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Case study: reduction in energy consumption with second generation thin-film nanocomposite membranes in La Caleta seawater desalination via reverse osmosis (Canary Islands, Spain)

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ABSTRACT

Nowadays, seawater desalination via reverse osmosis (SWRO) is one the most efficient methods to produce safe and reliable water for communities worldwide. However, energy consumption in SWRO, which can account for up to thirty to fifty percent of the total operational cost of a seawater desalination plant, remains the main handicap for further reduction in the cost of desalinated water. Thin-film nanocomposite (TFN) reverse osmosis (RO) membranes combining competitive permeability with very high salt rejection offer superior permeate water quality with potential energy savings in SWRO operation. The Canary Islands is a Spanish Archipelago located in the Atlantic Ocean off the coast of the Sahara Desert. Europe's first desalination facility, and a first of its kind globally, was established in the Canary Islands, making the region a global benchmark in the industry. Currently, there are over 300 plants within its seven islands. La Caleta is a SWRO plant located in Adeje, Tenerife, one of the two major islands in the archipelago. The plant had an initial capacity of 10,000 m^3/d. In 2019, the plant replaced one full train with a total capacity of 5,000 m^3/d with TFN membranes to improve performance in permeate quality and other operational parameters. In the same year, the plant capacity increased to 12,000 m^3/d by adding two containerized plants with TFN membranes installed. After a few months of operation, a pilot study to test the second generation of TFN membrane model with even higher rejection started at La Caleta SWRO. This study aimed to verify the performance of the newly developed TFN RO membrane, compare it with the previous generation membrane already operated in the plant, and assess its potential advantages regarding energy savings during operation.

Keywords: Seawater desalination via reverse osmosis; Energy; Thin-film nanocomposite

1. Seawater desalination with reverse osmosis

Reverse osmosis (RO) is a water purification process that uses a partially permeable membrane to separate ions, unwanted molecules, and larger particles from drinking water. In reverse osmosis, an applied pressure is used to overcome osmotic pressure, a colligative property that is driven by chemical potential differences of the solvent, a thermodynamic parameter. Reverse osmosis can remove many types of dissolved and suspended chemical species as well as biological ones from water, and is used in both industrial processes and the production of potable water [1].

At the University of California, Los Angeles in 1950 was the first time reverse osmosis and semipermeable membranes were investigated for seawater desalination. A few years later, freshwater was produced from seawater for the

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first time. However, membrane fluxes were still very low to be commercially viable [2].

In the early 1970s, polyamide chemistry for RO membranes was developed. The initial use of the membranes with this chemistry was limited to brackish water (BW) applications. Further evolution of this technology allowed its use for seawater at the beginning of the 1980s [3]. In Spain, the first seawater desalination plant using RO membranes was built in 1982 in Lanzarote (Canary Islands) [4,5].

Today, seawater desalination via reverse osmosis (SWRO) is one of the most efficient ways to produce a reliable source of potable water for mass populations [6]. Despite significant advancements in desalination technologies, it is still more energy-intensive than conventional methods for treating freshwater. energy consumption remains the main handicap of this process, and a tremendous amount of effort is centralized around this matter. The key energy factors in desalination and the potential energy savings are shown in Table 1 [7].

Table 1 shows that innovations and improvements in membrane element design and reduction of system energy consumption and productivity losses could contribute up to an additional 15% in energy savings.

The desalination industry has witnessed numerous innovations in engineering solutions for RO systems in the past years. Larger-sized pressure vessels and membranes, closed-circuit RO systems, permeate split, hybrid membrane design, or high pressure pumps array configuration are examples of improvements using the existing technology. Furthermore, the specific energy consumption of using SWRO decreased by approximately 90% over the past 40 years, from around 20 to 2 kWh/m^3 [8].

Today, polyamide-based chemistry is the most common technology used for RO membrane production. A typical polyamide (PA) thin-film composite RO membrane consists of three distinct layers: polyester nonwoven carrier, porous polysulfide, and thin polyamide active layer. Membrane sheets and other components such as feed and permeate carriers are spirally wound into a membrane element. Improvements in chemistry and full automation of PA membrane manufacturing allow for better control that results in a thinner membrane flat sheet while improving its durability, consistency, and precision. Consequently, more membrane material can fit into the same form-factor element translating into a larger active membrane area. These improvements have been major drivers for increased flow rate and salt rejection of RO membranes, the two factors that define the efficiency of the latest membranes and desalination. In the 1990s, the specifications of RO membranes went from 4,000 gallons/d (gpd) and less than 99.5% salt rejection to 6,000 and 99.6%, respectively. In the first decade of the new millennium, additional improvements in the technology allowed even higher permeability values up to 9,000 gpd, and the salt rejection was pushed from 99.7% to 99.8% [3].

Further achievements in seawater RO element design and performance improvement were relatively modest with just a few new products launched over the past decade. The RO technology seemed to have reached its limit, with novel achievements relating to other parts of the desalination process, such as energy recovery devices or system configurations. To further reduce the energy cost of SWRO systems, studies focused on developing membranes with higher water permeability. Nevertheless, an increase in water permeability needs to be accompanied by an increase in salt rejection, which otherwise would result in a mere trade-off in water-solute separation [7].

2. Thin-film nanocomposite technology

In 2007, the use of thin-film nanocomposite (TFN) membranes for water purification was first described for brackish water reverse osmosis (BWRO) membranes [9]. These mixed matrix membranes used zeolite nanoparticles dispersed within a traditional polyamide thin film. In that work, zeolite nanoparticles were dispersed in the organic solution of an interfacial polymerization. Because polymerization proceeds in the organic solution, nanoparticles near the aqueous-organic interface became incorporated within the polyamide layer.

Incorporating nanomaterial into a BWRO membrane formulation increased permeability and altered surface properties potentially related to fouling while maintaining salt rejection. Further development and optimization of TFN

Table 1
Key energy factors in desalination and potential energy savings

Factors	Energy saving technology trends	Potential for energy savings (as a percentage of industry average)
Source water temperature	Use of warmer source water (collocation with power generation plants)	3%–5%
Source water salinity	Use of lower-salinity source water or blend of seawater and brackish water	Over 50%
Membrane element and system energy and productivity losses	Use of higher productivity elements; Application of lower energy & cost; RO system configurations	5%–15%
High-pressure RO feed pump efficiency	Maximizing pump and motor efficiency by the use of large pumps serving multiple RO trains	5%–10%
Recovery of energy from RO concentrate	Use of isobaric chamber type technologies	10%–15%

membrane technology for SWRO enhanced flux with salt rejection at industry standards [10].

In 2011 a membrane model with TFN technology combining the existing polyamide chemistry with nanomaterial was commercially launched. This technology uses embedded nanomaterial into a thin-film composite with aromatic polyamide as the main component of the active layer.

It is challenging to manufacture SWRO membranes based on aromatic polyamide chemistry to produce competitive permeability and high rejection. As seen in the SWRO membrane evolution described in Section 1, it took more than 30 y of continuous incremental improvements to develop SWRO membranes with a range of permeability between 6,000 and 9,000 gpd and maximum salt rejection of 99.80%.

The use of nanomaterial enhances the water permeability of an RO membrane. At the same time, as described above, the level of rejection maintained can still be competitive. Alternatively, combining the nanomaterial with the PA chemistry enables higher salt rejection membrane elements to maintain competitive permeability. The chemistry used for the production of the PA layer can be further improved to deliver even higher salt rejection while the permeability is compensated through the nanomaterial embedded into this layer.

The production of SWRO membranes based on TFN technology has allowed the development of membranes with salt rejection to improve from 99.80% to 99.85% in the early 2010s. In 2018, the second generation of TFN SWRO membranes (G2) was launched. The chemistry used in the active layer was further optimized, achieving salt rejection at standard test conditions rated up to 99.89%, maintaining the same permeability of the equivalent models of the first generation of TFN SWRO membranes [11].

The use of higher rejection membranes can significantly impact energy consumption. Higher rejection membranes allow membrane configurations with higher permeability to deliver the same or better permeate quality as tighter membranes typically do. This advantage translates into lower feed pressure requirements for a system and, consequently, lower energy consumption.

3. The Canary Island: iconic location for the desalination industry

The Canary Islands is a Spanish Archipelago located in the Atlantic Ocean off the coast of the Sahara Desert. It is composed of seven islands: Fuerteventura, Lanzarote, Gran Canaria, Tenerife, La Palma, La Gomera and El Hierro.

The Canary Islands is one of the most historical places for desalination. The first desalination plant for municipal use installed in Europe was located in Lanzarote Island in 1964, producing 2,300 m^3/d using evaporation technology. Later on, in the 1970s, the first RO membrane systems treating brackish water were installed in the archipelago. In 1982, as previously pointed out in Section 1, the first desalination plant in Spain with RO membranes for seawater was installed on the island of Lanzarote. At the end of the past century, the Canary Islands became a global reference and test-bed for desalination, attracting various technologies for piloting and implementation and further creating a large variety of feedwater qualities for different applications. The use of desalination allowed stable population settlements, tourism growth, and the development of arid locations in the past 50 y [12].

There are more than 300 desalination installations with a daily production of almost 700,000 m^3/d [13]. Today, one hundred percent of the water production in Lanzarote and Fuerteventura islands comes from desalination, and 86% and 47% of water production in Gran Canaria and Tenerife, the largest islands, respectively [14].

TFN membranes were first introduced in the Canary Islands more than 10 y ago. Today, approximately 45% of the total desalinated water produced in the Canary Islands comes from facilities that use membranes with this technology.

4. La Caleta SWRO

La Caleta Seawater Reverse Osmosis plant is located in Adeje, Tenerife, one of the two major islands in the archipelago. The plant had an initial capacity of 10,000 m^3/d. In 2019, the plant replaced one full train with a total capacity of 5,000 m^3/d with TFN SWRO membranes to improve the operation in permeate quality and operational conditions. Moreover, the plant capacity increased up to 12,000 m^3/d in the same year by adding two containerized plants with TFN SWRO membranes installed. Currently, 55% of the SWRO membranes installed at this site use TFN technology.

Table 2 summarizes the operation conditions of this site.

Table 3 shows the individual ion feedwater analysis.

The membrane configuration installed in the train is composed of two different models, also known in the industry as a hybrid configuration. A hybrid membrane configuration combines membrane models with different specifications within the same pressure vessel. This type of configuration can provide the following benefits:

- Customized solution: it helps to achieve an optimized membrane performance in terms of permeability and rejection to deliver the water quality required with the plant operation conditions minimizing the feed pressure.
- Flux balance within each pressure vessel: hybrid solutions are typically configured with the membrane model with the lowest permeability at the front. This reduces the production and flux of the lead element/elements achieving a more balanced flux distribution along the pressure vessel and helping to reduce membrane fouling in the front membranes where it is typically more severe.

In this installation, a hybrid membrane configuration was selected for the train design to find a customized solution that would reduce the feed pressure to provide significant energy savings.

Table 4 shows the installed TFN membranes models. The specifications are evaluated at standard test conditions (STC). For SWRO membranes, those conditions are 32,000 ppm of NaCl, 25°C, pH 8, 8% recovery, 55 bar, and 5 ppm of boron.

5. Pilot

The TFN second generation membrane pilot was performed in a satellite pressure vessel for testing but

Table 2
Train operation conditions

Water source	Seawater from beach wells
Temperature range (°C)	19–21
Operating flux (lmh)	13–13.5
Production (m^3/d)	5,000
Configuration	54 PV × 7 membranes

Table 3
Feedwater individual ion composition

Ion	mg/L
Na	12,833
K	504
Mg	1,553
Ca	431
Sr	7.4
Ba	0.04
F	1.3
Cl	23,250
SO_4	3,054
CO_3	1.3
HCO_3	157
B	4.3
TDS	41,787

Table 4
TFN membrane model specifications installed in train at STC

Model	LG SW 440 GR	LG SW 440 R
Permeate flow rate, gpd	8,250	9,900
Salt rejection, %	99.85	99.85
Boron rejection, %	93	93

connected to the full-scale train operating with TFN first generation membranes described in the previous section and shown in Fig. 1. Certain modifications were required to monitor and control the operation of the pilot test pressure vessel. Those modifications were implemented in the permeate line and included the following: a bypass line with a rotameter to control permeate flowrate, pressure indicator, throttling valve, and a sampling port. Figs. 2, 4 and 5 show images of the pilot test vessel modifications required, membranes installed in the pilot and pilot test vessel. Fig. 3 shows a flow diagram with the modifications required.

Table 5 shows the specifications of the membrane model loaded in the pilot test pressure vessel.

The membranes were installed in January 2020. The pilot was in operation for over 15 months.

Fig. 6 shows the operation parameters for feed pressure and permeate conductivity during the first 15 months of operation.

Comparing the membrane configuration used in the full-scale train and the one in the pilot test pressure vessel, one can see a difference in permeability, as is shown in Table 6.

Fig. 1. Train with TFN membranes installed.

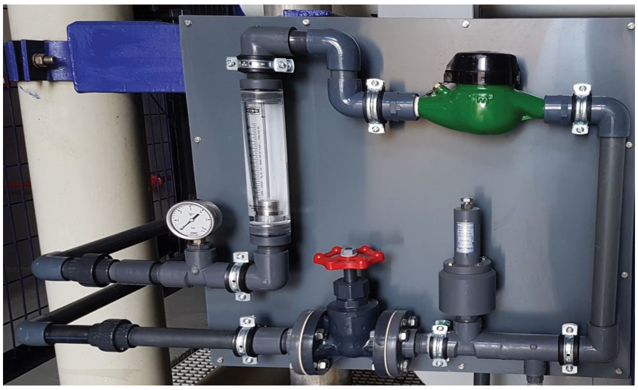

Fig. 2. Modifications implemented in the pressure vessel.

Table 5
TFN membrane model specifications installed in pilot at STC

Model	LG SW 440 R G2
Permeate flow rate, gpd	9,900
Salt rejection, %	99.88
Boron rejection, %	93

The percentage difference in permeability between the two configurations is 5%.

To compensate for this difference of permeability illustrated in Table 6, and ensure the same operating conditions for both the pilot vessel and the train, an additional 0.8 bar permeate back pressure is applied to the satellite test pressure vessel where second generation TFN membranes are installed. This adjustment ensures similar flux and production through all different pressure vessels, trains, and the pilot, to reproduce similar operation conditions for a fair comparison of the two membrane configurations.

Fig. 7 shows the permeate quality difference between the full-scale train and the pilot.

In Fig. 8, the normalized salt passage (NSP) for both train and pilot pressure vessels is plotted.

The NSP was studied to accurately evaluate the performance of both configurations (full-scale train and pilot test pressure vessels). RO membrane performance varies

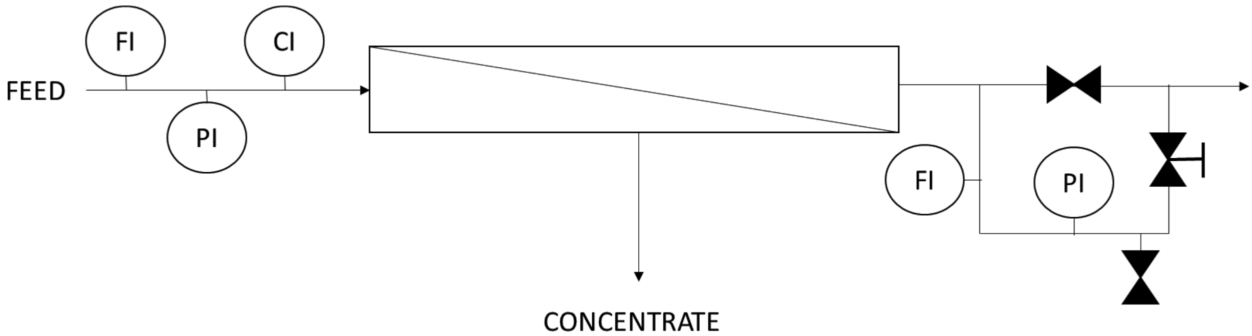

Fig. 3. Schematic of the modifications implemented in the test pressure vessel for the pilot.

Fig. 4. TFN second generation membranes.

Fig. 5. Test vessel.

Table 6
Permeability comparison between train and pilot

	Permeability at STC			
	Train		Pilot	
Membrane position	Model	Permeability at STC (gpd)	Model	Permeability at STC (gpd)
Position 1	LG SW 440 GR	8,250	LG SW 440 R G2	9,900
Position 2	LG SW 440 GR	8,250	LG SW 440 R G2	9,900
Position 3	LG SW 440 R	9,900	LG SW 440 R G2	9,900
Position 4	LG SW 440 R	9,900	LG SW 440 R G2	9,900
Position 5	LG SW 440 R	9,900	LG SW 440 R G2	9,900
Position 6	LG SW 440 R	9,900	LG SW 440 R G2	9,900
Position 7	LG SW 440 R	9,900	LG SW 440 R G2	9,900
	Total	66,000	Total	69,300

with the feedwater characteristics, composition, and operating conditions. Parameters such as feedwater temperature, feedwater total dissolved solids (TDS), membrane fouling, or system recovery can change key membrane performance characteristics such as feed pressure, permeate flow, and permeate quality. To determine whether a change in performance results from a change in feedwater or operating conditions or due to a change in actual membrane performance, operating data must be taken at regular intervals and then "normalized" to baseline reference conditions. Whether changes in the membrane performance are apparent or actual can only be concluded by comparing "normalized" performance over time with the baseline performance.

The normalized salt passage is obtained through Eq. (1):

$$\%SP_n = \left(EPF_a \div EPF_n\right) \times \left(STCF_n \div STCF_a\right) \times \%SP_a \quad (1)$$

where $\%SP_n$ is salt passage (percent) normalized to standard conditions; SP_a is salt passage (percent) at actual conditions; EPF_a is element permeate flow rate at standard test conditions; EPF_n is element permeate flow rate at actual

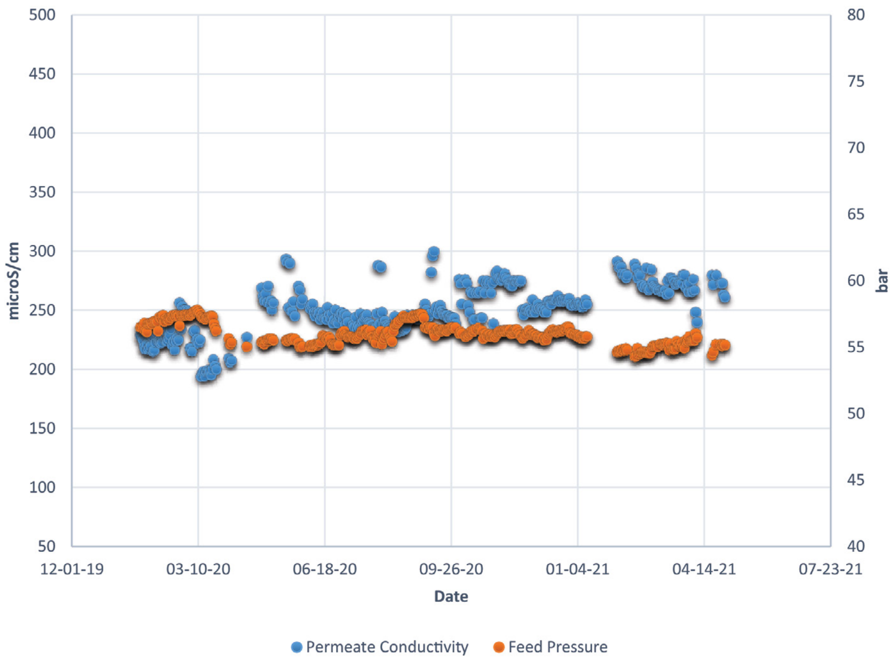

Fig. 6. Pilot feed pressure and permeate conductivity.

Fig. 7. Train permeate conductivity and pilot permeate conductivity.

conditions; $STCF_n$ is salt transport temperature correction factor at standard conditions; $STCF_a$ is salt transport temperature correction factor at actual conditions [14].

To obtain actual salt passage, Eq. (2) is used:

$$\%SP_a = C_p \div C_{fb} \quad (2)$$

where C_p is permeate concentration (ppm); C_{fb} is the average feed/brine concentration (ppm) [15].

To obtain the salt transport temperature correction factor, Eq. (3) is used:

$$STCF = \exp\left\{K \times \left[1 \div \left(273 + t\right) - 1 \div 298\right]\right\} \quad (3)$$

where t is temperature (°C); K is 5030 for PA composite RO membranes [15].

As observed in Figs. 7 and 8, TFN second generation membranes installed in the pilot test pressure vessel deliver

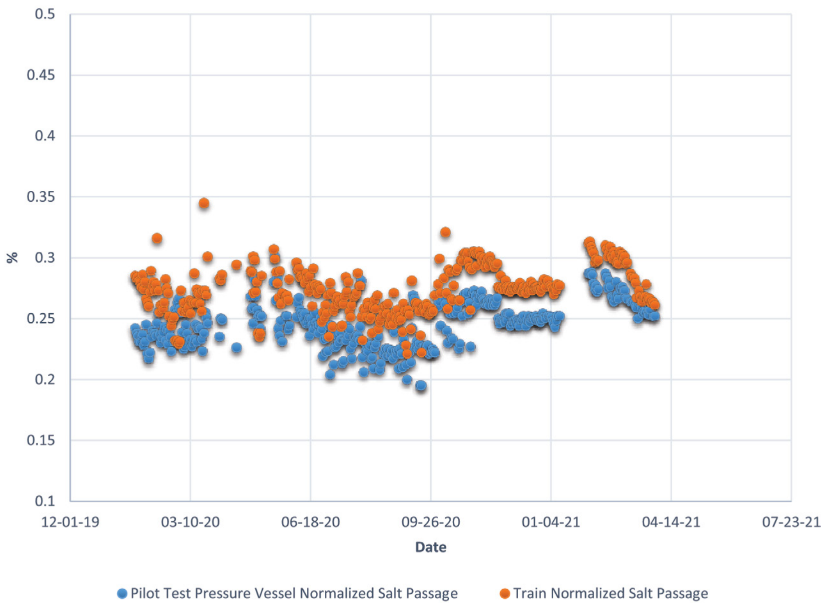

Fig. 8. Train normalized salt passage and pilot test pressure vessel normalized salt passage.

permeate water with lower conductivity and lower NSP than TFN first generation membranes installed in the full-scale train. The permeate quality is improved by up to 15% with 5% higher permeability while working at similar flux, as shown in Fig. 9.

6. Energy study

Using LG Chem's RO projection software, Q+ 3.1.1.0, two scenarios were studied to evaluate potential energy savings of using second generation TFN SWRO membranes as shown in Figs. 9 and 10.

- Scenario 1 using membrane configuration currently installed in the main train at La Caleta SWRO with first generation TFN SWRO membranes as shown in Figs. 9 and 10.
  - 2 × LG SW 440 GR G1
  - 5 × LG SW 440 R G1
- Scenario 2 using membrane configuration installed in the pilot test pressure vessel with second generation TFN SWRO membranes as shown in Figs. 9 and 10.
  - 7 × LG SW 440 R G2

Table 7 lists the operating conditions used in this study.

6.1. Scenario 1

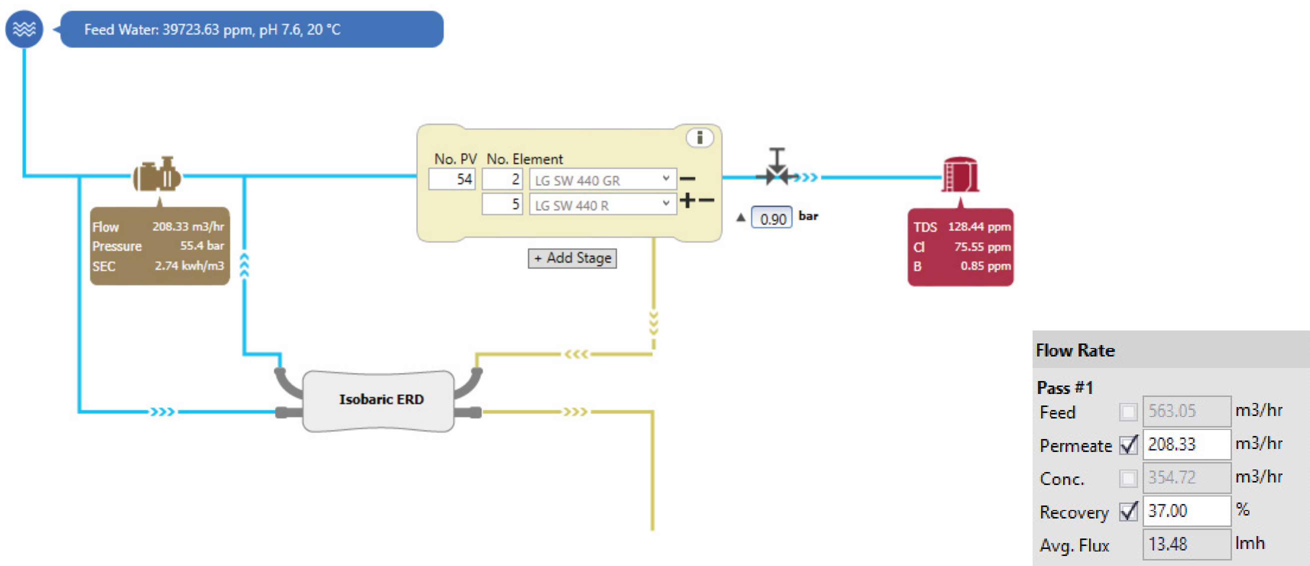

Fig. 9. Q+ full train design with (2) LG SW 440 GR G1 + (5) LG SW 440 R G1 [16].

6.2. Scenario 2

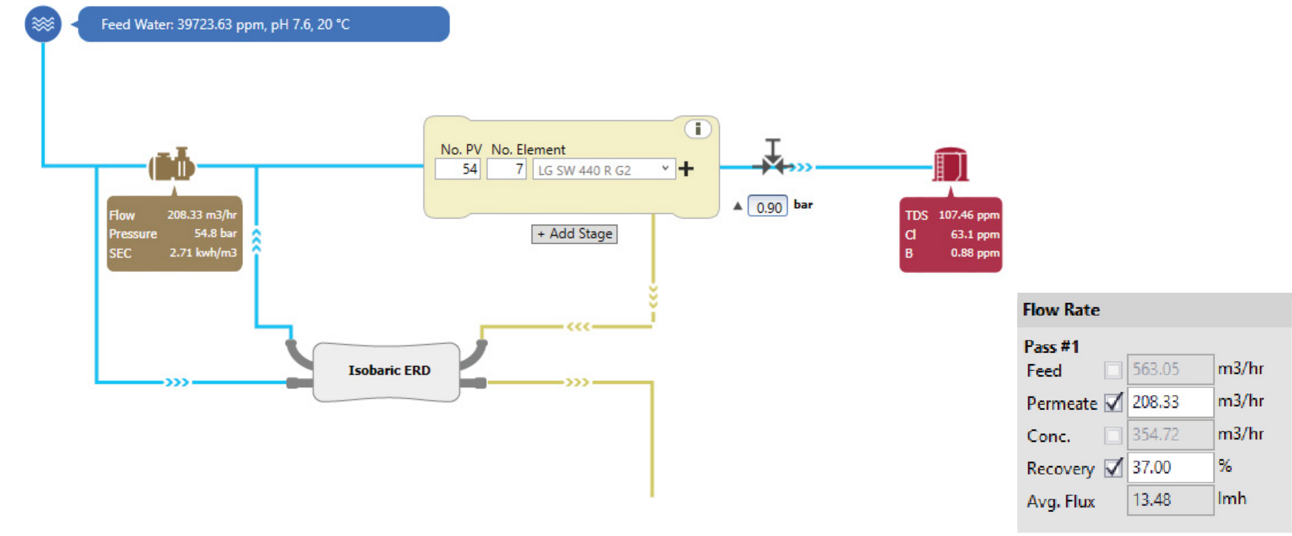

Fig. 10. Q+ full train design with LG SW 440 R G2 [16].

Table 7
Design operation conditions

Operation Conditions	
Feed salinity	40,000 ppm
Feed temperature	20°C
Feed pH	7.6
Recovery	37%
Flux	13.5 lmh

The design performed with Q+ shows differences between the two options as shown in Table 8. These results are well aligned with those obtained from the pilot test where the difference in terms of transmembrane pressure was around 0.8 bar.

The obtained results also show that a system design with second generation TFN SWRO membranes would reduce the energy consumption by 1.1% and improve permeate quality by up to 16.4% for these operating conditions.

Based on these findings, it can be calculated the total cost savings over 10 years of operating second generation TFN SWRO membranes. Assuming an annual operation of 24 h each day of the year and an estimated cost of electricity for industrial applications in the Canary Islands of 0.154 euros/kWh [17], the total cost savings can be around 85,000 euros in energy consumption for a system with a production capacity of 5,000 m^3/d.

7. Conclusions

The conclusions from this study can be summarized as follows:

- Energy consumption is one of the main handicaps in SWRO, where membrane developments might still contribute to further cost savings.
- TFN technology improves the rejection of PA chemistry-based SWRO membranes, bringing the rate up to 99.89% while maintaining similar permeability.
- The Canary Islands is an iconic location for desalination, with the first SWRO plant in Spain installed in 1982 and over 300 active installations today.
- TFN SWRO membranes were first installed in 2019 at the La Caleta SWRO desalination plant in a hybrid membrane configuration to optimize energy consumption while meeting the required permeate quality.
- Second generation TFN SWRO membranes tested at La Caleta SWRO demonstrated an improvement in permeate conductivity by up to 15%, with 5% higher permeability than the first generation TFN SWRO membranes.
- A design with second generation TFN SWRO membranes may result in significant energy and cost savings in the operation of SWRO systems.

Table 8
Comparison results with design scenarios using TFN first and second generation SWRO membranes

	Permeate TDS (mg/L)	Feed pressure (bar)	SEC (kWh/m^3)
(2) LG SW 440 GR + (5) LG SW 440 R	128	55.4	2.74
(7) LG SW 440 R G2	107	54.8	2.71
Difference (%)	16.4	1.1	1.1

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