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Cost savings by novel seawater reverse osmosis elements and design concepts

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ABSTRACT

Desalination market growth has triggered significant development in SWRO membrane and process development and the new extra high rejection and ultra low energy membranes from Dow, FILMTEC™ SW30XHR-400i and SW30ULE-400i, as well as the internally staged design concept, have been validated in extensive field testing and various commercial plants over the recent years and are now commercially available. These solutions from Dow can be used to increase membrane flux and system recovery and / or to reduce feed pressure. This yields capital cost and /or energy savings. These savings have been assessed in 4 different situations / geographies, using a thorough and validated cost model. These geographies are South Pacific (Australia), Persian Gulf (Saudi Arabia), with very different feed water qualities (in terms of feed salinity and temperature range) and product quality requirements (in terms of bromide, boron and salinity). Depending on the cost savings route chosen, there are strong differences in the consequences with regards to size of the RO stage (17–26% smaller), size of the pretreatment (9–12% smaller), and/or the feed pressure (2–6 bar lower). These cost savings are in the range of US cent 0.4–4.1/m^3 water produced. This is equivalent to 0.7–6.5% water cost saving. Considering that these considerable cost savings are readily available since 2008 from Dow Water Solutions, the industry should start to significantly benefit from these in the coming years.

Keywords: Desalination; Reverse osmosis; FilmTec membranes; Design; Economics

1. Introduction

The application of seawater reverse osmosis (SWRO) desalination technology has been strongly growing in recent years. This has caused industry development focused on reducing capital and operational cost, while complying with more stringent water quality standards.

1.1. More stringent water quality standards

One example for more stringent water quality standards is the boron target. European Union [1], the United States Environmental Protection Agency [2] and some local regulations (e.g. Israel) have caused development on meeting more stringent targets of boron in the range of 0.3–1.0 ppm. World Health Organization [3] had originally proposed boron limits of 0.3–0.5 ppm, but recent developments indicate that in future revisions, the limit might be as high as 2.4 ppm. Another example for more stringent water quality is Bromide, which in Australia is regulated to 0.1 ppm.

These lower limits have resulted in the development of

- Higher rejection SWRO elements for the first "roughing" stage

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- "Polishing" 2nd stage separation components such as boron-selective resin (BSR) or specific brackish water reverse osmosis (BWRO) and
- Specific system designs, usually multi-stage, with permeate split and one or more polishing technologies.

1.2. Cost reductions

Many different avenues have been proposed and used, to reduce desalination cost, and only a few of them shall be mentioned here:

- Ultrafiltration pretreatment
- Dissolved air flotation
- Pressure center concept [4]
- Longer pressure vessels
- Internally staged design [5]
- Higher productivity SWRO elements [5]
- Energy recovery devices

1.3. More stringent water quality at lower cost

Some of the cost reductions mentioned above are compatible with the concepts for meeting more stringent water quality (e.g. pressure center concept, energy recovery devices). However some of the concepts require optimization, especially when considering the selection of separation technology.

For example higher rejection SWRO elements reduce size and cost of a 2nd stage, however this results in higher energy requirement, hence higher cost, in the 1st stage. On the other hand, high productivity elements could reduce energy consumption in the 1st stage, but would likely require a larger 2nd pass.

Selecting technology that can reliably meet the requirement of meeting more stringent water quality at a lower cost is essential for the designer or operator of a SWRO plant. Dow Water Solutions has developed separation technology which enables better water quality at lowest cost:

- Novel SWRO membranes displaying an unprecedented, but proven, combination of high productivity and high rejection
- Novel design concepts, such as internally staged design (ISD), combining the benefits of elements with highest rejection and elements with highest productivity in an optimal way
- Advanced polishing stage separation technology, such as BWRO elements with high specific solute rejection (e.g. boron) and high pH resistance, or BSR.

This paper focuses on the advancements with regards to separation component technology in the SWRO stage, hence novel SWRO membranes and design concepts.

1.4. Novel SWRO membranes

The drive for lower cost with better water quality has obviously driven not only system design, but also development of SWRO membrane technology. An example of such development is membranes with higher productivity, which allow reducing the operational pressure, and with it, the energy consumption. Another example is membranes with better salt and boron rejection. The challenge is obviously to balance highest productivity with highest rejection. Fig. 1 shows this evolution of productivity and salt rejection at the example of FILMTEC elements.

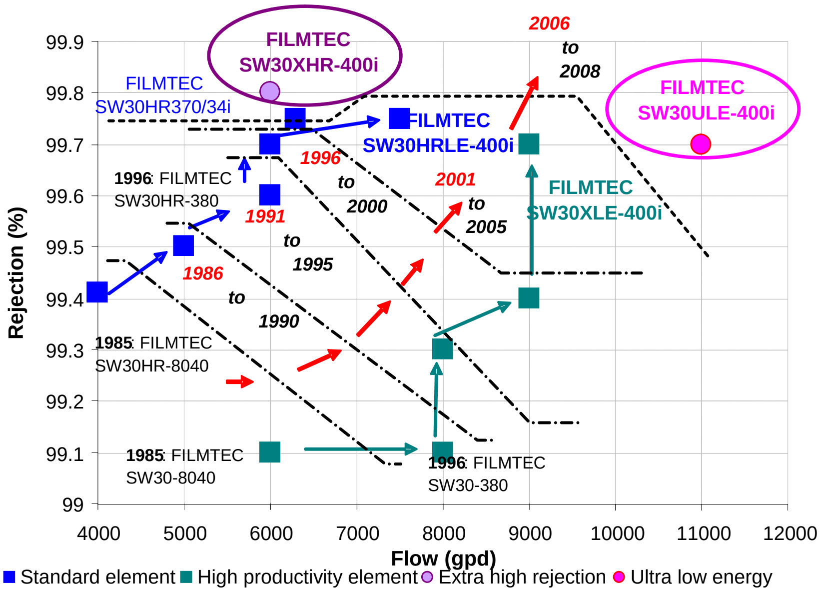

Fig. 1. Evolution of salt rejection and productivity of FILMTEC™ SWRO elements in standard conditions (32,000 mg/L NaCl, pH 8, 25°C, 8% recovery, 55.3 bar).

1.4.1. SWRO membranes with improved rejection

Most of the frequently used SWRO membrane models of the 3 main suppliers, can nowadays easily meet the standard requirements for total dissolved solids (TDS) or chloride (Cl) in the range of 500 and 250 ppm, after pH adjustment of permeate, in most geographies (Asia Pacific, the Americas, Mediterranean, Atlantic), except in the high temperature cases (>30°C) on Gulf water (>43,000 mg/L), where partial 2nd passes are still required.

However this is not the case for the more stringent boron and bromide requirements, in the range of 0.3–0.5 ppm and 0.1 ppm respectively. While a boron limit of 1.0 ppm can nowadays be met with some of the SWRO elements in the market, the 0.3–0.5 ppm limits usually require a partial 2nd pass. The bromide limit of 0.1 ppm usually requires an almost complete 2nd pass.

Taniguchi et al. [6] and Henmi et al. [7] have described SWRO membranes with better boron rejection in the range of 94–96%. Based on the oral presentation [7], it seems that after stabilization of initially declining boron rejection, the boron rejection is in the range of 93% for a roughly 6000 gpd product. Busch et al. [8] described similar problems of unstable boron rejection after exposure to cleaning conditions, for some type of membrane models.

Dow Water Solutions has recently commercialized a new SWRO element with higher boron and NaCl rejection (93.0 and 99.80% respectively) at a conventional flow rate (6000 gpd). This SWRO element, termed SW30XHR-400i, uses interlocking end caps, 400 ft^2 of active area, is quality tested with advanced protocol (Pulse Impulse Test, PIT) and is capable of operation at pressure / temperature conditions of up to 82 bar and 45°C.

1.4.2. SWRO membranes with higher productivity

As can be seen in Fig. 1, for a long term, the rejection of 99.7% (which is required to achieve acceptable permeate quality of 350 ppm TDS) was only available with elements having a flow rate of 6000 gpd or less. In 2004, Busch and Mickols [9] described new commercially available elements with higher flow rates (7500–9000 gpd) and this type of rejection. Use of this type of elements has since then been described in many plants, among them Ashkelon, Curacao, and Perth. The Affordable Desalination Corporation had demonstrated a record low energy consumption using SW30XLE-400i membranes [10].

Developmental element having a rejection of 99.7%, but with even higher flow rate of > 10,000 gpd had been described repeatedly [5,11]. These papers showed potential water cost savings enabled by this type of element, and already described early field experience.

Development of this type of element had been already started in 2004, but had to be extended after initial pilot trials showed the need for improved rejection. In the end of 2005, the recipe was optimized and small scale production was started. It has since then been tested in many more pilot trials and smaller scale plants. It was introduced to the market in 2008 as ultra low energy element SW30ULE-400i with 11,000 gpd and 99.70% NaCl rejection (see Fig. 1), in 400 ft^2 configuration, with interlocking end caps, having a boron rejection of 87%.

1.5. Internally staged design

High productivity membranes can be used for lower pressure and lower energy consumption. However, the most significant cost savings can be achieved when these membranes are used to increase flux and recovery. In this situation, higher flux enables higher system rejection, and the benefit is combined:

- Higher flux > less membranes and vessels > capital cost reduction
- Higher recovery > smaller pretreatment > capital cost reduction
- Higher flux at the same pressure > lower energy consumption
- Higher flux > better system rejection

An approach to successfully use higher productivity elements to operate at higher flux had been described in [5,11]. This is based on the internally staged design (ISD) approach, which has been disclosed in patent application PCT/US2005/006224 [12]. This concept is based on the following:

- Throttling the flux on the first element positions in a vessel, by using elements with lower productivity and better rejection on the front. The first positions in a SWRO pressure vessels are the ones most exposed to fouling, and would foul very fast if a high productivity element was used [5].
- Using higher productivity elements in the last positions. The last positions in a pressure vessel typically do not show a lot of fouling, since they typically operate far below the critical flux (or recovery) limit. Use of higher productivity elements significantly improves the utilization of these elements.

The use of higher rejection elements in the first positions offers another key advantage, especially where more stringent water quality limits have to be met: when a permeate split is used to use front permeate directly and treat rear permeate in a 2nd stage, then it is advisable to use high rejection elements in the front positions of which the water is directly used, and high productivity elements in the rear positions, which feed to the 2nd stage. This combines the features of high rejection elements in the best possible way with features of high productivity elements, and results in lowest possible cost.

1.6. Validation with field data

Dow Water Solutions has collected in the range of up to 4 years of field experience, using internally staged design and SW30ULE-400i elements. SW30XHR-400i elements have accumulated over a year of field experience. These field experiences are briefly summarized within this section.

FILMTEC(TM) SW30XHR-400i has been tested in 5 pilot trials, and also has been installed in two large scale plants in element quantities of 100–500, since summer 2007. It performed mainly on the Mediterranean water in Israel and Spain, but was also used on the Red Sea water in Israel, Atlantic Ocean water in Spain, as well as East Pacific feed water in California. It operated typically between 7 and 8 elements per vessel, at flux of 14 L/h/m^2 and recoveries around 45% (range of 30–50%); temperatures were around 25°C (range of 18–30°C). Boron level reached was in the range of 0.2–1.8 ppm, and on average 0.65 ppm. In all single stage operations except the Red Sea case, the boron level reached was below 0.7 ppm, hence safely providing water quality complying with the 1.0 ppm boron spec. It performed reliably (±10%) within the expectations for flow, salt passage, and boron passage.

FILMTEC(TM) SW30ULE-400i was used in 2 pilot trials and 1 real plant, where it was used in a conventional design with only this one product type. In addition SW30ULE-400i was used in 5 more cases in internally staged design configuration, but these will be described further below. The 3 cases, where SW30ULE-400i was used as the single product in the plant, were on Eastern Mediterranean water (Israel), seawater (Israel) and Atlantic Ocean water (Spain). Median recovery was 42% and median flux 18 L/h/m^2, average 7 elements/vessel, at mostly around 20°C. The observed productivity was slightly (13%) below the expected range, which is most likely due to the high average flux, that these elements were operated at. Salt passage was higher than expected, but boron passage was lower than expected (both by 30%).

Internally staged design was tested in 6 pilot trials and 1 real world case scale plant. In five of these seven cases, FILMTEC(TM) SW30ULE-400i elements were used, mostly in combination with SW30HR LE-400i and SW30XLE-400i elements. These cases used Bohai Sea water (North China), Red Sea water (Israel), Eastern Mediterranean water (Israel and Cyprus), North Mediterranean water (Spain), East Atlantic water (Spain) and East Pacific water (California). The average temperature was 25°C, and ranging from 20 to 35°C. Recoveries were tested in the range of 40–60% with a median of 50%, and average permeate fluxes tested in the range of 15–25, with a median of 20 L/h/m^2. Flow and salt rejection were within the expected range (±10%), but boron passage was lower than expected (20%).

Overall, it can be seen that the new SW30XHR-400i and SW30ULE-400i perform at the expected level, and that internally staged design indeed allows operation at much higher flux and recovery levels than conventional design.

2. Materials and methods

The aim of this paper is to show, based on the field demonstration of innovated products and design concepts, what cost savings are possible with the new products. The innovations were described in the previous chapter, and significantly improved operational results shown.

Based on the improved operation demonstrated in the previous chapter, the novel product and design concepts were applied to four different situations, designs were made with ROSA, and results evaluated with a financial model that Dow had developed with John Tonner from Water Consultants International.

2.1. Basic and advanced designs in four different examples

The four situations differ by geography (hence feed water quality, and product water expectation) and design philosophy (capital savings focus versus operational cost focus). These four different regions were South Pacific (West Australia, open intake, stringent bromide requirements), Persian Gulf (Saudi Arabia, open intake, high feed TDS and high temperature variation), East Mediterranean (Israel, open intake, stringent boron requirement), and Northwest Mediterranean (Spain, beach well, fairly easy to meet water quality).

All four cases were projects in development, and as such ideal show cases for the benefits of the innovated concept. Although these cases were relatively different, and could not directly be compared, the idea was to show the benefit of the innovated FILMTEC(TM) products and internally staged design in very different situations. The four projects were projected by two different designers, nevertheless, the approach was nearly identical.

For each situation a base case was designed with conventional products such as SW30HR LE-400i and SW30XLE-400i, which have been on the market since 2003/2004. Then an advanced case was developed, in which the new products SW30XHR-400i and SW30ULE-400i as well as the new internally staged design concept were used to yield advantages in energy consumption and/or capital cost.

The BWRO unit was based on the following design principles: 90% recovery, pH 10 (no scaling), a flux of 35 L/h/m^2, 3:1 staging, BW30-440i and LE-440i elements.

The rule was to apply the same design philosophy and limitations for the basic and advanced cases, and the water quality had to remain the same as well. The safety factors to safely warrant water quality were selected at typical levels of 1.35/1.45 (single pass/full double pass) for total dissolved solids, chloride and bromide (bromide was predicted with a passage of 1.3 times the chloride passage predicted by ROSA), and 1.25 for boron (regardless if single or double pass).

Some aspects were different between the projects, and are shown in Table 1. This was partly due to project

Table 1
Design approach for the 4 desalination plants

Aspect	Designer 1 South Pacific, Northwest Mediterranean	Designer 2 East Mediterranean, Persian Gulf
Design philosophy, SWRO stage	Design of the basic and advanced cases was made with a flux of 14 L/h/m², which is frequently used with conventional pretreatment. In the advanced case, the pressure, hence energy consumption, can be reduced.	Design base and advanced case at start-up fouling factor and highest temperature, limited by design guidelines. Maximum permeate flow and recovery of the first element will limit productivity. For the advanced case, higher average permeate flux can be used, because the flux of the first element(s) can be throttled.
Design philosophy, BWRO stage	In the BWRO stage, when less SWRO permeate is fed in winter scenarios, occasionally the brine flow in the last element is too low; then productivity of the BWRO stage was increased, or a full train taken out of operation.	In the BWRO stage, when less SWRO permeate is fed in winter scenarios, occasionally the brine flow in the last element is too low; then productivity of the BWRO stage was increased, or a full train taken out of operation.
Fouling factor	Both feed waters are open intake, thus, fouling factors of 0.9 and 0.7 were used for start-up conditions and long term operation respectively. Since internally staged design was not used to increase productivity (average flux kept constant), and since lower fouling tendency can be expected due to more balanced flux distribution, the cases with ISD used fouling factors of 0.75 instead of 0.7 for long term conditions.	Both feed waters were open intake, and were designed for the first year and the 5 year case, therefore fouling factors of 0.9 and 0.7 were applied.

needs (e.g. due to the underlying financing models the more heavily capital cost, shorter term focused projects required an approach that focused on reducing capital cost, while the more long term focus projects required an approach more focused on reducing operational cost), and partly due to the fact that the two designer took a slightly different approach.

Some project specific conditions for each of the four projects are shown in Table 2.

Projections were done using the Dow Water Solution design software for FIMTEC™ elements, Reverse Osmosis System Analysis (ROSA), version ROSA v6.1.5. A special configuration file containing the newly commercialized elements was used (ConfigDB u238786_71).

2.2. Cost modeling

A detailed cost model for the SWRO and BWRO stages was developed in the 2004 time frame and was presented in 2005 [5,11]. This model shows how capital and operation cost can be saved with different types of membranes and different designs.

It should be said that this cost model is based on an assessment done in the 2003/2004 timeframe. In the mean

Table 2
Project conditions in four different projects

	South Pacific	Persian Gulf	East Mediterranean	Northwest Mediterranean
Feed TDS, mg/L	37,000	50,000	41,000	39,500
Temperature range, °C	14–25	18–35	18–32	15–26
Limiting water quality parameter, limit	Br, 0.1 ppm	TDS, 300 ppm	B, 0.3 ppm	B, 0.5 ppm
Elements per vessel	7 & 8	7	8	7

time, increases of metal or energy prices might have led to increases in selected areas. However, since these increases impact both areas, capital and operational cost, the authors believe that the overall order of magnitude cost savings remain valid, and that based on the high level of detail in the cost estimate, these cost numbers are credible. Therefore the cost calculations based on that cost model, it is used to assess the economical differences between basic and advanced case in the four situations described.

Some of the key assumptions for the desalination plant, for which cost was assessed in the cost model, are briefly summarized as well:

- Plant capacity: 100,000– 50,000 m^3/d; 95% plant availability
- Feed treatment system consists of a traditional traveling screen in compliance with the US EPA Clean Water Act section 316(b), conventional dual media filtration system.
- Train size of up to 215 vessels per train, supplied by a single high pressure displacement pump.
- In the seawater stage, pump efficiency is 88%, motor efficiency is 94% and efficiency of the energy recovery section is 94%.
- In the BWRO stage, pump efficiency is 78%, motor efficiency is 92%, and energy recovery is not used.

3. Results

In this chapter, different reverse osmosis configurations are evaluated using different sea and brackish water modules. The procedure followed is described in detail in each section and the specifications at standard seawater and brackish water conditions of the modules used for the evaluation are shown in Table 3.

3.1. South Pacific (Australia)

For the given permeate production of 150,000 m^3/d while respecting the bromide concentration below 0.1 ppm, different designs have been evaluated. In all the different configurations a second pass is needed in order to meet the requested permeated quality. The different technical configurations for this SWRO plant include designs with 7 and 8 modules per pressure vessels in the first pass with and without split and with and without ISD. In addition, for each design, the two extreme conditions that are usually evaluated in terms of maximum feed pressure consumption and maximum salt passage are considered:

- Design at the highest temperature and highest fouling factor (new modules): this design corresponds to the worst hydraulic conditions and to the maximum salt passage.
- Design at the lowest temperature and lowest fouling factor: this is the design that requires the maximum feed pressure.

Table 3
Specifications under standard conditions of FilmTec reverse osmosis modules

Module	Flow (gpd)	Salt rejection (%)	Boron rejection (%)
SW30XHR-400i	6,000	99.80	93
SW30HRLE-400i	7,500	99.75	91.5
SW30XLE-400i	9,000	99.70	89
SW30ULE-400i	11,000	99.70	87
LE-440i	12,650	99.3	50
BW30-440i	11,500	99.5	65

Standard test conditions: (32,000 mg/L NaCl, pH 8, 25°C, 8% recovery, 55.3 bar).

The designs were made assuming conventional pretreatment and fixing the maximum average flux of the first pass at 14 L/m^2h and the one of the second pass at 35 L/m^2h. The number of pressure vessels needed for each one of the passes is fixed by the quality of the permeate to be attained, i.e. 0.1 ppm of bromide and the maximum flux allowed (14 and 35 L/m^2h).

It is especially important to note that in order to establish a fair comparison between the designs with and without ISD, a more tolerant fouling factor has been applied to the designs with ISD. In essence, for the basic designs a fouling factor of 0.7 was applied in the first pass for long term conditions, whereas for the designs with ISD in order to take into account the more favorable hydraulics, a fouling factor of 0.75 was used. These fouling factors are in agreement with FilmTec guidelines for seawater plants with a conventional pre-treatment and with a maximum flux in the first pass of 14 L/m^2h.

For the second pass, a long term conditions fouling factor of 0.85 was applied in all the cases since the configuration is basically the same. As previously mentioned, the cost of water was calculated in the two extreme conditions, i.e., high temperature + high fouling factors and low temperature + low fouling factors. The fouling factors used for the first year of operation were 0.9 for the first pass and 0.95 for the second pass in all the cases. All the different designs evaluated with pressure vessels containing 7 and 8 modules are shown in Table 4 and Table 5, respectively.

The number of pressure vessels as well as the maximum operating feed pressure calculated by ROSA (at the lowest fouling factor and temperature) in order to accomplish the final amount of permeate at the desired quality are shown in Table 6 and Table 7 for the designs with 7 and 8 modules per pressure vessel respectively.

From the previous tables it can be observed than when starting designing with ISD, the selection of the modules to be installed plays a vital role. More specifically, when comparing the conventional design with the one contain-

Table 4
Main features of the designs with 7 modules per pressure vessels

Configuration	Type of module first pass	ISD in the first pass	Permeate split in the first pass	Type of module second pass
Conventional	SW30HRLE-400i	No	No	LE-440i
Advanced 1	5×SW30XHR-400i and 2×SW30HRLE-400i	Yes	No	LE-440i
Advanced 2	2×SW30XHR-400i and 5×SW30ULE-400i	Yes	No	LE-440i
Advanced 3	2×SW30XHR-400i and 5×SW30ULE-400i	Yes	Yes	LE-440i

Table 5
Main features of the designs with 8 modules per pressure vessels

Configuration	Type of module first pass	ISD in the first pass	Permeate split in the first pass	Type of module second pass
Conventional	8×SW30HRLE-400i	No	No	LE-440i
Advanced 1	5×SW30XHR-400i and 3×SW30HRLE-400i	Yes	Yes	LE-440i
Advanced 2	4×SW30XHR-400i and 4×SW30ULE-400i	Yes	Yes	LE-440i
Advanced 3	3×SW30XHR-400i and 5×SW30ULE-400i	Yes	Yes	LE-440i
Advanced 4	2×SW30XHR-400i and 6×SW30ULE-400i	Yes	Yes	LE-440i

Table 6
Number of pressure vessels and operating conditions of the designs with 7 modules per pressure vessel

Configuration	Number of pressure vessels first pass	Feed pressure first pass (bar)	Number of pressure vessels second pass	Feed pressure second pass (bar)	Recovery of the system (%)
Conventional	1930	62.19	580	11.11	42.73
Advanced 1	1930	67	569	11.56	43.10
Advanced 2	1943	56	600	13.4	42.76
Advanced 3	1943	56.1	528	12.3	43.29

Table 7
Number of pressure vessels and operating conditions of the designs with 8 modules per pressure vessel

Configuration	Number of pressure vessels first pass	Feed pressure first pass (bar)	Number of pressure vessels second pass	Feed pressure second pass (bar)	Recovery of the system (%)
Conventional	1689	62.3	580	12.89	42.93
Advanced 1	1700	64.18	488	10.89	43.36
Advanced 2	1700	58.41	512	11.67	43.4
Advanced 3	1700	57	514	11.97	43.37
Advanced 4	1700	55.9	528	12.27	43.3

ing SW30XHR-400i and SW30HRLE-400i (advanced 1), it can be noted that the second configuration requires a much higher pressure (approx. 8 bar) in the first pass. Even though there might be a significant reduction in the capital costs of the second pass because of the lower number of vessels needed, most likely these savings in capital do not compensate the higher OPEX of the first pass. From the previous tables it can be also concluded that thanks to the installation of FilmTec high productivity modules SW30ULE-400i an important reduction in the feed pressure of the first pass is obtained at the same time that the size of the second pass increases.

In Fig. 2 and Table 8, the total and itemized costs of water are shown for all the configurations with 7 modules per pressure vessel.

As already indicated, the price of water was calculated in the two extreme conditions in terms of fouling of the membranes and temperature in order to cover a wide range of conditions. In Fig. 2, it can be observed that the highest cost of water corresponds to the ISD design which uses 5 SW30XHR-400i and 2 SW30HRLE-400i. According to the calculation, the cost of water with this configuration will range from 61.59 UScent/m^3 to 64.70 UScent/m^3. On the other hand, with the basic design, i.e., 7 modules SW30HRLE-400i in the first pass, the attained cost of water ranges from 60.46 UScent/m^3 to 63.99 UScts/m^3. Looking more carefully at the results of the calculations it can be concluded that both, capital and operating expenses are higher in the case of using the ISD with SW30XHR-400i + SW30HRLE-400i than the basic design.

On the other hand, the two last designs (consisting of ISD with SW30XHR-400i and SW30ULE-400i), achieved a considerable reduction in the final cost of water compared to the basic designs, and in fact, this reduction in the cost is most significant when the split is incorporated to the ISD design containing 2 SW30XHR-400i and 5 SW30ULE-400i. The cost of water with a basic design ranges from 60.46 UScent/m^3 to 63.99 UScent/m^3, with the ISD (2 SW30XHR-400i + 5 SW30ULE-400i) the costs is between 60.18 and 62.69 UScent/m^3 and finally with the

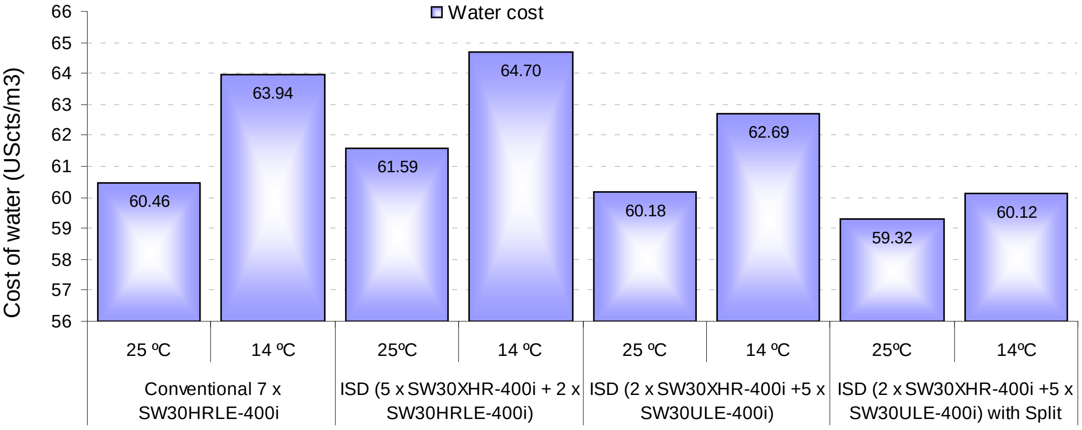

Fig. 2. Total cost of water for all the different configurations containing 7 modules per pressure vessel.

Table 8
Itemized cost of water for all the different configurations containing 7 modules per pressure vessel

	Conventional 7×SW30HRLE-400i		ISD (5×SW30XHR-400i + 2×SW30HRLE-400i)		ISD (2×SW30XHR-400i +5×SW30ULE-400i)		ISD (2×SW30XHR-400i + 5×SW30ULE-400i) with split	
Cost (UScent/m^3)	25°C	14°C	25°C	14°C	25°C	14°C	25°C	14°C
Subtotal O&M	41.64	45.16	42.58	45.74	41.00	43.54	40.29	41.14
O&M: cost of electricity	32.42	36.07	33.26	36.60	31.53	34.17	31.01	32.05
O&M: labor and overhead	1.48	1.48	1.48	1.48	1.48	1.48	1.48	1.48
O&M: chemicals	4.38	4.25	4.36	4.18	4.42	4.33	4.29	4.11
O&M: replacement and repair	2.94	2.94	3.05	3.04	3.14	3.13	3.07	3.07
O&M: insurance	0.43	0.43	0.43	0.43	0.44	0.44	0.43	0.43
Amortization	18.82	18.78	19.01	18.95	19.17	19.14	19.03	18.98
Water cost	60.46	63.94	61.59	64.70	60.18	62.69	59.32	60.12

split applied to the same ISD configuration, the price of water varies from: 59.32 UScent/m^3 to 60.12 UScent/m^3.

Due to the use of SW30ULE modules in the first pass of ISD designs, the size of the second pass is considerably larger in these configurations than in the basic designs, however, the saving in operating expenses when using the ISD and especially when using ISD + Split compensates the higher CAPEX.

In Fig. 3 and Table 9 the total and itemized cost of water for all the designs made using 8 pressure modules per pressure vessel are shown.

According to this data, the incorporation of the split + ISD to the first pass involves an important reduction of the cost of water. With the basic design, using 8 SW30HRLE-400i modules in the first pass, the final cost of water ranges from 59.53 to 63.06 UScts/m^3. With the first split + ISD configuration (5 SW30XHR-400i + 3 SW30HRLE-400i) the price of water is between 59.98–61.36 UScts/m^3. According to this, there is an important difference in the cost of water when doing the calculation at the worst conditions from an energetic point of view. Under these circumstances, the basic design involves a cost of 63.06 UScts/m^3 and the split + ISD 61.36 UScts/m^3. This difference is mainly due to the much smaller size of the second pass of the split + ISD option. The smaller size of this second pass results in important operating savings due to the smaller amount of water that needs to pumped.

In addition to this first split + ISD configuration, three more designs were evaluated consisting of combinations of SW30XHR-400i and SW30ULE-400i in the vessels of the first pass. The first option contained 4 elements of each, the second option, 3 SW30XHR-400i and 5 SW30ULE-400i, and the final option, 2 SW30XHR-400i and 6 SW30ULE-400i. From the calculation it can be observed that in all these split + ISD cost calculations, the price of water is lower than the basic designs. In addition to this, as soon as the number of SW30ULE-400i modules installed in the vessel increases, the price tends to decrease. This is an indication that, even though the size of the second pass increases when using SW30ULE-400i modules, the savings in energy due to the high production of these modules are much more significant. From the previous tables it can be seen that the capital/amortization costs are higher with the split + ISD designs compared to the basic designs, but, the operating costs are lower. These costs are summarized in Table 10.

Table 10
Amortization cost summary

Conventional design (8 SW30HRLE-400i):
  High *T* and high FF: O&M cost/m^3 41.74 UScent/m^3
  Amortization: 17.79 UScent/m^3
  Low *T* and low FF: O&M cost/m^3 45.32 UScent/m^3
  Amortization: 17.75 UScent/m^3

Split + ISD (4 SW30XHR-400i and 4 SW30ULE-400i):
  High T and high FF: O&M cost/m^3: 40.60 UScent/m^3
  Amortization: 17.90 UScts/m^3
  Low *T* and Low FF: O&M cost/m3: 41.64 UScent/m^3
  Amortization: 17.93 UScent/m^{33}

Split + ISD (3 SW30XHR-400i and 5 SW30ULE-400i):
  High *T* and high FF: O&M cost/m^3: 40.42 UScent/m^3
  Amortization: 17.94 UScts/m^3
  Low *T* and Low FF: O&M cost/m^3: 41.24 UScent/m^3
  Amortization: 17.79 UScent/m^{33}

Split + ISD (2 SW30XHR-400i and 6 SW30ULE-400i):
  High *T* and high FF: O&M cost/m^3: 40.23 UScent/m^3
  Amortization: 17.98 UScent/m^3
  Low *T* and Low FF: O&M cost/m^3: 41.07 UScent/m^3
  Amortization: 17.91 UScent/m^3

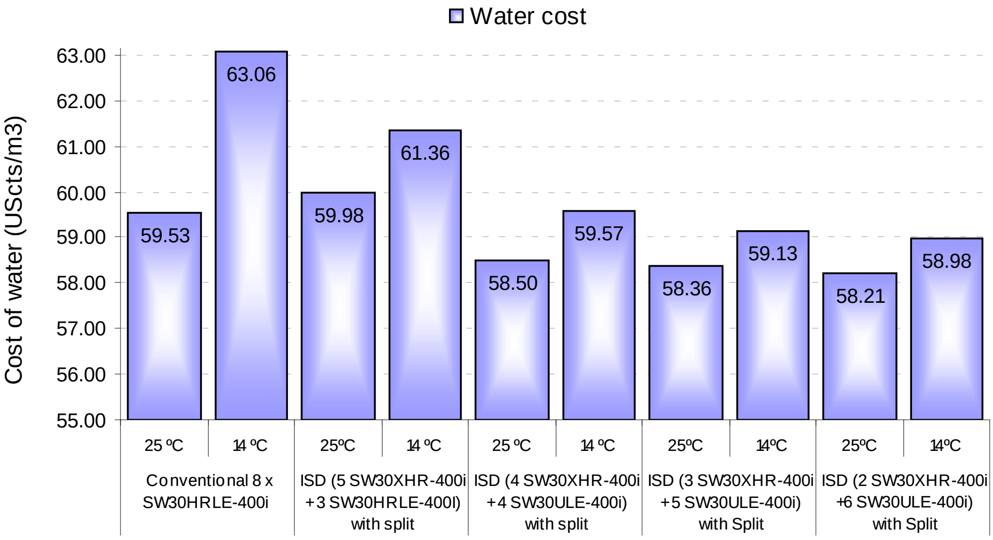

Fig. 3. Total cost of water for all the different configurations containing 8 modules per pressure vessel.

Table 9
Itemized cost of water for all the different configurations containing 8 modules per pressure vessel

	Conventional 8×SW30HRLE-400i		ISD (5 SW30XHR-400i + 3 SW30HRLE-400I) with split		ISD (4 SW30XHR-400i + 4 SW30ULE-400i) with split		ISD (3 SW30XHR-400i + 5 SW30ULE-400i) with split		ISD (2 SW30XHR-400i +6 SW30ULE-400i) with split	
Cost (UScent/m^3)	25°C	14°C	25°C	14°C	25°C	14°C	25°C	14°C	25°C	14°C
Subtotal O&M	41.74	45.32	42.19	43.65	40.60	41.64	40.42	41.24	40.23	41.07
O&M: cost of electricity	32.60	36.31	33.16	34.82	31.47	32.68	31.26	32.28	31.04	32.07
O&M: labor and overhead	1.48	1.48	1.48	1.47	1.47	1.48	1.47	1.47	1.48	1.47
O&M: chemicals	4.37	4.23	4.22	4.05	4.26	4.06	4.27	4.08	4.29	4.11
O&M: replacement and repair	2.89	2.89	2.92	2.91	3.00	3.01	3.00	3.00	3.02	3.01
O&M: insurance	0.41	0.40	0.41	0.40	0.41	0.41	0.41	0.41	0.41	0.41
Amortization	17.79	17.75	17.80	17.71	17.90	17.93	17.94	17.89	17.98	17.91
Water cost	59.53	63.06	59.98	61.36	58.50	59.57	58.36	59.13	58.21	58.98

According to the calculation, the most economically viable combination of modules is the one containing 2 modules SW30XHR-400i and 6 SW30ULE-400i using a split.

3.2. Northern Mediterranean (Spain)

This study was made for a hypothetical SWRO plant with a total production of 100,000 m^3/d and respecting a boron content in the permeate of 0.5 ppm. Because of this restrictive product water quality a second pass at elevated pH (10) is needed in all the cases. The feed water TDS is 39,500 ppm and the Boron concentration 5.45 ppm. The temperature is estimated to range between 15 and 26ºC.

In Table 11, all the cases evaluated are described. All the designs studied for this case are described in terms of SW and BW modules used in the first and second pass respectively. It is also indicated whether the design has a split or ISD in the first pass. The different configurations were selected in order to see the influence of the type of module installed in the first and in the second pass as well as to evaluate the improvements achieved in terms of costs reductions by the implementation of ISD and split in the sea water pass. As previously indicated the configurations named "conventional" refer to the ones based on the use of standard modules, whereas the ones named "advanced" use some of the recently developed RO modules.

In Table 12 the main information regarding number of pressure vessels of each pass as well as maximum feed pressure calculated in the worst scenario (minimum temperature and lowest fouling factor) in every configuration is shown. The recovery of the system is also shown in this table. It is actually expressed as a range because the recovery of the design depends very much on the ratio between the permeate of the first pass that is actually further treated in the second pass and the one that is by passed. At the highest temperature, the amount of permeate going into the second pass needs to be higher than at the lowest temperature in order to achieve the same final product water quality and thus the recovery of the system is lower.

With the information provided by the design software ROSA, in terms not only of operating conditions but also of number of modules needed in order to maintain the defined flux in each ones of the passes, the final and itemized cost of water was calculated.

This cost for each one of the configurations is shown in Fig. 4.

According to these results, the highest cost of water assuming an average of the two extreme scenarios (high

Table 11
Description of the type of modules, use of ISD and/or split in each configuration

Configuration	Type of module first pass	ISD in the first pass	Permeate split in the first pass	Type of module second pass
Conventional 1	SW30HRLE-400i	No	No	LE-440i
Conventional 1S	SW30HRLE-400i	No	Yes	LE-440i
Conventional 2	SW30HRLE-400i	No	No	BW30-440i
Conventional 2S	SW30HRLE-400i	No	Yes	BW30-440i
Conventional 3	SW30XLE-400i	No	No	LE-440i
Conventional 3S	SW30XLE-400i	No	Yes	LE-440i
Conventional 4	2 SW30HRLE-400i + 5 SW30XLE-400i	Yes	No	LE-440i
Conventional 4S	2 SW30HRLE-400i + 5 SW30XLE-400i	Yes	Yes	LE-440i
Conventional 5	4 SW30HRLE-400i + 3 SW30XLE-400i	Yes	No	LE-440i
Conventional 5S	4 SW30HRLE-400i + 3 SW30XLE-400i	Yes	Yes	LE-440i
Advanced 1	2 SW30HRLE-400i + 5 SW30ULE-400i	Yes	No	LE-440i
Advanced 1S	2 SW30HRLE-400i + 5 SW30ULE-400i	Yes	Yes	LE-440i
Advanced 2	4 SW30HRLE-400i + 3 SW30ULE-400i	Yes	No	LE-440i
Advanced 2S	4 SW30HRLE-400i + 3 SW30ULE-400i	Yes	Yes	LE-440i
Advanced 3	2 SW30XHR-400i + 5 SW30ULE-400i	Yes	No	LE-440i
Advanced 3S	2 SW30XHR-400i + 5 SW30ULE-400i	Yes	Yes	LE-440i
Advanced 4	4 SW30XHR-400i + 3 SW30ULE-400i	Yes	No	LE-440i
Advanced 4S	4 SW30XHR-400i + 3 SW30ULE-400i	Yes	Yes	LE-440i

Note: The only difference between the configurations including a final "S" in the name is that they include a split in the first pass. E.g. "Conventional 1" is without split and "Conventional 1S" with split.

Table 12
Number of pressure vessels, feed pressure and recovery calculated for each one of the configurations

Configuration	Number of pressure vessels first pass	Feed pressure first pass (bar)	Number of pressure vessels second pass	Recovery of the system (%)
Conventional 1	1278	65.71	348	45–45.8
Conventional 1S	1266	65.92	284	45.4–46.14
Conventional 2	1270	65.88	328	45.1–45.8
Conventional 2S	1256	66.13	248	45.6–46.2
Conventional 3	1295	61.47	388	44.7–45–27
Conventional 3S	1280	61.5	360	44.9–45.5
Conventional 4	1285	61.97	380	44.8–45.35
Conventional 4S	1280	62.12	332	45.12–45.86
Conventional 5	1285	63	364	44.92–45.5
Conventional 5S	1270	63.17	304	45.27–46.1
Advanced 1	1285	59.46	392	44.74–45.22
Advanced 1S	1280	59.79	348	45–45.78
Advanced 2	1285	61.29	375	44.84–45.37
Advanced 2S	1275	61.49	328	45.14–45.93
Advanced 3	1285	60.32	392	44.7–45.2
Advanced 3S	1275	60.59	328	45.14–45.8
Advanced 4	1285	63.54	360	44.95–45.53
Advanced 4S	1255	63.86	268	45.51–46.30

and low temperature) corresponds to the configuration using standard SW30HRLE-400i in the first pass and a non-low energy module in the second pass, i.e., BW30-440i instead of LE-440i. More in detail, the use of BW30-440i in the second pass results in a final cost of water 1.5% higher than when using LE-440i in both cases, with and without split in the first pass (cases conventional 1 and 1 S vs. conventional 2 and 2S). Regarding the use of split, it has been found that the fact of implementing this feature in any of the designs evaluated, the cost of water is reduced by a 3%.

The lowest cost of water was calculated when using the recently developed SW modules with a split and in ISD configuration 4×SW30XHR-400i + 3×SW30ULE-400i (Advanced 4S). In this case, comparing the standard design based on SW30HRLE-400i (Conventional 1) with this Advanced 4S, the final cost of water is 4% lower in this last configuration. The itemized cost of water, divided into Amortization, insurance, replacement and repair, chemicals, labor and overhead and cost of electricity for these two extreme cases can be observed in Table 13. From this picture it can be concluded that the main aspect influencing the different final cost of water is the cost of electricity, which is significant lower in the second con-

Table 13
Itemized cost of water of the conventional design with SW30HRLE-400i and of the advanced design with ISD and split

	Conventional 1- SW30HRLE-400i + LE440i		Advanced 4S – 4 SW30HRLE-400i and 3 SW30ULE-400i + LE440i	
Cost (UScent/m^3)	26°C	15°C	26°C	15°C
Subtotal O&M	43	43	41	41
O&M: cost of electricity	32.96	33.95	31.68	31.71
O&M: labor and overhead	2.27	2.27	2.27	2.27
O&M: chemicals	4.12	3.82	3.92	3.62
O&M: replacement and repair	2.94	2.93	2.80	2.79
O&M: insurance	0.43	0.43	0.43	0.43
Amortization	19.09	19.00	18.81	18.72
Water cost	61.80	62.41	59.91	59.55

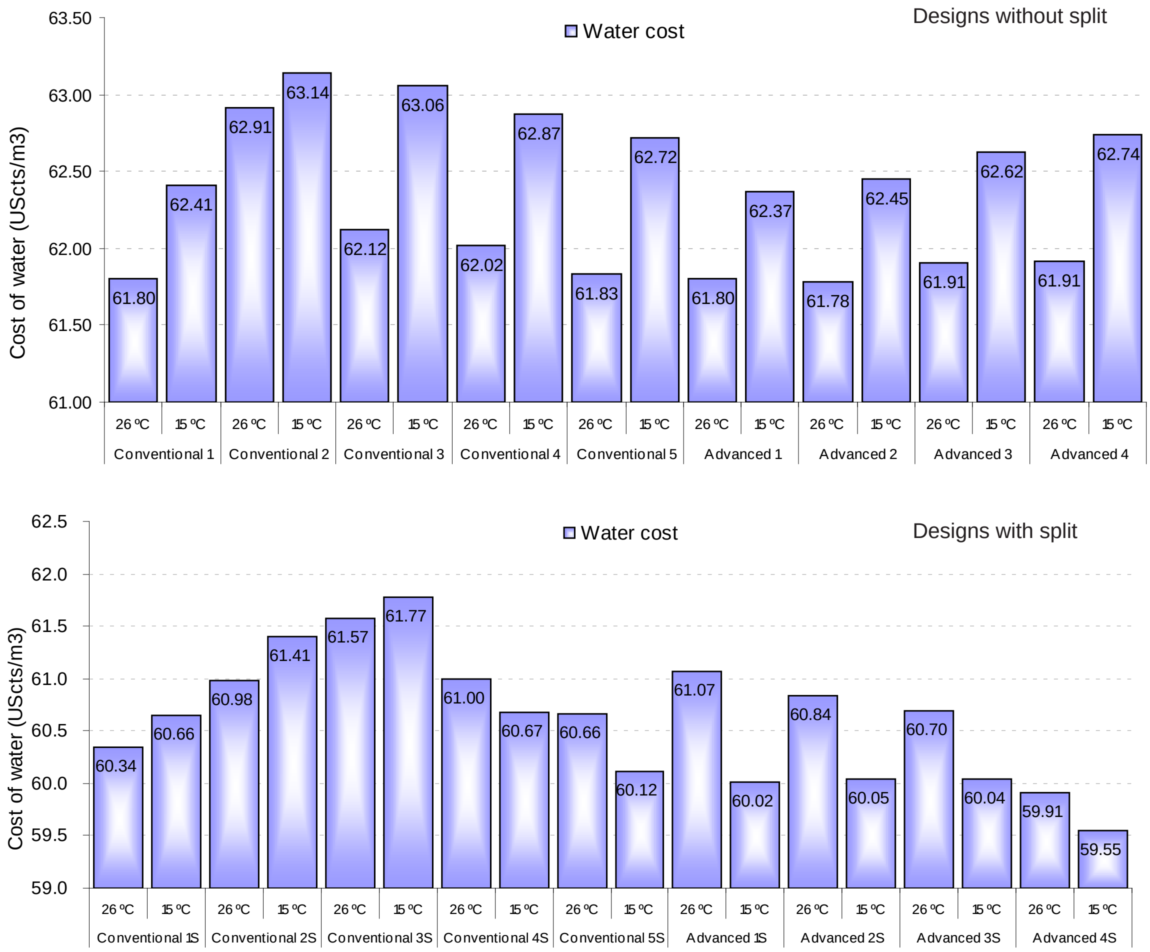

Fig. 4. Final cost of water of all the designs without split (graph of top) and without split (graph below) at the two extreme temperatures.

figuration. This aspect is especially important if one takes into account the growing tendency of the cost of energy.

3.3. *Persian Gulf (Saudi Arabia)*

For the Persian Gulf example, a feed water of 50,000 mg/L was taken as a reference for a SWRO plant of 96,000 m^3/d. The temperature range was estimated to be between 18 and 35°C and the quality of the permeate water produced by the SWRO plant should have a TDS below 300 ppm. As explained before the philosophy of the evaluation for this geography differs to a certain extent from the previous ones. In the current case, the design was optimized not by the maximum average flux but by the maximum permeate flow of the first element. Meaning that while in the previous geographies the whole evaluation was made maintaining the design criteria of maximum average flux of 14 L/m^2h, with the current case, the limit was set at the maximum allowed permeate flow of 1.14 m^3/h per element. It should be also pointed out that in the previous cases, since all the configurations were run at the same average flux, a more tolerant long term fouling factor was applied to the cases with ISD. In the current case the same fouling factor was applied to all the cases.

For this specific case two different configurations with split were evaluated. The first one consisted of standard sea water modules in the first pass SW30HRLE-400i and low energy modules in the second pass LE-440i. The second configuration consisted of a ISD with SW30XHR-400i in the first position, SW30HRLE-400i in the second position, SW30XLE-400i in the third position and SW30ULE-400i modules in the rear positions of the pressure vessels. In both cases, vessels containing 7 modules were considered.

In Table 14, some of the main features of each one of the designs at different scenarios in terms of temperature and fouling factors are shown.

In Fig. 5, the final cost of water per m^3 is represented for each one of the scenarios studied. It can be affirmed

Table 14
Number of pressure vessels, feed pressure and recovery of the system for each one of the designs evaluated

Configuration	Number of pressure vessels first pass	Number of pressure vessels second pass	*T* (°C) and fouling factor first pass	Feed pressure first pass (bar)	Recovery of the system (%)
Conventional	1168	176	35–0.9	69.4	39.81
			35–0.7	71.7	
			18–0.9	70.9	
			18–0.7	75.4	
Advanced	1000	176	35–0.9	74.5	45.3
			35–0.7	76.7	
			18–0.9	76.1	
			18–0.7	80.02	

that on average the use of the recently developed FilmTec SWRO modules in an ISD configuration results in a significant decrease of the cost of water. In the graph it can be also observed that the lowest cost corresponds to the scenario at the lowest temperature while the highest feed pressures were calculated under these conditions. This fact can be explain taking into account that at the lowest temperature, the final water quality is almost achieved after the first pass and thus, the use of the second pass is very low.

In Table 15, the cost of water is itemized for each one of the configurations into: cost of electricity, labor and overhead, chemicals, replacement and repair, insurance and amortization. The cost of electricity is on average 3% lower in the conventional design, however the expenses related to chemicals, replacement and repair, insurance and amortization are in the range of 11–14% higher in the conventional configuration. These results can be understood if we consider that with the advanced design the recovery of the system is higher.

3.4. Eastern Mediterranean (Israel)

A SWRO plant with a full capacity of 96,000 m^3/d was taken as an example for this evaluation. A feed water of 41,000 mg/L in TDS and 5.3 mg/L of boron content was assumed as reference water. The temperature was estimated to have a seasonal fluctuation from 18 to 32°C. The different configurations evaluated for this geography had the common criteria of producing the target amount of water while respecting a boron content of 0.3 ppm. For this evaluation two different designs were considered. The first one is based on a conventional configuration with SW30HRLE-400i modules in the first pass and BW30-440i in the second pass. The second designs consisted of a ISD with 1 module SW30XHR-400i in the first position, 1 module SW30HRLE-400i in the second position and SW30ULE-400i modules in the 6 remaining positions of the vessel. Both designs have 8 modules per pressure vessel in the seawater pass and they both account with split in this pass. In Table 16 some of the main features

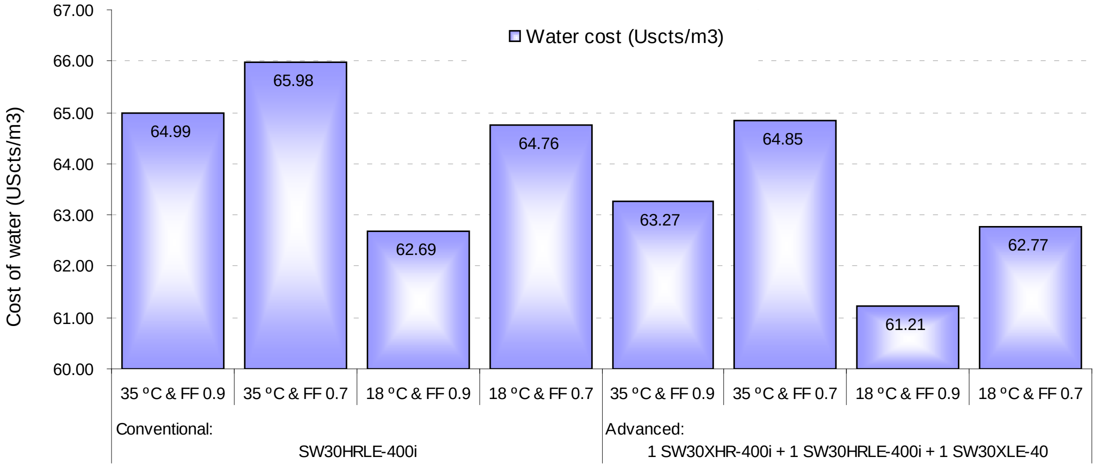

Fig. 5. Cost of water for the conventional and the advanced design at different operating scenarios.

Table 15
Itemization of the final cost of water

	Conventional: SW30HRLE-400i				Advanced: 1 SW30XHR-400i + 1SW30HRLE-400i + 1 SW30XLE-400i + 4 SW30ULE-400 i			
Cost (UScent/m^3)	35°C FF 0.9	35°C FF 0.7	18°C FF 0.9	18°C FF 0.7	35°C FF 0.9	35°C FF 0.7	18°C FF 0.9	18°C FF 0.7
Subtotal O&M	46.34	47.32	44.04	46.11	46.45	48.03	44.39	45.95
O&M: cost of electricity	37.00	37.98	34.70	36.77	37.93	39.51	35.88	37.44
O&M: labor and overhead	2.36	2.36	2.36	2.36	2.36	2.36	2.36	2.36
O&M: chemicals	3.90	3.90	3.90	3.90	3.43	3.43	3.43	3.43
O&M: replacement and repair	2.65	2.65	2.65	2.65	2.34	2.34	2.34	2.34
O&M: insurance	0.43	0.43	0.43	0.43	0.38	0.38	0.38	0.38
Amortization	18.65	18.65	18.65	18.65	16.82	16.82	16.82	16.82
Water cost	64.99	65.98	62.69	64.76	63.27	64.85	61.21	62.77

Table 16
Main features of each design: number of pressure vessels, feed pressure first pass, recovery of the system and total production

Configuration	Number of pressure vessels first pass	Number of pressure vessels second pass	*T* (°C) and fouling factor first pass	Feed pressure first pass (bar)	Recovery of the system (%)
Conventional	1620	264	32–0.9	60.38	43
			32–0.7	63.29	
			18–0.9	63.12	
			18–0.7	67.37	
Advanced	1000	264	32–0.9	62.93	47
			32–0.7	65.16	
			18–0.9	66.87	
			18–0.7	70.94	

of each one of the designs at different scenarios in terms of temperature and fouling factors are shown.

As in the previous geography, the designs were optimized respecting not the commonly recommended maximum average flux of 14 L/m^{2}h but the maximum permeate flow per element. According to this the conventional configuration actually respected both restrictions at the same time, obtaining an average flux of 13.91 L/m^{2}h. On the other hand, the design with the ISD accomplished the maximum permeate flow per element limitation at a flux of 18.37 L/m^{2}h.

In Fig. 6, the final cost of water calculated for the two configurations in the different operating scenarios is shown. It can be observed that the advanced designs offer a significant reduction in the cost of water. More specifically, the final cost is around 4% lower with such design vs. the conventional one. In Table 17, the cost calculation in itemized in the different categories already described before. Whereas the energy consumption is slightly higher (0.39%) in the advanced design, mainly because of the high recovery of the system, the rest of the costs contributing to the final cost of water are lower with such a design. More specifically, the cost of the chemicals needed are around 7% lower, the amortization 12% and the cost related to replacement and repairs 20% lower.

4. Summary and conclusions

Desalination market growth has triggered significant development in SWRO membrane and process development. New membranes from Dow have previously unknown productivity and rejection levels, such as SW30ULE-400i with 11,000 gpd and 99.70% NaCl rejection, and SW30XHR-400i with 6000 gpd and 93% boron rejection.

In addition, the internally staged design concept allows reaching much higher flux and recovery operation at a defined feed pressure, or a lower feed pressure at the same flux. This reduces capital and operational cost in the pretreatment and membrane stages (less SWRO and BWRO membranes, vessels, trains, smaller pretreatment, lower energy consumption).

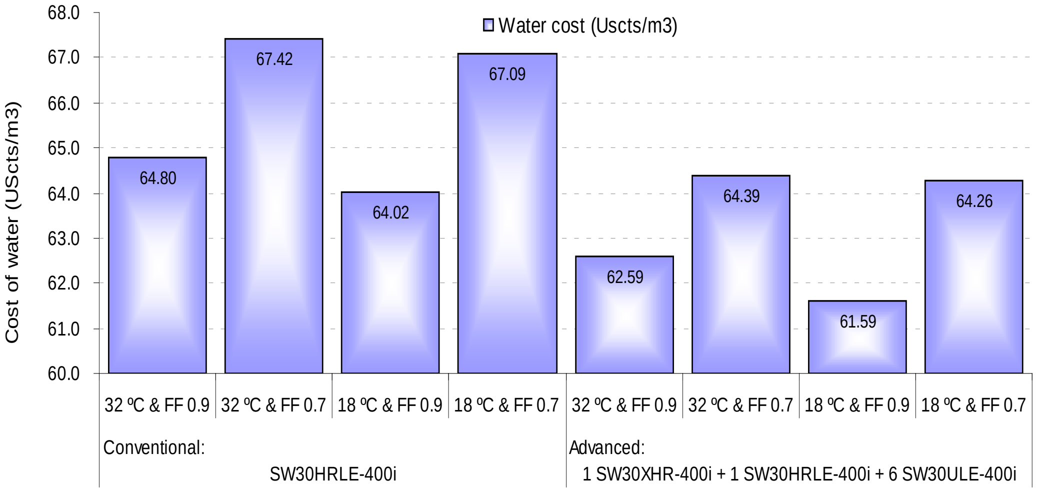

Fig. 6. Cost of water of the conventional and the advanced design at different operating conditions.

Table 17
Itemized cost of water of the conventional and the advanced design

	Conventional: SW30HRLE-400i				Advanced: 1 SW30XHR-400i + 1 SW30HRLE-400i + 6 SW30ULE-400i			
Cost (UScent/m^3)	32°C FF 0.9	32°C FF 0.7	18°C FF 0.9	18°C FF 0.7	32°C FF 0.9	32°C FF 0.7	18°C FF 0.9	18°C FF 0.7
Subtotal O&M	46.05	48.68	45.27	48.34	45.79	47.59	44.79	47.46
O&M: cost of electricity	35.90	38.51	35.42	38.45	36.44	38.23	35.75	38.40
O&M: labor and overhead	2.36	2.36	2.36	2.36	2.36	2.36	2.36	2.36
O&M: chemicals	4.34	4.36	4.04	4.07	4.09	4.09	3.78	3.80
O&M: replacement and repair	3.02	3.02	3.02	3.02	2.52	2.52	2.52	2.52
O&M: insurance	0.43	0.43	0.43	0.43	0.38	0.38	0.38	0.38
Amortization	18.75	18.75	18.75	18.75	16.80	16.80	16.80	16.80
Water cost	64.80	67.42	64.02	67.09	62.59	64.39	61.59	64.26

The performance of FILMTEC™ SW30XHR-400i, SW30ULE-400i and internally staged design have been proven in numerous pilot trials and various larger scale plants, in all geographies, and over various years, and these solutions are commercially available from Dow Water Solutions since 2008.

The use of these new element types FILMTEC™ SW30XHR-400i and SW30ULE-400i, in combination with the novel patent pending internally staged design (ISD) concept and permeate split, has been applied to four key seawater desalination market geographies, and the benefits shown in Table 18 have been observed.

In the Australian and Spanish case, there is a slight reduction in 2nd stage vessels, which comes in fact from using permeate split. Due to the larger imbalance between front and rear end permeate qualities in an ISD design, permeate split is crucial in an ISD case, to capture the key benefit.

Depending on the route chosen, there are strong differences in the consequences with regards to size of the RO stage (17–26% smaller), size of the pretreatment (9–12% smaller), and/or the feed pressure (2–6 bar lower).

The approaches selected in the framework of this evaluation are somewhat extreme in that they either focused on capital or on energy savings. In between these two extreme approaches, optimization could be done between the energy and the capital cost savings route, to yield the optimized design.

The evaluation shows that regardless of the cost savings route chosen, regardless of the geography and regardless of the design philosophy, there are significant cost savings in each case.

Table 18
Benefits of novel SWRO element types and ISDE configuration

Geography	Benefits
South Pacific (Australia)	Advancements mainly used to reduce energy consumption • Same flux and recovery • Larger 1st but smaller 2nd pass • 6.1 bar lower pressure
Northern Mediterranean (Spain)	Advancements mainly used to reduce energy consumption • Same flux and recovery • 1% less vessels & membrane elements in SWRO, 5% less in BWRO • 2 bar lower pressure in SWRO
Persian Gulf (Saudi Arabia)	Advancements mainly used to reduce capital cost • Pressure ~5 bar higher • Higher flux, resulting in 17% less vessel and membrane elements in SWRO stage • Recovery 5.5% points higher, resulting in 12% smaller pretreatment
Eastern Mediterranean (Israel)	Advancements mainly used to reduce capital cost • Pressure ~3 bar higher • Higher flux, resulting in 26% less vessel and membrane elements in SWRO stage • Recovery 4% points higher, resulting in 9% smaller pretreatment

Table 19
Summary of cost savings by novel SWRO element types and ISD configuration

Geography	Conventional	Advanced	Saving	Saving
Southern Pacific	Case 1 (no split)	Case 4S	US cent/m^3	%
25°C, FF 0.9	59.53	58.21	1.32	2.2
14°C, FF 0.7 conv./0.75 adv.	63.06	58.98	4.08	6.5
Persian Gulf	Conv. case	Adv. case		
35°C, FF 0.9	64.99	63.27	1.72	2.6
18°C, FF 0.7	64.76	62.77	1.99	3.1
Eastern Mediterranean	Conv. case	Adv. case		
32°C, FF 0.9	64.8	62.59	2.21	3.4
16°C, FF 0.7	67.09	64.26	2.83	4.2
Northern Mediterranean	Case 1S (split)	Case 4S		
26°C, FF 0.9	60.34	59.91	0.43	0.7
15°C, FF 0.7/0.75	60.66	59.55	1.11	1.8

Despite the fact that economic conditions chosen (20a depreciation, 5% interest rate, energy cost of 10 US cent/kWh) were more in favor of operational cost savings, it still seems that the capital savings approach (higher flux, higher recovery) chosen for the Persian Gulf and Eastern Mediterranean cases yielded slightly larger savings. This is inline with previous assessments [5].

These cost savings are in the range of 0.4–4.1 US cent/m^3 water produced. This is equivalent to 0.7– 6.5% water cost saving, and on average 3.1% water cost saving.

Considering that these considerable cost savings are readily available since 2008 from Dow Water Solutions, the industry should start to significantly benefit from these in the coming years.

Acknowledgements

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