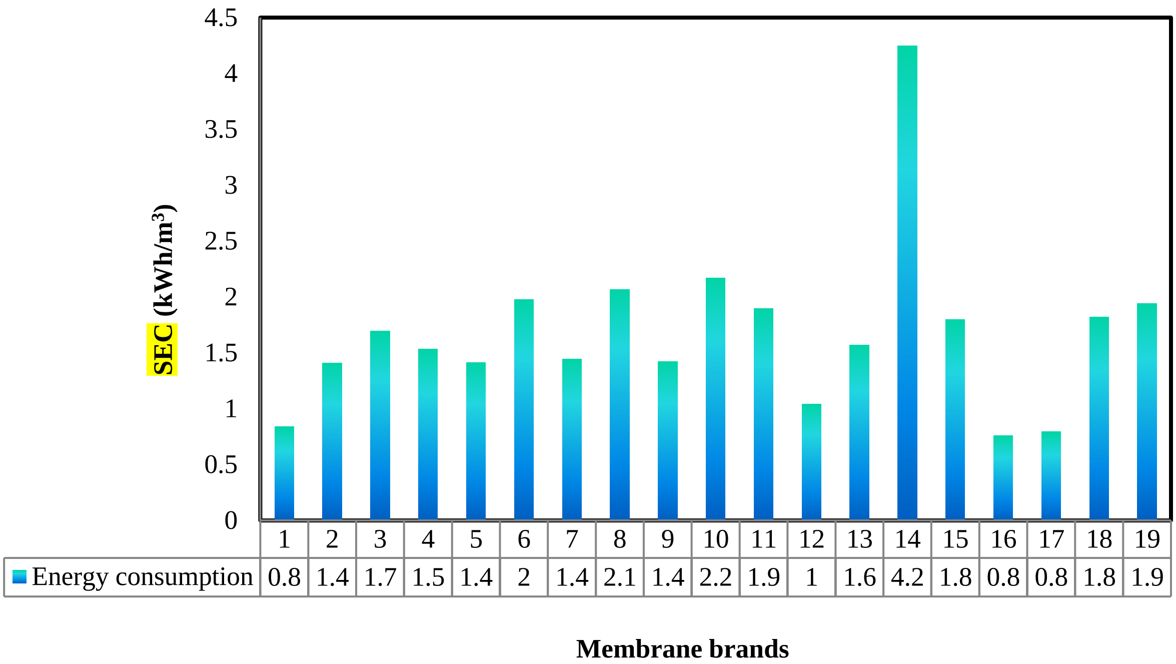


Fig. 6. Impact of membrane brands on the SEC of RO system

Overall, using membranes with high-water permeability parameter and low solute transport parameter would improve the treatment efficiency since there is a clear proportional relationship between these parameters and the performance metrics of RO system [47,48]. Based on the results shown in Table 4 and Figs. 2 – 6, it can be seen that installing the Filmtec BW30LE-440 membrane in the RO system of APC provides an improved operational performance compared with the existing membrane. The improvements of the total plant water recovery, the total product flowrate and the energy saving at plausible product salinity are highlighted in this research. However, the analysis of the performance indicators (presented in Table 4) with the proposed membrane (Filmtec BW30LE-440), need to be carried out to explore the levels of SEC at variable input parameters of the process including feed pressure, salinity, flowrate, and temperature.

Also, the Filmtec BW30LE-440 membrane has been characterised by several promising advantages [34] that can support the results of this research as follows.

- High salt rejection and freshwater productivity.

- Sufficient to be instilled in the RO systems that work under low pressure to produce fresh water from brackish water resources. This membrane has been designed to produce the desired productivity with a significant saving of energy and low number of pumps.
- Adequate in managing high feed flowrate with a maximum limit of 18 m^3/h.
- Large effective surface membrane area that would enhance the water productivity.
- Provides excellent structural stability.
- Fouling resistant.

5. Conclusions

This research has focused on testing different membranes from various suppliers on the multistage, multi pass medium-scale RO system of Arab Potash Company (APC) to determine which membrane gives the best performance. Specifically, the performance indicators of solute rejection, water recovery, productivity, product salinity and SEC were used to compare the efficiency of these membranes and compared to the original one. The tested membranes were characterised by different values of water and solute transport parameters. Among the nineteen membranes looked at, Filmtec BW30LE-440 has shown the best performance indicators with the highest energy saving. In this regard, the Filmtec BW30LE-440 membrane shows an improvement of 22.246% in water recovery, 15% in product salinity and 9.62% in the SEC compared to the original membrane. Therefore, it is recommended as the best choice to be used in the RO system of APC.

Acknowledgements

We acknowledge the support provided by the Arab Potash Company.

Appendix A

Table A.1. Mathematical model of spiral wound RO system of APC [32]

No.	Model equations	Specifications
1	Total water flux (m^3/s)	$Q_p = A_{w(T)}\, NDP_{fb}\, A_m$
2	Water permeability constant (m/s atm)	$A_{w(T)} = A_{w(25\,C)}\, TCF_p\, F_f$
3	Temperature correction factor of permeate (Toray Membrane USA Inc.) [49]	$TCF_p = \exp[0.0343\,(T-25)] < 25\,°C$ $TCF_p = \exp[0.0307\,(T-25)] > 25\,°C$
4	The driving pressure (atm)	$NDP_{fb} = P_{fb} - P_p - \pi_b + \pi_p$
5	Feed brine pressure (atm)	$P_{fb} = P_f - \frac{\Delta P_{drop,E}}{2}$
6	Pressure drop along the membrane element (atm)	$\Delta P_{drop,E} = \frac{9.8692x10^{-6}\, A^{*} \rho_b\, {U_b}^2\, L}{2 d_h\, Re_b^n}$
7	Bulk flow rate (m^3/s)	$Q_b = \frac{Q_f + Q_r}{2}$
8	Bulk and permeate osmotic pressures (Toray Membrane USA Inc.) [49]	$\pi_b = 0.7994\, C_b\, [1 + 0.003\,(T-25)]$ $\pi_p = 0.7994\, C_p\, [1 + 0.003\,(T-25)]$
9	Bulk salinity (kg/m^3)	$C_b = \frac{C_f + C_r}{2}$
10	Solute flux through the membrane (kg/m^2 s)	$Q_s = B_{s(T)}(C_w - C_p)$
11	Solute transport parameter (m/s)	$B_{s(T)} = B_{s(25\,C)}\, TCF_s$
12	Temperature correction factor of solute (Toray Membrane USA Inc.) [49]	$TCF_s = 1 + 0.05\,(T-25) < 25\,°C$ $TCF_s = 1 + 0.08\,(T-25) > 25\,°C$
13	Solute concentration at the membrane surface (kg/m^3)	$C_w = C_p + \left(\frac{C_f + C_r}{2} - C_p\right) exp\left(\frac{Q_p/A_m}{k}\right)$
14	Mass transfer coefficient (dimensionless) (Da Costa et al. [50])	$k = 0.664\, k_{dc}\, Re_b^{0.5}\, Sc^{0.33} \left(\frac{D_b}{d_h}\right)\left(\frac{2d_h}{L_f}\right)^{0.5}$
15	Schmidt number (dimensionless)	$Sc = \frac{\mu_b}{\rho_b\, D_b}$
16	Reynolds number (dimensionless)	$\mathrm{Re} = \frac{\rho\, d_e\, U_b}{\mu}$
17	Total water recovery (dimensionless)	$Rec = \frac{Q_p}{Q_f} = \frac{(C_r - C_f)}{(C_r - C_p)}$
18	Solute flux	$Q_s = \frac{Q_p\, C_p}{A_m}$
19	Real solute rejection (dimensionless)	$Rej_{real} = \frac{Q_p\,(1-Rej)}{A_m\, B_{s(T)}}\; Rej_{real} = \frac{C_w - C_p}{C_w}$
20	Observed solute rejection (dimensionless)	$Rej = \frac{C_f - C_p}{C_f}$
21	Water flux (m/s)	$J_w = \frac{B_{s(T)}\, Rej_{real}}{(1 - Rej)}$
22	Solute rejection by assuming that Rej equals Rej_{real}	$Rej = \left(1 + \frac{B_{s(T)}}{J_w}\right)^{-1}$
23	Average permeate salinity at the permeate channel	$C_p = \frac{C_f}{Rec}\,[1 - (1 - Rec)]^{(1-Rej)}$
24	Average retentate salinity at the permeate channel	$C_r = C_f\,[1 - Rec]^{-Rej}$
25	Specific energy consumption of the plant	$EC = \frac{Pf_{(in)(plant)}\, Qf_{(plant)}}{Qp_{(plant)}\, \varepsilon_{punp}}$

References

[1] Anis, S. F., Hashaikeh, R. and Hilal, N. (2019) Functional materials in desalination: A review. *Desalination* 468, 114077.

[2] Al-Obaidi M., Kara-Zaitri C., Mujtaba I., 2020. Wastewater Treatment by Reverse Osmosis Process. State of the Art and Process Modelling. Boca Raton: CRC Press, https://doi.org/10.1201/9781003019343

[3] Goosen, M., Sablani, S., Al-Hinai, H., Al-Obeidani, S., Al-Belushi, R. and Jackson, a. (2005) Fouling of reverse osmosis and ultrafiltration membranes: a critical review. *Separation science and technology* 39 (10), 2261-2297.

[4] Qasim, M., Badrelzaman, M., Darwish, N. N., Darwish, N. A. and Hilal, N. (2019) Reverse osmosis desalination: A state-of-the-art review. *Desalination* 459, 59-104.

[5] Pearce, W. and Kumar, M. (2003) Evaluation of new generation brackish water reverse osmosis membranes. *Proc of Membrane Technology Conference, American Water Works Association.*

[6] Droogers, P., Immerzeel, W., Terink, W., Hoogeveen, J., Bierkens, M., Van Beek, L. and Debele, B. (2012) Water resources trends in Middle East and North Africa towards 2050. *Hydrology and Earth System Sciences* 16, 3101-3114.

[7] Fujioka, T., Ishida, K. P., Shintani, T. and Kodamatani, H. (2018) High rejection reverse osmosis membrane for removal of N-nitrosamines and their precursors. *Water research* 131, 45-51.

[8] Sagle, A. and Freeman, B. (2004) Fundamentals of membranes for water treatment. *The future of desalination in Texas* 2 (363), 137.

[9] Van der Bruggen, B. and Vandecasteele, C. (2002) Distillation vs. membrane filtration: overview of process evolutions in seawater desalination. *Desalination* 143 (3), 207-218.

[10] Yang, X., Wang, R., Fane, A. G., Tang, C. Y. and Wenten, I. (2013) Membrane module design and dynamic shear-induced techniques to enhance liquid separation by hollow fiber modules: a review. *Desalination and Water Treatment* 51 (16-18), 3604-3627.

[11] Pandey, S. R. (2014) *Evaluation of pre-treatments for minimizing membrane fouling in water recovery*. Deakin University.

[12] Ruiz-García, A. and Nuez, I., 2020. Long-term intermittent operation of a full-scale BWRO desalination plant. *Desalination*, 489, p.114526.

[13] Ruiz-García, A. and Nuez, I., 2016. Long-term performance decline in a brackish water reverse osmosis desalination plant. Predictive model for the water permeability coefficient. *Desalination*, 397, pp.101-107.

[14] Du, Y., Xie, L., Wang, Y., Xu, Y. and Wang, S. (2012) Optimization of reverse osmosis networks with spiral-wound modules. *Industrial & engineering chemistry research* 51 (36), 11764-11777.

[15] Yan, W., Shi, M., Wang, Z., Zhou, Y., Liu, L., Zhao, S., Ji, Y., Wang, J. and Gao, C. (2019) Amino-modified hollow mesoporous silica nanospheres-incorporated reverse osmosis membrane with high performance. *Journal of Membrane Science* 581, 168-177.

[16] Ruiz-García, A. and de la Nuez Pestana, I. (2019) Feed Spacer Geometries and Permeability Coefficients. Effect on the Performance in BWRO Spriral-Wound Membrane Modules. *Water* 11 (1), 152.

[17] Osada, Y. and Nakagawa, T. (1992) *Membrane science and technology*. CRC Press.

[18] Khawaji, A. D., Kutubkhanah, I. K. and Wie, J.-M. (2008) Advances in seawater desalination technologies. *Desalination* 221 (1-3), 47-69.

[19] Taniguchi, M. and Kimura, S. (2000) Estimation of transport parameters of RO membranes for seawater desalination. *AIChE journal* 46 (10), 1967-1973.

[20] Goh, P.S., Zulhairun, A.K., Ismail, A.F. and Hilal, N., 2019. Contemporary antibiofouling modifications of reverse osmosis desalination membrane: A review. Desalination, 468, 114072.

[21] Anis, S.F., Hashaikeh, R. and Hilal, N., 2019. Functional materials in desalination: A review. Desalination, 468, p.114077.

[22] Saif, Y., Elkamel, A. and Pritzker, M. (2008) Optimal design of reverse-osmosis networks for wastewater treatment. *Chemical Engineering and Processing: Process Intensification* 47 (12), 2163-2174.

[23] Bartman, A. R., Zhu, A., Christofides, P. D. and Cohen, Y. (2010) Minimizing energy consumption in reverse osmosis membrane desalination using optimization-based control. *Journal of Process Control* 20 (10), 1261-1269.

[24] Ruiz-García, A. and de la Nuez-Pestana, I., 2018. A computational tool for designing BWRO systems with spiral wound modules. Desalination, 426, pp.69-77.

[25] Elimelech, M. and Phillip, W. A. (2011) The future of seawater desalination: energy, technology, and the environment. *science* 333 (6043), 712-717.

[26] Mazlan, N. M., Peshev, D. and Livingston, A. G. (2016) Energy consumption for desalination—A comparison of forward osmosis with reverse osmosis, and the potential for perfect membranes. *Desalination* 377, 138-151.

[27] Fethi, K. (2003) Optimization of energy consumption in the 3300 m3/d RO Kerkennah plant. *Desalination* 157 (1-3), 145-149.

[28] Stover, R. (2008) Low energy consumption SWRO. *submitted to Proceedings of Clean Technology*.

[29] Laine, J. (2009) Design & Operation Considerations: Two Large-Scale Case Studies, in. *Suez Environment*.

[30] Al-Obaidi, M.A., Kara-Zaitri, C. and Mujtaba, I.M., 2018. Significant energy savings by optimising membrane design in the multi-stage reverse osmosis wastewater treatment process. Environmental Science: Water Research and Technology, 4(3), 449-460.

[31] Al-Obaidi, M. A., Alsarayreh, A. A., Al-Hroub, A. M., Alsadaie, S. and Mujtaba, I. M. (2018) Performance analysis of a medium-sized industrial reverse osmosis brackish water desalination plant. *Desalination* 443, 272-284.

[32] Alsarayreh, A. A., Al-Obaidi, M. A., Al-Hroub, A. M., Patel, R. and Mujtaba, I. M. (2020) Performance evaluation of reverse osmosis brackish water desalination plant with different recycled ratios of retentate. *Computers and Chemical Engineering* 135, 106729.

[33] Lu, Y.-Y., Hu, Y.-D., Zhang, X.-L., Wu, L.-Y. and Liu, Q.-Z. (2007) Optimum design of reverse osmosis system under different feed concentration and product specification. *Journal of membrane science* 287 (2), 219-229.

[34] Avlonitis, S., Pappas, M. and Moutesidis, K. (2007) A unified model for the detailed investigation of membrane modules and RO plants performance. *Desalination* 203 (1-3), 218-228.

[35] Sassi, K. M. and Mujtaba, I. M. (2011) Optimal design and operation of reverse osmosis desalination process with membrane fouling. *Chemical engineering journal* 171 (2), 582-593.

[36] Boudinar, M. B., Hanbury, W. and Avlonitis, S. (1992) Numerical simulation and optimisation of spiral-wound modules. *Desalination* 86 (3), 273-290.

[37] Avlonitis, S., Hanbury, W. and Boudinar, M. B. (1991) Spiral wound modules performance. An analytical solution, part I. *Desalination* 81 (1-3), 191-208.

[38] Avlonitis, S., Hanbury, W. and Boudinar, M. B. (1993) Spiral wound modules performance an analytical solution: Part II. *Desalination* 89 (3), 227-246.

[39] Marriott, J. and Sørensen, E. (2003) A general approach to modelling membrane modules. *Chemical engineering science* 58 (22), 4975-4990.

[40] Geraldes, V., Pereira, N. E. and Norberta de Pinho, M. (2005) Simulation and optimization of medium-sized seawater reverse osmosis processes with spiral-wound modules. *Industrial & engineering chemistry research* 44 (6), 1897-1905.

[41] Majali, F., Ettouney, H., Abdel-Jabbar, N. and Qiblawey, H. (2008) Design and operating characteristics of pilot scale reverse osmosis plants. *Desalination* 222 (1-3), 441-450.

[42] Kaghazchi, T., Mehri, M., Ravanchi, M. T. and Kargari, A. (2010) A mathematical modeling of two industrial seawater desalination plants in the Persian Gulf region. *Desalination* 252 (1-3), 135-142.

[43] Dimitriou, E., Boutikos, P., Mohamed, E. S., Koziel, S. and Papadakis, G. (2017) Theoretical performance prediction of a reverse osmosis desalination membrane element under variable operating conditions. *Desalination* 419, 70-78.

[44] Vince, F., Marechal, F., Aoustin, E. and Bréant, P. (2008) Multi-objective optimization of RO desalination plants. *Desalination* 222 (1-3), 96-118.

[45] Djebedjian, B., Gad, H., Khaled, I. and Rayan, M. A. (2008) Optimization of reverse osmosis desalination system using genetic algorithms technique. *Twelfth International Water Technology Conference, IWTC12, Alexandria, Egypt.*

[46] Ettouney, H. M., El-Dessouky, H. T., Faibish, R. S. and Gowin, P. J. (2002) Evaluating the economics of desalination. *Chemical Engineering Progress* 98 (12), 32-39.

[47] Semiat, R. (2008) Energy issues in desalination processes. *Environmental science and technology* 42(22), 8193-8201.

[48] Karabelas, A.J., Koutsou, C.P., Kostoglou, M. and Sioutopoulos, D.C. (2018) Analysis of specific energy consumption in reverse osmosis desalination processes. *Desalination* 431, 15-21.

[49] Toray Membrane USA Inc., m. t. s. O., Maintenance and Handling Manual, 2015. *http://www.toraywater.com/* Accessed 10/3/2018.

[50] Da Costa, A., Fane, A. and Wiley, D. (1994) Spacer characterization and pressure drop modelling in spacer-filled channels for ultrafiltration. *Journal of membrane science* 87 (1-2), 79-98.