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Energy consumption assessment of 4,000 m^3/d SWRO desalination plants

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ABSTRACT

The Canary Islands has been pioneer on desalination in Europe since the 1960s and has continued to use intensively the desalination technologies in order to provide water resources. However, one of the most important problems related to the operating efficient of seawater reverse osmosis (SWRO) desalination plants is dealing with the high-energy consumption. The present article aims to study, define, and compare the energy consumption cost of five SWRO desalination plants with the same production of 4,000 m^3/d in the island of Fuerteventura (Canary Islands). The methodology for carrying out the work is based on analyzing the energy consumption data that directly affect to the operating cost. A comparison between different energy recovery systems was carried out using the data collected over 5 years of operation. The article presents an assessment of different ways to get more efficient operating conditions in order to reduce the operating cost.

Keywords: Seawater; Reverse osmosis; Desalination plants; Operating data; Normalization

1. Introduction

Approximately, 97.5% of the water on our planet is located in the oceans and therefore is classified as seawater. The 2.5% of the planet's freshwater, approximately 70% is in the form of polar ice and snow and 30% is groundwater, river and lake water, and air moisture. So even though the volume of the earth's water is vast, less than 35 million km^3 of the 1,386 million km^3 (8.4 million mi^3 of the 333 million mi^3) of water on the planet is of low salinity and is suitable for use after applying conventional water treatment only [1]. Desalination provides a means for tapping the world's main water resource—the ocean.

Reverse osmosis (RO) technology is a pivotal method for desalination. The global applications of

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RO technology for seawater desalination were projected to grow from a capacity of 40–100 million m^3/d from 2008 to 2015 [2]. However, the RO process is known to be relatively energy-intensive and system optimization can further reduce RO energy consumption. In particular, energy is required for the pumps that supply the pressure to overcome the membrane resistance, etc. The energy consumption minimization is key in seawater reverse osmosis (SWRO) desalination plants, especially in arid regions heavily dependent on desalination.

In the Canary Islands, 158.53 hm^3/year of fresh water is produced from desalination plants [3]. Currently, there are 322 desalination plants in the Canary Islands, 255 using RO technology, and 131 are SWRO desalination plants. As one of the most important aspect, the energy consumption, including energy recovery devices have been studied by many authors [4–18]. Usually, a SWRO desalination plant should have specific energy consumption (SEC) between 2 and 5 kW h/m^3.

The aim of this paper is to assess the SEC of five SWRO desalination plant with the same production capacity (4,000 m^3/d) located in the island of Fuerteventura.

2. Material and methods

2.1. Plants description

As the information is private, the location of the five SWRO desalination plants could not be revealed, so from now the plants are named *A*, *B*, *C*, *D*, and *E*, respectively. Table 1 shows the characteristics of each SWRO desalination plant between the years 2008 and 2012. The data summarized in Table 1 show that the lifetime of the plants is around 14–22 year, although it is noted that there are expansions that duplicate the capabilities of three plants.

Four of these plants had beach well as water intake and the other had an open intake. The type and configuration of the intake has a significant impact on the nature and quantity of foulants contained in the source water and on the complexity of the pretreatment system needed to control RO membrane fouling. The membrane fouling can turn into a SEC increase as a higher feed pressure would be required to keep the production with the time. The five plants had sand filters and cartridge filters in the pretreatment stage, but with different chemicals (see Table 1). The averaged recovery was in a range of 40 and 43% and the averaged operating temperature was quite close between the five plants, around 22˚C.

2.2. Data collection

The data were collected daily "*in situ*". Fig. 1 shows the average SEC per year taking into account the high-pressure pump and the booster pump if applicable.

The plant *A* showed a quite constant SEC over the years, with only a difference of 0.22 kW h/m^3, which indicates a proper plant operation. The desalination plant *B* has reduced its energy consumption in the last 3 years as some membrane elements were replaced. However, the SEC of plant *C* has been fluctuating considerably due to obsolete equipment. About the plant *D*, it was observed that the desalination plant was working properly with minor variations except in 2011 due to certain faults in the equipment. This plant has the lowest SEC. Clearly, the expansion in more than 66% in 2006 has been a great step in the SEC. Finally, the SEC of plant *E* was quite constant.

Table 2 shows the average SEC per year and the average over the years of each plant.

3. Results

3.1. Theoretical SEC

In order to perform a comprehensive analysis and comparison of different desalination plants, it has been determined the "theoretical" SEC based on ROSA software simulations (Table 3). The SEC for each plant was obtained taking into account and average of feedwater inorganic composition for each plant, average feedwater temperature and pH (Table 1), 80% as pump efficiency and a flow factor of 0.85.

After calculation, theoretical energy consumption has been used in an excel sheet recovery system power ERI PX-house and for the appropriate theoretical energy consumption for those desalination plants possessing ERS. On this basis, we obtain the following results summarized in Table 4.

And initially basic analysis, it is observed that the plant *D* is the one that better functioning and best adapted from the point of view of energy consumption.

3.2. Statistical analysis

With the above results, it has been carried out a statistical study so that they can provide other data and criteria that can be established with other findings. Initially, it has been calculated statistical values and the type of distribution.

With the results of statistical and distribution parameters studied (Tables 5 and 6), we could confirm that our values fit a normal distribution, although we

Table 1
Characteristics of each SWRO desalination plant

	Plant *A*	Plant *B*	Plant *C*	Plant *D*	Plant *E*
Start-up (year)	1999	1993	1993	2001	1999
Capacity expansion	NO	2001–50%	2009–50%	2006–66.6%	NO
N˚ membranes	392	336	427	420	405
Membrane type	SW30HR-380	SW30HR-380	SW30HR-320	TM820 M-440	SW30HR-380
Production lines	4	2	2	4	2
Pressure vessels/line	14	24	25/36	12	28
Elements/pressure vessel	7	7	7	7	7
Intake	Beach well	Beach well	Open Intake	Beach well	Beach well
Pretreatment (chemicals)	H_2SO_4 NaOCl $NaHSO_3$	$(NaPO_3)_6$	NaOCl $NaHSO_3$	NaOCl $NaHSO_3$	NaOCl $NaHSO_3$
Recovery	43%	43%	40%	42%	42%
Configuration	1 pass/1 stage	1 pass/1 stage	1 pass/1 stage	1 pass/1 stage	1 pass/1 stage
Energy recovery system (ERS)	DWEER	Pelton Turbine	Pelton Turbine	ERI-PX	Pelton Turbine
Maintenance	Medium–high	High	High	High	High
Feed temperature (average)	21	22	22	20	22
Feed pH (average)	7.9	7.6	7.6	6.8	7.7

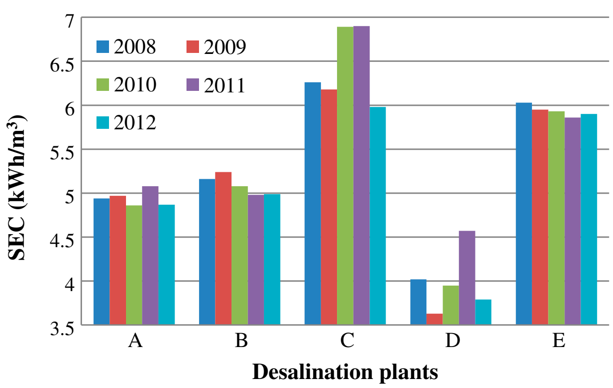

Fig. 1. Annual average SEC.

had initially set aside for each of the mean values of Table 1 February value considering it as dispersed and therefore defective for our sample. Same statistical study was done in a previous work [19], providing the expected normal value and the standard deviation by the following graphics (Figs. 2 and 3).

With the results of the statistical parameters and studied distribution (shown in Tables 5 and 6), it was confirmed that the obtained data followed a normal distribution.

The margin errors shows the comparison in percentage between the data collected and the average SEC values calculated with the ROSA software with ERI PX ERS.

Margin of error plant *A*: Me (without ERI PX) = $((4.94 - 4.52)/4.52) \times 100 = 9.29\%$

Table 2
Average SEC (kW h/m^3) of the SWRO desalination plants

Plant/Year	2008	2009	2010	2011	2012	Average
A	4.94	4.97	4.86	5.08	4.87	4.94
B	5.16	5.24	5.08	4.98	4.99	5.09
C	6.26	6.18	6.89	6.90	5.98	6.44
D	4.02	3.63	3.95	4.57	3.79	3.99
E	6.03	5.95	5.93	5.86	5.90	5.93

Table 3
Main data software ROSA

Plant	*A*	*B*	*C*	*D*	*E*
Feed press (bar)	55.61	57.84	51.44	52.65	55.28
Conc press (bar)	54.44	56.41	50.36	51.96	54.39
SEC (kW h/m^3)	4.52	4.70	4.50	4.38	4.60
Feed TDS (mg/L)	38,069	38,050	38,075	38,032	38,064

Table 4
SEC based on the ERS ERI-PX

Plant	*A*	*B*	*C*	*D*	*E*
SEC (kW h/m^3)	3.21	3.28	3.12	3.28	3.31

Table 5
Provided statistical values

Valid values	5
Missing values	0
Standard error of the mean	0.43096
Standard deviation	0.96365
Variance	0.929
Range	2.48
Minimum	3.84
Maximum	6.32
Periodicity	1, 1, 1, 1, 1

Table 6
Distribution type

Normal distribution. Location	5.2060
Normal distribution. scale	0.96365

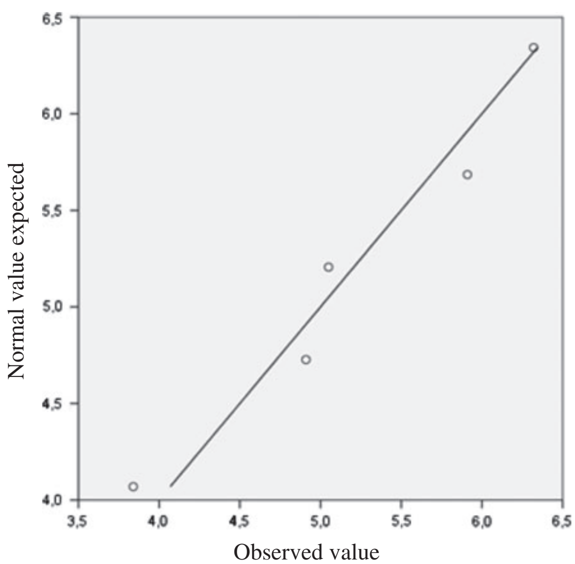

Fig. 2. Q-Q normal. Normal value expected.

Margin of error plant *B*: Me (without ERI PX) = ((5.09 – 4.70)/4.70) × 100 = 8.29%

Margin of error plant *C*: Me (without ERI PX) = ((6.44 – 4.50)/4.50) × 100 = 43.11%

Margin of error plant *D*: Me (With ERI PX) = ((3.99 – 3.28)/3.28) × 100 = 21.64%

Margin of error plant *E*: Me (without ERI PX) = ((5.93 – 4.60)/4.60) × 100 = 28.91%

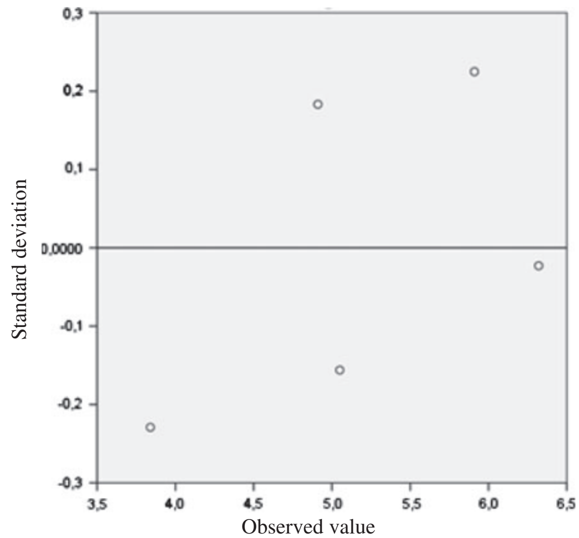

Fig. 3. Q-Q normal. Standard deviation.

4. Discussions

4.1. Analysis plant A

About plant *A*, it is a desalination plant that has been in operation for 15 years. The maintenance of this plant was not appropriate at all. The number of elements is appropriate and the type of elements is latest generations as a membrane replacement was carried out. Spite of having a DWEER ERS, the plant had an average SEC (4.94 kW h/m^3) above the estimated (4.52 kW h/m^3). To improve, it must performed maintenance regularly and introduce a ERI PX as ERS to substantially reduce the SEC.

4.2. Analysis plant B

The plant *B* is an old plant, but the machinary had been raplaced having an acceptable SEC. The number elements is low, although the elements have been replaced. The average SEC wa 5.09 kW h/m^3, which is not bad at all, since this plant should have had a SEC of about 4.70 kW h/m^3. An increased number of membrane elements and the installation of a ERI-PX ERS would reduce the SEC.

4.3. Analysis plant C

The plant *C* was built more than 20 years ago. It is noted that enlargement has not adequately influence on the SEC. The number of elements is adequate, although the type of elements are not of the last generation. The ERS is just installed in a small final phase of the expansion; as a result the average SEC was 6.44 kW h/m^3, which is very far from the 4.50 kW h/m^3. To improve the SEC, a machinary replacement should be replaced and the installation of a ERI-PX in the two lines.

4.4. Analysis plant D

Plan *D* is a plant with 13 years operating time, but notes that perfectly crafted and maintained. Regarding the membrane elements, the type and number is suitable. The ERS is an ERI-PX. The average SEC was 3.99 kW h/m^3, which indicates that the plant operates properly. Such consumption was slightly below comparing with the theoretical SEC (3.28 kW h/m^3).

4.5. Analysis plant E

This plant has a life of 15 years. The desalination plant does not have energy recovery system last generation. The average SEC was 5.93 kW h/m^3, which is far from the 4.60 kW h/m^3. The improvement of such installation would aim installing an ERI-PX ERS and carrying out a substitution of the machinery.

5. Conclusions

(1) Maintenance for desalination plants is one of the most important factors to keep the SEC more or less uniform throughout the years.
(2) To have a last generation ERS, since this leads to considerably reduce the SEC as it can be observed in plant *D*.
(3) The operating years of the plants affects to the SEC due to machinery performance, after 15 operating years, the machinery should be replaced.
(4) Membrane replacement is key in the SEC as feed pressure can be reduced considerably.
(5) The SEC of the plants *A* and *B* are quite close to the calculated values without ERS. Plants *C* and *E* are far away to the theoretical values and the plant *D* with the ERI PX ERS should have lower SEC comparing with the calculated values.

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