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# Techno-economic evaluation of forward/reverse osmosis hybrid system for saline water desalination

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**ABSTRACT**

Forward osmosis (FO) hybrid systems have been developed recently as an alternative to conventional high-pressure membrane processes (reverse osmosis (RO)) for seawater desalination and wastewater treatment and recovery. However, the technical economic comparison with the RO processes for seawater desalination has not been clearly studied. The main objective of this investigation is to evaluate the detailed technical and economical feasibilities of the forward/reverse osmosis hybrid process for saline water desalination. The achievement of this study was conducted with the development of an economic model to calculate the effect of osmotic dilution of seawater feed stream on membrane area. A process design for hybrid FO/RO system for the simultaneous treatment of impaired and saline water with a pre-determined capacity, including material balance calculations, equipment sizing and selection were represented in this paper. Preliminary economic studies of the proposed systems for selected two cases were under taken: Ezz Steel Company treated wastewater with seawater, and El-Salam Canal water with brackish water. The results indicated that the application of FO/RO hybrid system for desalination is a promising system in the case of high TDS draw solution (such as seawater) but it is not beneficial in the case of low TDS draw solutions (such as brackish water).

*Keywords:* Forward osmosis; Reverse osmosis; Membrane desalination; Impaired water; Seawater; Brackish water; Economic evaluation.

## 1. Introduction

In pressure-driven membrane processes such as RO or NF, economic feasibility is maximized by optimal recovery of pure water from saline water. Higher recoveries increase the reject concentration and increase energy requirements. The energy required for the seawater reverse osmosis (SWRO) plant to achieve the required recovery of the diluted seawater feed is marginally decreased with each increment of dilution [1].

Forward osmosis (FO) is a membrane process that has the ability to reduce the desalination cost by extraction of water from impaired drains. FO employs the concept of osmotic dilution which depends on the difference in salt concentration between two solutions to drive water through a membrane which rejects solutes. Consequently, a dilute stream will be concentrated and a concentrated stream will be diluted [2,3]. A hybrid system utilizes wastewater on one of the FO membrane sides and seawater on the other side, leading to water recovery from the wastewater stream [4]. FO process attains two objectives: i) wastewater volume-reduction, and ii) osmotic pressure reduction of seawater before desalination using RO process.

Application of a hybrid FO-low pressure RO system can reduce the energy and subsequently the cost in a SWRO facil-

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ity due to lowering the operating hydraulic pressure. Consequently, brackish water RO membranes (BWRO) can be used instead of SWRO membranes. In addition, higher flux can be achieved due to the increase in water recovery ratio of the whole system [5]. Environmental impacts are another benefits of the hybrid system, by reducing requirements of electricity, and also by discharging brines with lower salinity and lower volumes to the aquatic ecosystem [6,7].

The present paper reports the final results of a comprehensive research program undertaken by the authors [8–11]. These results are concerned with developing engineering design and cost estimation of the proposed FO/RO system for the simultaneous treatment of impaired and saline water. Firstly, the economic model was developed to calculate the effect of osmotic dilution of seawater feed stream on membrane area. Secondly, a preliminary economic study of the proposed systems for the selected two cases: Ezz Steel treated wastewater with seawater and El-Salam Canal water with brackish water. The financial indicators of the target derivatives, namely, capital costs, annual operating costs and depreciation rates were determined for a selective production capacity in order to obtain treatment cost per cubic meter of purified water.

## 2. Methodology

### 2.1. Model development for economic dilution rate

An economic model was developed using a spreadsheet program (Excel). The model calculates the effect of osmotic dilution membrane capacity on the osmotic dilution of a seawater feed stream. The cost of the membrane is assumed to dominate the capital cost of installing the required osmotic dilution FO system. The energy required for the SWRO plant to achieve the required recovery of the diluted seawater feed is marginally decreased with each incremental increase in dilution.

#### 2.1.1. Technologies analyzed

Based on the results of the pilot scale study with Ezz steel treated wastewater and synthetic sea water [10], a simulated sea water desalination plant was proposed as shown in Fig. 1.

In the proposed plant, the FO unit uses seawater as draw solution (DS) to extract water from Ezz steel treated wastewater. The diluted seawater is then processed through an RO desalination system that provides high salt rejection and dissolved contaminants that may have escaped the FO treatment, hence achieving a multi-barrier treatment system. Consequently, the concentrated Ezz steel wastewater stream could be returned to a wastewater treatment plant for retreatment. Both DS and FS were circulated through forward osmosis unit for definite retention times until reaching the required DS dilution percent.

It was previously concluded from the results of pilot scale experiments [10] that high water flux value was observed in the beginning of the operation and then slightly decreased by time, where it is decreased from 8.44 L/m$^2$h at 1 h to 6.61 at 6 h. Accordingly, 1 h retention time and 8.44 L/m$^2$h water flux were chosen as basis of design.

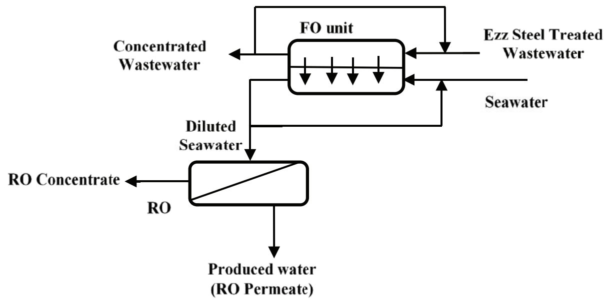


Fig. 1. Proposed FO/RO plant for seawater desalination using Ezz-Steel treated wastewater.

#### 2.1.2. Design basis

The model design basis are as follows; RO desalination plant feed seawater flow rate (100 m$^3$/day), seawater TDS concentration (35000 mg/l), dilution rate (0–250%), Ezz steel treated wastewater TDS concentration (1050 mg/l), FO water flux ( 8.44 L/m$^2$ h), FO circulation time (1 h), FO membrane type (Hydration Technology Innovations (HTI) module, 8040FO-FS-P element), element membrane area (17.6 m$^2$), FO membrane element service life (5 y).

#### 2.1.3. Cost indicators

The cost Indicators are as follows; cost of element with housing ($1,664), cost of element ($1, 364), FO membrane cost per m$^2$ ($77.5) [the membrane cost based on commercial offer from Future Technology Company in Dubai, which is HTI dealer in Middle East], cost of housing ($300) [Alibaba.com], energy cost (0.06 $/kWh) [local price, with 10% annual increasing], price of produced water from RO plant (0.92 $/m$^3$) [local price, with 10% annual increasing].

#### 2.1.4. Model calculations

2.1.4.1. FO membrane cost

The feed flow rate to RO unit (F) consists of sea water flow rate (X) and water recovered from FO unit. We assumed here fixed RO input flow rate, accordingly:

$$F = X + (DR^*X) \tag{1}$$

$$F = X\,(1 + DR) \tag{2}$$

$$X = \frac{F}{(1+\ DR)} \tag{3}$$

From salt mass balance, the concentration of diluted solution can be determined via:

$$TDS\ of\ DSW = \frac{Original\ SW\ TDS * X}{F} \tag{4}$$

Substituting the value of X from Eq. (3) and rearranging gives:

$$TDS\ of\ DSW = \frac{Original\ SW\ TDS}{(1+DR)} \tag{5}$$

The amount of recovered water from FO system (FORW) depends on the required dilution rate (DR) of sea water input (DR*X).

$$\left(FORW\right) = \frac{DR*F}{(1+DR)} \quad (6)$$

By definition:

$$FO\ membrane\ water\ flux\ \left(FOWF\right) = \frac{\left(FORW\right)}{\left(CT\right)*\ \left(FOMA\right)}$$

where CT is the circulation time and FOMA is the FO membrane area.

(FORW) = (FOWF)* (CT)* (FOMA)

By substituting Eq. (6) and rearranging for FOMA determination, we get:

$$\left(FOMA\right) = \frac{\left(DR\ *\ F\right)}{\left(FOWF\right)*\ \left(CT\right)*\ \left(1+\ DR\right)} \quad (7)$$

$$No.\ of\ elements\ = \frac{FOMA}{Membrane\ element\ area}$$

FO membrane Cost = FO membrane area* Cost of FO membrane per $m^2$

$$FO\ membrane\ Cost\ = \frac{\left(DR\ *\ F\right)\ *\ Cost\ of\ FO\ membrane\ per\ m^2}{\left(FOWF\right)*\ \left(CT\right)*\ \left(1+\ DR\right)} \quad (8)$$

2.1.4.2. Benefit cost ratio (BCR)

As recommended by RO supplier [Emco (water solution provider), Dubai, UAE], the RO water recovery is increased from 40 to 60% by reducing the SW salinity from 35000 to 10000 mg/l as shown in Fig. 2.

The total energy saving (ES) is the difference between the total RO energy consumption (EC) at zero seawater dilution (no FO) and the total RO energy consumption at the specified dilution rate, therefore:

$$ES = EC_{SW} * F * R_{SW} – EC_{dSW} * F * R_{dSW}$$
$$ES = F\ (EC_{SW} * R_{SW} – EC_{dSW} * R_{dSW}) \quad (9)$$

where $EC_{SW}$ (energy consumption at zero dilution), F (Feed flow rate), $R_{SW}$ (%seawater recovery), $EC_{dSW}$ (Energy consumption at selected DR%), $R_{dSW}$ (% recovery of diluted seawater).

EC at different TDS was calculated from ROSA software, F was assumed to be 100 $m^3$/day, $R_{SW}$ equal 40%, and $R_{dSW}$ was calculated according to dilution rate from the obtained linear regression equation [Fig. 2].

Annual energy cost saving = ES * Energy cost * 365 (10)

Price of additional produced water = [Volume of RO recovered water at selected DR% – Volume of RO recovered water at zero dilution] * water price.

Annual price of additional produced water
= $[R_{dSW} – R_{SW}]$ * F * water price * 365 (11)

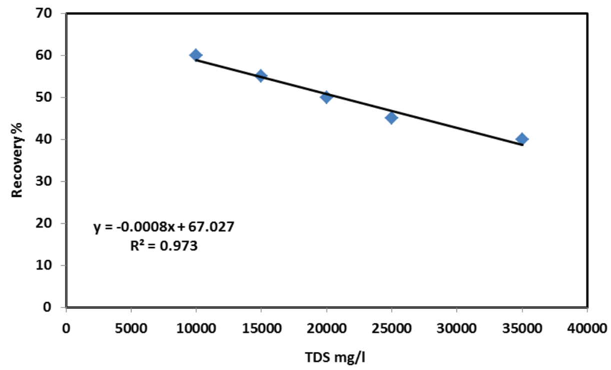


Fig. 2. RO recovery against feed water salinity.

$$BCR = \frac{Cumulative\ energy\ cost\ saving + Cumulative price\ of\ additional\ produced\ water}{FO\ membrane\ cost} \quad (12)$$

*2.2. Process design of hybrid FO/RO desalination systems*

In this section; process design of the integrated FO/RO system for desalination of seawater and brackish water are presented. In the desalination of sea water, the feed solution is industrial wastewater of Ezz steel factory. While, in brackish water desalination the feed solution used is El-Salam canal water (Egypt).

*2.2.1. Integrated FO/RO system using Ezz-steel treated wastewater*

Referring to the proposed system described in section 2.1.1, the integrated FO/RO plant consists of the following sections:

2.2.1.1. Seawater pretreatment section

The raw seawater is disinfected by dosing sodium hypochlorite and filtered through sand filters to remove any suspended particles or turbidity. Then the filtered seawater is chemically conditioned by injecting sodium bi-sulphite to de-chlorinate the feed water to the FO membranes. Also anti-scalant is injected in the feed water to inhibit any scaling potential inside the membranes. The filtered and chemically conditioned feed water is further filtered by 5 micron cartridge type filters to achieve good Silt Density Index (SDI).

2.2.1.2. Ezz Steel Company treated wastewater pretreatment section

The pretreatment procedures of Ezz steel wastewater are the same as mentioned above for pretreatment of seawater except that no anti-scalant is needed due to the low salinity of Ezz steel treated wastewater (around 1000 mg/l).

2.2.1.3. FO section

The filtered feed water is fed into seawater FO bank that is designed to produce adequate feed for RO unit to produce

100 $m^3$/d of RO permeate based on 24 h of operation. As mentioned above, 1 h retention time and 8.44 L/$m^2$ h water flux were chosen as basis of design. In addition, dilution rate of 250% was selected. Table 1 depicts the designed parameters of FO units estimated according to the developed model.

Based on pilot scale experimental results, total FO water recovery at DR 250% is 62.5%. Cath et al. investigated hybrid FO/RO system, they concluded that the integrated system is more economical at FO recovery rate more than 57%. Therefore, we assume here total recovery of FO unit to be 60% for the proposed integrated system.

Ezz steel wastewater flow rate = Recovered water in FO unit/0.6 = 5/0.6 = 8.3 $m^3$/h.

2.2.1.4. RO section

The RO feed water to RO bank will be pressurized by a high pressure pump to the required feed pressure in order to overcome the feed water osmotic pressure and drive the permeate water through the RO membranes. The brine water injecting the RO vessel under pressure will be utilized to drive an energy recovery unit which will boost the RO feed pressure in order to save electrical power consumption and reduce the operating cost of the plant. The RO bank is designed to operate at 60% recovery. Part of the RO permeate water will be used to flush saline water from the system each shut down, thus minimizing the possibility of corrosion of the stainless steel piping system and the scaling of the RO membranes due to high salt concentration. Brine reject from the RO membranes is continuously removed & disposed, while, the product water will be kept in storage tank. Fig. 3 represents the equipment Flow Diagram of Proposed FO/RO plant for seawater desalination using Ezz-Steel treated wastewater.

Table 1
Estimated design parameters of FO units

| Item | Equation | Value |
|---|---|---|
| F ($m^3$/day) | Permeate/% recovery | 167 |
| X ($m^3$/day) | $\frac{F}{(1+DR)}$ | 48 |
| FORW ($m^3$/day) | $\frac{DR*F}{(1+DR)}$ | 5 |
| FO membrane Cost ($) | $\frac{(DR*F)*\text{Cost of FO membrance per } m^2}{(FOWF)*(CT)*(1+DR)}$ | 593 |
| No. of elements | FOMA/module area | 34 |

*2.2.2. Integrated FO/RO system using El-Salam canal water*

The integrated FO/RO plant consists of the following sections:

2.2.2.1. Brackish water pretreatment section

Filter feed pump draw pre-chlorinated water from the raw water tank and feeds into the pressure multi-media filters provided with sand and supporting gravel. After the multi-media filter, the filtered water will be dosed by metered quantities of sodium bisulfite to remove any chlorine present in the raw water, then by acid and anti-scalant chemicals to reduce the risk of scaling in the membranes. This water is filtered further through 5-micron cartridge filter installed at the inlet of the FO train to protect the membranes from suspended solids that may have passed through the media filter.

2.2.2.2. El-Salam canal water pretreatment section

Due to the presence of organic contaminations in El-Salam Canal water, the pretreatment procedures are pro-

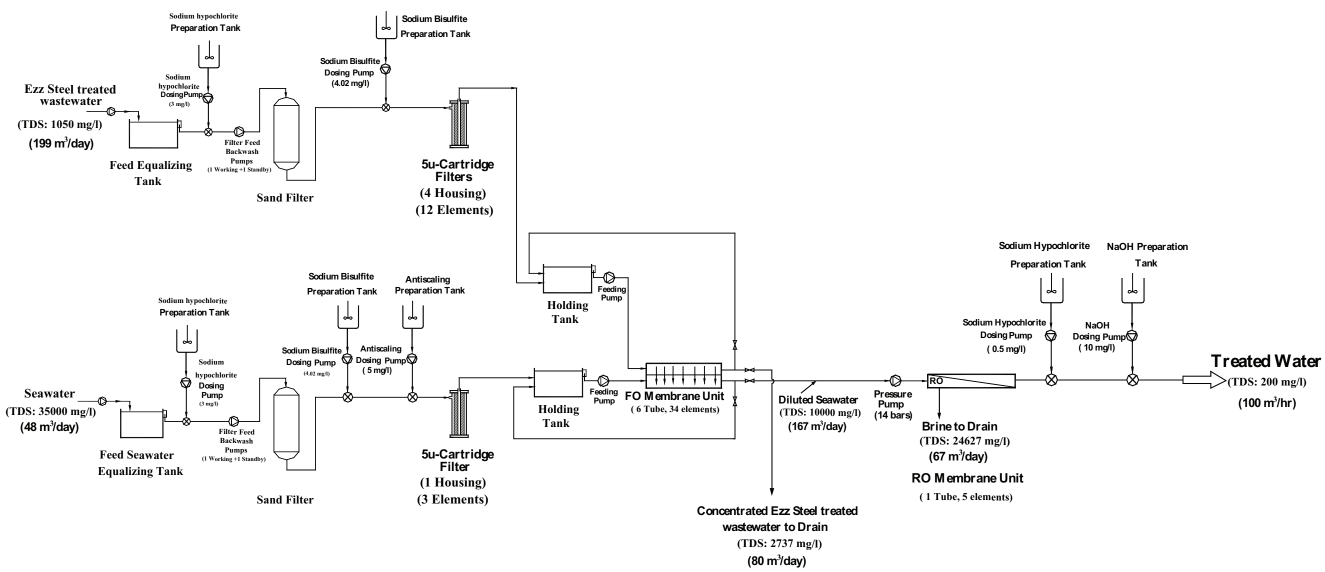


Fig. 3. Equipment flow diagram of proposed FO/RO plant for seawater desalination using Ezz-Steel treated wastewater.

posed to bethe same as mentioned above for pretreatment of brackish water to reduce the risk of membrane organic fouling.

2.2.2.3. FO section

The filtered feed water is fed into FO bank which is designed to produce adequate feed for RO unit to produce 100 $m^3$/d of RO permeate based on 24 h of operation. It was concluded from the results of pilot scale experiments that high water flux value was observed to be 4.58 L/$m^2$ h at 1.5 h. Accordingly, 1.5 h retention time and 4.58 L/$m^2$ h water flux were chosen as basis of design. Table 2 depicts the designed parameters of FO units estimated according to the developed model.

Assume 60% FO unit water recovery rate, hence

El-salam Canal flow rate = Recovered water in FO unit/0.6 = 3.5 /0.6 = 5.83 $m^3$/h ~ 6 $m^3$/h

Table 2
Estimated design parameters of FO units

| Item | Equation | Value |
|---|---|---|
| F ($m^3$/day) | Permeate/% recovery | 167 |
| X ($m^3$/day) | $\frac{F}{(1+DR)}$ | 83.5 |
| FORW ( $m^3$/day) | $\frac{DR*F}{(1+DR)}$ | 3.5 |
| FO membrane Cost ($) | $\frac{(DR*F)*\text{Cost of FO membrance per } m^2}{(FOWF)*(CT)*(1+DR)}$ | 506.4 |
| No. of elements | FOMA/module area | 29 |

2.2.2.4. RO section

The RO system consists of the same items as above. Fig. 4 demonstrates equipment flow diagram of proposed FO/RO plant for brackish water desalination using El-Salam Canal Water.

## 3. Results and discussions

### *3.1. Model results*

Table 3 summarizes the financial indicators of FO/RO hybrid system at the investigated dilution rates which include required FO membrane cost, RO power consumption, net energy saving, five years additional produced water price and benefit cost ration, and FO membrane cost payback time. Fig. 5 shows the effect of dilution rate on FO membrane required to attain the specified seawater dilution. It's obvious that the area increased gradually by increasing of dilution rate till 100% DR, then the increased rate lower slightly from 100 to 250%.

Based on the previous model calculations, the predicted relation that calculates the effect of osmotic dilution on FO membrane area is as follow:

$$FOMA = 4E\text{-}05\,(DR)^3 - 0.0198(DR)^2 + 4.1655\,(DR) \qquad (13)$$

Fig. 6 illustrates the effect of DR% on RO energy consumption and net FO/RO system net energy saving. It is clear that, by increasing of dilution rate the RO consumption decrease and consequently the net overall consumption of the hybrid system decrease. This can be attributed to the lowering of feed water salinty that reduce the required pumping of RO system.

The effect of DR% on annual benefit cost ratio during five years of operation is represented in Fig. 7. It is found that by increasing of time, the dependence of BCR on DR% is become obvious. Also, the highest BCR is obtained at higher dilution rates (200 and 250%).

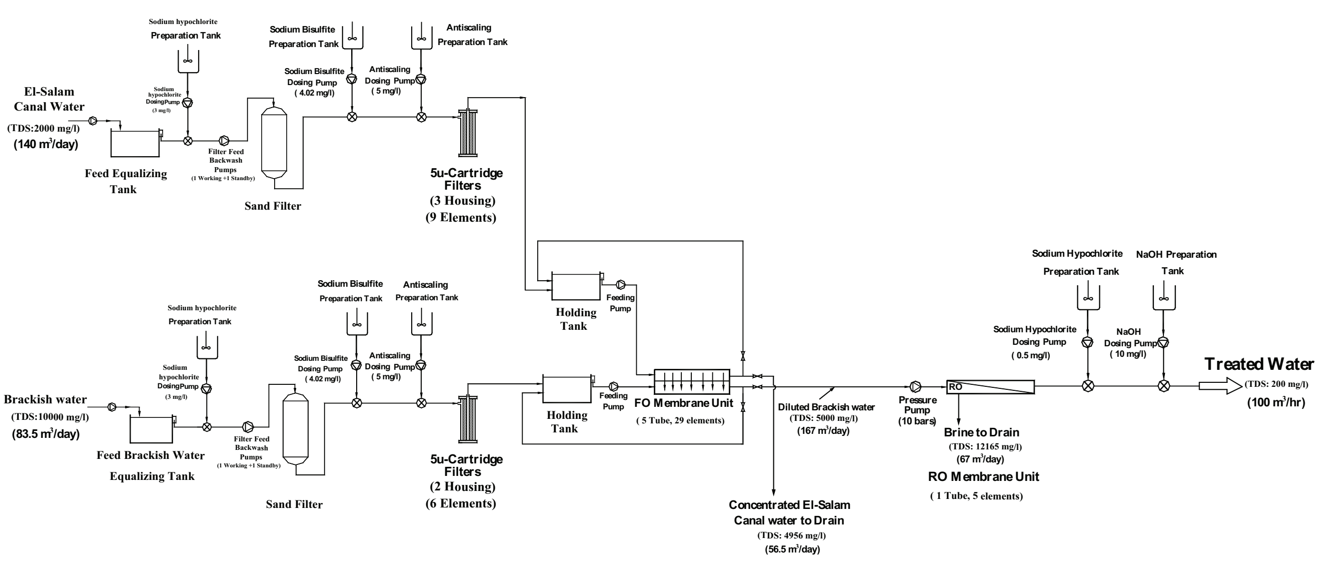


Fig. 4. Equipment flow diagram of proposed FO/RO plant for brackish water desalination using El-Salam Canal Water.

Table 3
Effect of seawater dilution rate on financial indicators of FO/RO hybrid system

| DR % | SWRO Feed TDS (mg/l) | FOMA ($m^2$) | FOMC ($) | RO NEC ($KWh/m^3$) | NES ($KWh/m^3$) | 5 Years NES Cost ($) | 5 Years APWP ($) | 5 Years BCR* | FOMC Payback Time (Years) |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 35000 | 0 | 0 | 4.51 | 0 | 0 | 0 | 0 | 0 |
| 10 | 31818 | 44.9 | 3475 | 4.12 | 0.39 | 1181 | 3263 | 1.3 | 5 |
| 20 | 29167 | 82.4 | 6377 | 3.68 | 0.83 | 2572 | 7545 | 1.59 | 4 |
| 40 | 25000 | 141.2 | 10927 | 3.20 | 1.31 | 3936 | 14275 | 1.67 | 4 |
| 60 | 21875 | 185.3 | 14340 | 2.81 | 1.7 | 5235 | 20392 | 1.79 | 4 |
| 100 | 17500 | 247 | 19114 | 2.33 | 2.18 | 7479 | 26510 | 1.78 | 4 |
| 150 | 14000 | 297 | 22984 | 1.98 | 2.53 | 9119 | 32628 | 1.82 | 4 |
| 200 | 11667 | 330 | 25537 | 1.74 | 2.77 | 10431 | 36706 | 1.85 | 3 |
| 250 | 10000 | 353 | 27317 | 1.57 | 2.94 | 11310 | 40785 | 1.91 | 3 |

*Based on membrane element life 5 y, NEC (net energy consumption), NES (net energy saving), APWP (additional produced waterprice)

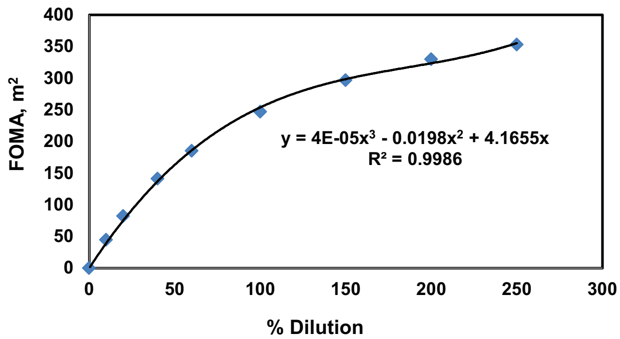


Fig. 5. Effect of % dilution rate on required FO membrane area.

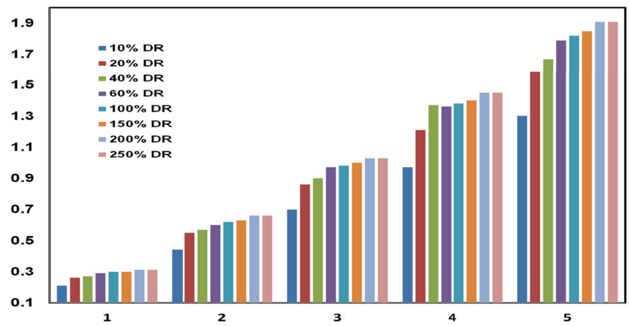


Fig. 7. Effect of dilution rate on annual BCR.

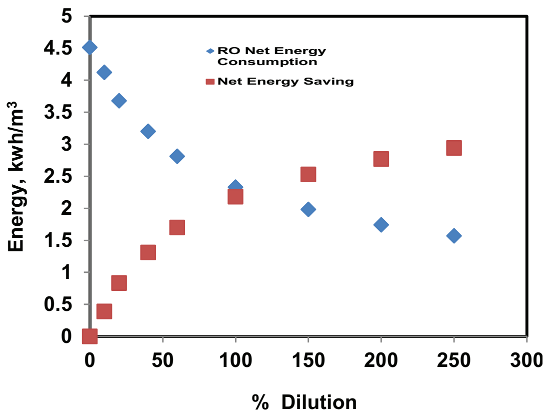


Fig. 6. Effect of dilution rate on RO energy consumption and net energy saving.

In conclusion, it is clear that all of financial indicators are positively affected by increasing of FO osmotic dilution which in turn decrease the payback time of the required FO membrane area.

## 3.2. Proposed hybrid systems preliminary economic estimation results

Cost estimation for the proposed hybrid system units is required for preliminary evaluation of the designed scheme. Production costs are basically divided into two categories; total fixed capital costs- incurred during plant construction- annual operating costs necessary to provide sustained operation for the plant after construction and depreciation rates. Data of fixed capital costs and annual operating costs were obtained from reliable sources.

### 3.2.1. Fixed capital costs

Fixed costs represent the capital necessary for the installed process equipment with all auxiliaries that are needed for complete process operation. This estimation requires determination of the purchased-equipment cost. The other items are then estimated as percentages of the purchased-equipment costs. Tables 4 and 5 present a list of purchased-equipment costs for the proposed hybrid system for Ezz-Steel and El-Salam canal water systems respectively. Values of the various percentages used in estimating the fixed-capital investment (F.C.I.) along with proportional costs of major components of total capital investment (T.C.I.) for both systems are demonstrated in Table 6.

### 3.2.2. Annual operating costs

The operating costs include; cost of chemicals, cost of utilities, cost of maintenance, and cost of labor. The various cost elements, directly connected with the treatment oper-

Table 4
List of purchased equipment and price for the integrated FO/RO system using Ezz-Steel treated wastewater

| Code No | Equipment item | Number of units | Capacity | Total price, $ |
|---|---|---|---|---|
| I-Pretreatment of seawater | | | | |
| 1 | Polyethylene water storage tank | 1 | 2.5 $m^3$ | 160 |
| 2 | Sodium hypochlorite dosing pump | 1 | 5 LPH | 395 |
| 3 | Day tank | 1 | 50 L | 35 |
| 4 | Sand media filter | | 2 $m^3$/h | 130 |
| 5 | Filter feed/backwash pumps | 2 | 2 $m^3$/h | 1310 |
| 6 | Sodium bisulfite dosing pump | 1 | 5 LPH | 395 |
| 7 | Day tank | 1 | 50 L | 35 |
| 8 | Tank mixer | 1 | 1500 rpm | 1310 |
| 9 | Dosing pump | 1 | 5 LPH | 395 |
| 10 | Day tank | 1 | 50 L | 65 |
| 11 | Tank mixer | 2 | 1500 rpm | 1310 |
| II-Ezz Steel wastewater pretreatment section | | | | |
| 12 | Polyethylene feed water storage tank | 1 | 11 $m^3$ | 720 |
| 13 | Sodium hypochlorite dosing pump | 1 | 5 LPH | 395 |
| 14 | Day tank | 1 | 50 $m^3$ | 35 |
| 15 | Sand media filter | 1 | 10 $m^3$/h | 655 |
| 16 | Filter feed/backwash pumps | 2 | 8.3 $m^3$/h | 1050 |
| 17 | Sodium bisulfite dosing pump | 1 | 5 LPH | 395 |
| 18 | Day tank | 1 | 50 $m^3$ | 35 |
| 19 | Tank mixer | 1 | 1500 rpm | 1310 |
| III- FO system | | | | |
| 20 | Polyethylene seawater holding tank | 1 | 2.5 $m^3$ | 165 |
| 21 | Polyethylene Ezzsteel pretreated wastewater holding tank | 1 | 11 $m^3$ | 720 |
| 22 | Seawater cartridge filter (5 – micron) | 1 housing (3 element) | | 130 |
| 23 | Ezz Steel pretreated wastewater cartridge filter (5 – micron) | 4 housing (12 element) | 5 – micron | 525 |
| 24 | Low pressure feed pump for seawater | 1 | 2 $m^3$/h | 655 |
| 25 | Low pressure feed pump for Ezz steel wastewater | 1 | 10 $m^3$/h | 525 |
| 26 | Membrane vessel | 6 | 200 mm (8″) diam. | 4210 |
| 27 | FO membrane elements | 34 | 17.6 $m^2$ | 46562 |
| IV- RO skid mounted system | | | | |
| 28 | Reverse osmosis membranes pressure vessels | 1 | 200 mm (8″) diam. | 785 |
| 29 | High pressure pump | 1 | 7$m^3$/h., 14 bars | 5900 |
| 30 | Reverse osmosis membranes | 5 | 8″ | 9150 |
| 31 | pH adjustment dosing pump | 1 | 5 LPH | 395 |
| 32 | Day tank | 1 | 50 $m^3$ | 35 |
| 33 | Post chlorination dosing pump | 1 | 5 LPH | 395 |
| 34 | Day tank | 1 | 200 L | 35 |
| 35 | Product water storage tank | 1 | 6 $m^3$ | 395 |
| Estimated total equipment cost ($ ) = 80717 | | | | |

ation for Ezz-Steel and El-Salam canal water systems are presented in Table 7.

### 3.2.3. Depreciation rate and treatment cost

Annual depreciation rate is estimated based on a useful-life period of 15 y of the fixed capital cost while the treatment cost is the sum of annual costs and depreciation per unit produced water, accordingly:

Depreciation rate = fixed capital cost/ life period

Estimated treatment cost = (Annual costs + Depreciation rate)/(Daily capacity × 365)

Table 8 summarizes the depreciation rate and treatment costfor both Ezz-Steel and El-Salam canal water systems.

Table 5

List of purchased equipment and price for theintegrated FO/RO system using El-Salam canal water

| Code No | Equipment item | Number of units | Capacity | Total price, $ |
|---|---|---|---|---|
| I-Pretreatment of Brackish water | | | | |
| 1 | Feed brackish water storage tank | 1 | 7 $m^3$ | 461 |
| 2 | Sodium hypochlorite dosing pump | 1 | 5 LPH | 395 |
| 3 | Day tank | 2 | 50 L | 33 |
| 4 | Sand media filter | | 4 $m^3$/h | 263 |
| 5 | Filter feed/backwash pumps | 2 | 3.5 $m^3$/h | 1316 |
| 6 | Sodium bisulfite dosing pump | 1 | 5 LPH | 395 |
| 7 | Day tank | 1 | 50 Liters | 33 |
| 8 | Tank mixer | 1 | 1500 rpm | 1316 |
| 9 | Dosing pump | 1 | 5 LPH | 395 |
| 10 | Day tank | 1 | 50 L | 33 |
| 11 | Tank mixer | 2 | 1500 rpm | 1316 |
| II- El-Salam Canal water pretreatment section | | | | |
| 12 | Feed water storage tank | 1 | 11 $m^3$ | 724 |
| 13 | Sodium hypochlorite dosing pump | 1 | 5 LPH | 395 |
| 14 | Day tank | 1 | 50 L | 33 |
| 15 | Sand media filter | 1 | 6 $m^3$/h | 395 |
| 16 | Filter feed/backwash pumps | 2 | 6 $m^3$/h | 1053 |
| 17 | Sodium bisulfite dosing pump | 1 | 5 LPH | 395 |
| 18 | Day tank | 1 | 50 L | 33 |
| 19 | Tank mixer | 1 | 1500 rpm | 1316 |
| III- FO system | | | | |
| 20 | Brackish water holding tank | 1 | 7 $m^3$ | 461 |
| 21 | El-Salam canal water holding tank | 1 | 11 $m^3$ | 724 |
| 22 | Brackish water cartridge filter (5 micron) | 2 housing (6 element) | | 263 |
| 23 | El-Salam canal water cartridge filter (5 micron) | 3 housing (3 element) | 5 – micron | 395 |
| 24 | Low pressure feed pump for brackish water | 1 | 3.5 $m^3$/h | 658 |
| 25 | Low pressure feed pump for El-Salam water | 1 | 6 $m^3$/h | 526 |
| 26 | Membrane vessel | 5 | 200 mm (8″) diam. | 3553 |
| 27 | FO membranes | 29 | 17.6 $m^2$ | 39868 |
| IV- RO skid mounted system | | | | |
| 28 | Reverse osmosis membranes pressure vessels | 1 | 200 mm (8″) diam. | 658 |
| 29 | High pressure pump | 1 | 7 $m^3$/h., 14. bars | 5921 |
| 30 | Reverse osmosis membranes | 5 | 8″ | 9211 |
| 31 | pH adjustment dosing pump | 1 | 5 LPH | 395 |
| 32 | Day tank | 1 | 50 L | 33 |
| 33 | Post chlorination dosing pump | 1 | 5 LPH | 395 |
| 34 | Day tank | 1 | 200 L | 66 |
| 35 | Polyethylene product water storage tank | 1 | 6 $m^3$ | 395 |
| Estimated total equipment cost ($) = 73819 | | | | |

#### *3.2.4. Economic comparison between proposed hybrid systems and RO system*

In this section, the proposed FO/RO systems for seawater and brackish water desalination are compared economically with the available standalone commercial RO desalination systems. The procedure of conventional RO commercial desalination plant is illustrated in Fig. 8.

Based on commercial offer from RO supplier [Emco (water solution provider), Dubai, UAE], the purchased equipment cost for 100 $m^3$/d RO seawater desalination plant is estimated to be $87,000. While, the purchased

Table 6
Estimation of total capital investment of proposed hybrid system for Ezz-Steel and El-Salam canal water systems

| Components | Price ($) (Ezz-Steel system) | Price ($) (El-Salam canal system) |
|---|---|---|
| I-Direct cost: | | |
| 1-Purchased equipment cost (E). | 80717 | 73819 |
| 2-Purchased equipment installation (7% E). | 5650 | 5167.33 |
| 3-Instrumentation and control (7% E). | 5650 | 5167.33 |
| 4-Piping (10%E). | 8071.7 | 7381.9 |
| 5-Electrical equipment and materials (5% E). | 4035.85 | 3690.95 |
| 6- Buildings (including services) (5 % E). | 4035.85 | 3690.95 |
| 7-Services facilities and yard improvement (3% E). | 2421.5 | 2214.57 |
| 8-Land (– % E). | – | – |
| Total direct cost (D) | 111581.9 | 101132.03 |
| II-Indirect cost: | | |
| 1-Engineering and supervision (5% D). | 5579 | 5056.6 |
| 2-Construction expenses and contractor's fee (7% D). | 7811 | 7079.24 |
| 3-Contingency (10% F.C.I.) | 13885.8 | 12585.32 |
| Total indirect cost (ID) | 24721.16 | |
| III-Fixed-capital investment (F.C.I.) | 138857.7 | 125853.2 |
| IV-Working capital (15% T.C.I.) | 24504.3 | 18878 |
| V-Total capital investment | 163362 | 144731.2 |

Table 7
Annual operating costs for Ezz-Steel and El-Salam canal water systems

| Component | Annual price in US $ (Ezz-Steel system) | Annual price in US $ (El-Salam canal system) |
|---|---|---|
| 1-Total chemicals costs (pre and post treatment) | 3158 | 4602 |
| 2-Utilities: | | |
| • Electrical Power consumption | 3371 | 2162 |
| • Cartridge filters | 1176 | 711 |
| • FO elements | 6184 | 5309 |
| • RO elements | 1220 | 1228 |
| 3-Maintenance (2.5% for installed equipment) | 2018 | 1845 |
| 4-Operating labor | 7059 | 7105 |
| Total Annual Operating Cost | 24186 | 22962 |

Table 8
Depreciation rate and treatment cost for Ezz-Steel and El-Salam canal water systems

| Item | (Ezz-Steel system) | (El-Salam canal system) |
|---|---|---|
| Depreciation rate ($/y) | 9257 | 8390 |
| Treatment cost ($/ m$^3$) | 0.92 | 0.86 |

equipment cost for 100 m$^3$/d RO brackish water desalination plant (10,000 mg/l) is estimated to be $45,000. Accordingly, as done in the previous section for the proposed FO/RO systems, preliminary economic evaluation for RO desalination plant for sea and brackish water was conducted. Table 9 represents the economic comparison of hybrid FO/RO system using Ezz-Steel treated wastewater with RO seawater desalination system, and hybrid FO/RO system using El-Salam Canal water with RO brackish water desalination system.

Firstly, with respect to Ezz-Steel case study at high FO dilution rate (250%), it is clear that the hybrid system is promising process. In which, all items of economic indicators are reduced with different percentages. For 100 m$^3$/d plant, the purchased equipment is reduced with about $6000, the annual chemical consumption reduced by 35%, while annual power consumption is markedly reduced by 67%. The reduction in chemicals cost is due to anti-scalant consumption decrease by reducing feed seawater flow rate in hybrid plant (from 250 to 48 m$^3$/d). In addition, FO sea-

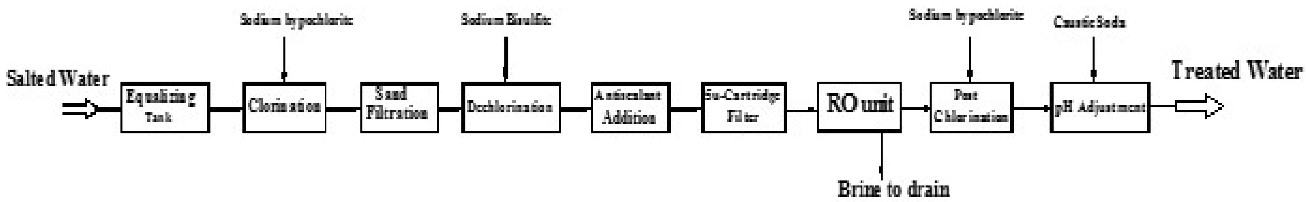


Fig. 8. Block flow diagram of conventional RO desalination plant for salted water.

Table 9
Economic comparison of FO/RO hybrid systems with conventional RO desalination processes

| Case study / Economic items ($) | FO/RO system using Ezz-Steel treated wastewater | RO seawater desalination | FO/RO system using El-Salam canal water | RO brackish water desalination |
|---|---|---|---|---|
| 1-Purchased equipment | 80717 | 87000 | 73819 | 45000 |
| 2-Chemicals | 3158 | 4887 | 4602 | 3826 |
| 3-Power consumption | 3371 | 9747 | 2162 | 3393 |
| 4-Cartridge filters | 1176 | 1184 | 711 | 789 |
| 5-FO elements | 6184 | – | 5309 | – |
| 6-RO elements | 1220 | 2947 | 1228 | 1228 |
| 7-Total annual operating costs | 24186 | 28060 | 22962 | 17474 |
| 8-Treatment cost | 0.92 $\m$^3$ | 1.04 $\m$^3$ | 0.86 LE\m$^3$ | 0.62 $\m$^3$ |

water dilution resulted in using brackish RO standalone system that used lower pressure and consequently the power consumption decreased (the energy consumption is 4.51 kW/m$^3$ for seawater desalination RO system and is 1.57 kW/m$^3$ for brackish water with TDS 10000 mg/l RO desalination system).

In spite of the above benefits of hybrid system, the cost of membranes replacement (FO and RO) is higher than that in RO system by 60%, this is attributed to higher numbers of FO elements that are used in hybrid process. But totally, the annual operating cost in hybrid system is lower than that in RO system by 13%. And, the water treatment cost is reduced from 1.04 to 0.92 $/m$^3$. It is obvious that, the only disadvantage of FO/RO hybrid system is using of high numbers of FO elements to attain the required dilution rate. This is contributed to the lower water flux and membrane surface area of the available commercial FO modules.

Secondly, with respect to El-Salam Canal case study at low FO dilution rate (100%), it is clear that the hybrid system is not economic process. In which, all items of economic indicators are higher with different percentages. For 100 m$^3$/d plant, the purchased equipment is higher than that of commercial RO unit by about 63%, the annual chemical consumption is higher by 20%, while annual power consumption is reduced by 36%.

### *3.3. Forecasting integrated FO/RO cost by FO membrane development*

One of the major challenges to be overcome is the lack of an optimized FO membrane that can produce a high water flux comparable to commercial RO membranes. Hydranautics Company is specialized in production of different membrane types and recently they have been working for many years on the development of novel membrane and modules that can be applied in FO-based processes. Hydranautics provided us with a technical offer for the proposed FO modules which have flux up to 24 LMH and 100 m$^2$ surface area. In addition, they concluded that the installed equipment cost for FO desalination unit with some basic pretreatment is ranged from $25–45 per m$^3$ of purified water. This means that, for FO desalination system with capacity of 100 m$^3$/d, the equipment cost is ranged from 2516 to 4529$ which is very promising indicator. They indicated that much more work is needed to validate the assumptions and come up with more reliable cost values.

Suggesting that this membrane is commercially available, a predicted cost indicators for the two cases under study can be estimated as follows:

### *3.4. Ezz Steel Company*

The number of modules used in this suggested system according to the above derived equations is shown in Table 10.

As observed, the required number of elements is three elements compared with 34 elements in our proposed system.

Based on the technical offer of Hydranautics Company [12], the preliminary estimate cost of seawater FO unit is around $25–45/m$^3$. Herein assuming that it equals $45/m$^3$, accordingly the price of three FO elements required for 100 m$^3$/d FO desalination plant is estimated to be $4500.

Table 10
Estimated design parameters of FO units

| Item | Equation | Value |
|---|---|---|
| F ($m^3$/d) | Permeate/% recovery | 167 |
| X ($m^3$/d) | $\frac{F}{(1+DR)}$ | 48 |
| FORW ($m^3$/d) | $\frac{DR*F}{(1+DR)}$ | 119 |
| FO membrane Cost ($) | $\frac{(DR*F)*\text{Cost of FO membrance per } m^2}{(FOWF)*(CT)*(1+DR)}$ | 275.5 |
| No. of elements | FOMA/module area | 3 |

Table 11
Comparison between the different systems proposed for Ezz Steel case study

| Item | Suggested system | Our proposed system | Commercial RO desalination |
|---|---|---|---|
| Purchased equipment cost ($) | 34445 | 73819 | 87000 |
| Membrane replacement cost ($) | 1820 | 7404 | 2947 |
| Annual operating cost ($) | 17445 | 24186 | 28060 |
| Total treatment cost ($) | 0.59 | 0.92 | 1.04 |

Accordingly, we can estimate the purchased equipment cost and annual operating cost for the suggested hybrid system and compare it with the proposed system and the commercial RO desalination system.

From the above comparison, we found that the suggested system is very promising for future application of FO desalination systems.

### *3.5. El Salam Canal*

As suggested above, if we use the Hydranautics membrane module, we can estimate the number of modules used according to the equations shown in Table 12.

Based on this data, the required numbers of elements are five elements compared with 29 elements in our proposed system.

As illustrated above, the cost of three elements is estimated to be $4500 (1500 $/elements). Accordingly, the cost of five elements is $7500, so the purchased equipment cost and annual operating cost for the suggested hybrid system can be estimated and compared with the proposed system and the commercial RO desalination system.

From the above comparison, it is clear that the economics of suggested system are lower than the proposed system and approximately the same as the commercial RO system for brackish water desalination.

Table 12
Estimated design parameters of FO units

| Item | Equation | Value |
|---|---|---|
| F ($m^3$/d) | Permeate/% recovery | 167 |
| X ($m^3$/d) | $\frac{F}{(1+DR)}$ | 48 |
| FORW ($m^3$/d) | $\frac{DR*F}{(1+DR)}$ | 83.5 |
| FO membrane Cost ($) | $\frac{(DR*F)*\text{Cost of FO membrance per } m^2}{(FOWF)*(CT)*(1+DR)}$ | 445.3 |
| No. of elements | FOMA/module area | 5 |

Table 13
Comparison between the different systems proposed for El-Salam Canal case study

| Item | Suggested system | Our proposed system | Commercial RO desalination |
|---|---|---|---|
| Purchased equipment cost ($) | 37898 | 561000 | 45000 |
| Membrane replacement cost ($) | 2228 | 6537 | 1228 |
| Annual operating cost ($) | 17756 | 22962 | 17474 |
| Total treatment cost ($) | 0.6 | 0.86 | 0.62 |

## 4. Conclusions

In this study, an economic model was developed to calculate the effect of osmotic dilution rate of seawater feed stream on the required FO membrane area. It is observed that all financial indicators are positively affected by the increasing of FO osmotic dilution which in turn decrease the payback time of the required FO membrane area.

In addition, a process design and a preliminary economic study for hybrid FO/RO system with 100 $m^3$/day capacity, including material and energy balance calculations, equipment sizing and selection were developed for the selected two cases: Ezz Steel treated wastewater with seawater and El-Salam Canal water with brackish water. From the calculated treatment cost,it was found that FO/RO hybrid system for desalination is a promising system in case of high TDS draw solution (such as seawater) but it is not benefit in case of low TDS draw solutions (such as brackish water).

Suggesting the availability of a modified FO membrane with higher flux (24 LMH) and higher surface area (100 $m^2$); the comparison between FO/RO hybrid systems with the commercial RO indicated that the suggested system will be economically in the two cases under study.

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## Symbols and abbreviations

| | | |
|---|---|---|
| BCR | — | Benefit cost ratio |
| BWRO | — | Brackish water RO membranes |
| CT | — | Circulation time |
| DR | — | Dilution rate |
| DS | — | Draw solution |
| EC | — | Energy consumption |
| $EC_{dSW}$ | — | Energy consumption at selected DR% |
| $EC_{SW}$ | — | Energy consumption at zero dilution |
| ES | — | Energy saving |
| F.C.I | — | Fixed-capital investment |
| F | — | Feed flow rate to RO unit |
| FO | — | Forward osmosis |
| FOMA | — | FO membrane area |
| FORW | — | Recovered water from FO system |
| FOWF | — | FO membrane water flux |
| FS | — | Feed solution |
| $R_{dSW}$ | — | Percent recovery of diluted seawater |
| RO | — | Reverse osmosis |
| $R_{SW}$ | — | Percent sea water recovery |
| SDI | — | Silt Density Index |
| SWRO | — | Seawater reverse osmosis |
| T.C.I | — | total capital investment |
| X | — | Sea water flow rate |

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