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Design optimization of large SWRO plants utilizing time-of-use (TOU) energy prices

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ABSTRACT

The Israeli electricity pricing system is characterized by a sophisticated TOU (time-of-use) tariff. Different prices apply to different hours of the day and different seasons of the year following the electricity system management considerations. Current pricing system defines three yearly seasons, each having peak, shoulder and off-peak prices. This obviously can significantly affect design optimization of large SWRO desalination plants by shifting the Capex/Opex tradeoff. The effect of utilizing TOU differential prices to reduce energy and consequently unit water cost is demonstrated and parametrically analyzed. Two design options satisfying the same water demand are compared: (a) a plant having constant hourly production capacity; (b) a larger plant designed to avoid operation at electricity peak loads. Unit water cost savings demonstrated are in the range of (–1.8)–9.1 UScent/m^3 depending strongly on prevailing average electricity price and economy of scale factor. A TOU utilization optimization model is proposed, composed of two steps: (i) optimizing plant design to achieve the lowest possible specific energy consumption, especially while operating at high energy prices; (ii) maximizing water production while operating at off-peak energy prices. Energy cost savings of approximately 18% are achieved given a peak to off-peak price ratio of 2.8:1.

Keywords: SWRO design optimization; TOU energy price; Desalination energy cost reduction

1. Introduction

In the last several years very large SWRO plants have been constructed in many locations worldwide. Among them three large plants were installed in Israel (Ashkelon, Palmachim and Hadera) and two additional will be constructed in the next 2–3 years (Ashdod and Soreq).

While Ashkelon plant receives electricity from its own power plant, Palmachim and Hadera plants are powered by the national electricity grid and are operated to utilize the Israeli TOU (time-of-use) tariff differentials to a certain extent.

Israel's electricity grid as in many other developed countries (Spain, the Netherlands, France and others) produce and sell electricity at different prices adjusting to variable daily and seasonal demand curves and to variable operating costs stemming from different fuel cost (coal, fuel oil, natural gas and — in some European countries — nuclear fuel). Until recently the price ratio of power supplied at peak load periods to power supplied at off-peak had reached a value in the range of 5–6. Since February 2010, a new scheme of differential TOU energy prices is applied, reducing the above mentioned price ratio to 2–4.

In large SWRO plants energy cost comprises about 30–40% of total unit water cost and therefore there is a

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strong motivation to reduce it as much as possible. The effect of utilizing TOU prices to reduce energy and consequently total desalination cost shall be demonstrated for two typical case studies in the following sections of this paper.

One path to reduce energy cost can be by avoiding operation at peak loads of the electricity grid. However, this could be accomplished only by increasing plant capacity, affecting investment cost and corresponding capital cost. In case of very high electricity prices and relative low investment and/ or low interest rates increasing plant capacity in order to reduce energy cost is beneficial. If the contrary is true then increasing plant capacity would not be competitive. Cost effectiveness of such a path is explored and parametrically analyzed in case study 1 described below.

Naturally additional factors need to be taken into account to properly assess the Capex/Opex tradeoff. One of these factors is consideration of future plant capacity to comply with growing water demand. Another factor is specific conditions of seasonal water use requiring, for example, large production in summer season and lower in winter season.

All new Israeli large desalination plants are required under the BOT project delivery method to produce about 20% higher water quantities at summer months and about 10% lower quantities at winter months. Therefore, as plant size must be specified according to the higher regulated summer capacity, inherent excess capacity exists in winter months and obviously operation at electricity peak load can be reduced. An optimization methodology utilizing both this inherent excess capacity and TOU price differentials is presented in case study 2 described below.

This methodology calls for a plant design accommodating several operation modes. While at low electricity prices the plant should operate at “Maximal” operation mode, at high electricity prices a reduced capacity limited by specified product quality, affected by membrane flux is determined. This is usually defined as the “Nominal” operation mode.

In case where the SWRO plant uses a conventional pretreatment it is not advisable to apply a full shut down of the plant, but rather reduce the capacity to a lowest feasible minimum termed by some designers an “Idle” operation mode. Thus this small capacity is, whenever possible, operated at peak electricity price, especially at times of existing excess capacity.

2. Case study 1

This case study represents a typical Capex/Opex tradeoff when either sizing a new SWRO plant or considering incremental extension of an existing SWRO plant. In a TOU-based energy pricing system, extra production capacity allowing the reduction of energy cost by avoiding operation at peak load periods might be especially beneficial.

Given a TOU energy pricing system where average electricity price excluding peak hours is 74.8% of average price including peak hours and 32% of the total yearly hours are peak load hours, avoiding use of high peak power shall decrease the desalination energy cost by about 25%. However, in order to allow the same yearly production exploiting less operating hours the base plant capacity has to be increased by about 47%.

A parametric study was carried out to investigate the tradeoff between the incremental additional investment and the reduced specific energy cost given the TOU pricing system described above and an average electricity price ranging from 8 to 12 UScent/kWh.

The incremental investment cost has been evaluated using an economy of scale factor in the range of 0.25–0.75.

Design and cost evaluation assumptions were as follows:

- Base case refers to a 20,000 m^3/d full load plant capacity operated continuously including during electricity peak periods.
- When an existing SWRO plant extension is being considered, the existing infrastructure including seawater intake, brine disposal and pretreatment can accommodate a capacity increase of about 50%.
- 91% plant availability.
- Single pass SWRO system.
- Specific energy consumption including seawater intake and product delivery is 4.0 kWh/m^3.
- Investment cost of 1000 US$/ ($m^3$/d).
- 20 years lifetime, 7.5% interest rate, i.e. capital recovery factor of 9.8%.

Partial desalination costs of the increased capacity plant not operated during peak hours calculated at various average electricity prices and scale factors were compared to the base case cost. These costs as well as achieved water cost saving and total annual savings are summarized in Table 1. Partial desalination specific cost and total annual savings vs. average electricity price at the extreme scale factor values examined are presented in Figs. 1 and 2 respectively.

It can be observed in Table 1 that at any economy of scale factor smaller than 0.65 avoiding operation at peak load is cost effective for the whole electricity price range examined. However, if a scale factor of 0.75 better describes a given project, avoiding operation at peak load shall be economically attractive only when the prevailing average electricity price is above 10 UScent/kWh.

3. Case study 2

This case study demonstrates the evaluation of potential energy cost savings when designing a large SWRO plant given a water demand which varies with the yearly

Table 1
Case study 1: Partial desalination cost(4), water cost saving and total annual savings vs. average electricity prices and scale factors

		Annualized Capex, UScent/m^3	Desalination specific energy cost, UScent/m^3			Partial desalination specific cost, UScent/m^3			Water cost saving, UScent/m^3			Total annual savings, kUS$/$m^3$		
Average electricity price, UScent/kWh			8	10	12	8	10	12	8	10	12	8	10	12
Case	EOS (3)													
Base (1)	1	29.5	32.0	40.0	48.0	61.5	69.5	77.5						
Extended (2)	0.25	32.4	23.9	29.9	35.9	56.4	62.4	68.3	5.1	7.1	9.1	338	473	607
Extended (2)	0.35	33.7	23.9	29.9	35.9	57.7	63.6	69.6	3.8	5.8	7.8	254	388	522
Extended (2)	0.45	35.0	23.9	29.9	35.9	59.0	65.0	70.9	2.5	4.5	6.5	165	300	434
Extended (2)	0.55	36.4	23.9	29.9	35.9	60.4	66.3	72.3	1.1	3.1	5.1	73	208	342
Extended (2)	0.65	37.8	23.9	29.9	35.9	61.8	67.8	73.8	–0.3	1.7	3.7	–22	112	247
Extended (2)	0.75	39.3	23.9	29.9	35.9	63.3	69.3	75.2	–1.8	0.2	2.2	–121	13	148

(1) Base plant having 20,000 m^3/d capacity operated continuously including during peak hours.
(2) Hourly capacity extended by 47%, plant is not operated during peak hours.
(3) Economy of scale factor.
(4) Including only Capex amortization and energy cost.

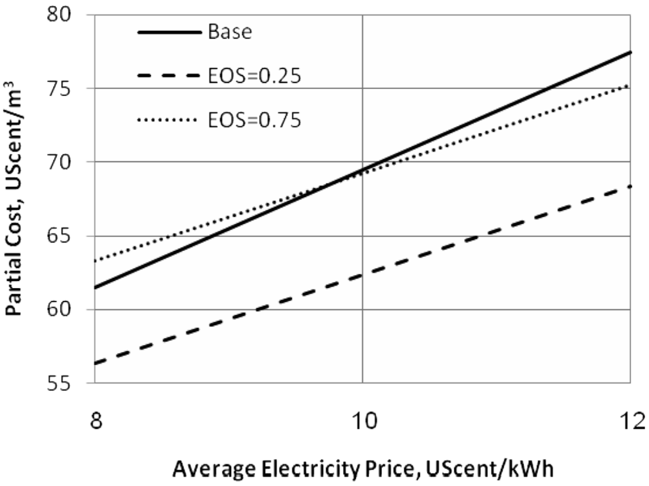

Fig. 1. Partial desalination specific cost vs. average electricity price in case study 1.

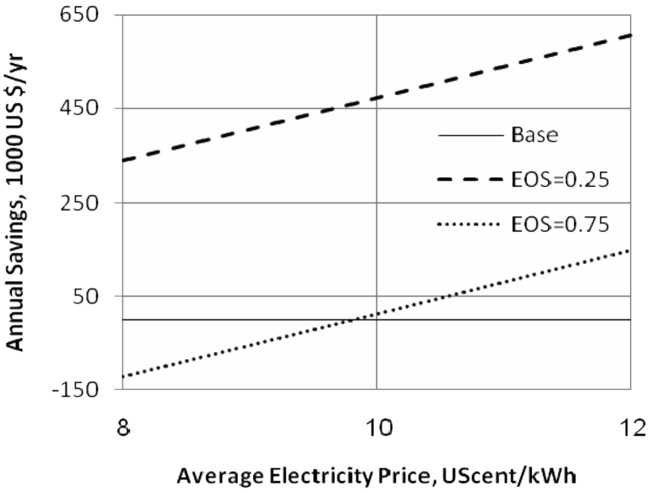

Fig. 2. Total annual savings vs. average electricity price in case study 1.

seasons and a specific TOU pricing system. Naturally, the plant capacity sizing shall accommodate the highest required demand and the inherent over capacity of such a plant during low demand seasons, coupled with full utilization of off-peak energy prices, is basically used to optimize energy cost and thus total water cost. This may be of special interest in water markets subject to both variable regulated water demand and TOU electricity tariff.

The proposed design concept was studied for a 100,000 m^3/d full load capacity plant complying with 80 ppm chlorides and 0.5 ppm boron specs typical to some recently awarded desalination projects (e.g. Adelaide desalination plant [1]).

Required variable water demand was given as follows: 95,000 m^3/d throughout a three months peak demand season (July, August and September); 80,000 m^3/d throughout a three months intermediate demand season (April, May and October); 60,000 m^3/d throughout a six months low demand season (January, February, March, June, November and December).

Energy cost evaluation was subject to the following TOU power pricing: peak electricity price of

14 UScent/kWh for 60 h a week and off-peak electricity price of 5 UScent/kWh for 108 h a week throughout all yearly seasons.

Main optimization methodology steps were:

(a) Determination of plant's sizing and configuration to accommodate required peak demand while satisfying maximal average flux limit of 14 lmh for the first pass and 35 lmh for the second pass respectively. Attained capacity determines the maximal train capacity defining the maximal operation mode used to maximize water production during electricity off-peak load hours.

(b) Optimization of plant design to minimize desalination specific energy consumption while the plant is operated at high electricity price. Nominal train capacity, in which specific energy consumption is optimal, is determined at the minimal possible flux enabling compliance with water quality requirements. This lower capacity defines the nominal operation mode to be used at high electricity prices.

Other key design considerations taken into account in the optimization concept described above were the following:

(i) Since the limiting water quality parameter for the seawater temperature range examined was found to be boron, (a) second pass concentrate recycle back to the first pass feed had an adverse effect on results and therefore was not used [2]; and (b) increasing the operating pH level of the first pass at the high temperature range proved favourable, as already reported in literature for pilot plants as well as several operating large SWRO plants (e.g. Larnaca, Palmachim, Barcelona- Llobregat) [2–6].

(ii) Product quality safety factors were applied according to Dow's recommendations [7] hence the 0.5 ppm boron requirement translates into 0.4 ppm design criterion.

General process design inputs were as follows:

- Raw water: Mediterranean seawater, 22,200 ppm chlorides, 5.2 ppm boron.
- Design temperature: 32°C.
- Plant full load capacity: 100,000 m^3/d.
- Plant availability: 95%.
- Pretreatment: Media filtration.

Split partial second pass design has been evaluated, the second pass including three stages. FilmTec membrane elements were used for the design. Projections were carried out using the ROSA software tool [8]. Staging in the first pass has been examined but was not energy- wise advantageous and therefore was not implemented.

Desalination process design data is briefly summarized in Table 2.

Main assumptions used for energy calculations were:

- Intake specific energy consumption is 0.3 kWh/m^3.
- Auxiliaries specific energy consumption is 0.1 kWh/m^3.
- Efficiencies: HP pump — 88%; all other process pumps — 86%; motors — 96%, VFDs — 98%.
- Work exchanger pump boost pressure compensates for the membrane differential corresponding to each operating mode plus additional 1.5 bar.
- Additional total energy consumption safety factor is 5%.

An optimal production plan for the annual desalinated water demand of 26,960,000 m^3 obtained from the TOU utilization optimization model are shown in Table 3.

As can be seen in Table 3, the total annual energy cost is 6,058,732 US$/y. If the desalination plant were to be operated continuously at a constant capacity throughout the year, its energy cost would have been 26,960,000 m^3/y · 3.33 kWh/m^3 · 0.082 US$/kWh = 7,374,523 US$/y (8.2 UScent/kWh being the weighted average electricity price). Hence the TOU utilization optimization methodology proposed resulted in approximately 18% energy cost savings.

4. Summary and conclusions

Substantial reduction of specific energy cost and consequently total desalination cost can be achieved by intelligent utilization of existing TOU price differentials.

The cost effectiveness of increasing plant capacity to avoid operation at peak load periods has been evaluated in case study 1. Unit water cost savings demonstrated were 0.2–9.1 UScent/m^3 depending strongly on prevailing average electricity price and economy of scale factor. Profitability was questionable only in a small portion of the search space examined, i.e. high scale factor and low average electricity price.

The methodology demonstrated for case study 1 provides a rapid design screening tool readily enabling sensitivity analysis of project — specific data as well as future predicted trends of electricity tariffs.

Plant optimization concept aimed at utilizing a TOU pricing system coupled with a partial inherent excess capacity has been presented in case study 2. Such a concept might prove beneficial in the Israeli desalination market where these coupled optimization constraints prevail. Energy cost savings of approximately 18% were achieved for a peak to off-peak price ratio of 2.8:1.

Some complications ignored in this paper for the sake of clarity were:

- TOU pricing system is usually more sophisticated (e.g. nine TOU different electricity prices are currently in use in Israel: peak, shoulder and off-peak price for each of the three yearly seasons.
- Regulated desalinated water demand variation pattern is usually more complicated (e.g. hourly, daily

Table 2
Case study 2: Desalination process design summary

RO island design				
No. of trains	5			
	Pass 1		Pass 2	
Pressure vessels per train	188		28 + 9 + 3	
Membrane elements per PV	8		8	
Membrane element type	SW30HRLE-440i		BW30HR-440i	
Feed pH	8.4		10	
Pass 2 3rd stage booster pressure, bar	5		5	
TOU optimization design				
	Maximal mode		Nominal mode	
Train product capacity, m^3/d	20,000		12,000	
Product quality, ppm Cl	40		38	
Product quality, ppm B	0.39		0.40	
Split ratio, %	45		31	
	Pass 1	Pass 2	Pass 1	Pass 2
Operating flux, lmh	13.9	34.2	8.5	26.3
Recovery, %	45	95	42	95
Feed pressure, bar	62.8	13.2	55.0	11.2
Specific energy consumption(1), kWh/m^3	3.33		3.07	

(1) Excluding product delivery.

Table 3
Case study 2: Results of the TOU utilization optimization model

Season	Electricity tariff	Plant operating point			Water production, m^3/season	Energy cost, US$/season
		Operating mode, No. of trains in operation	Hourly plant capacity, m^3/h	Duration, h/wk(1)		
Peak demand season (Jul–Sep)	Peak	Maximal, 5	4,167	60.0	3,121,429	1,455,210
	Off-peak	Maximal, 5	4,167	108.0	5,618,571	935,492
	Total				8,740,000	2,390,702
Intermediate demand season (Apr, May, Oct)	Peak	Nominal, 4	2,000	21.1	525,714	225,952
		Nominal, 5	2,500	38.9	1,215,714	522,514
	Off-peak	Maximal, 5	4,167	108.0	5,618,571	935,492
	Total				7,360,000	1,683,958
Low demand season (Jan–Mar, Jun, Nov–Dec)	Peak	Nominal, 1	500	60.0	736,929	316,732
	Off-peak	Nominal, 5	2,500	22.7	1,396,286	214,330
		Maximal, 5	4,167	85.3	8,726,786	1,453,010
	Total				10,860,000	1,984,072
Annual summary					26,960,000	6,058,732

(1) Plant availability incorporated, actual number of operating hours at corresponding mode would be 95% of this value.

and bimonthly quantities for each season are regulated under all recent Israeli BOT projects).

- Seawater temperature variations along yearly seasons shall be taken into account in the design model.
- An “Idle” operation mode to be used at peak hours whenever water demand can still be satisfied with this minimal capacity shall be incorporated into the model especially when conventional pretreatment

is being used. This is of great importance from the operational point of view to ensure trouble free operation of the equipment, minimum downtime and minimum maintenance.

However, these additional constraints can be readily incorporated in the proposed methodology providing a powerful parametric assessment tool for designers and operators.

References

[1] Hydranautics, Nitto Denko/Hydranautics announces Adelaide project award, press release, April 21, 2010.

[2] Boron removal by Hydranautics RO membranes, Hydranautics Technical Application Bulletin 113, November 2005.

[3] C.R. Bartels, S. Rybar, K. Andes and R. Franks, Optimized removal of boron and other specific contaminants by SWRO membranes, IDA World Congress, Dubai, UAE, November 7–12, 2009.

[4] B. Andrews, B. Davé, P. López Serrano, S. Tsai, R. Frank, M. Wilf and E. Koutsakos, Effective scale control for seawater RO operating with high feed water pH and temperature, Desalination, 220 (2008) 295–304.

[5] Featured plants: Palmachim SWRO project — Israel, IDA Desalination Yearbook 2008–2009, pp. 23–25.

[6] Featured plants: Barcelona — Llobregat desalination plant — Spain, IDA Desalination Yearbook 2009–2010, pp. 25–26.

[7] V. Garcia Molina, M. Busch and P. Sehn, Cost savings by novel seawater reverse osmosis elements and design concepts, Desal. Wat. Treat., 7 (2009) 160–177.

[8] Reverse Osmosis System Analysis for FILMTECTM Membranes, ROSA version 7.0.1 ConfigDB u392554_101, 2009.