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More water, less energy and reduced CO_2 emissions — the Larnaca desalination plant

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ABSTRACT

An objective of the Larnaca seawater desalination plant (LDP) was to reduce specific energy consumption while producing the same or more water while maintaining water quality criteria. A critical water quality issue was the removal of boron to levels such as those defined by the WHO. The LDP (a 10-year BOOT project) has been operating since 2001, and has the challenge of meeting a 1 mg/L boron standard. In order to cope with the boron requirement, the plant is designed with a double-stage RO configuration in order to produce boron concentrations consistently below 1 mg/L. Other innovative design features of the LDP are the eight membranes per pressure vessel, permeate from both ends of the pressure vessels and a fully automated operation. As part of a wider plant operation strategy, the plant processes have been optimized and a stable high plant performance was achieved. Further developments such as the membrane management system have improved the performance of the SWRO process and the operation of the first stage at elevated pH further improved the boron rejection of the first SWRO stage such that a second BWRO stage was not required to operate for more than 6 months of the year. Such innovative plant operation and the subsequent energy savings—translated into reduced CO_2 emissions (energy obtained from the national electricity grid) per cubic meter of water produced—has allowed the LDP to win the 2007 National Innovation Industry Prize. This paper describes the changes made and advancements in achieving lower specific plant energy while producing more water and at the same time meeting its quality and all other contractual requirements.

Keywords: Desalination; Energy; CO_2 emission/m^3; Boron

1. Introduction

Desalination is a major, multi-billion-dollar, fast-growing and much in demand industry world wide. As shown in Fig. 1, the annual installed desalination capacity world wide in 2007 exceeded the 4.5 Mm^3/d, while the estimated cumulative installed desalination capacity by the end of 2008 is estimated to be beyond 5 Mm^3/d.

A main industry driver is the reduction of the cost of desalinated water (see Fig. 2) with some 70% reduction in price ($\$/m^3$) in the last 15 years [1,2]. This is supported by substantial improvements in technology, processes, membrane performance, energy recovery systems etc., and not least, innovative plant operations.

As SWRO plants grow in number and size, consequently the price of water produced is being reduced. However, for long-term O&M contracts (20 years being

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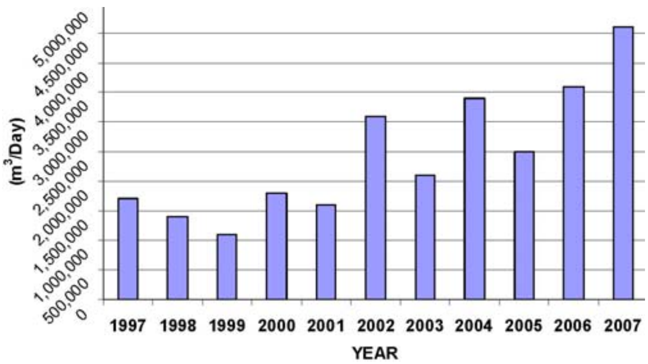

Fig. 1. Annual installed desalination capacity.

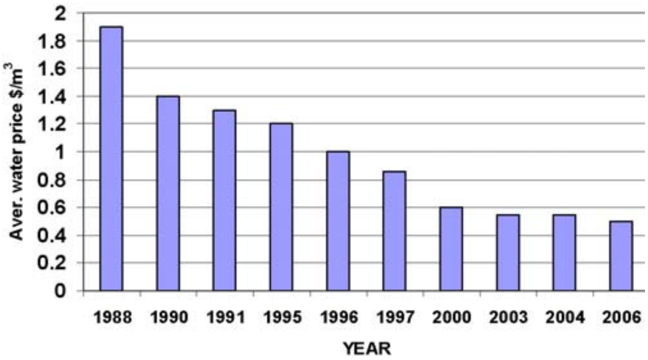

Fig. 2. Cost of water for large SWRO plants.

normal for BOOT projects) in order to maintain and even improve performance (utilizing technological advancements, new innovations, etc.), it is vital to have a plant operation strategy in place.

The general plant operation strategy (Fig. 3) of the Larnaca desalination plant (LDP) was to (a) optimize the plant processes, (b) standardize the plant operation, (c) stabilize operations to high plant performance and then through innovation maintain/improve plant performance [3]. Having achieved successfully parts (a) to (c), this has set the basis for innovative plant operation where the initially installed second-stage operation was not operated for more than 6 months of the year while at the same time continuously producing good-quality EU standard water and also achieving higher water production with less specific energy (kWh/m^3). The work, leading up to the achieved results described in this paper, was carried out over several years and has been described in previous publications [4–7].

The energy for the plant operation is obtained from the local electricity authority (EAC) producing electricity from oil-fired power stations. The achievement of more water with less specific energy had an added major benefit to Cyprus in general by reducing the CO_2 emissions of EAC for over 5,000 tons in its last 3 years of operation. This substantial contribution towards the environment has

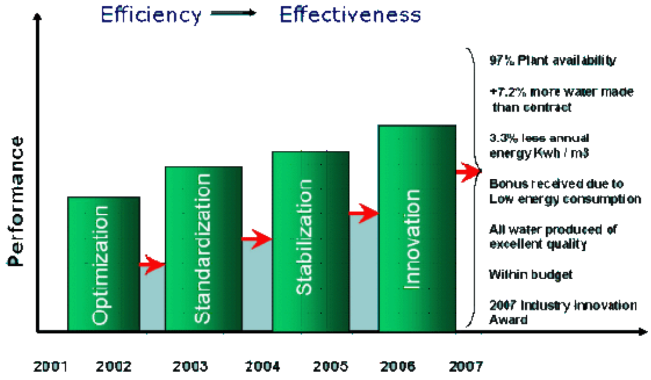

Fig. 3. Plant operational strategy.

been recognized by the Industrial Federation of Cyprus, who awarded the 2007 Industry Innovation Award to the LDP.

2. Boron removal — theory and practice

Desalination processes have been challenged by stringent water quality standards. A main water quality challenge for many SWRO plants is to remove boron in order to meet the WHO guidelines for drinking water quality as low as 0.5 mg/L or lower. This requirement has affected SWRO plant designs and energy requirements because of the difficulty in achieving such low boron concentrations. The LDP, operating since 2001, has a contractual commitment to produce water with boron less than 1.0 mg/L.

Seawater contains on average 5 mg/L of boron. The difficulty in removing boron is derived from the fact that at natural seawater pH the majority of boron exists as uncharged boric acid with a small fraction as negatively charged borate ion. The SWRO membrane process is much better at removing charged ions. The dominant form of boron depends on the pH of the seawater.

In the natural seawater pH of around 7.5, the boric acid, which has an acid dissociation constant (pK_{al}) of 9.14 at 25°C, is not ionized [9]. However, the fractions of negatively charged borate ions increase as pH increases and borate ion becomes a dominate species as pH increases beyond pK_{al} as dictated by the equilibrium Eq. (1) and shown in Fig. 4:

$$H_3BO_3 \leftrightarrow H_3BO_2^- + H^+ \; pK_{al} = 9.14 \qquad (1)$$

However, a preferred seawater pH for coagulation (pretreatment process) is 7 [7]. Thus optimum pH is required between boron removal and coagulation requirements. This is a completely new subject needing special attention (part of the optimization strategy of the plant, Fig. 3).

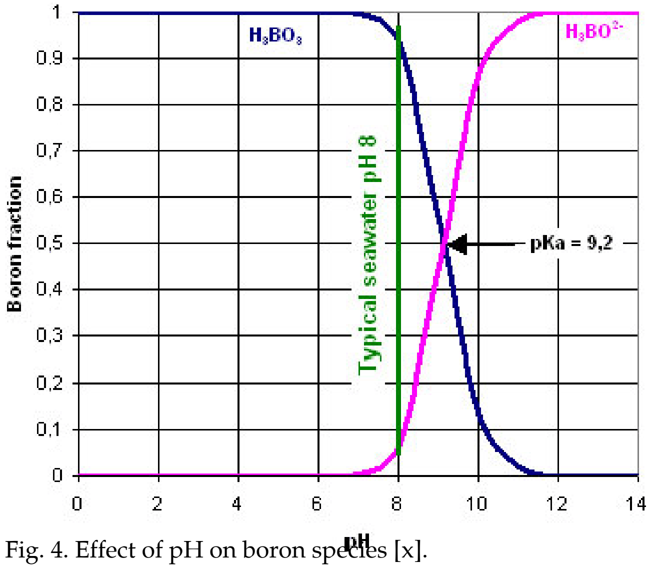

Fig. 4. Effect of pH on boron species [x].

The surfaces of SWRO membranes are negatively charged. Consequently, as pH increases, the charge repulsion between negatively charged borate ions produced and the negatively charged membrane surfaces effectively decrease diffusive transport of boron through the membranes [10]. Boron rejection is thus largely dependent on pH as established in the literature and other studies. Typical boron removal at pH 8 is between 75% to 90%. Even for specialized designed boron rejection membranes it is difficult for a single pass full-scale RO plant to meet the stringent WHO boron guidelines unless additional treatment stages are employed. It has been reported [9] that salt rejection for a given seawater pH is linearly correlated with boron rejection.

However, at high seawater pH potential precipitation of calcium carbonate and magnesium hydroxide could take place and must be avoided; otherwise, scale formation can take place within the membranes. This phenomenon is enhanced in the rear-end membranes and in particular in our system since pressure vessels with eight membranes in each have been installed. Membrane scaling is an important issue and LDP operations team has gone through substantial investigation and trials and tests in order to determine a cost-effective, performing antiscalant [3]. Furthermore, investigations were carried out for optimum dosing and mixing of the antiscalant — an important step underestimated and often overlooked.

Seawater temperature variations (uncontrolled parameter; see Fig. 9) effect the transport of water and solute across RO membranes. Increases in water temperature increase both the seawater permeation through the membranes and the solute transport through the membranes. The latter is much more affected by temperature [x]. It is generally reported that boron removal decreases as water temperature increases as depicted in Fig. 5. For high salinity seawater with high boron content in hot climates, e.g. Cyprus at 30 °C, boron removal drops to about 75% at the first stage with permeate in the order of 1.1–1.2 mg/L boron in the first stage. Thus, a second stage is needed (Fig. 7).

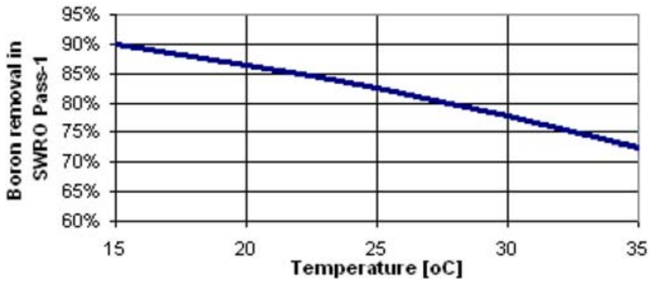

Fig. 5. Effect of seawater temperature on boron removal [x].

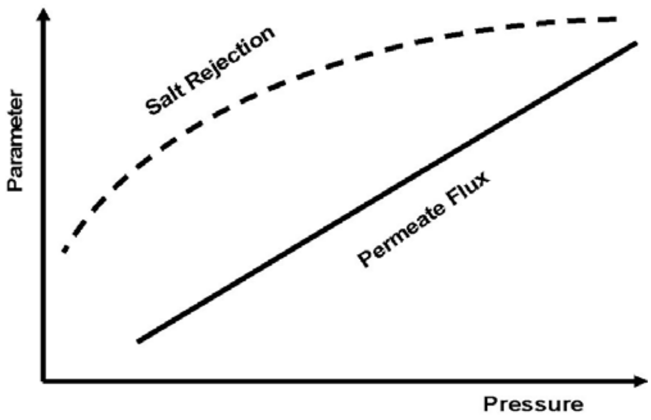

Fig. 6. Effect of feed pressure on membrane performance.

In addition to seawater temperature and pH, another main process parameter affecting boron removal in SWRO is the feed water pressure. As shown in Fig. 6, permeate flux increases almost linearly with pressure if all other operational parameters are kept constant. But in a real plant not all is constant. The feed pressure itself is affected by seasonal as well as plant operational variations (e.g., recovery, feed concentration, seawater temperature, etc.) and subsequently water quality, e.g. boron, is affected.

As seawater temperature increases, this can cause an increase in feed flow and thus an increase in the permeate flux while at the same time increases in solute transport through membranes takes place. As a result of this sequence of events, an additional boron removal process is required, particularly in the hot months of the year, in order to achieve the stringent product water boron requirements of <1.0 ppm.

In a continuously changing plant operation environment where the critical operational parameters must be optimized in order to continually meet contractual requirements all the time (e.g. water quality, quantity and specific energy). It is vital that in any plant, an annual

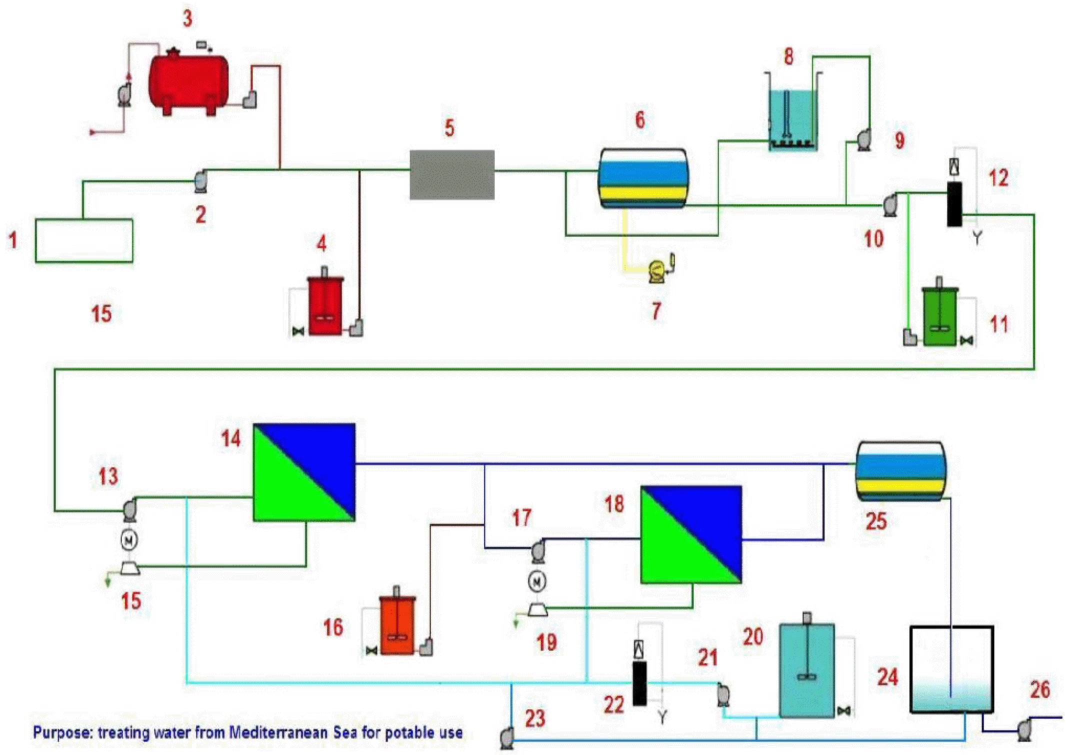

Fig. 7. Schematic diagram of Larnaca desalination plant. 1 seawater intake, 2 seawater pumps, 3 sulphuric acid dosing system, 4 coagulant dosing system, 5 mixer room, 6 open gravity sand filters, 7 air blower, 8 backwash tank for sand filters, 9 booster pump for sand filters backwash tank, 10 booster pumps, 11 antiscalant dosing system for first pass, 12 cartridge filters, 13 high-pressure pumps for trains in first pass, 14 RO trains in first pass, 15 energy recovery turbine first pass, 16 antiscalant dosing system for second pass, 17 high-pressure pumps for trains in second pass, 18 RO trains in second pass, 19 energy recovery turbine second pass, 20 chemical cleaning tank, 21 chemical cleaning pump, 22 cartridge filter (from chemical cleaning system), 23 diesel pump for train flushing in case of energy power failure, 24 permeate water tank, 25 limestone gravel reactors, 26 permeate pumps for distribution to the client (13 km pipe at room elevation).

operational plan is defined in order to obtain best plant performance specific to a given plant throughout the year/seasonal variations.

3. Achieving more water from less energy

The LDP RO process has two stages: (a) first stage with eight membrane pressure vessels operating at over 70 bar feed pressure and 50% recovery, and (b) second stage brackish water reverse osmosis (BWRO), which can reduce boron further in the permeate as shown in Fig. 7). Part of the plant operational strategy was to maintain train membrane performance, and this was carried out via the membrane management system (MMS) [7] and systematic chemical cleaning of membranes [14]. Choosing the non-performing membranes (Fig. 8) within an eight-membrane PV was done by a special probe inserted in the PVs during normal plant operation where data and samples were collected for further analysis.

Both the chemical cleaning and membrane changes were carried out, taking into consideration the seawater temperature variations (as shown in Fig. 9). The results of Fig. 9, chosen as representative, indicate that the combination of membrane changes with appropriate chemical cleaning of the membranes restored the train performance e.g., pressure difference of train returning to its original value. Essential to maintaining high plant performance was the appropriate timing of membrane changes in relation to the chemical cleaning (part of the MMS procedure developed internally).

Although several parameters affect the plant operation, an essential controlled parameter for boron removal was the pH of the seawater. Previous work at the LDP at elevated seawater pH has proven successful in further reducing boron in the product water [x]. The water pH was not only adjusted for the first stage but also for the second stage (when operating) in order to prolonged the operation with one pump before switching the second pump, i.e. second stage at full capacity. This resulted in two main achievements: (a) operating the second stage at lower energy for longer periods, or not operating it at all; and (b) reducing the loss of water in the second stage by

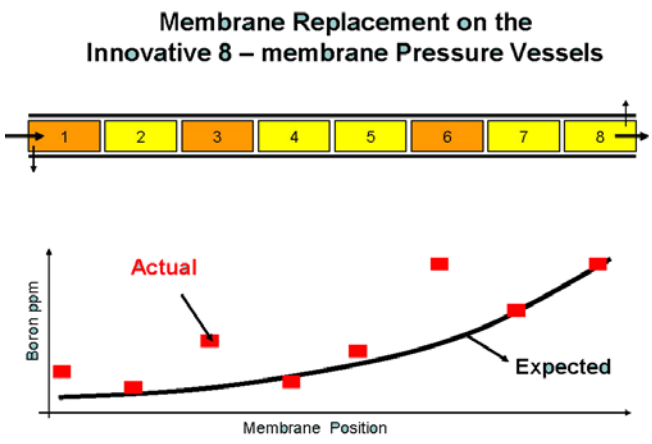

Fig. 8. Selecting non-performing membranes using defined boron levels (= *f* membrane age).

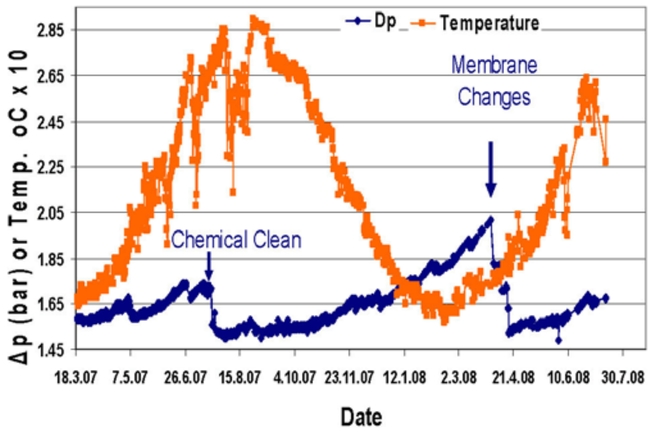

Fig. 9. Seasonal pressure drop and temperature profiles for one of the membrane trains.

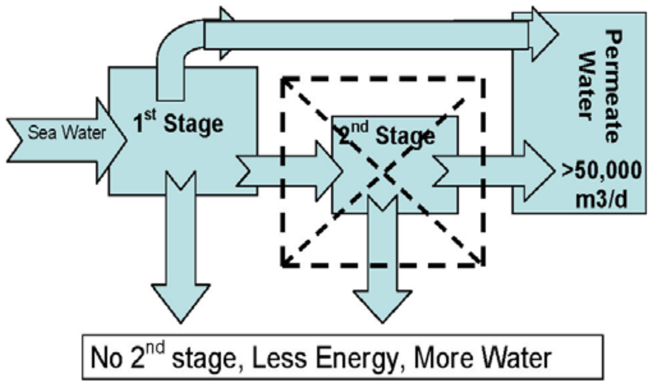

Fig. 10. Operating the plant without the second stage.

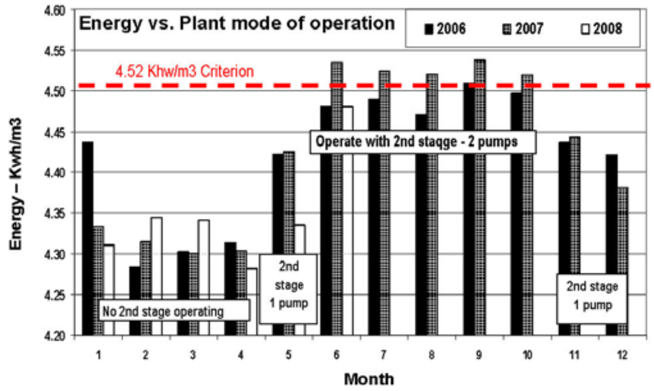

Fig. 11. Specific energy consumption 2006–2008 (no second stage in the winter months).

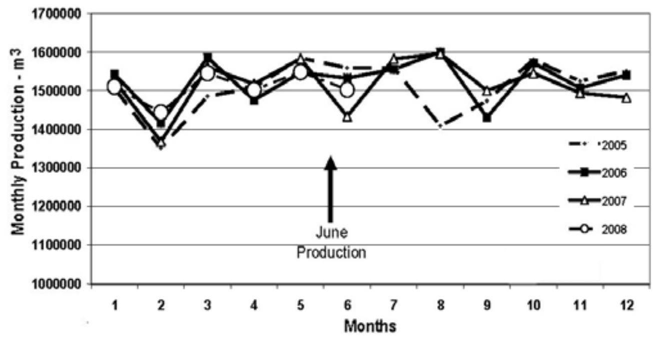

Fig. 12. Monthly water production 2005–June 2008.

either not operating it or operating at a lower flow rate for longer periods (Fig. 10). With the above plant operation strategy and with a background of a well optimized pre treatment (achieving SDI <3 continuously after micron filtration), it was possible to operate without the second

either not operating it or operating at a lower flow rate for longer periods (Fig. 10). With the above plant operation strategy and with a background of a well optimized pre treatment (achieving SDI <3 continuously after micron filtration), it was possible to operate without the second stage for more then 4 months of the year and with one pump (instead of two pumps) for over 2 months of the year (Fig. 11).

As shown in Table 1, the overall result was the lower average annual average specific energy consumption which was equivalent to 6.4 million kWh savings in 4 years, resulting in more than 5,000 t of CO_2 reduction not emitted by the local electricity authority while at the same time producing 7% more water.

The monthly water production for the last 5 years is shown in Fig. 12. This indicates a consistent and stable water production based on an average 98% availability of the plant (i.e. in total out of the 365 days continuous operation the plant was shut down less than 8 days for routine maintenance, unexpected events and annual planned maintenance).

The plant performance over the last 3 years was such that the plant produced, on average, 7% more water than the expected contractual requirement with 2% less energy

Table 1
Summary of energy reduction/CO_2 emissions

Year	M^3 production	Av. annual specific energy (kWh/m^3)	kWh/m^3 savings <4.52 kWh/m^3	kWh reduction
2004	16355121	4.43	0.09	1471960
2005	18093453	4.435	0.085	1537943
2006	18302262	4.423	0.097	1755064
2007	18188714	4.43	0.09	1636984
Total kWh saved (2004–2007)				6401951
Tons of reduction CO_2 emissions (based on EAC estimates)				>5,000 t of CO_2

(essentially reducing CO_2 emissions per m^3 of water produced) while at the same time all water produced was within contractual specifications.

4. Conclusions

- Exponential growth of number and size of desalination plants and technological advances are driving the price of desalinated water $\$/m^3$ down to less than $\$0.5/m^3$.
- Increasingly stringent boron standards have to be met — the boron challenge.
- Difficulty in boron removal by SWRO membranes requires innovative plant operation.
- LDP operational strategy introduced a blend of an internally developed MMS and high pH seawater operation.
- The goal was to enhance the performance of the first stage SWRO, thus precluding the operation of the second-stage BWRO (dedicated to boron removal) for more than 4 months of the year.
- The results were 7% more water production with 2% less annual specific energy (i.e., reducing CO_2 emissions per m^3 of water produced) while meeting all water quality contractual criteria.
- The LDP was awarded the 2007 Industry Innovation Award by the Cyprus Federation of Industry.

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