

Energy and Retentate Reuses in Reverse Osmosis Alone and in Hybrid Processes for Sea Water Remediation

DELIA TERESA SPONZA, RUKIYE ÖZTEKİN*

Department of Environmental Engineering,
Dokuz Eylül University,
Tınaztepe Campus, 35160 Buca/Izmir,
TURKEY

**Corresponding Author*

Abstract: - The membranes are very important treatment way for seawater desalination due to low energy and costs. In this study; the effects of increasing retentates fluxes (6.0, 14.0, 19.0 and 23.0 l/m².h), temperatures (25oC, 35oC and 45oC) and transmembrane pressures (8.0 bar, 14.0 bar, 22.0 bar and 27.0 bar) on the removal efficiencies of the alone and sequential hybrid reverse osmosis (RO) operations was investigated for salt and retentate recoveries from the sequential reactor system. The energy reuse yields were provided by taken into consideration the hybrid reverse osmosis process. In the RO alone and in hybrid RO processes elevated rejection yields (99.80% and 99.99%) was detected, respectively. In both treatment processes, the specific energy utilization was compared. For maximum Br-1, SO₄-2, NO₃-1, PO₄—3 rejections (99.95%) the energy was minimized in the hybrid reverse osmosis proses. This process exhibited lower energy consumption. Retentate recycling from the hybrid sequential reverse osmosis to the inlet/feed of RO alone minimize the specific energy use. The steady-state operational conditions to minimize the energy amount were a water flux of 19.1 l/m².h, a transmembrane pressure of 7.6 bar and a temperature of 32oC.

Key-Words: - Br-1, SO₄-2, NO₃-1, PO₄—3 Reuse, Energy, Hybrid reverse osmosis, Membrane systems, Rejection, Retentate, Reverse osmosis (RO), Reverse osmosis alone, Salt, Sea water remediation.

Received: March 13, 2026. Revised: May 16, 2026. Accepted: September 3, 2026. Published: October 29, 2026.

1 Introduction

The treatment of phosphorus-based flame retardants (PFRs) can be performed by membrane process which is extensively used in the treatment of wastewater and in saline water and wastewaters. Membrane fouling problem and membrane changes increase the cost of treatment. Furthermore, the costs of RO consisting from electricity, labour, and operational spends, [1], [2], [3]. Energy utilization is an important point since directly affect the treated water expenses in RO. Energy should be re-used in the salt removing processes. In order to detect lowest specific energy is very important phenomenon during treatment since the brine, film deformation and high-pressure cause to increase of permeate charges, [1]. Since these costs, energy reuse solely with treatment of salts can be a good way to lowered the energy spends in the RO applications, [2]. Energy utilization is a main ratio of the total spends during water treatment. These spends relevant to permeate were elevated with sea water amelioration due to elevated pressures. In order to decrease the specific energy

utilization penetrable films were utilized due to small amount of salt was emitted, [4], [5]. This cause low spends of RO films. In order to lowered the energy in the sequential RO, the treatment plants should be operated by utilizing energy reuse apparatus. Recent jobs indicated that the sequential RO film desalination plants were energy saving treatments in the comparison of RO solely plants, [6], [7], [8]. Film treatment plants use elevated level electrical and mechanical fuels generated from the carbonated energy, [6]. With elevated costs of energy, it is important to decrease the aforementioned costs with economical the goals sometimes cannot reach to the required level. The reasons can be: to generate a small amount of treated water volume with minimum energy levels. The seawater should be pre-treated before sending to RO plants, [9]. The primarily steps should be the addition of some chemicals and then and the water should be passed from some films. High electricity spends and excessive flows in desalinated water are extremely high in the comparison to what is excellent in the RO. The

lowering of the reuse percentage is very important point affecting the electricity spends of the RO. The important elevation of energy and spends in the pre-treating the seawater can be provided by elevation of the reusing since film processes have low recovery percentages. This increases the spends in the membrane, [10].

In a study, in a film process the film was separated with a permeable membrane. The first column contains seawater and the second one contained freshwater respectively at 23°C. It is possible to send the clean water to the film process and treat the seawater since different vapor pressures can go throughout film. If some artificial force sent to the wastewater containing salts a reuse can be observed. Therefore, an osmotic flow is necessary, [11].

Special energy (SEC) can be explained by the force necessary for the flow of the treated water generated per unit flow of the salinized water. For the treated of a from a very large amount pollutant from the salinized water, the calculated minimal energy level is 0.70 kWh/m³ (2.57 kJ/kg) of clean water produced. This calculated value elevated to 0.83, 0.99 and 250 V.G, [12]. Energy reuse in RO can be obtained by operating in different conditions resulting in lower energy mode. The important RO operating parameters for maximum pollutant removals in RO process for ERDs can be given as follows: (i) Optimized by the inlet flowrate, reuse by a special turbine; (ii) operation by permeate flowing, recovery by Pelton turbine; (iii) Control by different operational conditions; (iv) Reuse by hydraulic charger (v); operation and reuse by a charger ; (vi); energy reusing by exchangers controlled by some pumps; (vii) energy reuse by operational properties at elevated inlet pump; (ix) energy reuse by work exchangers controlled by VFD at the booster pump; (x) energy reuse by exchangers controlled by high force feed flows; (xi) energy recovery with inlet pumps, [3], [13]. [7], discussed the specific pumps of a sequential RO/RO film containing a salination process, without an energy reuse device in a RO alone. They found that this process has a big electricity reusing property from 4% to 55% permeate clean water reuse. In the recent literature, the energy reuse in RO alone and in sequential RO processes was not performed and was not discussed, [14], [15].

Therefore, in this study in order to decrease the specific electricity utilization for a sequential RO/RO saline water treatment process; RO reactors were operated alone and sequential mode with and without specific energy device and energy yield were calculated. Furthermore, the water and concentrate

reusing's from the secondary RO to the primarily RO were evaluated.

2 Results and Discussions

2.1 RO Membrane Process Alone, No Specific Energy Consumption with no Electricity Reuse Device

In order to decrease the energy consumption in a reverse osmosis process in a single RO to reuse the salt an energy reuse apparatus (ERA) was not utilized (Figure 1). The specific electricity consumption, should be located to RO, and this process can be called as the energy is required to treat the salt from the permeate.

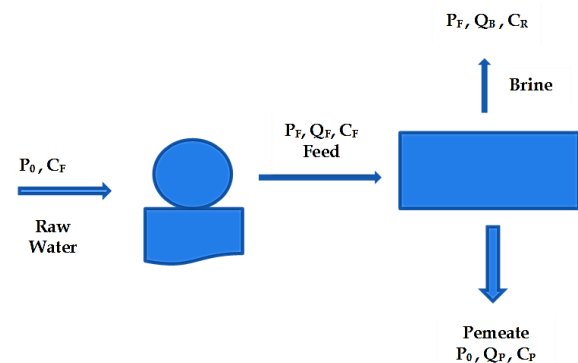


Fig. 1: The configuration of RO alone

Source: Authors' own work.

Specific electricity consumption for the desalination plant (Figure 1) is illustrated in Eq. (1):

$$ERA = \frac{W_{pump}}{n_p Q_p} \quad (1)$$

Where; n_p is the pump efficiency, Q_p is the brine and W is the velocity of pump, illustrated by Eq. (2):

$$v_{pump} = \Delta P \times Q_f \quad (2)$$

ΔP is the force of raw influent, given by Eq. (3):

$$\Delta P = P_f - P_0 \quad (3)$$

where; P_f and P_0 are the water forces at the influent of the film desk and raw inlet water at the source, respectively. The power decrease, along the film and affect slightly the minimum ERA, [4].

The total water reuse for the RO, Y_t , measures the process productivity and can be shown with Eq. (4) as:

$$Y_t = \frac{Q_p}{Q_f} \quad (4)$$

and by the mixing of Eq. (1), Eq. (2) and Eq. (4), the ERA can be defined with Eq. (5) as:

$$ERA = \frac{\Delta P}{n_p Y_t} \quad (5)$$

Here; the brine flow, Q_p , can be illustrated with reverse osmosis rate equation Eq. (6):

$$Q_p = A_m L_p (\Delta P_m - \sigma \Delta \pi) = A_m L_p (MTF) \quad (6)$$

where; A_m and L_p are the film longitudinal place and hydraulic conductivity, respectively, σ is the flow constant, and the mean membrane force is defined by $\Delta P_m = P_m - P_p$, here P_m and P_p are the inlet side and brine forces, respectively). Given the simplification of negligible force drop, it is reasonable to set $P_m = P_f$ and also set $P_p = P_0$.

The average osmotic force difference between the concentrate and the brine samples can be defined by $\Delta \pi$, and $MTF (= \Delta P_m - \sigma \Delta \pi)$ is the mean transmembrane conducting force. The osmotic forces at the inlet and outlet of the film are responsible from the brine rate, can be illustrated by Eq. (7) and Eq. (8):

$$\Delta \pi_{entrance} = \pi_f - \pi_p \quad (7)$$

$$\Delta \pi_{exit} = \pi_r - \pi_p \quad (8)$$

where; π_f , π_r , π_p are the osmotic forces of the inlet, brine and clean water flows, respectively. The approach is the osmotic force variation linearly with concentration, [16], in Eq. (9):

$$\pi_i = f_{os} C_i \quad (9)$$

where; f_{os} is the osmotic force constant, C_i is the salty flow dose, and where the subscript (i), illustrates the inlet (f), treated water (r), or brine (p) flows. By using Eq. (10) can be written;

$$\begin{aligned} (FLUX)_{opt} &= \frac{Q_p}{A_m} \\ &= L_p \left[\frac{R_t \pi_0}{1 - Y_t} - R_t \pi_0 \frac{\ln[1/(1 - Y_t)]}{Y_t} \right] \\ &= 8 \times 10^7 \text{ m}^3/\text{m}^2 \text{ s} \end{aligned} \quad (10)$$

where; $Y_{opt} = 0.6$ and $(\Delta P)_{opt} = 3 R_t \pi_0$. For the results, the mean salty water forces up to the necessary limit of clean water recovery, is associated by the mean during the film area, [17], by Eq. (11):

$$\Delta \pi = f_{os} C_f \frac{\ln[1/(1 - Y_t)]}{Y_t} \quad (11)$$

where; C_f is the inlet salt RO-pass film desalination for an alone film is first illustrated for

the relevant ultimate reuse, for alone and sequential utilization of electricity recovery apparatus (ERA).

2.2 Electricity Utilization in RO

The main ingredients in RO film reactors the energy consummation is illustrated in Figure 3. These: (1) inlet water intake; (2) pre-treatment; (3) elevated for inflates containing and containing electricity recovery; (4) film properties and device; (5) last removal; and (6) clean water effluent. The influent clean water and the limit of clean water an important result in the efficiency of a film. Sometimes the clean water should be sent to very far points. Under these conditions the electricity utilization can be attributed pre-treatment systems includes membrane systems. The films with elevated feed containing an index of 3.1 in membrane system cannot be osmosis with conventional treatment process, [18], [19], [20], [21]. Film processes for reverse osmosis process can be defined with microfilm or ultra filtration processes. Film pre-treatment procedures also decrease the costs of the reverse osmosis.

2.3 ERA Calculation for RO Alone with No Electricity Recovery

For discuss the ERA for an alone membrane to a sequential film process with two reactor desalination membrane, the ERA for an alone reactor can be recommended as a reuse process, alone reactor and an electricity recovery apparatus (ERA).

The characteristic electricity use apparatus for a Reverse osmosis alone desalination when an electricity recovery (Figure 1) was generated by using both the Eq. (1) and Eq. (11). In the Eq. (12):

$$ERA \geq \frac{\pi_0 R_t}{Y_t(1 - Y_t)n_p} \quad (12)$$

the ERA unit was the force unit.

It can be possible to put equivalent the ERA based on the target of hydrodynamic force based on the inlet water force like in Eq. (13):

$$ERA_{tr,norm} = \frac{SEC_{tr}}{(\pi_0)} = \frac{R_t}{n_p Y_t(1 - Y_t)} \quad (13)$$

In a system containing ERA the clean water recovery (i.e., Eq. 13) was illustrated in Figure 2 for a final salt recovery of 99% with a minimum $ERA_{tr,norm}$ elevated with lowering pump yield.

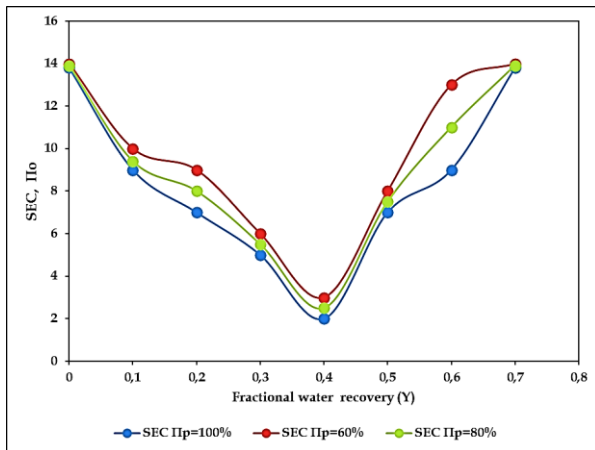


Fig. 2: Changes of the normalized SEC with a water recovery for a RO alone membrane reactor containing salt rejections

Source: Authors' own work.

2.4 Electricity Recovery and ERA Calculation for Sequential RO/RO Films

To decrease the electricity necessary for reverse osmosis / nanofiltration desalting, electricity can be obtained from the brine flow (Figure 3) by taken into consideration an electricity recovery flow, [22].

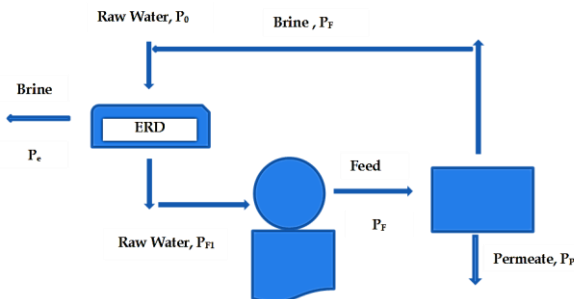


Fig. 3: RO/RO sequential system with energy recovery device

Source: Authors' own work.

The efficiency of the data given above carried out by a flow on the dirty water, in the presence of an electricity recycling apparatus (ERA), is illustrated via Eq. (14):

$$W_{pump} = \Delta P \times (Q_f - n_E Q_b) \quad (14)$$

where; Q_b is the concentrate flow, attributed to the treated water (Q_p) and clean water recycling (Eq. 4), and η_p and η_E are the efficiencies of the influent force and of the ERA, respectively. The particular electricity spends cost for reverse osmosis desalination, in the presence of an ERA, ($Y, \Delta P, \eta$), is given by Eq. (15):

$$\begin{aligned} ERA(Y, \Delta P, n_p, n_E) &= \frac{\Delta P (Q_f - n_g Q_b)}{Q_p n_p} \\ &= \frac{\Delta P [1 - n_g (1 - Y_t)]}{Y_t n_p} \end{aligned} \quad (15)$$

The steady-state ERA for this mode (Figure 3), $SEC_{tr, norm}^{ERD}$, at a clean liquid recovery taking into consideration, Y_t , and saline water recycling, R_t , at the inhibition of the chemokinetic limits in the existence of an ERA, is measured by using Eq. (15) by using Eq. (13) and Eq. (14) to detect the efficiency in Eq. (16):

$$SEC_{tr, norm}^{ERD} = \frac{[1 - n_E (1 - Y_t)] R_t}{n_p Y_t (1 - Y_t)} \quad (16)$$

The clean water recycling is not affected by force yield supplied from the yield is in not dependent of the water reuse and occurring in inlet force. The small ERA_{tr} , for a salt recycling, R_t , was measured by optimizing $\partial(ERA_{tr, norm})/\partial Y_t = 0$ from lower at $Y_t = 0.5$ (or 50% recovery) when $(ERA_{tr, norm})_{min}$ is equal to $4R_t/p$ (or $(ERA_{tr})_{min} = 4R_t \pi_0/p$). In order to design the minimal ERA, the desalination unite should be managed with a force around $2R_{t0}$ with a reuse of 50%. The operation lower 60% electricity in an elevated concentrate flow, and management more than 50% reuse results in quickly occurring of brine osmotic force and inlet force.

It is very important to show the consequences of the test given above by discussing the sample of a single-pass seawater reverse osmosis system generating clean water of 500 mg/l solids from a salty water influent of 67000 mg/l with a $\pi_0 = 2980$ bar force and a salt reuse of 98%, the lowest electricity consumption for the process given higher is $5R_t \pi_0 = 2.98 \text{ Wh/m}^2$. This exhibited the optimum concentrate flow, if it was discussed the raw reverse osmosis with a permeability of $L_p = 0.98 \times 10^{-12}$ Bar. The conditions for the aforementioned optimal state are measured with Eq. (10).

The mean electricity relevant to the influent, concentrate and clean water are constant for a reverse osmosis illustrated with A_m and L_p . The global minimum energy utilization is illustrated here for an alone reactor containing no electricity recycling apparatus.

2.5 Impact of ERD Yield on the ERD for Two Reverse Osmosis Plants

For a specific condition the ERDs have 99% yield, the utilization of energy reuse apparatus, the lowest electricity, for two reactor containing systems carried out when a rejection is zero in the primary

and secondary flows. In the condition $R_2 = 0$, the steady-state $SEC^{tr, ERD}$ was obtained under $R_1 = R_t$, $Y_1 = Y_t$, and under these conditions the management conditions for the second reactor are $R_2 = 0$, $Y_2 = 1$ measuring with Eqs from 1 to 16. The aforementioned result illustrates that the primary reactor with the limited clean liquid recycling and salty water desalination.

For this reason, the secondary reactor is not necessary and not be into consideration to the membranes. The SEC under steady state conditions (Figure 3), $SEC_{tr, norm}^{ERD}$, for a clean water reuse, Y_t , and salty water recovery, R_t , under limited thermo-hydro- dynamic inhibition in the presence of ERD, is taken from Eq. (10) by utilizing Eq. (14) and Eq. (15) to detect the efficiency in Eq. (16). The dependency of the ERD under steady state conditions (Eq. 16) on the clean water reuse and force and ERD efficiencies is illustrated in Figure 4.

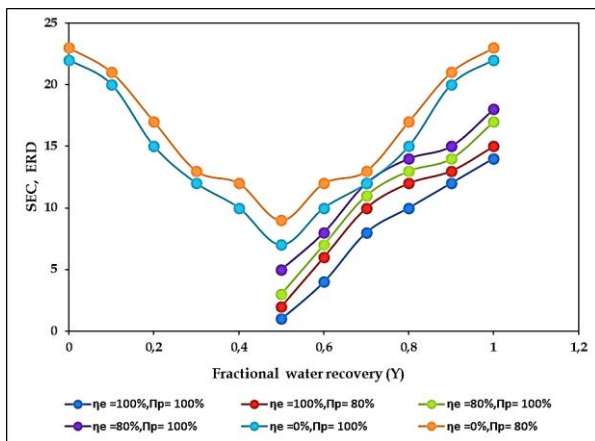


Fig. 4: Changes of the normalized SEC for a salt rejection of 99% with fractional water recovery using an ERD in RO alone (p and E represent the pump and ERD efficiencies, respectively)

Source: Authors' own work.

Critical total reuse, $Y_{ts}^{critical}$, at which the transmission carried out can be found by Eq. (17) and Eq. (18) to create the Eq. (19):

$$Y_{2,opt} = \frac{\sqrt{1-n_{erd}}}{1+\sqrt{1-n_{erd}}} \quad (17)$$

$$Y_{1-opt} = Y_t \quad (18)$$

$$Y_t^{critical} = \frac{\sqrt{1-arn_E}}{1+\sqrt{1-n_E}} \quad (19)$$

At Eq. (19), illustrated in Figure 5, shows that in the not electricity reuse conditions (i.e., $\eta_E = 0$) $Y_t^{critical}$ lowering of the reuse when a reactor was used alone under steady-state conditions as is

showed in Section 2.2 [i.e., $Y_t^{critical} = Y_{opt} = 0.5$, (Eq. 17 and Eq. 19)]. For an reactor under steady-state and very effective conditions, $ERD(\eta_E = 1)$ $Y_t^{critical} = 0$, exhibited that a reactor alone has enormous electricity efficiency than a 2 reactors. For $Y_t \geq Y_t^{critical}$, a reactor alone has extremely electricity than two reactor system, but for, $Y_t < Y_t^{critical}$, then 2 reactors having a lot electricity. This phenomenon can be occurred when the single-stage process is not managed at optimum reuse. Under these conditions the minimum SEC is detected.

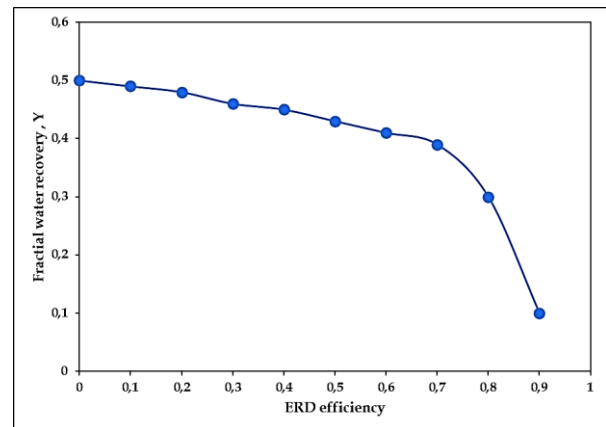


Fig. 5: The impact of ERD yield on the critical water recovery in RO membrane treating saline process

Source: Authors' own work.

2.6 RO Alone and Sequential Hybrid Reverse Osmosis/Reverse Osmosis Efficiencies

The RO alone film reactor was operated at elevating forces of 7.0, 13.0, 17.0 and 22.0 bar without heating. During operation, the permeate volume, reuse temperature, and managing time were measured. Table 1 shows the mean permeate flux and final retentate temperature.

Table 1. Impact of permeate flux, and pressure on the variation of final retentate temperature at RO

Assay no	Permeate flux (l/m ² .h)	retentates	
		Pressure (bar)	Final retentate temperature(°C)
1	4	5.0	21
2	12	10.0	23
3	20	15.0	32
4	17	20.0	28

Source: Authors' own work.

It was shown that as the force was elevated, the permeate flux also elevated. The high permeate flux was found at a pressure of 17.0 bar as 20 ml/m².h.

The lowest clean water up-flow was detected at 8.0 bar at a flux of 7 ml/m².h at a 20°C temperature. The last retentate temperature elevated with elevating of pressure. The maximum last retentate temperature was measured at a pressure of 17.0 bar at an elevated temperature of 36°C. The minimal final retentate temperature was detected at 5.0 bar pressure at 20°C.

With continuous management of RO; 1.99 litres of retentate and 2.90 litres of permeate were generated. The maximum volume decreasing percentage was measured as 2.53 and 2.680 unitless, after 75 and 190 mins, respectively. The volume lowering ratio was found to be elevated during continuous operation of RO based on the lowering of the brin volume (Figure 6).

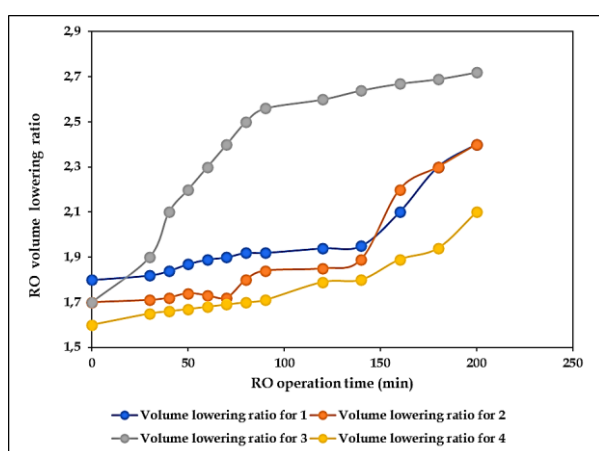


Fig. 6: The variation of volume lowering ratio during continuous operation of RO
Source: Authors' own work.

When the permeate flux lowered at low pressures and temperatures extended times were required to mention that the required volume decreasing rate increased. The permeate flux decrease can be minimizing when film fouling was detected. Especially at small detention times and at low osmotic pressures increased in the RO films. This cause to concentration polarization, [8]. At small and elevated pressures such as 7.0 and 29 bar the RO management duration extended to 200 min when the optimal pressure of 19.0 bar in the RO management time the duration lowered to 60 min (Figure 7).

In order to measure the fouling in the RO film whether cause decreasing of permeate flow, a fouling coefficient was detected. With this aim, the pure water flow was detected at 8.0, 14.0, 19.0 and 29.0 bar forces before and after each assay were occurred. Mean values of clogging shows that of all experiments at chosen forces were measured, and are illustrated in Figure 7. It was detected that the water flow was elevated at high forces. After the concentration process, the water flow was reduced in

the comparison to the water inlet before the concentration process at the same forcer. The water flow declined and this was pronounced as the fouling percentage (Table 2). The clogging percentage varied from 28.20% to 32.20%, and was insufficiently upper when elevated pressure was supplied to the RO.

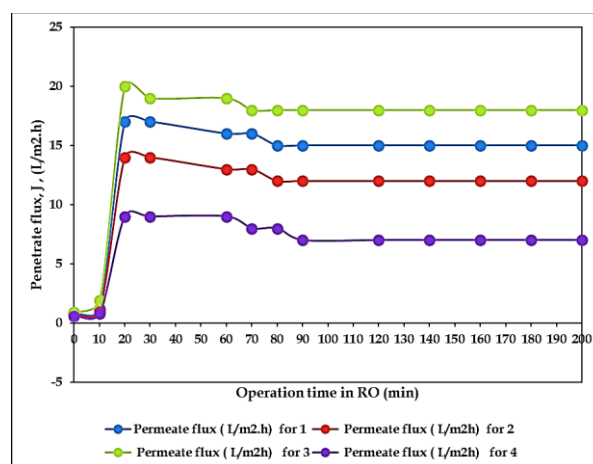


Fig. 7: The variation of Permeate fluxes versus time at different pressures
Source: Authors' own work.

In order to measure the fouling in the RO film whether cause decreasing of permeate flow, a fouling coefficient was detected. With this aim, the pure water flow was detected at 8.0, 14.0, 19.0 and 29.0 bar forces before and after each assay were occurred. Mean values of clogging shows that of all experiments at chosen forces were measured, and are illustrated in Figure 7. It was detected that the water flow was elevated at high forces. After the concentration process, the water flow was reduced in the comparison to the water inlet before the concentration process at the same forcer. The water flow declined and this was pronounced as the fouling percentage (Table 2). The clogging percentage varied from 28.20% to 32.20%, and was insufficiently upper when elevated pressure was supplied to the RO.

Table 2. The variation of fouling index versus applied pressure

Rejected ions	Rejection percentages (%)
Br ⁻¹	99.90
SO ₄ ⁻²	99.90
NO ₃ ⁻¹	99.90
PO ₄ ⁻³	99.90

Source: Authors' own work.

Very high ion recoveries were found as high as 99.99% (Table 3). To very ultimate reuses were

attained for Br^{-1} , SO_4^{-2} , NO_3^{-1} and PO_4^{-3} in RO (Table 3).

Table 3. Br-1, SO4-2, NO3-1, PO4—3 rejections in RO at a flux of 20 l/m².h and at a pressure of 15.0 bar

Pressure (bar)	Fouling index (%)
5.0	26.20
10.0	27.30
15.0	28.10
20.0	29.20

Source: Authors' own work.

Water flows for new flow and after brined in RO depending on elevated forces was illustrated in Figure 8.

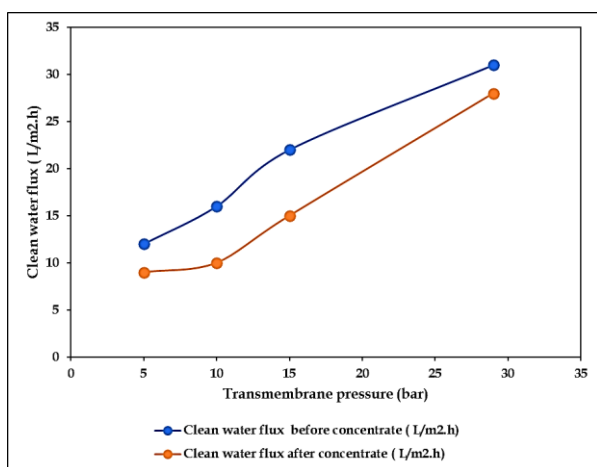


Fig. 8: Water fluxes before and after concentrated in RO versus increasing pressures

Source: Authors' own work.

2.7 Energy Consumption in RO

The inlet of the reverse osmosis after first removal is connected to an elevated force and clean water is emitted to the force in air. The concentrate is sending to an ERC to recovery the electricity relevant with the clean water produced from the last-treated to obtain the clean flow meeting the flow and is connected with water distributed flow, [23], [24], [25], [26]. As a result, the electricity requires in the whole reverse osmosis plant and can be defined with Equation 20, [27], in Eq. (20):

$$E_T = E_{in} + E_{pt} + E_{hp} + E_A - E_{ERD} \quad (20)$$

Here, E_T is the electricity consummation, E_{in} is the electricity consummation for the influent, E_{pt} is the electricity for alone and secondary reactors for clean water, E_{hp} is the electricity for elevated forces, E_A is the electricity for different apparatus and SEC is the electricity recycled by the SEC, [1], [28].

3 Case Study

In order to optimize of seawater desalination in a RO, the management conditions was illustrated in Table 4. The optimization of the film seawater desalting process is complex and necessary long duration since the relevant measures are required to detect the clean water reuse from the film system.

Table 4. Parameters for an RO seawater desalination process

Parameters	Symbol	Value	Unit
Membrane resistance	R_m	3.0×10^6	bar.s/m
Channel height	H	3.5×10^{-4}	m
Salt concentration	C_{salt}	34,500	mg/l
Osmotic pressure coefficient	f_{os}	73.9×10^{-5}	bar/(mg/l)
Feed cross flow velocity	u_0	0.1	m/s
Channel length	L	8	m
Osmotic pressure ($f_{os}C_0$)	$\Delta\pi_0$	25.9	bar
Characteristic pressure ($\frac{u_0 H R_m}{L}$)	ΔP^*	13.1	bar

Source: Authors' own work.

Efficiency of seawater desalting is attributed to the spends of clean water to form an volume of clean water. The spends of the clean water originated by reverse osmosis consist from 4 ingredientss: the initial treatment spends, the electricity spends, the film spends, and the spends for brine, [29], i.e., Eq. (21):

$$C = C_f + C_e + C_m + C_c \quad (21)$$

where, C is the special spends of clean water, C_f , C_e , C_m , and C_c are the ingredients of the special spends for the influent, electricity, film, and brine cleaning. These spends is for steady-state operation of the film at a certain duration. The properties of the film, such as clogging versus duration and suitable spends of film cleaning are not taken into consideration. Film clogging is under steady state conditions with the first reactor and the the film did not cause anomalies during time. However, the optimal conditions can be done timely when the constituents of the desalting apparatus are varied, like spends of film, electricity, and clogging.

For an film reactor to produce a clean water with the calculated reuse, R , the surface of the influent which is necessary for inlet removal it was sending to the reverse osmosis is $1/R$. Fort his reason, the

spends of influent, primary reactor cleaning and the electricity ingredients are exhibited with Eq. (22) and Eq. (23):

$$C_f = c_f \frac{1}{R} \quad (22)$$

and

$$C_e = c_e \Delta P \frac{1}{R} \quad (23)$$

Here, C_f is the first inlet spends per surface of first reactor, C_e is the spends of electricity and ΔP was the force in inlet which is sending to the film.

The properties of first reactor necessary spends equations. At the beginning, the specific spends of first reactor associates on the clogging level of inlet. High spends is required for first reactor with this spends elevated the clogging degree. Secondly, the electricity spends are associated to the some forces, which is associated with the salty water and heat of influent.

The amount of brine generated for clean water is $(1-R)/R$. Therefore, the spends for brine yield is Eq. (24):

$$C_c = c_c \frac{1-R}{R} \quad (24)$$

where, c_c is the cost for an unit of brine, consisting of the spends for brine removal. Determination of the film spends is more complex compared to other spends. The clean water upflow of the film is relevant to the recovery and can be defined by Eq. (25):

$$\bar{v} = \frac{u_0 H}{L} R \quad (25)$$

where, v is the mean clean water upflow, u_0 is the influent recycling, H is the pipe longitudinal, and L is the pipe wide. The film area necessitates to produce a area of clean water as is in Eq. (26):

$$S = \frac{1}{\bar{v} T} = \frac{L}{u_0 H R T} \quad (26)$$

Here, T is the duration of the clean water generated. As a result, the reactor spends can be defined with Eq. (27):

$$C_m = c_m S = c_m \frac{1}{T} \frac{L}{u_0 H R} = c'_m \frac{L}{u_0 H R} \quad (27)$$

where, c_m is the spends of film, and c'_m is the film spends during time, which is Eq. (28):

$$c'_m = c_m \frac{1}{T} \quad (28)$$

The film to be entirely utilized, the c'_m will be measured during reactor was operated. The force glasses should be taken into consideration in the first

reactor. Since the film and force glasses contained separate durations, the impact of force glasses in the reactor spends should be taken into consideration by suitable ratios.

Special spends of the first reactor and relevant spends is measured by Eq. (29):

$$c'_m = \frac{P_e}{T_e S_e} + \frac{P_v}{n T_v S_e} \quad (29)$$

where, p_e and T_e are the spends and time of a reactor, and p_v and T_v are the spends and duration of a force glass, respectively, S_e is the reactor surface in a film, and n is the total amounts of film ingredients in a force glasse.

By locating of Eq. (22), Eq. (23), Eq. (24), and Eq. (27) to Eq. (21), the special spends of clean water in an reverse osmosis desalting reactor was defined in Eq. (30):

$$C = c_f \frac{1}{R} + c_e \frac{\Delta P}{R} + c'_m \frac{L}{u_0 H R} + c_c \frac{1-R}{R} \quad (30)$$

In Eq. (30), the special spend constants of inlet water first reactor and brine can be measured. The film spends rates can be measured with Eq. (29) from the spends of film ingredients and force glasses. The inlet rate, the width and longitudinal of the film can be measured by the specialities of film and force glasses. For example, the pipe length is usually 500 cm for salt removal and the pipe height was measured inlet flow in the reactor. In order to measure the special spends in Eq. (30) is the reuse. The main point is to detect the reuse of the reactor and lowering of the special spends of the salty water. This is important step in the optimization of the problems to detect the main force for any designated reuse.

3.1 Main Forces

In order to detect an amount of clean water reuse of an reactor desalting, the force utilized with tree mistakes equations with a lot of force. For an assay force, the clean water was found for numerous points during pipe. Later, the reuse was found by mathematical equations of the clean water in the whole pipe. This reuse was investigated with limited reuse to control if they are close. This membrane should operated up to limited forces was obtained. The main method illustrated aforementioned is the main equation of the reactor.

The target reverse osmosis is a pipe containing the items given below:

- 1) A force pressure working during reactor operation,
- 2) A film for remove the salty ingredients, and

- 3) Continuously stirring of salt in the longitudinal way of the reactor. An mathematical matrix was found with the operations rrsponding to the dependent operational conditions of the reactor, [30], [31].

It was observed that the reactor utilized in the removal of the salty ingredients was defined by the target reverse osmosis, [31]. The matrix mentioned for target reverse osmosis was defined by Eq. (31):

$$R = \left(1 - \frac{\Delta\pi_0}{\Delta P}\right) \left[1 - e^{-\frac{\Delta P}{\Delta\pi_0} \left(\frac{\Delta P}{\Delta P^*} - R\right)}\right] \quad (31)$$

where, $\Delta\pi_0$ is the osmosis force of influent, ΔP is the main force, and ΔP^* is the special force of the film pipe, which is an important item and can be characterized as Eq. (32):

$$\Delta P^* = \frac{u_0 H R_m}{L} \quad (32)$$

where, R_m is the film resistance. The osmotic force is linearly relevant to salt dose and can be defined by Eq. (33):

$$\Delta\pi_0 = f_{os} C_{salt} \quad (33)$$

where, C_{salt} is the salty water dose in the first reactor, and f_{os} is the osmosis rate of the first reactor relevant on the structure and heat of the inlet water. For some matrixs for the reverse osmosis defining the efficiency at a point in the film channel, the equation explain the yield (in terms of brine reuse) of the whole reactor. The matrix for detect an target reverse osmosis was investigated with studies taken from a 5-m longitudinal film brine with dimmensions of 3.5" × 50" ingredients elevated efficiencies was detected, [30].

For a target reuse, the necessary force was measured by arranging Eq. (31) to Eq. (34):

$$\Delta P = \left(\frac{\Delta P - \Delta\pi_0}{R}\right) \left[1 - e^{-\frac{\Delta P}{\Delta\pi_0} \left(\frac{\Delta P}{\Delta P^*} - R\right)}\right] \quad (34)$$

Eq. (34) is an excellent matrix since forse are present on two scheme lateral of the matrix. The force for a reuse was measured by a scheme which is the same to the alone reactor mentioned above for the measure the reuse for a certain flux, [31]. In the scheme, Eq. (34) the first part of the matrix is not dependent to the equivalent item given in Eq. (35) and Eq. (36):

$$y_1 = \Delta P \quad (35)$$

$$y_2 = \left(\frac{\Delta P - \Delta\pi_0}{R}\right) \left[1 - e^{-\frac{\Delta P}{\Delta\pi_0} \left(\frac{\Delta P}{\Delta P^*} - R\right)}\right] \quad (36)$$

where, y_1 and y_2 are equations of ΔP , which they are independent items in Eq. (35) and Eq. (36). The 2 matrix are calculated for certain ΔP values and the points are schemed in a y - ΔP longitudinal form. The lines of Eq. (35) and Eq. (36) is the necessary forces for the illustrated reuse under discussion since it is enough Eq. (34).

This scheme way was illustrated for water containig salt and its treatment. The items used to detect this is showing in Table 4. In the operation unitless force ($\Delta P/\Delta\pi_0$) is utilized longitudinally. The matrix y_1 is illustrated using an angled streak. The matrix y_2 for the numerous reuses are illustrated by a group of slanted from 1.20 on the plot using reuse showed on each line. The necessary force for each reuse is showed by the relations with slanted plot (y_1). To detect the scores for the smal recoveries, the sections namely of (1, 1.4) × (1, 1.4) in Figure 9 should be used and re-plotted in Figure 10.

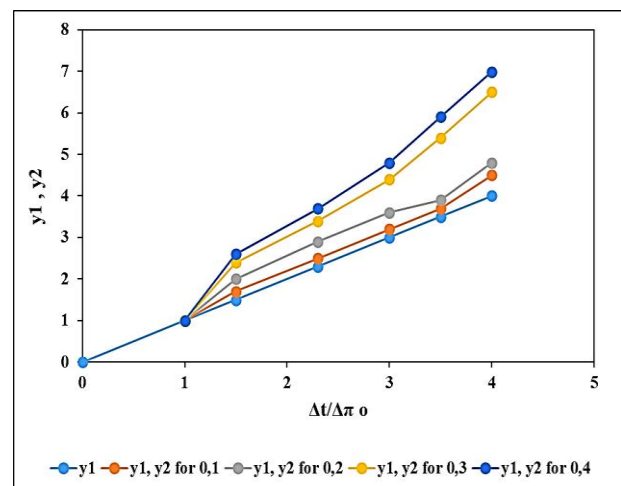


Fig. 9: The diagonal line is for Eq. (35) and other lines are for Eq. (36) of various recoveries as indicated on the lines. The intersection point of the lines for the two equations is the pressures required for the indicated recovery. The parameters used in the calculations are given in Table 4

Source: Authors' own work.

The unitless forces for reuses of 0.2, 0.3, and 0.4 should be corrected and showed in the plot to be 1.298, 1.398, and 1.649, respectively. The unitless forces for high reuses can be not be taken into consideration. The data was illustrated in Table 2. The last forces are measured from unitless forces and is illustrated in Table 2. The pressures determined graphically for various recoveries were shown in Table 5.

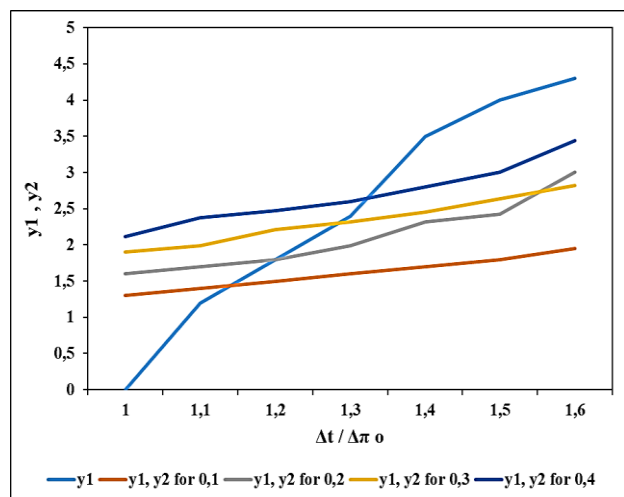


Fig. 10: More accurate pressures for recoveries of 0.1, 0.2, and 0.3 can be graphically determined by enlarging the corresponding section of Figure 9
Source: Authors' own work.

Table 5. The pressures determined graphically for various recoveries

R	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7
$\Delta P / \Delta \pi_0$	1.00	1.12	1.27	1.44	1.67	2.00	2.50	3.33
ΔP	25.8	29.0	32.8	37.3	43.3	51.7	64.6	86.2
	7	7	5	7	2	3	6	2

Source: Authors' own work.

When the main force for a reuse is mentioned with the main matrix, the special spends of clean water can be calculated using Eq. (30). In order to detect a steady-state reuse the special spends of salty water treatment should be measured by discussing the special spends at certain reuses. The optimal conditions of reverse osmosis plants will be optimized for three items. These are as follows:

Case 1. Lowering of the special electricity. Removal of salt where the influent is present it was flowing to the influent of the reverse osmosis, and the brine should be pumped by a pipe. The spends in alone reactor and brine treatment can not be taken into consideration when discussed the electricity spends. The only spend item is for the electricity. Fort his reason, the optimal conditions for reactor plant is important to detect the recycling in order to reduce the characteristic electricity.

Case 2. Lowering of the all spends of film and electricity. All the other operational rules are similar as Case 1 with the exception for reverse osmosis. The reverse osmosis should be operated under optimized conditions. It was two spend items should be taken into account in case 2, which are the fim and energy spends. As a result, the target was to find out the reuse and to lowering the complex spends of film and electricity.

Case 3. Lowering of the whole spends for removal of salts. This is the target situation in which all spend items for salt removal should be taken into consideration. The whole spend for salt removal in this situation are for film, electricity, influent liquid removal and brine. Fort his reason, the aim of the optimal conditions to detect the reuse for lowering the whole spends for salt removal.

3.2 Case 1: Lowering of Characteristic Electricity

Under these conditions, the secondary expression in Eq. (30) should be taken into consideration.

The lowering of the spends should be equal to the optimal conditions and to the special electricity for the clear water production, which is explained with Eq. (37):

$$E = \frac{\Delta P}{R} \quad (37)$$

Here, E is the characteristic electricity. For a reuse, the force necessary for an reverse osmosis should be plotted and calculated with the main matrix as illustrated in the sections mentioned. Then the characteristic electricity is quickly measured with Eq. (37). The characteristic electricities for salt removal can be detected for certain reuses with the other items summarized in Table 4. The ultimate force and characteristic electricity for salt removals are matrise of reuse as illustrated Figure 11.

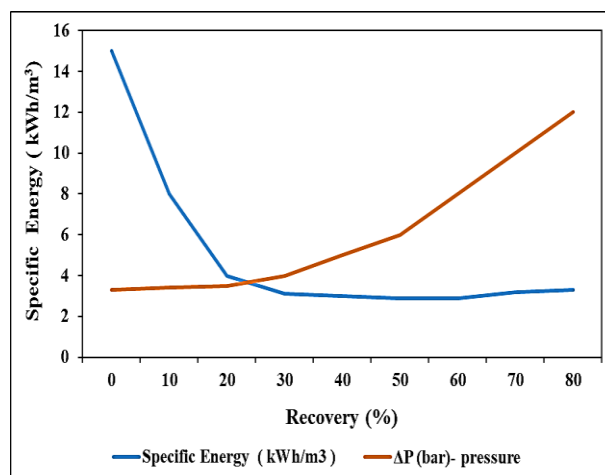


Fig. 11: The minimal specific energy for seawater desalination occurs at recovery of 50%. The parameters of the membrane channel used in calculation are given in Table 4
Source: Authors' own work.

In Figure 11 the main force elevated with increasing of reuse. The characteristic electricity lowered rapidly with high reuse when the reuse is low. It as apart in which the characteristic electricity

decrease slightly with the reuse before it obtained. The line illustrated that there is a minimum characteristic electricity at the reuse of 63%. It was observed that the minimum characteristic electricity for salt removal is 2.08 kWh/m³. This minimal characteristic electricity for salt removal is a longitudinal film pipe which is extremely bigger than the hydrodynamic lowest value of 0.97 kWh/m³, [32]. By using an electricity reuse apparatus build up and operated with 99% efficiency in reusing the electricity from the brine, the lowest special electricity is 45% which is bigger than the hydrodynamic minimal level. This minimum characteristic electricity of 2.66 kWh/m³ should be a better point to detect the electricity efficiency of a special film than the hydrodynamic minimal level. It is important to mention that is a bigger range of reuse with the characteristic electricity was small. For instance, Figure 11 exhibited the characteristic electricity changes between 1.87 and 2.12 kWh/m³ for the reuse percentages varied between 39% and 72%.

3.3 Case 2: Lowering of the whole Spends of Film and Electricity

The spend items detected in influent for pre-removal and brine spends are not taken into consideration in the comparison of film and electricity. Under these conditions Eq. (30) is summarized to Eq. (38):

$$C = c_e \frac{\Delta P}{R} + c'_m \frac{L}{u_0 HR} \quad (38)$$

The problems for steady-state conditions is the reuse and lowering of the mixed spends of film and electricity. The spend constants in Eq. (38) are required before utilized this matrix. The electricity to generate the spends in an reverse osmosis pipes is electricity. The spend constant for electricity can be measured from the electricity price and transformation yields of the relevant devices. To measure the electricity spends and transformation yields was calculated as \$0.099/kWh and 91%, respectively. Therefore, the spend constant for electricity was defined with Eq. (39):

$$c_e = \frac{E_p}{\eta} = \frac{\$0.08/kWh}{80\%} = \frac{\$0.10}{kWh} \times \frac{1 kWh}{3.6 \times 10^6 J} = \frac{1}{3.6 \times 10^7} \$/(Pa \cdot m^3) \quad (39)$$

Here, E_p is the spend of electricity, and η is the transformation yield of pipe. The electricity unit joule (J) is substituted by a force (Pa · m³) for a suitable calculations. The spend constant for film c'_m can be found from the price of the film item and auxiliary item. The score in Table 6 are utilised to

found the constant for the relevant mathematical applications.

Table 6. Calculation of the cost coefficient (cm') for membrane

Parameters	Values	Units
Membrane element		
Size	8' x 40''	
Price	750	\$
Membrane area	37	m ²
Service time	5 (15768000)	Year (second)
Contribution to c'_m	4.05 (1.29 x 10 ⁻⁷)	\$/m ² .yr (\$/m ² .s)
Pressure vessel		
Size	8	Element
Price	2000	\$
Number of elements	8	m ²
Service time	20 (630720000)	Year (second)
Contribution to c'_m	0.34 (1.07 x 10 ⁻⁸)	\$/m ² .yr (\$/m ² .s)
Overall		
c'_m	4.39 (1.39 x 10 ⁻⁷)	\$/m ² .yr (\$/m ² .s)

Source: Authors' own work.

The spend constant for film can be found with Eq. (39) as:

$$c'_m = \frac{\$ 750}{5y \times 37 m^2} + \frac{\$ 2000}{8 \times 20y \times 37 m^2} = 4.39 \frac{\$}{(m^2.yr)} = 1.39 \times 10^{-7} \$/(m^2.s)$$

By using the spend constants, the whole spends of film and electricity was measured for a certain reuse. As aforementioned in Case 1, the main force is measured firstly with a plot using Eq. (35) and Eq. (36). The characteristic electricity is calculated by Eq. (38). The data for salty waster removal items are illustrated in Table 4 and the results are showed in Figure 12.

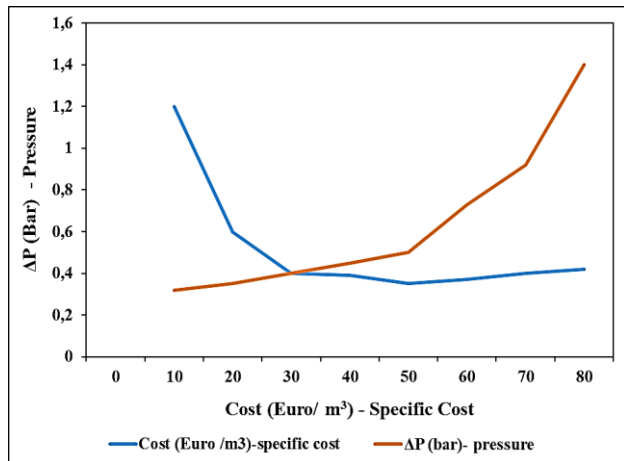


Fig. 12: The minimal combined cost for membrane and energy in seawater desalination occurs at recovery of 55 %. The parameters of the membrane channel used in calculation are given in Table 4
Source: Authors' own work.

In Figure 12 the lowest characteristic spends of \$0.41/m³ for salty water removal a reuse efficiency of 57% was detected. For this clean water the whole force is 54 bar. The mean clean water flow rate was measured using the Eq. 25 as follows:

$$J \text{ (or } \bar{v}) = \frac{u_0 H}{L} R = \frac{0.1 \frac{m}{s} \times 0.35 \times 10^{-3} m}{8m} \times 55\% \\ = 2.4 \times \frac{10^{-6} m^3}{m^2} \cdot s \text{ (or } m/s)$$

From the mean clean water flow rate, a film surface is required for a certain salty water removal should be performed. For instance, a salt removal treatment process has a volume of 497 m³/d and is required 1967 m² of film area as measured,

Membrane area

$$= \frac{500 \text{ m}^3/d}{2.4 \times 10^{-6} \text{ m}^3/m^2 \cdot s} \times \frac{86400 \text{ s}}{1 d} = 2405 \text{ m}^2$$

In the comparison of the mean reuse of 63% to reduce the electricity spends in Case 1, the inlet of the film spends necessitates the lowering of the problems of the film pipes. More assays on salty water treatment showed elevated film spends, the elevated reuse is necessary to lowering the whole spends.

3.4 Case 3: Lowering of the whole Spends for Salty Water Removal

All four spend items were taken into consideration in this part of the. The overall, Eq. (30) is utilized to detect the optimum reuse to lowering the whole spends for a salt removal plant. In this study, the film spends constant was measured in the previous case is used because of the same film. Furthermore, the

following spend $c_f = \$0.04/\text{m}^3$ and $c_c = \$0.005/\text{m}^3$ are utilized in the optimization. Following the same procedure, the main force at different reuse is first calculated with the graphical method. Then the characteristic spend is found with Eq. (30). The parameters in Table 4 are chosen in the calculation. Both resultant force and characteristic spend are presented as functions of reuse in Figure 6.

In Figure 13 that the minimal characteristic spend of \$0.39/m³ for salty water treatment the reuse of 72.89% with relevant main force of about 79 bar. In the comparison with the results in Case 2 for the whole spend of film and electricity, the characteristic spend is elevated by \$0.05 to pay the spend on the influent treatment and brine costs. The involvements of the spends for influent and brine removals should be taken into consideration to detect the maximum reuse for the film pipe and whole forces. Table 7 (Appendix) exhibited the ingredients of sea wastewater and yields after reverse osmosis treatment.

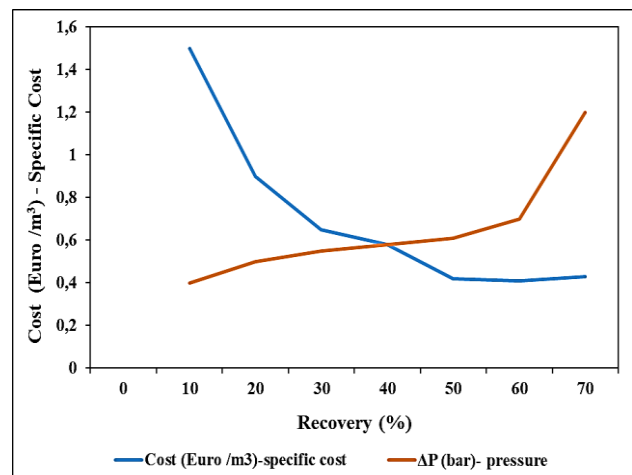


Fig. 13: Total cost for seawater desalination. The lowest cost occurs at recovery of 60.50%. The parameters of the membrane channel used in calculation are given in Table 4

Source: Authors' own work.

4 Conclusions

An optimum force of 18.0 bar was used in the RO process the operation period can be minimized to 79-80 min. In order to calculate the film clogging by lowering of clean water flux; the clogging ratio was calculated as 26.00% and 29.20%. At elevated forces the clogging was slightly elevated.

At elevated forces the permeate flux was not lowered significantly since the water permeability was not elevated excessively. High temperature did not significantly affect the permeate flux, [33], since no important increase in viscosity of wastewater

contrarily to the studies performed by Gurak et al. [34], [35], [36]. This can be defined by the changes of the wastewater type, retentate quality, concentration polarization, to film clogging and to the hydraulic resistances of the films resulting in flux decreasing. Some evaluations were performed for energy utilization in a RO alone and sequential RO/RO film device. The effects of pump and energy reuse yields, film reuse and retentate reuse from the second RO the first RO were investigated. The results showed that if the target whole salt recovery was detected in reverse osmosis system for a reactor alone has more energy than that two sequential reverse osmosis reactor system for the same volume of whole water reuse and salt recovery. However, if a film is not present to target reuse in a reactor alone and then, a sequential two reactor should be operated, with the lowest electricity utilization when the reactor alone was used the biggest salt recovery was detected.

Based on this research in RO operation for sea water desalination an important target built up of reactor system and operational conditions for treat the salty water is to detect the target clean water recycling by lowering the spends of the clean water. The important target in the optimization is to found the whole forces for a clean water recycling. It was detected that this target can be performed with the lowest efforts by utilizing a target reverse osmosis by plotting all the data The utilization of optimal design and operational conditions for a reverse osmosis can be performed. On the other hand, the optimum reuse to decrease the characteristic spends of salt removal was performed for three different operations. It is an optimal reuse lowering the special spends when energy is the main item. The optimum reuse to lowered the characteristic elevated spends, when the film spends, influent water treatment spends and brine spend should be taken into consideration.

Acknowledgement:

Experimental analyzes in this study were performed at the Laboratories of the Canada Research Center, Ottawa, Canada. The authors would like to thank this body for providing financial support.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process During the preparation of this work, the author(s) utilized artificial intelligence (AI) technologies solely for the purpose of linguistic refinement and grammatical correction. Following the application of these tools, the author(s) comprehensively reviewed, verified, and edited the resulting text. The author(s) maintain

full accountability and responsibility for the accuracy, integrity, and final content of the publication.

References:

- [1] M. Wilf, C. Bartels, Optimization of Seawater RO Systems Design, Desalination, Vol.173, No.1, 2005, pp. 1-12.
- [2] M. Busch, W. E. Mickols, Reducing Energy Consumption in Seawater Desalination, Desalination, Vol.165, 2004, pp. 299-312.
- [3] T. Manth, M. Gabor, E. Oklejas, Minimizing RO Energy Consumption under Variable Conditions of Operation, Desalination, Vol.157, No.1-3, 2003, pp. 9-21.
- [4] A. Zhu, P. D. Christofides, Y. Cohen, Effect of Thermodynamic Restriction on Energy Cost Optimization of RO Membrane Water Desalination, Industrial & Engineering Chemistry Research, Vol.48, No.13, 2009, pp. 6010–6021.
- [5] M. Wilf, Design Consequences of Recent Improvements in Membrane Performance', Desalination, Vol.113, No.2-3, 1997, pp. 157-163.
- [6] Y.A. Le Gouellec, D. A. Cornwell, R. C. Cheng, T. J. Tseng, D. X. Vuong, K. L. Wattier, C. J. Harrison, A. Childress, A Novel Approach to Seawater Desalination Using Dual-Stage Nanofiltration (Awwaf Report), AWWA Research Foundation: American Water Works Association. SBN-10: 1843399709, ISBN-13: 978-1843399704, 2007.
- [7] E. Cardona, A. Piacentino, F. Marchese, Energy Saving in Two-Stage Reverse Osmosis Systems Coupled with Ultrafiltration Processes, Desalination, Vol.184, No.1-3, 2005, pp. 125-137.
- [8] M. Noronha, V. Mavrov, H. Chmiel, Simulation Model for Optimization of Two-Stage Membrane Filtration Plants–Minimizing the Specific Costs of Power Consumption, Journal of Membrane Science, Vol.202, No.1, 2002, pp. 217-232.
- [9] A. M. Fin arooque, A. T. M. Jamaluddin, A. R. Al-Reweli, P. A. M. Jamaluddin, S. M., Al-Marwani, A. A. Al-Mobayed A. H. Qasim, Parametric Analyses of Energy Consumption and Losses in SWCC SWRO Plants Utilizing Energy Recovery Devices, Desalination, Vol.219, 2008, pp. 137–159.
- [10] U. Lachish, Optimizing the Efficiency of Reverse Osmosis Seawater Desalination, Vol.30, 2015, 1-22, [Online].

- https://www.researchgate.net/profile/Uri-Lachish/publication/310458654_Optimizing_the_Efficiency_of_Reverse_Osmosis_Seawater_Desalination/links/582de6b408aef19cb813dfa0/Optimizing-the-Efficiency-of-Reverse-Osmosis-Seawater-Desalination.pdf (Accessed Date: January 6, 2026)
- [11] K. S. Spiegler, Salt-Water Purification, 2nd ed., Plenum Press, New York, USA, pp.189, 1977.
- [12] V. G. Gude, Energy Consumption and Recovery in Reverse Osmosis, Desalination and Water Treatment, Vol.36, 2011, pp. 239–260.
- [13] S. Mirza, Reduction of Energy Consumption in Process Plants Using Nanofiltration and Reverse Osmosis, Desalination, Vol.224, 2008, pp. 132–142.
- [14] L. Song, J. Y. Hu, S. L. Ong, W. J. Ng, M. Elimelech, M. Wilf, Emergence of Thermodynamic Restriction and its Implications for Full-Scale Reverse Osmosis Processes, Desalination, Vol.155, No.3, 2003, pp. 213–228.
- [15] L. Song, K. G. Tay, Performance Prediction of a Long Crossflow Reverse Osmosis Membrane Channel, Journal of Membrane Science, Vol.281, No.1, 2006, pp. 163–169.
- [16] M. Mulder, Basic Principles of Membrane Technology, (2nd edition). Kluwer Academic Publishers, Boston. ISBN-13: 978-0792342489, ISBN-10: 0792342488, 1997.
- [17] ASTM International (April, 2019) Standard Practice for Standardizing Reverse Osmosis Performance Data, ASTM international. ASTM D4516-19a, 2019, [Online]. https://standards.iteh.ai/catalog/standards/astm/2bffc0c6-1f3e-4e94-832b-f58cd7fe653e/astm-d4516-19a?srsId=AfmBOOpYQLFgEQDB9TRNLxcA0EsdclAE1vM5FZKVHSSadkxr7iac_ksc (Accessed Date: January 6, 2026)
- [18] M. Shawn, A. von Gottberg, J. L. Talavera, Seawater Reverse Osmosis Plants in the Caribbean Recover Energy and Brine and Reduce Costs Technical Paper, GE Water Process Technology, TP1029EN 0601, 2005, pp. 1–13.
- [19] N. P. Isaias, N.P. Experience in Reverse Osmosis Pretreatment, Desalination, Vol.139, 2001, pp. 57–64.
- [20] J. A. Redondo, Brackish-, Sea- and Wastewater Desalination, Desalination, Vol.138, 2001, pp. 29–40.
- [21] B. Durham, A. Walton, Membrane Pretreatment of Reverse Osmosis: Long Term Experience on Difficult Waters, Desalination, Vol.122, 1999, pp. 157–170.
- [22] S. Avlonitis, K. Kouroumbas, N. Vlachakis, Energy Consumption and Membrane Replacement Cost for Seawater RO Desalination Plants Desalination, Desalination, Vol.157, No.1-3, 2003, pp. 151–158.
- [23] P. Corsin, G. Cartier, C. Masson, Pumps in Seawater Reverse Osmosis, [Online]. <http://www1.cetim.fr/eemods09/pages/programme/051-Corsin-final.pdf> (Accessed Date: January 15, 2026).
- [24] S. Dundorf, J. MacHarg, T. F. Seacord, Optimizing Lower Energy Seawater Desalination, The Affordable Desalination Collaboration, International Desalination Association World Congress REF: MP07-150, Aug-2009, 2009.
- [25] H. Valdés, A. Saavedra, M. Flores, I. Vera-Puerto, H. Aviña, M. Belmonte, Reverse Osmosis Concentrate: Physicochemical Characteristics, Environmental Impact, and Technologies, Membranes (Basel), Vol.11, No.10, 2021, 753, pp. 1–21. <https://pmc.ncbi.nlm.nih.gov/articles/PMC8541667/> (Accessed Date: January 6, 2026).
- [26] M. A. Sanz, R. L. Stover, Low Energy Consumption in the Perth Seawater Desalination Plant. IDA World Congress', Maspalomas, Gran Canaria –Spain 2007, 2007, pp. 1–7.
- [27] A. O. Sharif, A. A. Merdaw, H. Al-Bahadili, A. Al-Tae, S. Al-Aibi, Z. Rahal, G. A. W. Derwish, A New Theoretical Approach to Estimate the Specific Energy Consumption of Reverse Osmosis and Other Pressure-Driven Liquid-Phase Membrane Processes, Desalination Water Treatment, Vol.3, 2009, pp. 111–119.
- [28] D. Akgul, M. Cakmakce, N. Kayaalp, I. Koyuncu, Cost Analysis of Seawater Desalination with Reverse Osmosis in Turkey', Desalination, Vol.220, 2008, pp. 123–131.
- [29] S. Liang, C. Liu, L. Song, Two-Step Optimization of Pressure and Recovery of Reverse Osmosis Desalination Process, Environmental Science & Technology, Vol.43, 2009, pp. 3272–3277.
- [30] L. Song, K.G. Tay, Performance Prediction of a Long Crossflow Reverse Osmosis

- Membrane Channel, Journal of Membrane Science, Vol.281, 2006, pp. 163–169.
- [31] L. Song, A Concise Analytical Model for the Ideal Reverse Osmosis Desalination Processes, Water Environment Research, Vol.95, 2023, e10939.
- [32] C. Liu, K. Rainwater, L. Song, Energy Analysis and Efficiency Assessment of Reverse Osmosis Desalination Process, Desalination, Vol.276, 2011, pp. 352–358.
- [33] D. Akgul, M. Cakmakce, N. Kayaalp, I. Koyuncu, Cost Analysis of Seawater Desalination with Reverse Osmosis in Turkey', Desalination, Vol.220, 2008, pp. 123–131.
- [34] P. D. Gurak, L. M. C. Cabral, M. H. M. Rocha-Leão, V. M. Matta, S. P. Freitas, Quality Evaluation of Grape Juice Concentrated by Reverse Osmosis, Journal of Food Engineering, Vol.96, No.3, 2010, pp. 421–426.
- [35] F. J. García Latorre, S. O. Pérez Báez, A. Gómez Gotor, Energy Performance of a Reverse Osmosis Desalination Plant Operating with Variable Pressure and Flow, Desalination, Vol.366, 2015, pp. 146–153.
- [36] E. Dimitriou, P. Boutikos, E. S. Mohamed, S. Koziel, G. Papadakis, Theoretical Performance Prediction of a Reverse Osmosis Desalination Membrane Element under Variable Operating Conditions, Desalination, Vol.419, 2017, pp. 70–78.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

Prof. Dr. Delia Teresa Sponza and Post-Dr. Rukiye Öztekin took an active role in every stage of the preparation of this article. The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

K. K. Turekian, Oceans, Second edition, The Prentice-Hall Foundations of Earth Science Series, 168 pages, 1968.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

The experimental phases of this research study were conducted at the National Research Council (NRC) of Canada, Research Centers, Ontario, Canada. The authors would like to thank this body for providing financial support.

Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Creative Commons Attribution License 4.0 (Attribution 4.0 International, CC BY 4.0)

This article is published under the terms of the Creative Commons Attribution License 4.0
https://creativecommons.org/licenses/by/4.0/deed.en_US

APPENDIX

Table 7. Detailed composition of seawater at 3.5% salinity

Element	At weight	ppm	Removal (%)	Element	At weight	ppm	Removal (%)
Hydrogen H ₂ O	1.00797	110,000	99.99%	Molybdenum Mo	0.09594	0.01	99.99%
Oxygen H ₂ O	15.9994	883,000	99.99%	Ruthenium Ru	101.07	0.0000007	99.99%
Sodium NaCl	22.9898	10,800	99.99%	Rhodium Rh	102.905	.	99.99%
Chlorine NaCl	35.453	19,400	99.99%	Palladium Pd	106.4	.	99.99%
Magnesium Mg	24.312	1,290	99.99%	Argentum (silver) Ag	107.870	0.00028	99.99%
Sulfur S	32.064	904	99.99%	Cadmium Cd	112.4	0.00011	99.99%
Potassium K	39.102	392	99.99%	Indium In	114.82	.	99.99%
Calcium Ca	40.08	411	99.99%	Stannum (tin) Sn	118.69	0.00081	99.99%
Bromine Br	79.909	67.3	99.99%	Antimony Sb	121.75	0.00033	99.99%
Helium He	4.0026	0.0000072	99.99%	Tellurium Te	127.6	.	99.99%
Lithium Li	6.939	0.170	99.99%	Iodine I	166.904	0.064	99.99%
Beryllium Be	9.0133	0.0000006	99.99%	Xenon Xe	131.30	0.000047	99.99%
Boron B	10.811	4.450	99.99%	Cesium Cs	132.905	0.0003	99.99%
Carbon C	12.011	28.0	99.99%	Barium Ba	137.34	0.021	99.99%
Nitrogen ion	14.007	15.5	99.99%	Lanthanum La	138.91	0.0000029	99.99%
Fluorine F	18.998	13	99.99%	Cerium Ce	140.12	0.0000012	99.99%
Neon Ne	20.183	0.00012	99.99%	Praesodymium Pr	140.907	0.00000064	99.99%
Aluminium Al	26.982	0.001	99.99%	Neodymium Nd	144.24	0.0000028	99.99%
Silicon Si	28.086	2.9	99.99%	Samarium Sm	150.35	0.00000045	99.99%
Phosphorus P	30.974	0.088	99.99%	Europium Eu	151.96	0.0000013	99.99%
Argon Ar	39.948	0.450	99.99%	Gadolinium Gd	157.25	0.0000007	99.99%
Scandium Sc	44.956	<0.000004	99.99%	Terbium Tb	158.924	0.00000014	99.99%
Titanium Ti	47.90	0.001	99.99%	Dysprosium Dy	162.50	0.00000091	99.99%
Vanadium V	50.942	0.0019	99.99%	Holmium Ho	164.930	0.00000022	99.99%
Chromium Cr	51.996	0.0002	99.99%	Erbium Er	167.26	0.00000087	99.99%
Manganese Mn	54.938	0.0004	99.99%	Thulium Tm	168.934	0.00000017	99.99%
Ferrum (Iron) Fe	55.847	0.0034	99.99%	Ytterbium Yb	173.04	0.00000082	99.99%
Cobalt Co	58.933	0.00039	99.99%	Lutetium Lu	174.97	0.00000015	99.99%
Nickel Ni	58.71	0.0066	99.99%	Hafnium Hf	178.49	<0.000008	99.99%
Copper Cu	63.54	0.0009	99.99%	Tantalum Ta	180.948	<0.0000025	99.99%
Zinc Zn	65.37	0.005	99.99%	Tungsten W	183.85	<0.000001	99.99%
Gallium Ga	69.72	0.00003	99.99%	Rhenium Re	186.2	0.0000084	99.99%
Germanium Ge	72.59	0.00006	99.99%	Osmium Os	190.2	.	99.99%
Arsenic As	74.922	0.0026	99.99%	Iridium Ir	192.2	.	99.99%
Selenium Se	78.96	0.0009	99.99%	Platinum Pt	195.09	.	99.99%
Krypton Kr	83.80	0.00021	99.99%	Aurum (gold) Au	196.967	0.000011	99.99%
Rubidium Rb	85.47	0.120	99.99%	Mercury Hg	200.59	0.00015	99.99%
Strontium Sr	87.62	8.1	99.99%	Thallium Tl	204.37	.	99.99%
Yttrium Y	88.905	0.000013	99.99%	Lead Pb	207.19	0.00003	99.99%
Zirconium Zr	91.22	0.000026	99.99%	Bismuth Bi	208.980	0.00002	99.99%
Niobium Nb	92.906	0.000015	99.99%	Thorium Th	232.04	0.0000004	99.99%
				Uranium U	238.03	0.0033	99.99%
				Plutonium Pu	244	.	99.99%

Note! ppm= parts per million = mg/litre = 0.001g/kg.

Source: Authors' own work