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Cost assessment in SWRO desalination plants with a production of 600 m^3/d in Canary Islands

J. Feo-García[a,*], A. Ruiz-García[b], E. Ruiz-Saavedra[c], N. Melian-Martel[d]

[a]*Departamento de Ingeniería Electrónica y Automática, Escuela de Ingenierías Industriales y Civiles, University of Las Palmas de Gran Canaria, Edificio de Ingenierías, Campus Universitario de Tafira, 35017 Las Palmas de Gran Canaria, Spain, Tel. +34 928 451228; Fax: +34 928 457319; emails: jfeo@diea.ulpgc.es, jose.feo@ulpgc.es*
[b]*Instituto SIANI, University of Las Palmas de Gran Canaria, Parque Científico-Tecnológico, Campus Universitario de Tafira, 35017 Las Palmas de Gran Canaria, Spain*
[c]*Departamento de Cartografía y Expresión Gráfica en la Ingeniería, Escuela de Ingenierías Industriales y Civiles, University of Las Palmas de Gran Canaria, Edificio de Ingenierías, Campus Universitario de Tafira, 35017 Las Palmas de Gran Canaria, Spain*
[d]*Departamento de Ingeniería de Procesos, Escuela de Ingenierías Industriales y Civiles, University of Las Palmas de Gran Canaria, Edificio de Ingenierías, Campus Universitario de Tafira, 35017 Las Palmas de Gran Canaria, Spain*

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ABSTRACT

Water resources available in the island of Fuerteventura come mostly from small-scale capacity seawater desalination plants. Desalted water demand in the island has grown considerably in the last decade forcing managers to adapt desalinated water supply constantly. Additionally, the operating cost of the plants is relevant. The staff, chemical consumption, cartridge filter, and membrane replacement cost are essential in order to establish more efficient operation conditions of a reverse osmosis desalination plant. This article aims to study and compare the mentioned cost of six different seawater reverse osmosis desalination plants with the same production of 600 m^3/d in the island of Fuerteventura. The results show for each of the six cases how costs can be reduced and the essential role of automation dealing with the staff cost with the particular capacity of 600 m^3/d.

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

1. Desalination in the Canary Islands

In the national Spanish framework, the Canary Islands are emerging as part of the national territory where more water is produced by seawater reverse osmosis (SWRO) desalination plants.

Although technological development enables the construction of plants increasingly larger, about half of the desalination plants that are in operation have a capacity less than 500 m^3/d, while 7% have a capacity of 20,000 m^3/d.

From existing desalination technologies, reverse osmosis has been erected as the most established

*Corresponding author.

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technology to be the most inexpensive and efficient as a result of lower energy consumption and space. In Fig. 1, the number of desalination plants in the Canary Islands, a function of the desalination technology, is summarized [1].

Although initially it could be interpreted that the production of desalinated water from seawater and brackish water would be at par, by the following Fig. 2 it is shown that 75% of the desalinated water comes from seawater and 25% comes from brackish water. The desalinated seawater is used in the tourism and residential sector [1].

2. The different costs RO desalination plants

It is known that reverse osmosis desalination plants have other different costs of energy consumption, although this is the most important in the economic aspect.

In 2001, an article by Poullikkas [2] highlights these costs and begins to comment on the replacement of membranes and filter cartridges, reagent consumption and staff among others.

Avlonitis [3] studied the costs of desalinated seawater by reverse osmosis plants in small Greek islands and also highlights the costs that have been studied in this article [4–6].

In 2007, Fritzmann et al. published an article on the state of the art of desalination by reverse osmosis and therein a section of interest on the costs discussed in this article is specified [7]. Costs as a relevant issue in SWRO desalination plant have been studied by many authors [8–16].

In general, reverse osmosis desalination plants have the following costs: (a) reagent consumption, (b) replacement cartridge filters and membranes, (c) staff, (d) maintenance and (e) finally known costs energy.

In this article, the costs of six SWRO desalination plants in Fuerteventura (Canary Islands) have been studied.

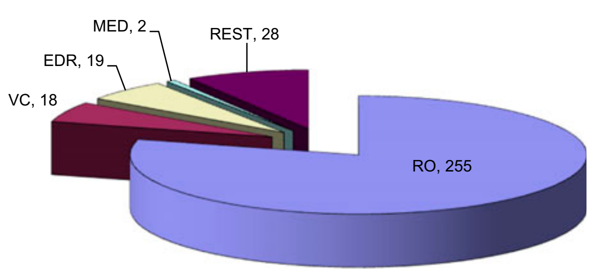

Fig. 1. Desalination plants in the Canary Islands (RO: reverse osmosis, VC: vapor compression, EDR: electrodialysis reversal, MED: multiple-effect distillation) [1].

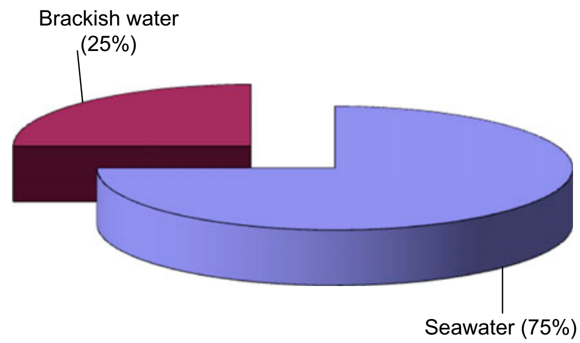

Fig. 2. Desalinated water production in the Canary Islands (January 2010) [1].

3. Experience in the field and collected data

In the study [8], it is evident that besides the cost corresponding to energy consumption, other consumptions affecting desalination plants within which staff costs were cited were the cost of consumption of reagents, replacement cartridge filters and membranes, etc.

Due to the privacy of the information and the inability to make public the status of each desalination plant, the plants were named with the numbers 1–6. The characteristics of each are summarized in Table 1.

From Table 1, it is clear that small plants never choose enlargement. They are plants that are installed with the technology of the time and absolutely nothing invested in them. As almost all old, all but one has 6 membranes per tube and pretreatment is the same for all. It is important to note that maintenance is not adequate but this will be explained in staff costs.

The methodology to calculate the costs is based on the data average of every year from 2008 to 2013, and on this basis, we determined the average of the last 5 years on each plant.

3.1. Staff cost

This cost was calculated by taking into account the data of the number of staffs in the plant and the total cost per year. On this basis, we have calculated the cost of m^3 in c€.

Results of the data are provided in Table 2 and Fig. 3 when the cost of personnel is concerned, there is a difference of almost double the majority and is triple with respect to a particular plant, number 5. First, it is noticeable that the plant 5 has 2 people working, it is a plant with beach well, and the level of maintenance is high. With all this, it is clear that the responsibility and concern is high.

Table 1
Characteristics of each SWRO desalination plant

	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6
Year	2004	1993	2006	1979	2001	2000
Enforcement	No	No	No	No	No	No
N° membranes	60	36	70	54	36	36
Membranes	KOCH 8040-SW-400	TORAY T-400	KOCH 8040-SW-400	TORAY T-320	SW30HR-380	SW30HR-380
Elements/Pressure vessel	6	6	7	6	6	6
Intake	Open intake	Beach well	Open intake	Open intake	Beach well	Beach well
Pretreatment	NaOCl	NaOCl	NaOCl	NaOCl	NaOCl	NaOCl
	$NaHSO_3$	$NaHSO_3$	$NaHSO_3$	$NaHSO_3$	$NaHSO_3$	$NaHSO_3$
Recovery	42%	42%	42%	42%	42%	42%
Configuration	1 pass/1 stage	1 pass/1 stage	1 pass/1 stage	1 pass/1 stage	1 pass/1 stage	1 pass/1 stage
Energy recovery system	Isobaric	NO	Pelton turbine	NO	Pelton turbine	Pelton turbine
Maintenance	Low	Low	Medium	Medium	High	Medium
Temperature	23	23	24	21	22	23

Table 2
Summary of staff costs

N° plant	Staff members	Cost (€/yr)	Cost (c€/m^3)
1	1	12,500	5.8
2	1	15,600	7.3
3	1	18,500	8.66
4	1	20,350	9.52
5	2	32,400	15.16
6	1	18,500	8.66

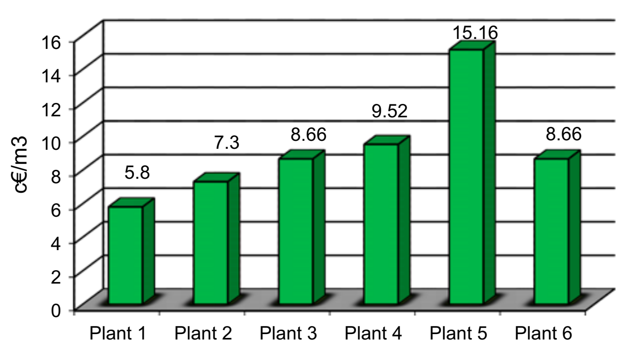

Fig. 3. Staff cost of the different desalination plants.

The cost of staff integrates maintenance costs as regards people as it stands to reason, should not be tempted to slow it down as it is in the life of the desalination plant.

3.2. Reagent consumption cost

For the study of the consumption of reagents, we have initially provided the kilograms of each item purchased annually. With this data and based on the formula that follows, we obtained the cost relating to the consumption of reagents. Importantly, in all plants visited, only two reagents are used in the pretreatment. We understand that the desalinated water complies at all times with current regulations [9]:

$$\text{Cost}\,(€/\text{m}^3) = \text{Quantity}\,(\text{kg/y}) \cdot \frac{€}{\text{kg}} \cdot \frac{1\text{y}}{365\ \text{d}} \cdot \frac{1\text{d}}{Q(\text{m}^3)}$$

Based on the data given in Table 3 and Fig. 4, we can see that virtually all plants are around 0.5 c€/m^3, while the plants 3 and 5 have a higher cost. Importantly, these plants are also consistent with a medium and high level of maintenance. However, it has been observed in these small plants that reagents used are the minimum to get drinking water.

3.3. Membrane replacement cost and filter cartridges

The cost of replacement of membranes is determined by the number of membranes recovered a year and thereby the annual cost of membranes is obtained. In the same way, we have obtained the replacement cost of cartridge filters. After this, we calculate the individual cost c€/m^3 and the total cost.

From Table 4 and Fig. 5, it can be seen that there is homogeneity in these costs, the cost of the 5th plant being the highest. Reruns of membranes and filter cartridges are very important because in this chapter, it is part of the life of the desalination plant. These two costs are not very high, and therefore, we must be clear that the membranes and filters should always be in the best conditions, especially in small production plants such as these cases.

Table 3
Summary of the cost of reagents consumption

N° Plant	NaOCl (kg/year)	$NaHSO_3$ (kg/ year)	NaOCl (c€/m^3)	$NaHSO_3$ (c€/m^3)	Cost (c€/m^3)
1	1,350	1,675	0.117	0.459	0.576
2	1,150	1,523	0.099	0.417	0.516
3	1,725	2,102	0.149	0.576	0.725
4	1,095	1,450	0.095	0.397	0.492
5	1,852	2,135	0.161	0.585	0.746
6	1,798	1,956	0.160	0.536	0.696

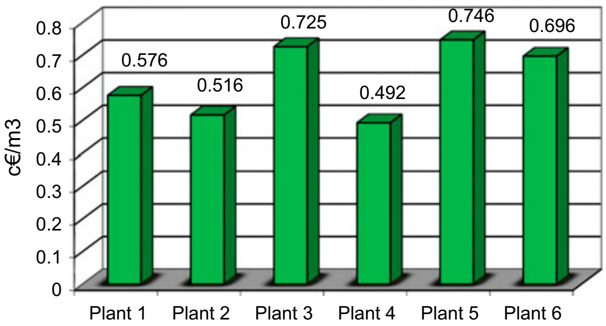

Fig. 4. Reagents consumption cost of the different desalination plants.

3.4. Total cost

The Table 5 and Fig. 6 show the total costs. The plant with better maintenance is the one with a higher total cost. An upcoming study would be of interest to note that energy consumption is so we can make other conclusions. Also this table and this graph will be useful to present in this article the characteristic mathematical model for this type of reverse osmosis desalination plants.

4. Analysis of the plants and their costs

4.1. Analysis plant 1

This plant had the lowest cost. It is a quite new facility although the maintenance is not very appropriate and it has 60 membranes, which makes the operation adequate in terms of the studied cost. The operating years of the plants are quite important in terms of costs. The energy recovery system was based on isobaric chambers.

4.2. Analysis plant 2

The 2nd plant is quite ancient, the maintenance is poor but it had a beach well as intake. The number of membranes is usual for this capacity, and the cost of staff is relatively low. No energy recovery system in this case so it can be deduced that the energy cost was high.

4.3. Analysis plant 3

The 3rd plant is the most recent plant in this work. In this case, the staff also worked on weekends, reason for the high cost in this section. The number of membranes is usual taking into account the production of this SWRO desalination plant. It had a Pelton turbine as energy recovery system indicating that it is not a quite new technology for this purpose.

4.4. Analysis plant 4

The staff cost is high because of the years the staff are working at the plant. It is a plant that should be

Table 4
Summary of replacement cost of membranes and filter cartridges

N° plant	N° mem. rep.	Cost mem. (€/year)	Cost mem. (c€/m^3)	Cost *F.* cart. (€/year)	Cost *F.* cart. (c€/m^3)	Total cost (c€/m^3)
1	4	2,400	1.09	288	0.13	1.22
2	5	3,000	1.36	288	0.13	1.49
3	5	3,000	1.36	360	0.16	1.52
4	5	3,000	1.36	384	0.17	1.53
5	6	3,600	1.64	432	0.19	1.83
6	5	3,000	1.36	336	0.15	1.51

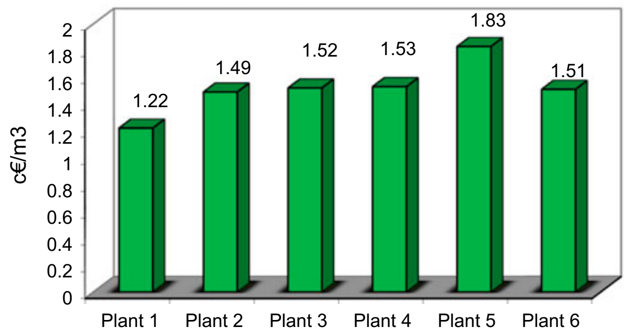

Fig. 5. Cartridge filters and membranes replacement costs of the desalination plants.

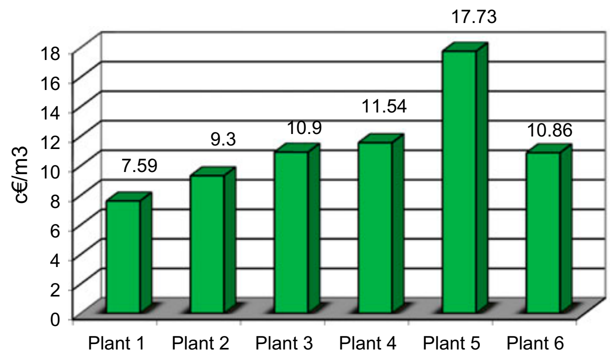

Fig. 6. Summary of all costs of the different desalination plants.

closed, but has not been made as a result of the staff working in it. As shown, the average maintenance is not adequate, and it is understood that investment should be made in energy recovery system to make the plant more profitable.

4.5. Analysis plant 5

The 5th plant has been 14 years in operation. Having 2 people working, the personnel cost is high playing an important role in the total cost. This plant is monitored 7 d a week. The remaining costs are close to the average.

4.6. Analysis plant 6

The costs of the 6th plant were appropriate. The cost of staff is average as well as other costs studied in this article. Additionally, it is appreciated that there is a regular replacement of cartridge filters and membranes.

5. Statistical analysis of the results

With the above graph results provided in Tables 5 and 6, we will conduct a statistical study so that we get a mathematical model that meets the conditions of these plants and similar plants through which you can get the total cost of this type of reverse osmosis desalination plants. In order to resolve what we mentioned earlier, we will rely on Article.

To conclude the investigation of this article, we study the obtained results so that we can find the mathematical model which will define our investigation. We represent graphically all data. Therefore, we have used the program SPSS, version 20, which is a software tool to represent statistical functions. For each cost, we represent the results in a bar diagram, dispersion diagram, and box and whisker diagram, obtaining some data which are important for the study and for possible elimination of certain values.

In order to study possible values which can be anomalous for our model, besides the information obtained before, we make control graphics for each cost to be sure of the values we are going to retire of the study.

To said costs, previously defined as fundamentals, we make the Kolmogórov–Smirnov and Shapiro–Wilk tests based on estimations of M de Hubera, biponderate of Tukey, M de Hampel y onda de Andrews observing that the contrast distribution keeps normal

Table 5
Summary of all costs

N° plant	Staff	Reagent consumption	Membrane replacement	Cartridge filters replacement	Total cost (c€/m^3)
1	5.8	0.576	1.09	0.13	7.59
2	7.3	0.516	1.36	0.13	9.30
3	8.66	0.725	1.36	0.16	10.90
4	9.52	0.492	1.36	0.17	11.54
5	15.16	0.746	1.64	0.19	17.73
6	8.66	0.696	1.36	0.15	10.86

Table 6
Tests of between-subjects effects

Dependent variable: total

Origin	Sum of squares	gl	Mean square	F	Sig.	Partial Eta squared	Parameter noncentrality	Observed power
Corrected model	59.518	4	14.879	974404949.709	0.000	1.000	3897619798.837	1.000
Intersection	3.177E-6	1	3.177E-6	208.055	0.044	0.995	208.055	0.742
Staff	2.798	1	2.798	183219673.252	0.000	1.000	183219673.252	1.000
Reagents	0.043	1	0.043	2797272.730	0.000	1.000	27,97272.730	1.000
Membranes	0.019	1	0.019	1263705.267	0.001	1.000	12,63705.267	1.000
Filters	0.001	1	0.001	32,987.014	0.004	1.000	32,987.014	1.000
Error	1.527E-8	1	1.527E-8					
Total	828.372	6						
Total corrected	59.518	5						

Table 7
Model parameters

Dependent variable: total

Parameter	B	Error típ.	t	Sig.	Confidence interval 95% lower limit	Confidence interval 95% Upper limit	Partial Eta squared	Parameter noncentrality	Observed power
Intersection	–0.017	0.001	–14.424	0.044	–0.032	–0.002	0.995	14.424	0.742
Staff	0.999	7.381E-5	13,535.866	0.000	0.998	1.000	1.000	13535.866	1.000
Reagents	0.990	0.001	1,672.505	0.000	0.983	0.998	1.000	1672.505	1.000
Membranes	1.003	0.001	1,124.146	0.001	0.992	1.014	1.000	1124.146	1.000
Filters	1.144	0.006	181.623	0.004	1.064	1.225	1.000	181.623	1.000

during the whole process, as well as the total cost. We proceeded afterward to make the factorial analysis with the Barlett y de Kaiser–Meyer–Olkin tests.

Based on all this, we analyze the possible mathematical models, with the program SPSS, version 20, we have analyzed the possible models in our investigation, stating that the cost is a unique variable which depends on the other 4 independent variables.

In Table 6 are shown the tests of between-subjects effects where you can see a number of basic results for the model calculation and in Table 7 the parameters obtained in this model, responding to a confidence interval of 95%.

$$F\,(\text{univariate}) = -0.17 + 0.999\,P + 0.990\,R + 1.003\,M + 1.144\,F$$

where the coefficients (P, R, M, and F) correspond to the values of the staff, reagent consumption, membrane replacement, and replacement cartridge filters costs.

6. Conclusions

(1) The mathematical model is a univariate model based on the total cost. It depends on four variables that match the more common cost types in SWRO desalination plants.
(2) The model of univariate had a better fitting than the weighted least squares model.
(3) The fitting of the mathematical model chosen was higher than 98.5% compared to the real data in the worst case.

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