Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2014.989631

55 (2015) 3040–3047
September

Taylor & Francis
Taylor & Francis Group

Lahat BWRO plant: technical and economic evaluation of energy recovery alternatives

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Received 13 April 2014; Accepted 16 June 2014

ABSTRACT

The Lahat BWRO plant was constructed as part of the southern Israel coastal aquifer rehabilitation project. Two RO trains, with a capacity of 10,000 m^3/d each, were commissioned in August 2010. In both trains a turbocharger (TC) energy recovery device was installed, wherein the turbine side utilizes the energy of the second stage brine to boost the second stage feed. Lahat plant expansion with two additional 11,300 m^3/d BWRO trains is currently under construction. As part of the pre-design phase, a techno-economic analysis was conducted with the purpose of finding the most cost-effective energy recovery configuration. Comparing existing design of TC added with a booster pump with alternative isobaric energy recovery with ERI PX devices, it was shown that implementation of isobaric PX results in a life cycle saving of 1,091,882$, about 1.5 times more than the TC alternative. Accordingly, in the design of the two additional RO units, isobaric energy recovery device was implemented. Apart from the cost benefit, this configuration has several advantages versus the TC, mainly the control of the second stage booster pressure with increased accuracy and flexibility. This enables a better balance of the first and second stage flux in comparison with TC option. The current paper includes an introduction about the southern Israel coastal aquifer rehabilitation project, and the construction plan of the Gat, Granot, and Lahat brackish water RO BWRO desalination plants. In addition, it presents the complexity of the marine brine disposal pipeline of these inland plants, and the rational that led to the innovative idea of energy recovery in the Lahat BWRO plant. Finally, the technical and economic considerations of energy recovery alternatives in BWRO plants are discussed and summarized.

Keywords: Brackish water desalination; Energy recovery

1. The southern coastal aquifer rehabilitation project

The coastal aquifer, one of the Israel's main groundwater resources, expanses from the Carmel Range in the north to the Sinai Peninsula in the south, and from the Judea and Samaria foothills in the east to the Mediterranean Sea in the west (Figs. 1 and 2), [1]. The basin has been divided into four parts: Northern, Central, Southern, and the Gaza Strip, while the general groundwater flow direction is perpendicular to the Mediterranean Sea shore line [1] (Fig. 2).

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Presented at the Conference on Desalination for the Environment: Clean Water and Energy 11–15 May 2014, Limassol, Cyprus

In the west, the coastal aquifer is in direct contact with the sea, what creates a delicate balance between flow of fresh groundwater to the sea and seawater intrusion to the aquifer. In the east, the coastal aquifer is in direct contact with the western mountain aquifer where brackish groundwater flows into the coastal aquifer [1] (Fig. 1). Over the years, due to excessive over-pumping, the water of the coastal aquifer has been salinized [2]. In addition, due to the fact that the aquifer is located under the most populated area in Israel, it was extremely exposed to urban and industrial pollution as well as salinization due to irrigation with treated effluents.

Consequently, in 2004, Mekorot and the Israeli Water Authority have introduced the "southern coastal aquifer rehabilitation project," as part of the "eastern drain" project. The main objectives of the project were to: (1) prevent the salinization process by stabilizing the groundwater level of the coastal aquifer; (2) remove salts from the aquifer by pumping brackish water; (3) improve the water quality of supplied drinking water and decrease salinization processes due to production of better treated effluents for irrigation; and (4) rehabilitate and preserve the aquifer.

In the framework of the project Mekorot has drilled 35 new wells, at a capacity of about 40 M m^3/year, along the eastern side of the aquifer. These wells, together with the existing wells, constituted a hydrological buffer preventing the continued penetration of brackish water into the coastal aquifer. The new wells brackish groundwater were planned to be further desalinated in the Mekorot's Granot and Lahat brackish water RO (BWRO) desalination plants [2,3].

2. The Gat, Granot, and Lahat BWRO desalination plants

The construction of the Gat, Granot, and Lahat BWRO desalination plants, near the city of Ashkelon (in the south of Israel), has been done in four stages (Table 1, Fig. 3). In 2004, Mekorot established the Gat and Granot desalination plants, with capacities of 4,200 and 9,000 m^3/d, respectively. The RO processes included two desalination stages using BWRO membranes with an inter booster pump for flux and recovery adjustment.

In 2011, in the framework of the southern coastal aquifer rehabilitation project, the Granot plant was expanded with another 10,000 m^3/d RO train ("Granot 2"). In addition, the Lahat desalination plant

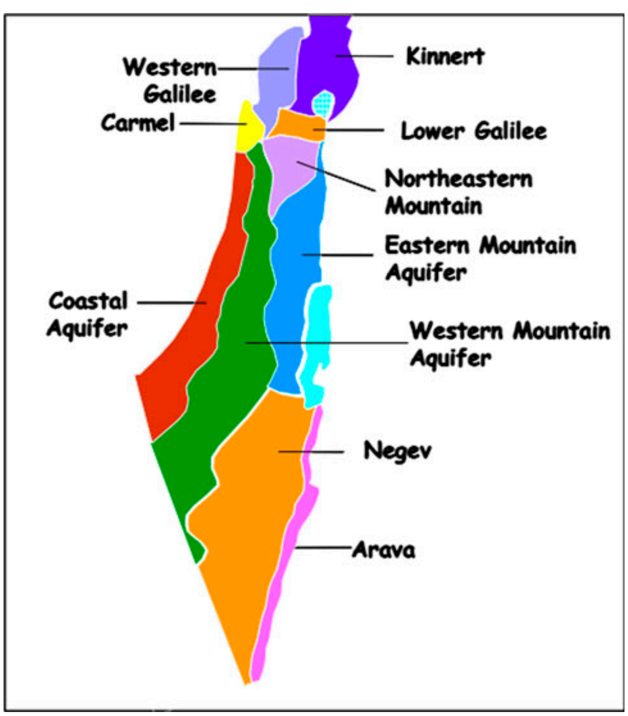


Fig. 1. The major water basins in Israel.
Source: [1].

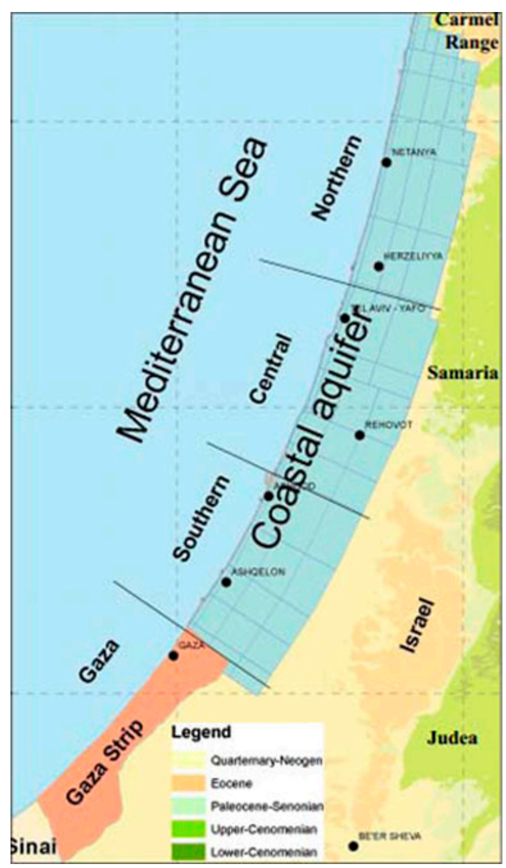


Fig. 2. The Israeli coastal aquifer.
Source: [1].

Table 1
Capacities of the Gat, Granot, and Lahat BWRO desalination plants throughout the years of 2004-2016

Year	Plant	Capacity (m^3/day)	Total capacity (m^3/day)
2004	Gat	4,200	13,200
	Granot 1	9,000	
2011	Gat	4,200	43,200
	Granot 1 and 2	19,000	
	Lahat 1 and 2	20,000	
2014	Gat	4,200	88,400
	Granot 1,2,3,4	41,600	
	Lahat 1,2,3,4	42,600	
2016	Gat	4,200	102,300
	Granot 1,2,3,4,5	52,900	
	Lahat 1,2,3,4	45,200	

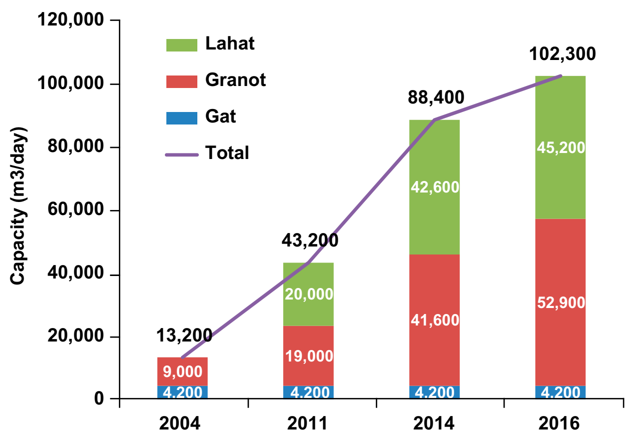


Fig. 3. Capacities of the Gat, Granot, and Lahat BWRO desalination plants throughout the years of 2004–2016.

was constructed, comprising two identical RO trains, with a capacity of 10,000 m^3/d each (“Lahat 1 and 2”). Due to the new requirements of the Israeli Water Authority to maintain 0.3–0.40 mg/L boron concentration in the product water, and based on the forecast of 0.8–0.9 mg/L boron content in the raw water from the Eastern Buffer Zone wells; the RO membranes that were selected for the Granot 2 and Lahat 1 and 2 units were seawater RO (SWRO) membranes. The RO process at all of these units included two desalination stages using SWRO membranes with an inter booster pump at Granot 2 and an inter turbocharger (TC) energy recovery device at Lahat 1 and 2. The innovative selection of an energy recovery device in the Lahat BWRO plant is further discussed in Section 5.

Nowadays, both Granot and Lahat plants are being expanded to total capacities of 41,600 and 42,600 m^3/d, respectively, by addition of two identical 11,300 m^3/d RO trains to each of the plants (“Granot 3 and 4,” “Lahat 3 and 4”). The RO process at all of these units will comprise two desalination stages using SWRO membranes with an inter booster pump at Granot 3 and 4, and an inter isobaric energy recovery device (ERI PX) at Lahat 3 and 4. The considerations for selecting ERI PX over TC at the current Lahat expansion are further discussed in Section 5.

In 2016, the final stage of the project is planned. Granot is expected to be expanded with a fifth 11,300 m^3/d RO train with a similar RO process design as in Granot 3 and 4. The Lahat 1 and 2 units are expected to be expanded to a capacity of 11,300 m^3/d each. Upon their completion, the Granot and Lahat desalination plants will yield 52,900 and 45,200 m^3/d, respectively, while the future total daily capacity of the overall Gat, Granot, and Lahat desalination plants will be 102,300 m^3/d (Table 1, Fig. 3). Fig. 4 represents photos from both Granot and Lahat plants.

3. The unique brine disposal pipeline of the Gat, Granot, and Lahat plants

One of the challenges Mekorot had to face within the aquifer rehabilitation project was the ability to handle the concentrate effluent (brine) generated at the Gat, Granot, and Lahat desalination plants, in a manner that will not harm the environment. Marine brine disposal was chosen as the best solution considering the alternatives and the location considerations [3].

In 2004, Mekorot laid an exclusive underground brine disposal pipeline, of 6–20″ diameter and about 30 km long, which connected the inland Gat and Granot (and in 2011 also Lahat) BWRO desalination plants to the Mediterranean Sea. Fig. 5 illustrates the geographical locations of the new wells, the desalination plants, and the brine disposal pipeline [2]. At the end of the pipeline, the brine from the Mekorot’s desalination plants is combined with the VID’s (IDE Technologies,

(a) Granot RO hall

(b) Lahat RO hall

(c) Granot BWRO plant, general view

(d) Lahat BWRO plant, general view

Fig. 4. Pictures of the Granot and Lahat BWRO plants: the RO hall and a general view.

Veolia and Dankner–Ellern Infrastructure) SWRO desalination plant at Ashkelon, resulting in a combined outlet stream of brine to the sea [3].

The pipeline, which was designed for disposal of up to 1,000 m^3/h (at the future 102,300 m^3 daily plants capacity), has been operated by Mekorot and authorized by the Ministry of Environmental Protection. The main concerns when operating such a long underground brine disposal pipeline, with a retention time of about 40 h, are scale precipitations along the pipe, as well as soil and marine contaminations [3].

In an experimental flow simulation study, the main pipeline design parameters were identified in order to prevent scale precipitation along the pipe. The parameters included: Ensuring a full pipe flow (in order to prevent CO_2 emissions which increase pH and thus enhance precipitation), controlling Langelier Saturation Index (LSI), and defining pH and antiscalant dosage [4].

Based on the results and on experiments conducted by Mekorot, a comprehensive monitoring program of the brine disposal pipeline has been developed and performed. The results showed that through optimal operation of the pipeline, Mekorot avoids scale deposition and prevents soil and marine contamination. In addition, it was shown that since the desalination plants startup, large amounts of chloride and silica have been removed from the aquifer [3].

4. Pressure design along the brine disposal pipeline

In order to ensure a full pipe flow in the exclusive ~30 km long brine disposal pipeline, it is required to maintain positive pressure along the pipeline. To do so, the topography of the pipeline and the head losses along it should be taken into account. Fig. 6 illustrates a topographic section of the brine disposal pipeline and the Gat, Granot, and Lahat desalination plants [3]. It can be seen that the pipeline varies in elevation from ~40 m height at Granot and Gat plants at the beginning of the pipe, up to ~100 m at Negba (the highest point) and ~90 m at Lahat plant in the middle, and down to ~10 m at Ashkelon, at the end of the pipe.

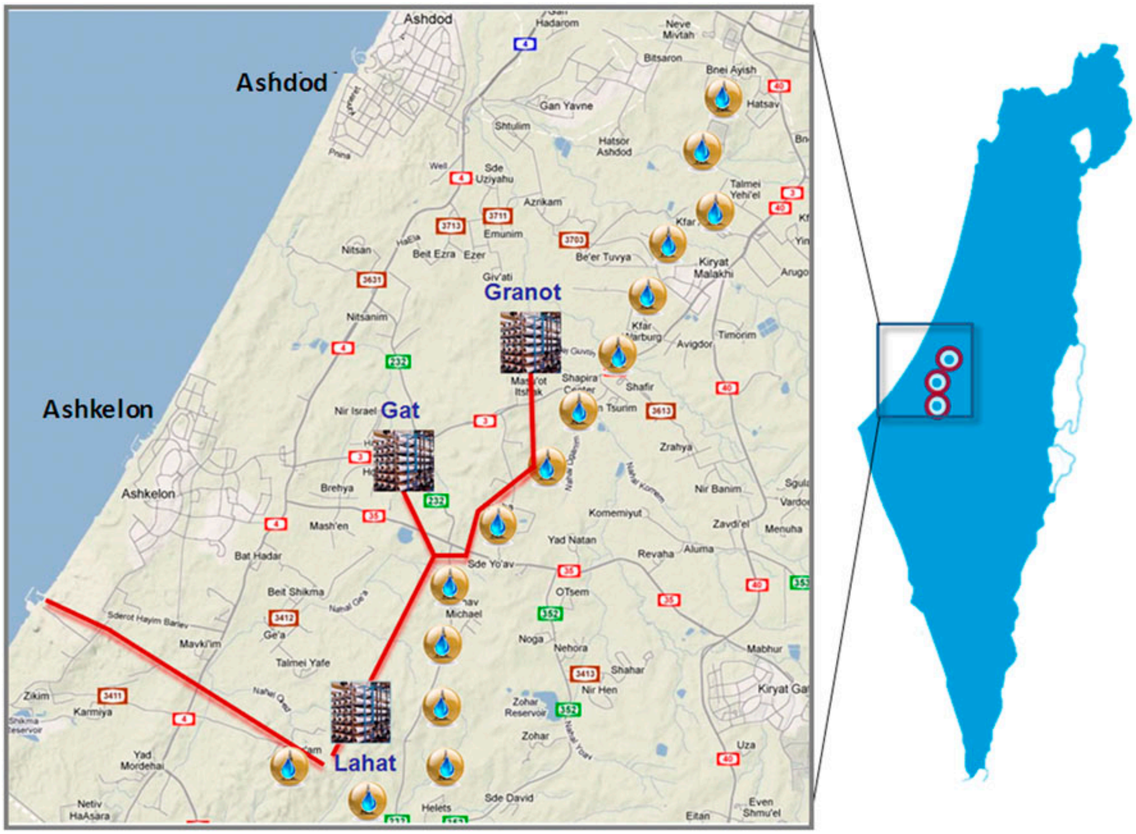


Fig. 5. The southern coastal aquifer rehabilitation project—a schematic map of the location of the new wells (yellow circles), the Gat, Granot, and Lahat desalination plants, and the brine disposal pipeline (red line).
Source: [2].

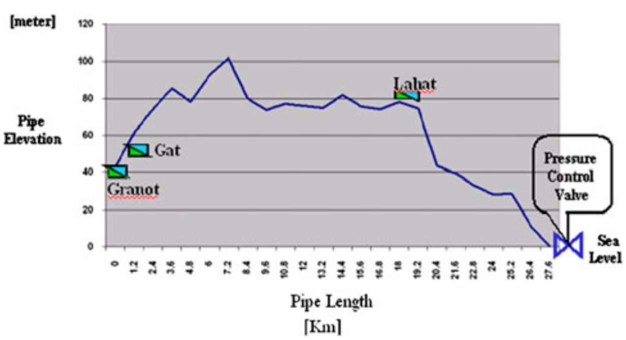


Fig. 6. A topographic section of the brine disposal pipeline and the Gat, Granot, and Lahat desalination plants.
Source: [3].

With the aim of maintaining positive pressure along the pipeline, it was decided to keep a minimal pressure of ~15 m at the Lahat plant, which is almost the highest point along the pipe. Mekorot, together with Agat Engineering LTD, designed a model in which the total head along the pipeline (at every 300 m distances) is calculated, taking into account the initial pressure at the Granot plant (at the beginning of the pipe), the changing elevation, and the head losses along it. The head losses were calculated using the friction coefficient, brine flow rates, distances, and pipe diameters. Using this model, it is possible to calculate the required initial pressure at the Granot plant, which enables to maintain ~15 m at the Lahat plant, for every scenario of flow rates and recovery ratios of the Granot, Gat, and Lahat plants.

Tables 2(a) and (b) present, respectively, the current and the future (end of 2014) required pressures at the Granot plant and along the pipeline, based on the above model. The designed recovery ratios of Granot 1–2, Gat, and Lahat 1–4 are 80%, while the designed recovery ratio of Granot 3–4 is 84%. The flow rates of the Gat, Lahat 1–4 plants includes 20 and 60 m^3/h washing flow rates, respectively. Fig. 7 describes the future total head line, changing elevations, and designed pressures along the Granot to Ashkelon pipeline with respect to Table 2(b) (end of 2014).

Table 2a
Current plants flow rates and pressures

Plant	Elevation (m)	Pressure (m)	Flow rate (m^3/h)
Granot 1-2, 80% recovery	43.5	77.5	198
Gat, 80% recovery	43.3	85.1	55
Lahat 1-2, 80% recovery	91.1	15.8[a]	268
Ashkelon	11.6	82.6	521

Table 2b
Future plants flow rates and pressures (end of 2014)

Plant	Elevation (m)	Pressure (m)	Flow rate (m^3/h)
Granot 1-2, 80% recovery	43.5	107.5	378
Granot 3-4, 84% recovery			
Gat 80% recovery	43.3	91.4	55
Lahat 1-4, 80% recovery	91.1	15.5[a]	504
Ashkelon	11.6	57.5	937

[a]In order to prevent air penetration into the pipeline, a minimal pressure of ~15 m is maintained at the Lahat plant.

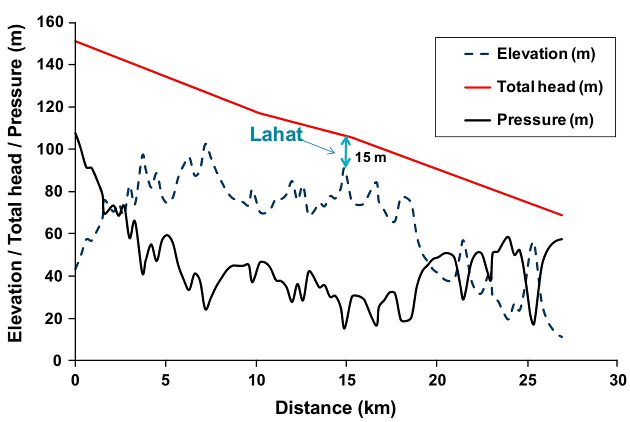


Fig. 7. The future total head line (red), changing elevations (dashed blue line), and designed pressures (black line) along the Granot to Ashkelon pipeline.

It can be shown that the current required pressures at the Granot and Gat plants, in order to maintain ~15 m at the Lahat plant, are 77.5 and 85.1 m, respectively, while the subsequent pressure obtains at Ashkelon is 82.6 m (Table 2(a)). Adding the flow rates of Granot 3–4 and Lahat 3–4 expansions, the required pressures at Granot and Gat will increase to 107.5 and 91.4 m, respectively (addition of 30 and 6.3 m, respectively), and the subsequent pressure in Ashkelon will decrease to 57.5 m (25.1 m decrease, Table 2(b)). In general, it can be shown from Fig. 7 that due to the characteristics of the total head line, addition of flow rates due to Granot plants expansions make the Lahat point more vulnerable to reduced (e.g. negative) pressure. This is the reason, why a minimal pressure of 15 m was chosen to be maintained at this point specifically.

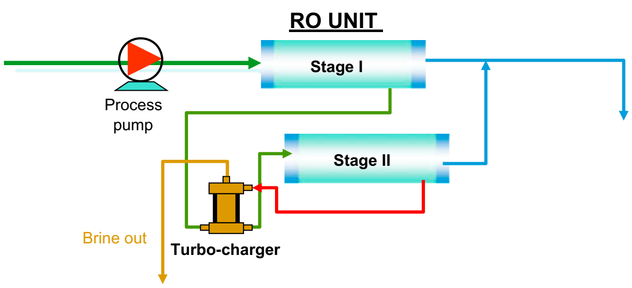
5. Energy recovery at the Lahat plant

As was previously mentioned in Section 2, the RO membranes that were selected for the Granot 3–4 and Lahat 1–4 units were seawater RO SWRO membranes. It is well known that the use of SWRO membranes, compared with BWRO membranes, requires higher operating pressure and increased energy consumption. Accordingly, it results in higher pressures at the first and especially at the second stage brines.

As was discussed in Section 4, since Granot is located at the beginning of the brine pipeline, it requires high pressure (HP) to maintain positive pressures along the pipeline. This HP requirement increases with increased flow rates. Thus, the RO process of Granot 3–4 using SWRO membranes can be designed in a way that the second stage brine will provide the required pressure for the pipeline. Compared with that, the pressure required at the Lahat plant due to pipeline conditions is only 15 m, because of its high elevation (Section 4). Hence, at the Lahat plant there is an obvious gap between the pressure obtained by the SWRO membranes and the pressure required for the brine pipeline. This circumstance has led to the innovative idea of energy recovery at the Lahat plant.

Energy recovery devices (ERDs) are typically used in SWRO plants in order to save operational costs. SWRO systems operate at HPs and low recovery rates, thus, the brine contains high amount of energy which

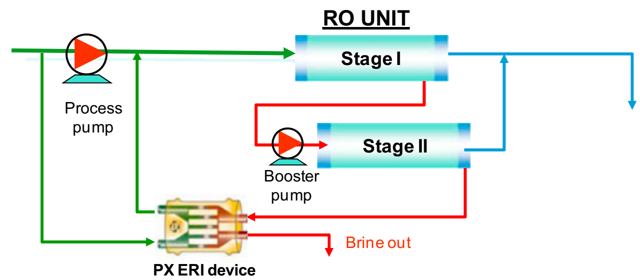
(a)



(b)

Fig. 8. (a) A schematic illustration of a two stage BWRO system with an interstage TC. (b) A photo of one of the TCs in Lahat 1 and 2 plants.

(a)



(b)

Fig. 9. (a) A schematic illustration of a typical two stage BWRO system with an interstage booster pump and isobaric PX. (b) A photo of one of the PX ERIs in the Lahat 3 and 4 plants during construction.

can be recovered. Compared with that implementation of ERDs in BWRO plants is not very common since the available energy that could be recovered from the brine is much lower. Moreover, BWRO plants usually comprise two or more stages, thus an interstage booster pump is usually applied in order to balance the stages flux and recovery rates.

Due to the special conditions prevailing at the Lahat plant, it was decided, in the framework of the Lahat 1 and 2 plants construction in 2011, to recover the excess energy of the second stage brine by implementing an interstage TC energy recovery device. This device was used to replace an interstage booster pump. Fig. 8(a) illustrates schematically a BWRO system with two stages and an interstage TC device. The TC in such application uses a turbine to extract the energy from the second stage brine to spin an impeller that pumps the second stage feed. The main advantage of TC is in its operational simplicity. However, the disadvantage of such a device is in its efficiency susceptibility to varying flows and pressures [5]. Fig. 8(b) illustrates a photo of one of the TCs in Lahat 1 and 2 units.

As part of the pre-design phase of the Lahat 3 and 4 plants expansion, which are currently under construction, a techno-economic analysis was conducted with the purpose of finding the most cost-effective energy recovery solution to the new units. The option of a TC similar to that applied in Lahat 1 and 2 added with an interstage booster pump (in order to enable stages flux balance) was compared with an alternative isobaric ERD of ERI PX. Fig. 9(a) illustrates schematically a BWRO system with two stages, an interstage booster pump, and an isobaric PX, as was considered at the Lahat 3 and 4 units. The isobaric PX operates by directly pressurizing the feed stream by exposure to the second stage brine stream. As a result, the salinity of the feed stream increases (up to 5%) results in slightly higher feed pressure [5].

Table 3 represents the results of the techno-economic analysis which compared a conventional BWRO system with an interstage booster pump (no ER) to addition of either TC or PX ERDs in the above-mentioned configurations. The assumptions taken into account were:

(1) Lahat 3 and 4 plants capacities of 11,300 m^3/d with 84% recovery rate, thus 470 and 560 m^3/h permeate and feed flow rates, respectively; 215 m^3/h second stage feed flow rate.

Table 3
Techno-economic analysis results comparing a conventional BWRO system with an interstage booster pump (no ER) with either TC or isobaric PX (PX) ERDs

Component	Units	No ER	TC	PX
Specific energy consumption	kWh/m^3	0.98	0.91	0.89
Capital cost (pumps & energy recovery)	cent/m^3	0.66	0.81	0.75
Energy cost	cent/m^3	9.80	9.13	8.91
Total cost (capital + energy)	cent/m^3	10.45	9.92	9.63
Life cycle saving (compared to no ER) for two RO units	Dollar		700,090	1,091,882

(2) Total discharge head (TDH) of 4 and 15 bar for feed and HP pumps, respectively. A 0.4 bar increase in HP TDH of PX (to 15.4) due to increased salinity. Required second stage booster pump TDH of 6 bars at both no ER and PX options, based on SWRO membranes projections; TDH of 4 bars for TC, thus required additional 2 bars for the second stage booster pump.

The results showed that implementation of isobaric PX ERD, results in a life cycle saving of 1,091,882$, about 1.5 times more than the TC alternative (700,090$ life cycle saving, Table 3). Accordingly, in the design of the two additional Lahat 3 and 4 RO units, isobaric PX ERD was implemented. Apart from the cost benefit, this configuration has several advantages versus the TC, mainly the control of the second stage booster pressure with increased accuracy and flexibility. This enables a better balance of the first and second stage flux in comparison with TC option. Fig. 9(b) illustrates a photo of one of the PX systems in the Lahat 3 and 4 expansions, which are currently under construction.

6. Summary

Due to the special conditions prevailing at the Lahat plant, the gap between the high second stage brine pressure resulting from the use of SWRO membranes, and the low (~15 m) pressure required for the brine disposal pipeline, the idea of energy recovery at the Lahat plant was initiated.

In the framework of the Lahat 1 and 2 plants construction in 2011, an interstage TC energy recovery device was installed, wherein the turbine side utilizes the energy of the second stage brine to boost the second stage feed.

In the design of the two additional Lahat 3 and 4 units, a techno-economic analysis was conducted with the purpose of finding the most cost-effective energy recovery configuration.

Comparing existing design of TC added with a booster pump with alternative isobaric energy recovery with ERI PX devices, it was shown that implementation of isobaric PX results in a life cycle saving of 1,091,882$, about 1.5 times more than the TC alternative. Thus, the ERI PX device was chosen to be implemented.

Apart from the cost benefit, this configuration has several advantages versus TC, mainly the control of the second stage booster pressure with increased accuracy and flexibility. This enables a better balance of the first and second stage flux in comparison with TC option.

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