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Retrofitting assessment of a full-scale brackish water reverse osmosis desalination plant with a feed capacity of 600 m^3/d

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ABSTRACT

Reverse osmosis (RO) is the most widespread technology in the desalination of seawater (SW) and brackish water (BW). In BW desalination, the use of energy recovery systems is not as evident as in the desalination of SW, due to the other factors such as higher flux recoveries and lower specific energy consumptions. This paper studied the economic feasibility of installing interstage pump and RO membrane replacement by nanofiltration in a BWRO desalination plant with a feed capacity of 600 m^3/d. Experimental data over the course of more than 2 y of nonstop operation were collected. The BWRO desalination plant had microfiltration and antiscalant dosing as pretreatment and RO system with two stages, 3 pressure vessels (PV) in the first stage and 2 in the second stage with 6 RO membrane elements for each PV. The production of the plant is for agricultural irrigation. A study was made considering different scenarios regarding the plant's efficiency, permeate quality, and economic viability.

Keywords: Brackish water; Reverse osmosis; Long term; Nanofiltration; Hybrid system; Irrigation

1. Introduction

Reverse osmosis (RO) is the leading desalination technology in the world as 80% of today's desalination plants use it, and the global tendency is expected to be increased [1]. In fact, important efforts are being made to improve the efficiency of this technology by using new materials [2,3] and feed spacer geometries [4]. Usually, this technology is used to desalinate seawater (SW) and brackish water (BW). In full-scale SWRO desalination plants, the specific energy consumption (SEC) of the RO system ranges between 2 and 4 kWh/m^3, whereas for BWRO desalination plants, it sits between 0.5 and 1.5 kWh/m^3 [5,6]. In BWRO, higher recovery rates than in SWRO can be achieved due to water salinity [7], which makes BWRO more efficient in most cases despite the environmental issues of inland plants [8–10]. In BWRO, there may be multiple designs and operating points that satisfy the desired conditions of water production and quality [11–13].

The design and operating conditions of an RO system are key in its performance in the long term [14]. There is a substantial amount of researches that had been done on BWRO. BWRO systems can be designed in a variety of ways depending on the number of membranes in a module and the arrangement of the RO system. Vince et al. [15] discussed about the number of membranes in a module. The author has shown that using seven membranes for both first and second stages will result in a recovery rate of 82%, with a recovery rate of 64% for the first stage and a recovery rate of 50% for the second stage. Nemeth [16] provides insight into optimizing the performance of ultra-low-pressure RO membranes in an innovative system design. This author proposed utilizing a hybrid combination of ultra-low and conventional RO membranes. Additional changes are incorporating interstage pressure boosting and utilizing permeates throttling in the

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first stage. There is a lack of data available on the long-term performance of BWRO desalination plants, and there are even less data compiled before and after changing the RO system design in the same desalination plant.

Nanofiltration (NF) technology proved to be a solid alternative to RO in BW desalination [17]. This technology allows to reduce the SEC, but it implies a higher total dissolved solids (TDS) in the permeate when compared with RO [18–20]. Several studies have proposed NF/RO hybrid systems due to SEC reduction [21–23]. The weakness of NF is the low rejection of salts in comparison with RO. This is a handicap when the permeate is for drinking water. However, if the permeate is for agricultural purposes, there would be no such problem, since there are crops that can tolerate high salinity [24–27].

This paper studied the different possibilities of retrofitting in order to improve the performance of a full-scale BWRO desalination plant for agricultural purposes. The installation of energy recovery devices is ruled out since their performance in BWRO is not high (i.e. turbocharger, around 45% for the turbocharges); hence, it is not economically viable. This study is focused on membrane replacement cost considering NF, RO, and hybrid NF/RO systems.

2. Materials and methods

The full-scale BWRO desalination plant is located in Gran Canaria (Canary Islands, Spain). It was designed to desalinate groundwater well in order to irrigate banana crops. The operating data from 2004 to 2015 of this plant have been already published [14]. In September 2015, a membrane replacement was performed keeping the same arrangement in the RO system (3 pressure vessels (PV) of 6 elements in the first stage and 2 PV of 6 elements in the second stage). Fig. 1 shows a flow diagram of the BWRO desalination plant. The antiscalant used was Osmotech® 1141, and the membrane installed was the BW30-400 in both stages due to its stability and robustness. A single chemical cleaning took place by the 11,000th hour approximately. A detailed plant description is provided in a previous paper [14]. From September 2015 to January 2018, the desalination plant was operative for around 20,000 h. Operating parameters such as feed pressure, feed conductivity, pressure drop in both stages, permeate flow, and permeate conductivity were collected. Water analyses were carried out, so that a relation between conductivity and TDS in the permeate was used in order to calculate the osmotic pressures. As expected, there were some differences between the actual operating data and the simulated data by the manufacturer software (WAVE). The same gap between the actual and the simulated data for the NF membranes was maintained for our study. Four scenarios were studied; the first and the second comprised a membrane replacement for both stages by NF-270 and NF-90, while the third and the fourth included only a membrane replacement in the first stage by NF-270 and NF-90 keeping the BW30-400 in the second stage.

2.1. Operating data

The intake of the plant is a groundwater well. Table 1 shows the inorganic composition of the feedwater. It bears mentioning that these values fluctuate throughout the year, which play an important role in the performance of the BWRO desalination plant. Fig. 2 shows the fluctuation of the feedwater conductivity during the operating time: between 3,900 and 5,300 µS/cm, in terms of osmotic pressure (π) around 100 kPa. The raw water temperature was quite constant at around 22°C. The feed pressure experienced an increase of 200 kPa in 2.5 y (Fig. 3). After the chemical cleaning (11,000th hour), the feed pressure was reduced around 100 kPa, keeping the same water production. The chemical cleaning products were from Kurita Water Industries Ltd, Osmotech 2691 (alkaline) and Osmotech 2575 (acid). Fig. 4 shows the flux recovery, which was around 60% during this

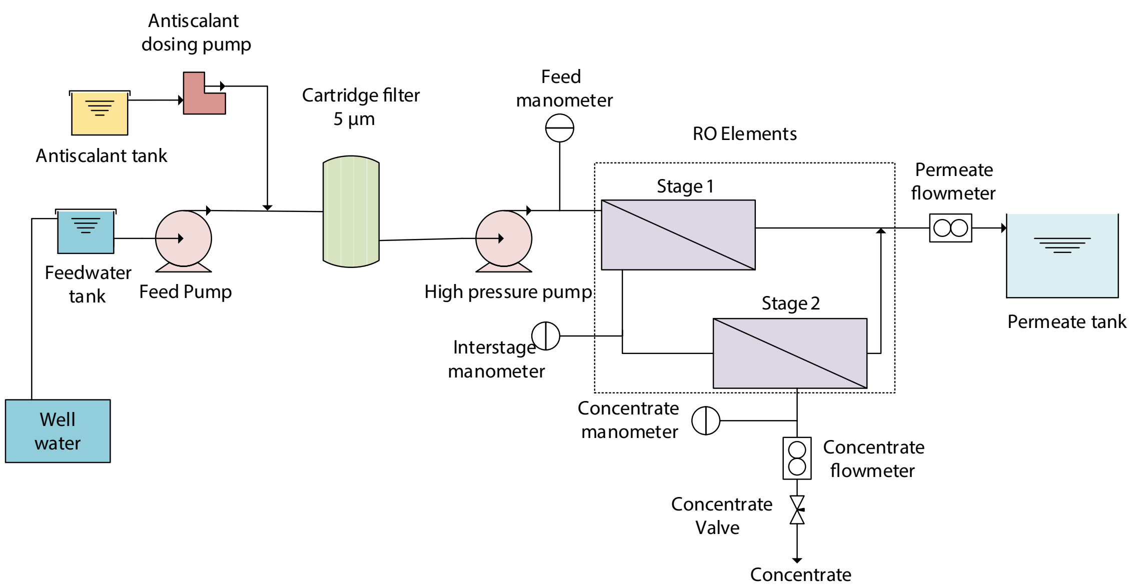

Fig. 1. Desalination plant flow diagram.

Table 1
Feedwater inorganic composition

	Concentration (mg/L)
Ca^{2+}	55
Mg^{2+}	71
Na^{+}	940
K^{+}	24
HCO_3^-	920
SO_4^-	380
NO_3^-	150
Cl^-	900
SiO_2	44
B	5.74
TDS	3,439

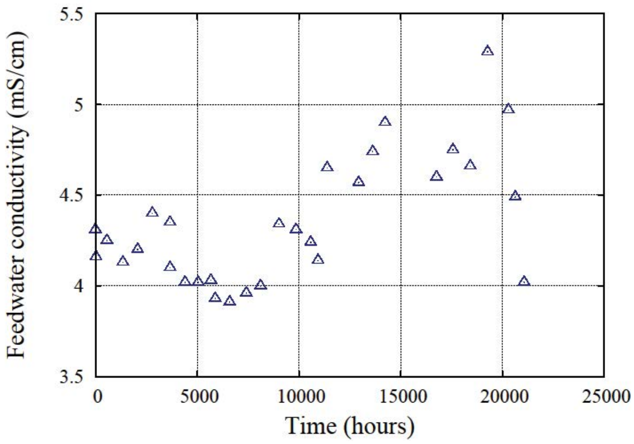

Fig. 2. Feedwater conductivity.

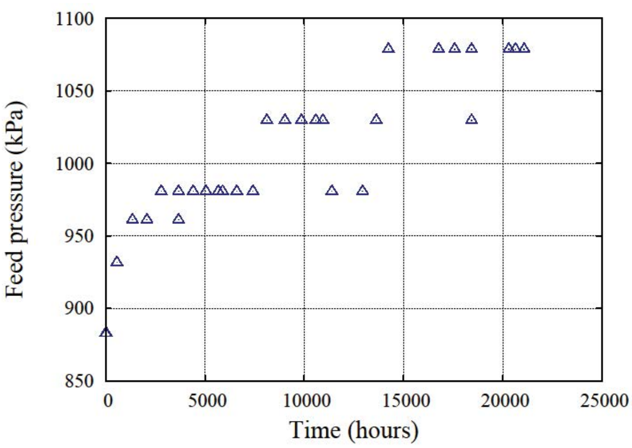

Fig. 3. Feed pressure.

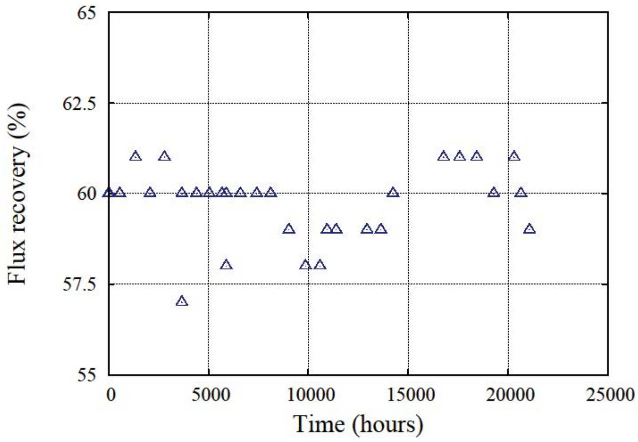

Fig. 4. Flux recovery.

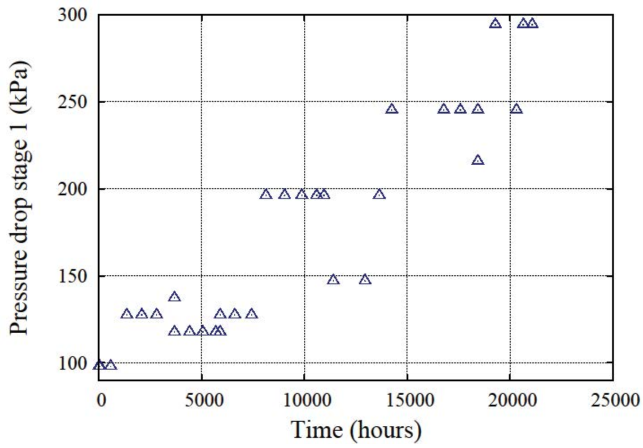

Fig. 5. Pressure drop in stage 1.

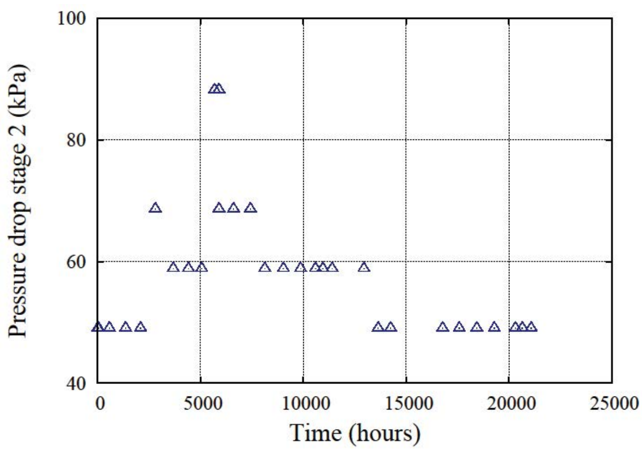

Fig. 6. Pressure drop in stage 2.

operating period. Figs. 5 and 6 show the pressure drop in both stages. Due to water requirements, the permeate flow was close to 15 m^3/h and the permeate water conductivity ranged from 100 to 300 μS/cm (Fig. 7) most of the time, which is quite acceptable for irrigation. Fig. 8 shows the average water permeability coefficient (*A*) decay. This parameter is a good reference to estimate the performance decrease of the RO system. Coefficient A was calculated using the Eq. 1.

$$J = A\left(\Delta p - \Delta \pi\right) \quad (1)$$

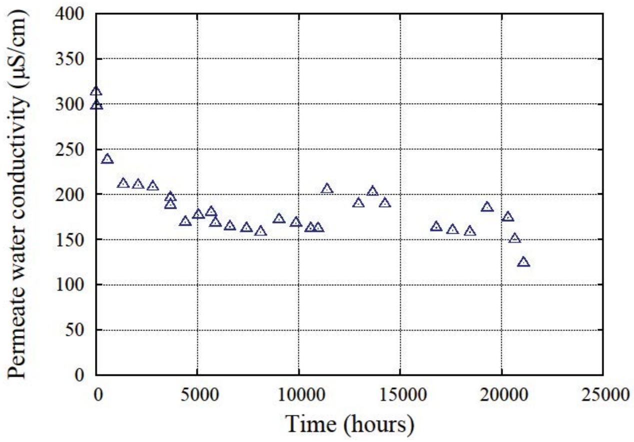

Fig. 7. Permeate conductivity.

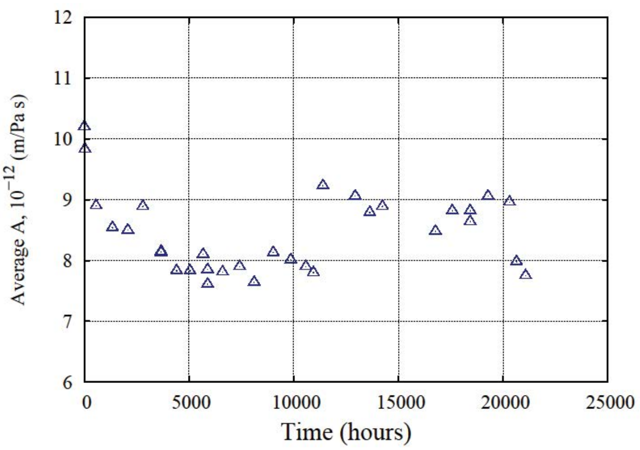

Fig. 8. Average *A*.

where J is the permeate flux per unit area in m/s and $(\Delta p - \Delta\pi)$ is the net driving pressure:

$$(\Delta p - \Delta\pi) = p_f - \frac{\Delta p_{fb}}{2} - p_p - \pi_{fb} + \pi_p \quad (2)$$

where p_f is the feed pressure (Pa), $\Delta p_{fb}/2$ is the average pressure drop (Pa), p_p is the permeate pressure (Pa), π_{fb} is the feed-brine osmotic pressure (Pa), and π_p is the permeate pressure (Pa).

The solute permeability coefficient (B) is different for each ion. In this paper, an average B was calculated following the next equation [12] according to the solution-diffusion model:

$$B = \frac{C_p}{\mathrm{PF} \times \mathrm{TCF} \times \frac{S_m}{Q_p}\left(\frac{C_f(1+\mathrm{CF})}{2}\right)} \quad (3)$$

$$\mathrm{PF} = \exp(0.7 \times Y) \quad (4)$$

$$\mathrm{CF} = \frac{C_b}{C_f} \quad (5)$$

where C_p is the permeate concentration (mg/L), PF is the average polarization factor, S_m is the active area (m^2), Q_p is the permeate flow (m^3/s), C_f is the feed concentration (mg/L), CF is the average concentration factor, Y is the system recovery as a fraction, and C_b is the brine concentration (mg/L).

2.2. Simulations

The software WAVE v1.5 from Dow® was used to run different arrangements. Although it allows different RO elements to be chosen for different stages, there can be only one type of element per stage. The feedwater composition of Table 1 was used in these simulations. First, the current RO system (Fig. 9) was simulated in order to determine the difference with the initial operating point. The actual p_f and the obtained value by the manufacturer software for the same operating condition in the existing RO system were very close, so the results obtained from the simulations for the different scenarios were used in the cost analysis. The SEC was calculated assuming a 70% as high pressure pump performance. The increase of the SEC in the RO systems due to fouling effect was assumed to be the same for the different arrangements. Including interstage pump did not represent a considerable improvement as the actual performances of these devices are between 55% and 60%, being the price around €3,000. It also increases the difficulty of operation. So the simulations and results including this device was not included.

Four scenarios were considered: two total RO membrane replacements by NF membranes (Figs. 10 and 11) and two hybrid systems (Figs. 12 and 13).

2.3. Cost analysis

The net present value (NPV) [Eq. (6)] and the internal rate of return (IRR) were calculated for a period of 7 y. This period in addition to 3 y that the membranes have been in operation would be 10 y, which is a reasonable operating life for this kind of membranes. Only the membrane replacement was considered as the investment costs (I_c). The membrane elements NF90-400/34i and NF270-400/34i cost €813 and €792, respectively (including transport and replacement).

$$\mathrm{NPV} = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t} - I_c \quad (6)$$

where R_t is the net cash flow, i the discount rate (10%), and t is the time of the cash flow. It should be noted that this study is based on the cost savings by reducing the SEC due to membrane replacement as the rest of the operating and maintenance costs (chemical cleaning frequency, antiscalant dose, etc.) were assumed the same for all scenarios. The cases evaluated were number 2 (Fig. 10) and 4 (Fig. 12) due to water quality requirements. The study of case 4 is delicate because it has a first stage with new membranes (NF90) and a second stage with an almost 3-y-old membrane. To evaluate the SEC in this case, a coefficient was applied based on the production of the second stage (10%) in the simulation and the age of the membranes in the aforementioned stage.

The electrical energy price became complex from the beginning of the free market in Spain. There are prices in

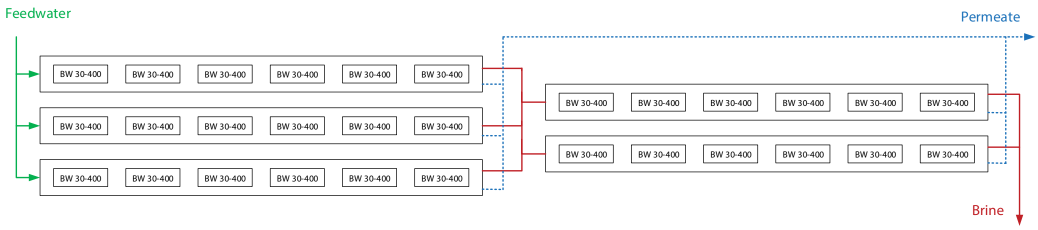

Fig. 9. Current RO system.

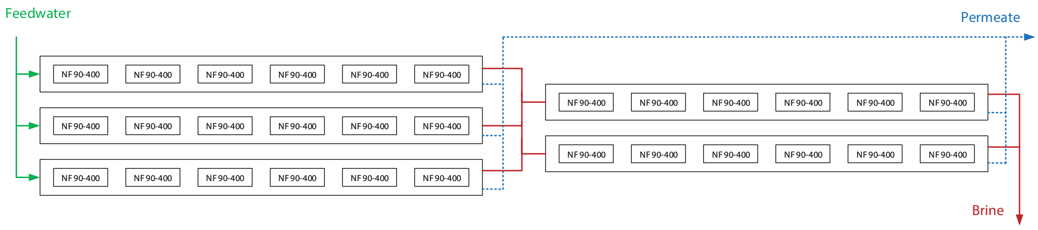

Fig. 10. RO system with NF90-400/34i membrane.

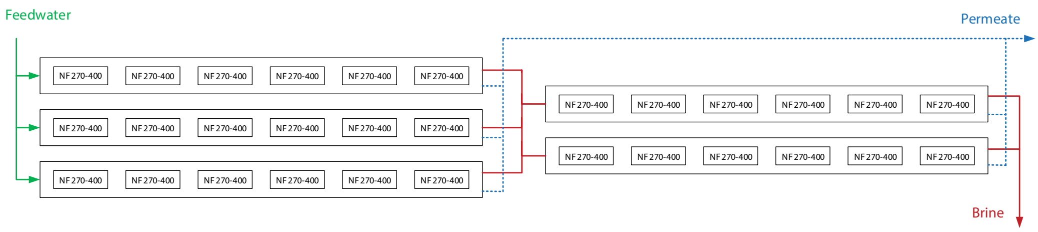

Fig. 11. RO system with NF270-400/34i membrane.

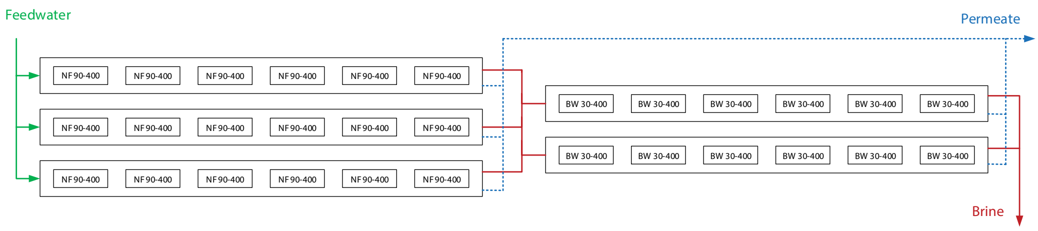

Fig. 12. Hybrid RO system with NF90-400/34i and BW30-400 membranes.

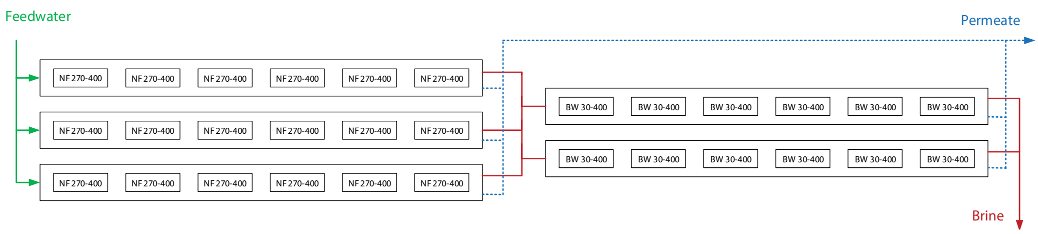

Fig. 13. Hybrid RO system with NF270-400/34i and BW30-400 membranes.

terms of power and consumption, different prices for each day of the week and periods per day. This is the reason why a current average price was used in this work (13 c€/kWh), disregarding the fluctuations of the electrical energy price.

3. Results and discussion

Table 2 shows the different performances in terms of water and salt permeability, which is related to the TDS in the permeate and the SEC of the five RO arrangements. The coefficients *A* and *B* were expressed as averages in the entire RO system as well as in the current system due to the experimental data availability. The membrane with the lowest SEC had the less solute rejection. An SEC reduction of about 62% could be achieved with the membrane NF270-400/34i in both stages; however, it would result in an increase of more than ten times the TDS in the permeate in comparison with the current system. For banana crops, TDS < 700 mg/L is recommended; the type of crop plays an important role in the performance of the RO system. Another factor that should be taken into account is the concentration of some specific ions that may be harmful for the crop, like boron, etc. [24,25].

Figs. 14 and 15 show the TDS in the permeate and the SEC of the possible arrangements compared with the real operating data in the current system. Considering the type of crop, we studied the two alternatives that kept the TDS in the permeate below 500 mg/L. The rest of the arrangements could be feasible for other types of crops.

Table 2
Simulations of the RO arrangements

Membranes	Average A (m/Pa·s)	Average B (m/s)	TDS_p (mg/L)	SEC (kWh/m³)
BW30-400	8.3802E-09	1.0870E-07	113	0.60
NF90	2.2930E-08	4.6154E-07	503	0.34
NF270	3.0142E-08	1.4177E-06	1,778	0.23
NF90-BW30-400	2.0203E-08	3.4493E-07	370	0.39
NF270-BW30-400	2.7686E-08	1.2194E-06	1,483	0.29

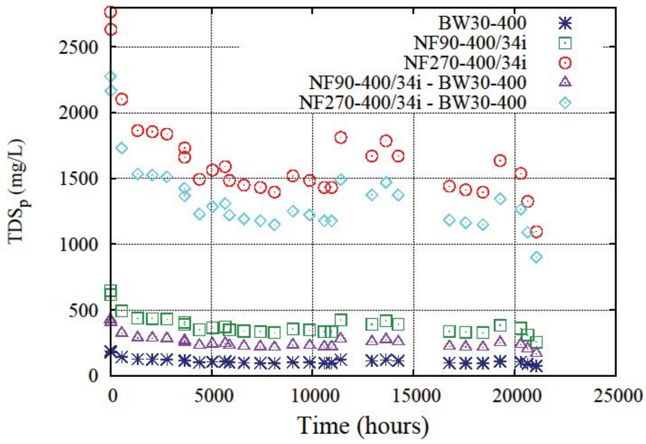

Fig. 14. TDS in the permeate for the different arrangements.

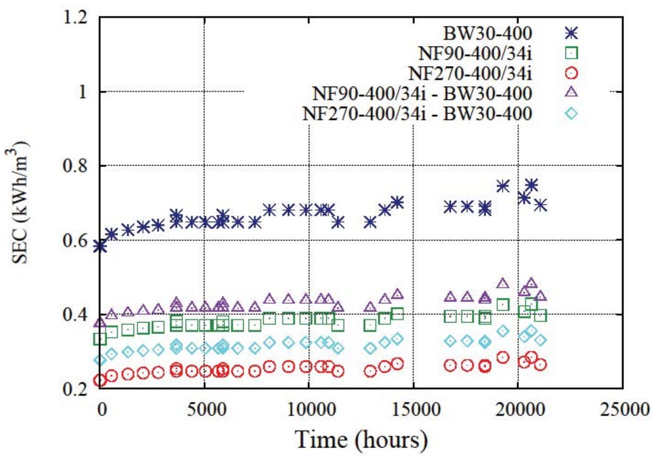

Fig. 15. SEC for the different arrangements.

Table 3
NPV and IRR for the arrangements of Figs. 10 and 12

Membranes	NPV (€)	IRR (%)	Amortized after (years)
NF90	8,586.14	20	4
NF90-BW30-400	11,773.34	32	3

Table 3 shows the results of the cost analyses. From an economic point of view, the best option would be to replace the first stage with the membrane NF90-400/34i. The cost of this replacement would be amortized after 3 y of operation; however, the amortization of the complete membrane replacement of the RO system would take 4 y of operation. The savings for the partial replacement were between €5,000 and €7,000/y. For the complete replacement, they were between €6,000 and €8,000/y. But the replacement costs were €24,390 and €14,634 for the complete and partial replacements, respectively.

4. Conclusions

This study has shown the performance of a BWRO desalination plant working with a production of 360 m³/d for irrigation purposes. After evaluating a partial and complete membrane replacement of the RO system, one can conclude that the membrane NF90-400/34i could be suitable for banana crop due to permeate quality requirements.

For crops with more solute tolerance, the membrane NF270-400/34i would be more interesting. The fouling effects on membranes were considered the same as there is a lack of literature pertaining to operating data in the long term and under similar operating conditions. NF membranes work with higher permeate fluxes, which can be an issue when dealing with biofouling. As a consequence, there is a chance that chemical cleaning could increase in comparison with the current system. We can conclude that, if the permeate quality requirements are not very high in terms of TDS or concentration of some specific harmful ions for the crops, the use of NF membrane alone or in combination with BWRO membranes could reduce notably the operating costs when dealing with energy consumption. Long-term experimental data of industrial hybrid systems NF/RO would help to understand the possible operating problems and the real viability of these plants working under real conditions.

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