Desalination and Water Treatment
www.deswater.com
46 (2012) 304–311
August

doi: 10.1080/19443994.2012.677561

Optimization of energy costs for SWRO desalination plants

Aharon Yechiel*, Yehuda Shevah

Tahal Consulting Engineers Ltd, 154 Menachem Begin Road, Tel-Aviv 64921, Israel
Tel. +972 3 6924478; email: Yechiel-a@tahal.com

Received 10 November 2011; Accepted 5 February 2012

ABSTRACT

The global expansion of seawater desalination and the associated excessive energy consumption have serious economic and environmental consequences. Various technological and operational approaches have been applied in an attempt to mitigate these impacts by improving the desalination process and by increasing plant efficiency, with the emphasis on reduction of the energy consumption and costs. In this study, a Linear Programming (LP) model was developed to optimize operation of a large Seawater Reverse Osmosis desalination plant (140 MLD). The objective was to minimize energy costs, using the extra hourly installed capacity of the plant and the advantages offered by the power pricing system, based on time and peak load demand (Time Load Tariff [TLT]). For annual production of 45 million m^3 of desalinated water (88% of the maximum possible production capacity), a reduction of 15% of the electricity bill, equal to a saving of about US$ 2 million, can be achieved reflecting a weighted average cost of 7.66 ¢/kWh vs. a normative weighted average tariff of 8.95 ¢/kWh. The results indicate that the LP model could serve as an effective decision-making tool of desalination plants that are dependent on the supply of power from the national grid, where the price of energy is based on TLT. The model can assist in the daily operation and maintenance of the plant. It can also serve as a planning tool during the design stage. The model can be used to optimize the trade-off between plant capacity and its related investment cost to the energy expenses. It can be used to compare a smaller capacity plant having a lower investment cost but higher annual energy costs, to a plant with extended capacity having a higher investment cost but lower annual energy costs.

Keywords: Seawater desalination; SWRO; Linear Programming model; Energy consumption; Electricity price; Israel

1. Introduction

Under the current environment of rising energy costs, the water industry is under pressure to reduce power consumption while continuing to maintain the quality and efficiency of public infrastructure. In California, 10% of all electricity production is consumed in moving water around the state and another 9% for treating, disposing, pumping, heating, cooling, and pressurizing water [1]. In California and elsewhere, where the water industry is confronting the warming climate and growing population, the energy costs will rise in parallel to the increasing demand for water which can be produced only from non-conventional sources.

In recent years, seawater desalination has been proposed to meet the increasing demand for water [2]. Seawater desalination is also seen as a proven solution to insure against drought in a state of diminishing natural water resources. However, much of the criticism of desalination plants centers around their large use of power and possible impact on the environment, to the

*Corresponding author.

marine life from the inlet structures and from the brine that is pumped back to the sea. In terms of Specific Energy Consumption (SEC), water recycling requires 400 kWh/acre feet, groundwater: 950–1,500, surface water: 2,000–3,200, and desalination: 3,500–5,500 kWh/acre feet [1]. Nevertheless, construction of desalination plants has accelerated around the globe, with prominent examples in Abu Dhabi, Australia, Israel, Saudi Arabia, Spain, and the USA (Tampa Bay).

In Israel, the large-scale seawater desalination facilities are based on reverse osmosis technology (Seawater Reverse Osmosis [SWRO]) and are among the most energy-efficient and cost-efficient plants. Currently, the national average SEC is 3.5 kWh/m^3 and the average total water cost is US 65 ¢/m^3. In the most recent tender for the Sorek facility of 500 MLD (million liters per day) and for annual supply of 150 million m^3, the awarded bidder price was only US 52 ¢/m^3 [3]. The increased competition in the market has dramatically reduced the capital (fixed) cost from US 40 to US 25 ¢/m^3. The focus now is on how to reduce the operating costs, particularly energy costs, using improved operation and maintenance and advanced tools aiming to optimize energy usage and energy costs. The search for optimization and decision support system and their incorporation in the management of SWRO facilities are a real concern in search for technical, financial, and economic efficiency.

This paper aims to analyze and optimize the energy usage in SWRO plant considering operational constraints and economic variables that influence the Electricity Price (EP) and the total cost of energy. It follows previous attempts to develop optimization models for energy pricing in power plants [4,5] expanded in this study using an applied Linear Programming (LP) model. This approach was found to be effective to correct power factor in industrial and power plants [6-8]. Sensitivity analysis of the models can be done to evaluate the influence of economic and operational parameters on EP.

2. Methodology

A LP optimization model was developed and used to simulate the energy and operation regime of the Palmachim SWRO facility, as a case study, to illustrate the optimization tool capacities of the LP model.

2.1. Energy tariffs policy

2.1.1. Energy price structure for large consumers: time and load tariff

In Israel, major power consumers enjoy a differential price paid for power purchased from the National Grid (Upper Voltage). The price varies seasonally and during the day, based on time and peak load demand (termed Time Load tariff [TLT]). The aim is to minimize energy consumption by large commercial and industrial consumers during peak demand, employing economic incentives. The TLT comprises of three price categories, corresponding to the grid load demand over the day. The number of hours and the price in each category vary within the day, the day of the weak, and season of the year, as shown in Table 1. The average exchange rate is used in the analysis: 3.7 NIS/USD.

Table 1 indicates that the current prices for upper voltage vary during the winter season, between 6.9 and 23.4 US ¢/kWh and in the summer season, between 5.9 and 25.4 ¢/kWh, for the base and peak load demand, respectively. The weighted average annual electricity tariff is 8.95 ¢/kWh.

2.1.2. Applying the TLT for large-scale seawater desalination plants

Large SWRO plants without an Independent Power Plant (IPP) also benefit from the TLT structure and therefore, in need to optimize their daily operation and production to make the full use of the base load and to minimize energy consumption during the shoulder and peak load hours. Such analysis is also relevant during the design stage of new SWRO facilities, in order to optimize the overall plant design capacity, taking into consideration daily operation to commensurate with fluctuating energy prices as compared to the plant investment costs. The model can also be used as a planning tool to optimize the trade-off between plant capacity and its related investment cost, to the energy expenses. It can be used to compare a smaller capacity plant having a lower investment cost but higher annual energy costs, to a plant with extended capacity having a higher investment cost but lower annual energy costs.

2.2. The case study: Palmachim Desalination Plant

The Palmachim Desalination Plant (PDP) is located on the Mediterranean coast 20 km south of Tel-Aviv, Israel. The plant was built under a Built Operate Own (BOO) agreement by a consortium of companies, named—via Maris Desalination Ltd. and commissioned in May 2007. The plant was originally designed for a capacity of 110 MLD and for an annual contract production of 30 million m^3. The plant capacity was increased, April 2010, to a capacity of 140 MLD for an annual contract production of 45 million m^3, 6.1 mil-

Table 1
Time and load tariff for the upper voltage tariff in Israel

	Power demand category	No. of hours by season			Total annual
		Winter: December, January, and February	Transition: March–June and September–November	Summer: July and August	
Hours per day					
Mid-week	Peak	6	14	7	
	Shoulder	2	2	7	
	Base	16	8	10	
Weekend/holidays Eve.	Peak	0	0	0	
	Shoulder	4	14	0	
	Base	20	10	24	
Weekend/holidays	Peak	2	0	0	
	Shoulder	2	4	0	
	Base	20	20	24	
Total hours in season	Peak	406	1,946	308	*2,660*
	Shoulder	206	944	308	*1,458*
	Base	1,548	2,222	872	*4,642*
	Total	*2,160*	*5,112*	*1,488*	*8,760*
Upper voltage price (US ¢/kWh)	Peak	*23.42*	*9.90*	*25.39*	
	Shoulder	*13.36*	*7.62*	*9.79*	
	Base	*6.90*	*5.85*	*5.92*	
	Weighted Average Price in US ¢ (exchange rate: 3.7 NIS/USD)				*8.95*

Source: Public Utility Authority—Electricity, August 2011. (Tariffs Table 1–5.2.)

lion m^3 below the maximum possible production of 51.1 million m^3.

The plant is fed with Mediterranean seawater from an open sea intake, pumping feed water with total dissolved solids of up to 42,000 mg/l and at a varying temperature of 17–32°C. The pretreatment system consists of multimedia and cartridge filters, feeding six parallel RO trains, each with a permeate production capacity of about 24 MLD. Each train has a dedicated high-pressure pump (HPP) equipped with an energy recovery turbine (ERT)—Pelton wheels. The hydraulic efficiency of the HPPs is 88% and the net transfer energy recovery efficiency of the ERT is 76% [9]. The plant optimal recovery rate is 45%, producing a permeate with 70 mg/l of chlorides and 0.4 mg/l of boron. The RO process of SEC is 2.91 kWh/m^3, out of a total plant SEC of 3.5 kWh/m^3. The emission of CO_2 amounts to 286 g/m^3. The brine is returned back to the sea by gravity. Water produced by the plant is delivered to the national water supply system and blended with other resources for use by domestic, industrial, and agricultural consumers [9].

2.2.1. The plant operational mode

The plant operates on a flexible mode using the excess capacity in which the equipment is easily turned on and off (leaving one train on) or slowed down to make most of the varying TLT EPs, utilizing the plant extra hourly installed capacity. The motors for the high-pressure feed-booster pumps are equipped with variable frequency drivers to allow the pressure to be varied, at the pump outlets, from 4 to 18 bars. The pumps produce 1,540 m^3/h at their best efficiency points and up to 1,800 m^3/h. They are consuming up to 1,980 kW of power and deliver up to 1,920 kW of brake power [9]. Normally, each RO train is operated in order to produce 16 MLD, but can produce up to a capacity of 24 MLD. The actual production is dictated by the contact with the Client—the Water Authority, which determines the quantities of water to be delivered on a daily and bimonthly basis. Those quantities are aimed to match consumers' water demand which is higher in the summer months and lower in winter months, as shown in Fig. 1.

2.3. Energy time and load consumption optimization model

2.3.1. The LP model

The objective function of the model is to minimize the energy costs of the plant for the defined production levels and regimes. Following similar studies [10,11], the model is a dynamic, multivariable, and performance-based/the model considers outages, breakdown maintenance, peak/off-peak loads, and availability of the plant, including plant internal peak loads such as the starting and stopping of power for equipment backwashing, cleaning, flushing, and maintenance. The LP model is able to balance these peaks against lower load requirements and maintain an even power demand.

2.3.2. Model structure

The model is a daily model (over a calendar 365 days), further divided into three periods per day, according to the three TLT tiers, incorporating two sets of variables.

The main variables and constraints of the model are as follows:

Variables	1. The number of trains (operating units) operated every day at each one of the three TLT tiers 2. Water quantity sold at the various TLT hours' tiers
Demand constraints (contract limits)	1. Bimonthly quantity: minimum and maximum 2. Daily quantity: minimum and maximum 3. Hourly quantity: maximum
Operational constraints	1. Operational reservoir volume: 10,000 m^3 2. Reservoir water balance: residual water quantity in the reservoir plus the additional production and minus the delivered quantity 3. Operational failures: twice a month for 24 h each

The trains are operated in each one of the following operating TLT tiers modes:

(1) Full operation at base load (six trains).
(2) Partial operation at shoulder load.
(3) Minimal operation at peak load.

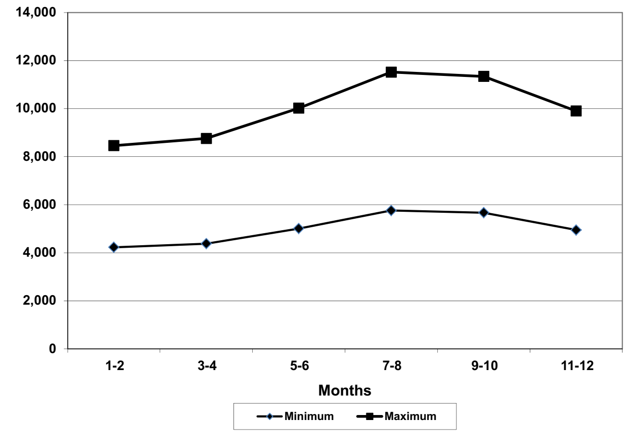

Fig. 1. Palmachim SWRO plant bimonthly water delivery plan (thousand m^3).

2.3.3. Model variables and input data

Input data

Number of trains operated daily in any of the three power tariff categories (clusters), based on time of the day and peak load demand	Total number of trains—six Train installed capacity: 980 m^3/h Total plant capacity: 51 MCM/year Total water demand: 45 MCM/year
Water quantity	Daily water quantities produced and delivered to the end product reservoir Bimonthly, daily, and hourly contract quantities
Product reservoir, storage capacity	10,000 m^3
Energy consumption (SEC)	SEC estimates in kWh/m^3
Plant maintenance	Full stoppage of the plant for several days, (during the winter months, when water demand is low)
Operation inputs	Shutdowns a scenario of complete shutdown up to twice a month for 24 h each time. The restart is gradual over 1 h, of which half is at the shoulder price and a half hour at the peak price One train is operated continuously, to enable continuous process Basic energy consumption during redundancy amounts to 1,000 kWh, assumed to be at the shoulder and peak prices

Unknown variables

Operating trains	Number of trains which are operated in any of the three daily categories of TTL
Water quantity	Daily water quantities produced and delivered to the end product reservoir. Bimonthly, daily, and hourly produced quantities

Total number of model variables amounts to 2,190 (two series of variables, each contains 365 days × 3 tariff categories).

The main inputs including: daily and bimonthly water delivery limits (Contract limits) and SEC are presented in Table 2.

2.4. Model configuration

2.4.1. Mathematical formulation of the model

Subscripts:

- Day, month, bimonthly period, operating TLT category (part of day).

Variables:

- Number of operating trains in a day and TLT category.
- Water quantity produced in a day and TLT category (m^3).

Other parameters:

- Unit capacity per train (m^3/h).
- Energy consumption (in kWh and kWh/m^3).
- Electricity price.
- Daily and bimonthly water quantity sold (m^3).
- Reservoir volume (m^3).
  (See details in Section 5)

The model configuration is as follows:

Objective function:

The objective function is to minimize the total cost of energy over the predetermined period (i.e. one full calendar year).

$$\text{Minimum} \sum_{d} \sum_{i} EQ_{di} * PR_{di} \tag{1}$$

Where: $d = 1 \ldots 365$; $i = 1, 2, 3$
Objective function calculation steps:

Energy cost:

Water quantity produced :

$$QP_{di} = \text{Units}_{di} * \text{Unit Cap} * H_{di} \tag{2}$$

$$\text{Energy consumption : } EQ_{di} = QP_{di} \times ES_{m} \tag{3}$$

$$\text{Energy cost : } EC_{di} = EQ_{di} \times PR_{di} \tag{4}$$

Where the energy cost, at each day (d) and each TLT category (i), is obtained as follows:

- The produced water quantity, QP_{di} = obtained by multiplication of the number of units (Units_{di}) with the unit capacity (Unit Cap) and with number of hours in each TLT per day (H_{di}).
- The energy consumption, EQ_{di} = obtained by the multiplication of the produced water quantity (QP_{di}) by the SEC (ES_m).
- The energy cost, EC_{di} = is equal to the total energy consumption (EQ_{di}) multiplied by the EP (PR_{di}).

The objective function value is the aggregated annual energy cost.

Unknown variables:

(1) The number of operating trains in a day (d) for each TLT category (i): Units_{di}.
(2) Daily water quantities sold at the each one of the TLT hours' categories: QS_{di}.

Constraints:

(1) Technological constraints: Number of trains operated in a day, in each TLT category, is at least equal to one train (minimum) and at best 6 trains (maximum).

$$1 \leqslant \text{Units}_{di} \leqslant 6 \tag{5}$$

(2) Contractual daily constraints: Quantity of the water sold every day is at least equal to the contractual minimum quantity $QD_{d\,\min}$ and at best the maximum quantity $QD_{d\,\min}$ (at times the minimum is 0).

$$QD_{d\,\min} \leqslant QS_{d} \leqslant QD_{d\,\max} \tag{6}$$

(3) Constraints of contractual bimonthly demand: the sold water quantity is at least equal to the quantity of the contractual bimonthly minimum demand:

$$QS_{bm} \geqslant QD_{bm} \tag{7}$$

(4) Daily reservoir volume limit:

$$0 \leqslant Res_{d} \leqslant Res_{max} \tag{8}$$

Table 2
Water contract delivery limits and specific energy consumption

Month	TLT by season	Contract limits				Specific energy consumption (kWh/m^3)
		Daily delivery (thousand m^3)		Bimonthly delivery (thousand m^3)		
		Min.	Max.	Min.	Max.	
1	Winter	0	245	4,230	8,460	3.585
2	Winter	0	245	4,230	8,460	3.585
3	Transition	0	245	4,380	8,760	3.585
4	Transition	0	245	4,380	8,760	3.539
5	Transition	75	263	5,010	10,020	3.458
6	Transition	75	263	5,010	10,020	3.421
7	Summer	84	298	5,760	11,520	3.467
8	Summer	84	298	5,760	11,520	3.439
9	Transition	84	298	5,670	11,340	3.439
10	Transition	0	298	5,670	11,340	3.430
11	Transition	0	274	4,950	9,900	3.485
12	Winter	0	274	4,950	9,900	3.567

Note: The SEC corresponds to average temperature, average age of membranes (3.5 years), and HP pumps efficiency of 88%, and the flux rate of $13.8 l/m^2/h$ amounting to $3.30–4.45 kWh/m^3$.

The water quantity in the reservoir varies between 0 and maximum reservoir capacity.

(5) Reservoir water balance = Initial reservoir volume on previous TLT category (or previous day) plus the present day production, minus present day water sale.

$$\mathrm{Res}_{di} = \mathrm{Res}_{di-1} + \mathrm{QP}_{di} - \mathrm{QS}_{di} \quad (9)$$

2.4.2. The optimization tool: software

The computer software used for the optimization process is Solver Premium by Frontline Co., incorporated within Microsoft Excel spreadsheet, as an input-output interface which greatly enhances the calculation and easy to use the input-output.

2.5. Alternative model configuration

The LP Model was also configured using the number of the working hours of the plant as variables (WH *di*), instead of the number of the trains.

The objective function remains unchanged as in the base formulation (Section 2.4), but it is constructed in a different way:

$$\text{Minimum} \sum_{d} \sum_{i} \mathrm{EQ}_{di} * \mathrm{PR}_{di} \quad (1)$$

Where:
EQ_{di} = the total energy consumption
PR_{di} = the electricity price

The variables are:

(1) The operating hours of the plant, in each day and TLT category: WH_{di}.
(2) Daily water quantities sold at the various TLT hours' categories: QS_{di}.

Where: WH_{di} = working hours at each day and TLT category

The produced water quantity is calculated as:

$$\mathrm{QP}_{di} = \mathrm{WH}_{di} * \text{Unit Cap} \times 6 \quad (2)$$

The technological constraints are:

(1) Maximum TLT hours cluster (at each day/TLT category).

(2) Plant operation varies between minimal operation of the facility at 1/6 of the time and maximum full capacity operation:

$$\mathrm{WH}_{di} \times 1/6 \le H_{di} \le H_{di} \quad (3)$$

The contract water demand constraints 3 and 4 remain unchanged (Section 2.4).

The number of operating desalination trains (Units_{di}) is calculated as a by-product by the division of the produced water quantity (QP_{di}) with the TLT hours cluster (H_{di}):

$$\text{Units}_{di} = QP_{di}/H_{di} \quad (4)$$

3. Results

The results of the optimization exercise using the LP model to simulate the daily operation, over one calendar year using Palmahim Desalination Plant data as a case study, generated the following output parameters:

- Number of full operating hours for each of the TLT categories.
- Water produced quantities (thousand m^3).
- Electricity consumption (thousand kWh).
- Average SEC (kWh/m^3).
- Electricity costs: total cost (USD thousand) and unit costs (US ¢/kWh).

The results of the LP model for the two configurations, described in sections 2.4 and 2.5 above, are summarized, on a monthly basis, in Table 3.

For a base SEC of 3.54 kWh/m^3 and the other predetermined variables, the model optimized the total consumption and cost of energy for the representative production year 2011. The model indicates an annual cost of USD 12.2 million compared to USD 14.3 million, amounting to a substantial saving of 15% in the cost of energy USD 2.1 million reflecting a weighted average cost of 7.66 ¢/kWh vs. normative weighted average of 8.95 ¢/kwh derived in Table 1.

The resulting energy cost was validated, using the actual energy costs of the plant, in 2010.

4. Discussion

Great progress was made in the recent years in the RO desalination process, including improved membranes, efficient pumps, and energy saving systems [12] to the point where desalination technologies now compete with "conventional" treatment processes in many applications [13]. But the current cost of energy at about 25–30 ¢/m^3 is still considerable, fueling the general water industry's perception that SWRO is too expensive and prohibitive because of the high energy consumption [14], the potential environmental impacts, and the associated costs [15,16]. The current study indicates that development and use of optimization tools, addressing plant operation and energy consumption could yield significant savings of 15% in the energy cost, as was demonstrated in this study.

The results indicate that the LP model, designed for the optimization of energy consumption, could serve as an effective decision-making tool, assisting in the daily operation and maintenance of the operating plants. The model can also be used to as a planning tool for the design of the plant, optimizing the trade-off between plant capacity and its initial investment capital cost, to the energy expenses over the project life.

Introduction of mathematical optimization models for the routine operation would enhance the positive impact of energy efficiency in SWRO desalination

Table 3
Monthly operation simulation results for Palmachim Desalination Plant (2011 data)

Month	Number of TLT hours (full operating hours)			Produced water quantity	Power consumption	SEC average	Electricity costs	
	Peak	Shoulder	Base	m^3 000	kWh 000	(kWh/m^3)	USD 000	(US ¢/kWh)
1	142	70	532	3,311	12,039	3.636	930	7.25
2	128	64	480	2,988	10,865	3.636	839	7.25
3	322	118	304	3,423	12,444	3.636	923	6.91
4	224	158	338	3,780	13,570	3.590	998	6.85
5	294	132	318	4,185	14,677	3.507	1,132	7.17
6	280	130	310	4,050	14,054	3.470	1,081	7.15
7	147	147	450	3,627	12,754	3.516	970	6.96
8	161	161	422	3,559	12,416	3.489	968	7.14
9	266	142	312	4,202	14,660	3.489	1,128	7.16
10	252	148	344	4,342	15,108	3.479	1,145	7.05
11	308	116	296	4,202	14,853	3.535	1,169	7.31
12	136	72	536	3,331	12,048	3.618	927	7.22
Total	*2,660*	*1,458*	*4,642*	*45,000*	*159,488*	*3.544*	*12,210*	*7.66*

plants, adding another dimension to other process optimization approaches [17,18], and the anticipated achievements in the development of innovative membranes (carbon nanotube based membranes), and electrochemical seawater desalination processes [16,19,20]. The combined effect of such developments would reduce energy consumption and energy cost to many folds of the current levels, thus rendering sea water desalination into an attractive solution for the fast changing world, the global warming, and the expanding water scarcity.

Symbols

d	—	day
i	—	operating TLT category (part of day)
m	—	month
bm	—	bimonthly period
EC_{di}	—	cost of energy in a day and at each TLT category
EQ_{di}	—	daily electricity consumption in each TLT category, kWh
ES_m	—	monthly SEC, kWh/m^3
H_{di}	—	number of hours in a day and TLT category
PR_{di}	—	EP in a day and TLT category, US ¢/m^3
QP_{di}	—	daily water quantity produced in a day and at TLT category, m^3
QS_{bm}	—	bimonthly sold water quantity, m^3
QS_d	—	daily sold water quantity, m^3
QD_{bm}	—	bimonthly demanded water quantity, m^3
QD_d	—	daily demanded water quantity, m^3
Res_d	—	reservoir daily volume, m^3
Res_{max}	—	maximum reservoir capacity, m^3
TLT	—	Time Load Tariff
WH_{di}	—	working hours at each day
$Units_{di}$	—	number of trains operating in a day and at TLT category
Unit Cap	—	unit capacity per train, m^3/h

References

[1] M. Clayton, Santa Paula: A case study in energy efficiency, Desalin. Water Reuse 20(9) (2011) 16–22.

[2] DESWARE, Energy Requirements of Desalination Processes, Encyclopedia of Desalination and Water Resources (DESWARE), UNESCO Encyclopedia of Life Support Systems (EOLSS), 2011.

[3] A. Tenneh. Sea Water Desalination in Israel: Planning, Coping with Difficulties, and Economic Aspects of Long-Term Risks. Israel Water authority, Ministry of Infrastructure Publication, Tel Aviv, 2010.

[4] C. Ioannis, A. Karagiannis, P.G. Soldatosa, Water desalination cost literature: Review and assessment, Desalination 223(1–3) (2008) 448–456.

[5] P. Reji, S. Ashok, K.M. Moideenkutty, Optimum price of electricity in thermal-generating station under deregulation, Int. J. Energy Technol. Policy 7(3) (2010) 254–274.

[6] M. Osama, N. Aloquili, M. Abu-Shikhah, Power factor correction capacitors for utilizing power consumption in industrial plants, Int. J. Energy Technol. Policy 7(3) (2010) 288–308.

[7] R. Romero, A.F. Zobaa, E.N. Asada, W. Freitas, Mathematical optimization techniques applied to power system operation and planning, Int. J. Energy Technol. Policy 5(4) (2007) 393–403.

[8] S. Jebaraj, S. Iniyan, An optimal energy allocation model using fuzzy linear programming for energy planning in India for the year 2020, Int. J. Energy Technol. Policy 5(4) (2007) 509–531.

[9] A. Hermony, J.M. Pinto. New concept of upgrade energy recovery systems within an operating desalination plant. EuroMed 2010, Proc. Desalination for Clean Water and Energy Cooperation among Mediterranean Countries, Tel Aviv, Israel, 2010.

[10] Meerganz von Medeazza, G., Vincent Moreau, Modeling of water–energy systems, Case Desalin. Energy 32(6) (2007) 1024–1031.

[11] Cui Liu., K. Rainwater, L. Song Rainwater, Energy analysis and efficiency assessment of reverse osmosis desalination process, Desalination 276(3) (2011) 352–356.

[12] B. Liberman, The importance of energy recovery devices in reverse osmosis desalination, in: The Future of Desalination in Texas-Volume 2, Technical Papers, Case Studies and Desalination Technology Resources (Report #363), Texas Water Development Board, 2004.

[13] T.M. Pankratz, Advances in desalination technology, Int. J. Nucl. Desalin. 1(4) (2005) 450–455.

[14] A. Zhu, P.D. Christofides, Y. Cohen, Effect of thermodynamic restriction on energy cost optimization of RO membrane water desalination, Ind. Eng. Chem. Res. 48(13) (2009) 6010–6021.

[15] Sung Jae Kim, Sung Hee Ko, Kwan Hyoung Kang, Jongyoon Han. Direct seawater desalination by ion concentration polarization, Nat. Nanotechnol. 5 (2010) 297–301.

[16] Menachem Elimelech, William A. Phillip, The future of seawater desalination: Energy, technology, and the environment, Science 333(6043) (2011) 712–717.

[17] Mingheng Li,. Optimization of energy in reverse osmosis water desalination using constrained nonlinear optimization, Ind. Eng. Chem. Res. 49(4) (2010) 1822–1831.

[18] Aihua Zhu., D. Panagiotis, Christofides, Yoram Cohen, Energy consumption optimization of reverse osmosis membrane water desalination subject to feed salinity fluctuation, Ind. Eng. Chem. Res. 48(21) (2009) 9581–9589.

[19] A.R. Bartman, A. Zhu, D. Panagiotis, D. Christofides, Y. Cohen, Minimizing energy consumption in reverse osmosis membrane desalination using optimization-based control, J. Process Control 20(10) (2010) 1261–1269.

[20] L. Mingheng, Reducing specific energy consumption in reverse osmosis (RO) water desalination: An analysis from first principles, Desalination 276(1–3) (2011).