More Efficient Production Line: Desalination Plants by Using Reverse Osmosis

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***Abstract*- The cost analysis of desalinated water cubic meter produced by reverse osmosis has been widely studied. However, the production lines capacities in these plants are normally different. Usually, a desalination plant has a number of lines with identical productions, whose summary corresponds to the total production capacity. Cost optimization of the most efficient production line affects the scale economy.**

The destination of this article is within reach of small desalination plants in the range between 500 to 15,000 m^3/day in the Canary Islands. This specified range is the most established in the islands. More than 90% of the desalination plants have a production capacity corresponding to the selected range.

The methodology used consists in calculating each one of the costs involved in the seawater desalination process, applying actual prices and obtaining a graphic serial according to prices tolerance, from -5% to a value of +5%. Concerning staff costs, it has been recovered data from the iron and steel industrial sector collective agreement of the Autonomous Community.

In this article it presents that all the elements directly affect each one of the costs, equations and formula based on factors affecting each one of them, with actual market prices in the Autonomous Community of Canary Islands, making all calculations and obtaining a family of costs graphics for each one.

As an innovative and original article, it presents the real costs for small desalination plants, for the established range. It presents a new cost, to bear in mind, according to current regulations, which is the environmental cost, based, among other things, on solving the problem of brine spills directly into the sea.

Lastly, this article, as a final result, presents the total value of the cost in €/m^3 with the results and graphics for each plant between the before established range in the Canary Islands, obtaining according to them, the most efficient production line. The results are based on a small fluctuating scale economy.

The aim of our work is to study the influence of the fouling factor and temperature according to the desired production on the cost in €/m^3. Based on it we study the operational and functional costs searching for the production line with the best efficiency. The temperature and the fouling factor are fundamental, observing that there is a saving of 0.3 €/m^3.

The most efficient production line for reverse osmosis desalination plants in the range of 500 to 15,000 m^3/day correspond to a production of 5,000 m^3/day, with a conversion factor of 45% at 21ºC of temperature and with a fouling factor of 1.

Keywords*- *Reverse Osmosis; Unit Costs; Canary Islands; Desalination; Operating Parameters

I. REVERSE OSMOSIS SEAWATER DESALINATION IN CANARY ISLANDS

Canary Islands are pioneers in desalination process in Spain. In fact, the first seawater desalination plant in Canary Islands and Spain was installed in Lanzarote in 1964. Said plant produced 2,500 m^3/day of drinking water, although it used the technological process M.S.F.

In this last decade, thanks to the development of the technology, it has made great strides and consequently, a boom never before known. Reverse osmosis technology has been greatly developed during this time. Particularly, in Canary Islands, which have served as a model for the rest of the Spanish territory, more than 95% of the desalinated water uses the reverse osmosis process as shown in Figure 1.

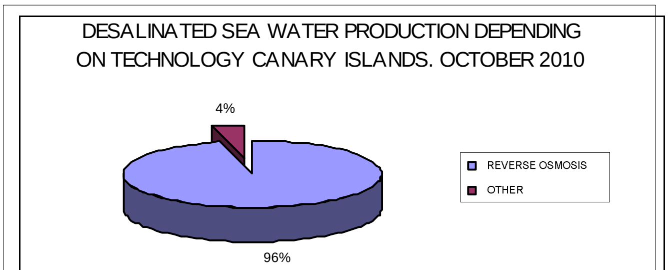

Fig. 1 Desalinated sea water production in Canary Islands [2]

II. REVERSE OSMOSIS DESALINATED WATER M^3 COST ANALYSIS

In this section it analyzes all the events happened during the last years in relationship with the reverse osmosis water desalination and the impact in the m^3 cost due to the installation design factors.

In 2001, in Spain, the Government of Aragon publishes an article stating the Desalination as an alternative to the National Hydrological Plan. In said article it is commented that, for 2010, the cost of reverse osmosis desalinated water could be around 0,36 and 0,39 €/m^3 [3].

In 2001, Andreas Poullikkas concludes an article estimating a worldwide cost of 0,44 €/m^3 [4].

Also in the same year, D. Prats Rico and M.F.Chillón reveal that the cost of the electric part can be around 0,19 – 0,22 €/m^3 [5].

In 2002, the magazine "Agriculture" presents an article by María Amparo Melián Navarro and José María Cámara Zapata about the desalination techniques and costs, stating that during 2001 the cost of reverse osmosis desalinated sea-water was around 0,42€/m^3 and 0,84 €/m^3 [6].

In 2002, the magazine Desalination, in its number 142, publishes an article by S.A. Avlomitis, with a study of the costs of reverse osmosis desalinated sea-water in small plants of the Greek Islands and 4 different else places. He reaches the conclusion that, in the best case, the cost is 0,6 \$/m^3 and refers slightly to the Canary Islands where the cost for a plant of 36,000 m^3/day is said to be around 1,62 \$/m^3 [7-10].

In 2002, the magazine Desalination publishes an article by Azza Hafez and Samir El-Manharawy in which they study an approximation to the costs of desalinated sea-water for the region of the Red Sea in Egypt. In the best case, their estimation results are in a value of 0.86 \$/m^3 [11-16].

It was during the year 2002 when costs studies are finally presented through a Doctoral Thesis done by Mr. David Martinez Vicente. In said thesis he studies the costs of desalination with reverse osmosis in big plants, from 10,000 to 14,000 m^3 of desalinated water production, considering an energy consumption of 4,4 kWh/m^3 and a cost of 4 cents€/kW. The author, based on data of different desalination plants in Spain and on his own investigation proved in his thesis shows us total costs for plants producing 10,000 m^3 around 0,5576 and 0,6276 €/m^3 depending on the source of water, (well or direct source) [17].

For the plants with productions of 140,000 m^3 of desalinated waters, the values fluctuate between 0,4095 and 0,4678 €/m^3 depending on the soured of water, (well or direct source).

In 2004, during the Water Management and Planning Iberian Congress comments talk about the cost of desalinated water in Spain near 0,53 €/m^3 [18].

In 2005, the magazine Desalination publishes an article by Wilf M. And Bartels C. in which it is shown that the boosting pumps efficiency has to be around 88%, the Pelton turbines and interchangers should be around 94% and electrical engines near 96% [19].

In November 2006, the company Acciona publishes an article by Luis Catilla, general manager of Acciona Agua, in which he presents a graphics serial related to the cost of desalination, reaching the conclusion that the costs of desalinated water are around 0,4 and 0,8 €/m^3 [20].

In 2008, the magazine Desalination publishes an article by Akili D. Khawaji, Ibrahim K. Kutubkanah and Jong-Mihn Wie talking about the advances in new technologies in sea water desalination. More specifically they comment on the improvement in the membranes production technologies and the introduction of energy recovery systems. For them, the cost of sea water desalination by reverse osmosis is around 0.53 €/m^3 [21].

Also in 2008, the same magazine publishes an article by Salah Friouri and Rabah Oumeddour in which it is stated that the cost can reach 1,81 €/m^3 in the case of the reverse osmosis technology [22].

In 2009, the magazine Desalination publishes an article by Catherine Charcosset based on a revision of the desalination process membranes using renewable energy. In said article it is commented that the reverse osmosis requires, in particular, between 3 and 10 kWh/m^3 of electrical energy for drinking water production and that the conversion factor fluctuates between 25 to 45% [23].

In the last two years, 2010 and 2011, the realized studies show a cost of 0,4 €/m^3 for big desalinating plants.

As has been analyzed, all studies carried out up to now, refer to big desalinating plants. In this paper it has studied plants within a production range from 500 to 15,000 m^3/day, which belongs to more than 90% of the reverse osmosis desalinating plants in the Canary Islands. It is important to state that the tendency in the Canary Islands of building up small-sized desalinating plants is due to the fact of the existence of many gullies in the landscape, spreading many small population areas quite far from each other.

III. COST ANALYSIS METHODOLOGY AND CALCULATION HYPOTHESIS

A. Applied Methodology

The used methodology is based on the costs distribution in fixed and variables costs. Performing a first study of these costs was observed that the influence of the total cost energy is fundamental aspect was to study, why was studied separately the energy cost compared to other costs. The variables were divided into two groups attending to the fact that they were part of the plant design conditions or part of the different combinations used in the study. First of them correspond to the pressure and salinity. The second correspond to temperature, fouling factor, percentage of conversion and the production. The Fig. 2 shows the scheme of basis for the study of the costs of seawater desalination by reverse osmosis.

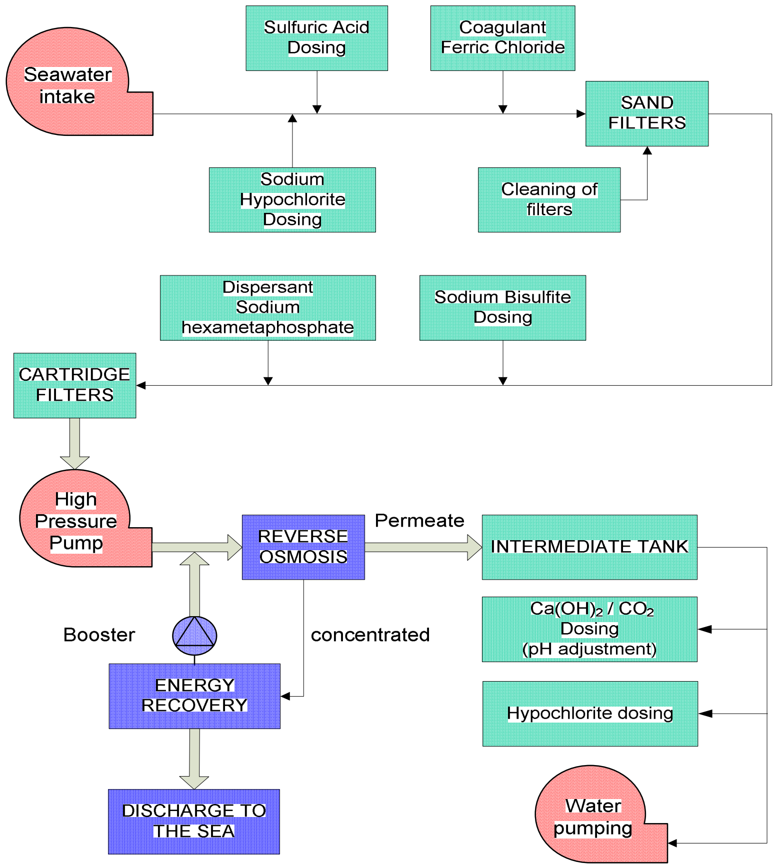

Fig. 2 Basic scheme of the desalinating plant

B. Calculation Hypothesis

As stated, the calculation hypothesis is based on two well-differentiated studies, considering their influence in the total cost per m^3. On that basis it is commented the hypothesis.

1) Energetic Cost:

From all the phases involved in energetic consumption, the reverse osmosis process is the one showing a bigger consumption. For the calculation of the high pressure pump and the boost pump and both consumptions, it has used two software programs, ROSA [24] and Excel spreadsheet of the manufacturer ERI-PX.

With the help of the software program ROSA it was obtained the results for pressure, salinity, energetic consumption without ERI, etc, which will allow us to define the right point for each production.

The different alternatives studied affect the fouling factor value (0.85 – 1), the temperature (19 ºC, 20 ºC or 21ºC), the conversion factor (42% or 45%) and the production (500, 1,000, 2,000, 5,000, 7,500, 10,000, 12,000 or 15,000 m^3/day)

It was obtained an average of 20 different options depending on the quantity of membranes per each combination, throwing a result of 1920 different options in the work.

For each of the 96 combinations it obtained the following results showed in the figures of salinity TDS and pressure against energetic consumption as shown in Figs. 3 and 4, not introducing and introducing the energy recovery system, which shows a total of 192 graphics. As an example, it presents two types of graphics for a better explanation of it.

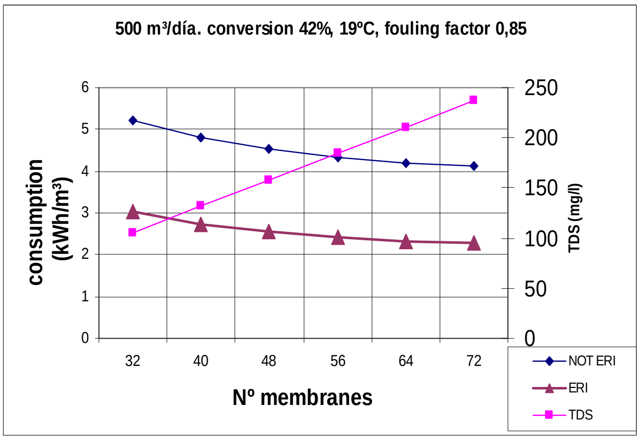

Fig. 3 Energetic consumption against TDS

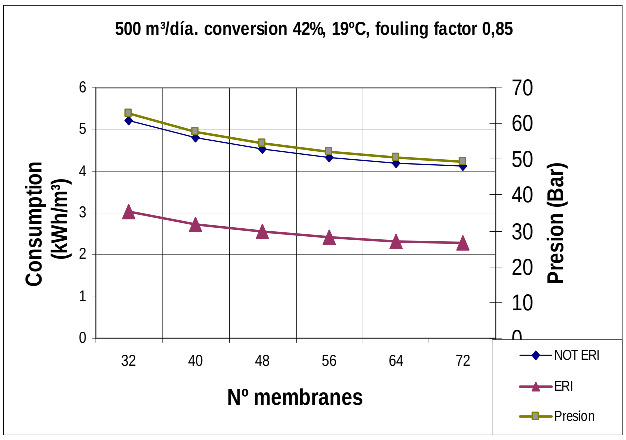

Fig. 4 Energetic consumption against pressure

For each of the different options, which correspond to a specified number of elements or membranes, it has been introduced in each case an energy recovery system adopting a value of 80% of the output of all the machinery.

2) Rest of Costs:

Costs affecting this section are amortization, reagents consumption, cartridge filters replacement, membranes replacement, staff, maintenance and environmental costs.

For said costs, hypothesis is based on calculating each one of the costs for each one of the combinations shown in Table 4.

For each one of said combinations the total costs have been studied so that it is possible to obtain throughout this investigation the most efficient production line.

C. Costs Description

1) Investment Cost/Amortization:

To start the study of the investment cost, the cost of the process is split in 10 sections corresponding to 6 stages of the desalination process, a section of various components, a section of electrical installation, a section for pumping water to consumers and a section on permissions, land acquisition and civil works. All these phases include the calculations of all the of pumps, canalizations, tanks, pressure groups, filters, high pressure group, membranes, energy recovery system, as well as a small amount of components such as different gauges for measuring flow, pressure and temperature.

All equipments, strictly calculated in this section, meet the requirements and performances of pressure, salinity, flow, temperature, conversion and flor factor based on the different combinations made in this study.

Once it has obtained the total investment cost for each of the combinations, the cost of depreciation has been studied, assuming an interest rate of 4.5% and 15 years amortization period, according to the banks in the Community Canary Islands.

2) Reagents Consumption Cost:

The methodology used to calculate the cost of reagents, for the pre-treatment and the post-treatment, is based on an initial calculation of the average dosage and price per kilo of each reagent, actualized to January 2012, and on a second calculation to obtain the needed quantity of each product and, finally, it is performed an initial analysis of the cost in €/m^3. Table 1 shows the average dosage in mg/l of each chemical reagent and its price in €/kg.

TABLE 1 REAGENTS DOSAGES

Chemical reagents in pre-treatment	mg/l	Aver.Value mg/l	Price €/kg
Sulfuric acid (H_2SO_4)	20 a 30	25	0,13
Ferric chloride – Coagulant (Cl_3Fe)	3 a 7	5	0,24
Sodium hipochlorite (NaOCl)	2 a 6	4	0,19
Sodium bisulfite ($NaHSO_3$)	2 a 7	4,5	0,6
Sodium Hexa meta phosphate - disperser ($(NaPO_3)_6$)	3 a 6	4,5	0,45
Chemical reagents in post-treatment	mg/l	Valor medio mg/l	Precio €/kg
Sodium hipochlorite (NaOCl)	0,4 a 0,6	0,5	0,19
Carbon dioxide (CO_2)	30 a 40	35	0,14
Lime $Ca(OH)_2$	22 a 42	32	0,05

Based on the above, it calculates the amount of chemicals needed per year and it calculates the cost of each of the chemical reagents per m^3 and the total of each of the combinations caudal – conversion factor.

3) Cartridge Filters Replacement Cost

Once defined the flow Q to work with, it was defined the normal operating flow, design factor given by the cartridge model (for each simple cartridge of 250 mm corresponds 10 l/min), which corresponds to 0.6 m^3/h.

For this work a cartridge filter to be divided in 5 simple cartridges is considered. The main cartridge is 1250 mm long incorporating 5 simple cartridges of 250 mm, each.

Base on it, it calculates the number of cartridges of 1250 mm and therefore the replacement cost of cartridge filters.

4) Membranes Replacement Cost:

For the realization of this work has been chosen DOW membrane manufacturer, who supplies membranes under the trade mark FILMTEC, type SW30HR LE-400, of aromatic polyamide, with spiral winding configuration and with a nominal production flow of 28 m^3/day.

To calculate this cost, in all cases a yearly membranes replacement percentage of 7% has been estimated, according to the manufacturer.

5) Staff Cost:

The staff needed for the maintenance of a reverse osmosis desalination plant depends clearly on its daily production and on its automation degree. This paper assumes that the desalination plant is not automated.

Notwithstanding the foregoing, the minimum number of staff needed by the plant is estimated to be addressed throughout the year, 365 days a year, 24 hours a day. It is important to note in this section, although it has been estimated that the plant operates for 356 days a year, the staff is working although the plant is stopped in these nine days.

The minimum needed staff can be calculated by two different systems, choosing the less favorable, complying with the "Iron and Steel Collective Agreement of the Province of Las Palmas" of the regional Employment, Industry and Commerce Ministry, signed in the Province of Las Palmas on June, the 26th, 2009 [25].

Based on the calculations performed in this paper, it can be concluded that a desalination plant needs a minimum of 7 employees to be addressed throughout the year, for a production of 500 m^3/day.

The seventh employee is the one responsible to cover during the whole year round the holidays of the other employees.

6) Maintenance Cost:

For the cost of the maintenance of the whole desalination plant it has used the Manual for Implementation of Treatment Systems in small towns, written jointly by CENTA and CEDEX [26], from which it has taken the necessary data, as well as on the estimated values of the average life of each item and the percentage of deterioration based on the initial investment. The basic table with the necessary data to elaborate the maintenance cost is shown in Table 2.

TABLE 2 AVERAGE LIFE OF ITEMS

Item	Average life (years)	(%) Annual Inversion
Recipients and Tanks	25	0.8
Rotary mechanical equipments	17	4.3
Machines driving equipments	25	1.5
Instrumentation	25	4.5
Pipes, valves and accessories	25	3.0
Centrifugal pumps	17	4.2
Electricity	25	4.3
Civil work (construction)	75	0.3

Based on the table above and knowing that the operating limit that has been adopted in the desalination plant is 15 years, these coefficients were applied to each of the investment items which are affected by the maintenance.

7) Environmental Cost:

The environmental cost is a type of cost, as a result of the environmental impact generated by the desalination plants into the sea. As is well known, the rejected water (brine) is thrown away into the sea. It is our intention for this work to calculate this cost, theoretically new, and based on reducing the environmental impact generated in the sea by the dumping of the desalination plants.

Said cost is based on mixing the brine with sea water with the help of the corresponding pipe line and pump, in sending said mixture back to the sea and with similar characteristics as the sea water, in controlling to avoid any suspension particles and to keep an adequate pH.

In order to realize it, we shall need a sea water pipe, a sea water boost pump to the brine pipei, a decantation tank, a pH meter for the water to be pumped back into the sea and the mixed water expulsion pipe.

As a design factor, it is noted that the boost speed can be between the range of 0.4 to 1.2 m/s, although it is recommended to keep a speed of 1 m/s in order to guarantee the right functioning of the design. This value has been taken into consideration in all calculations of the present article.

To control the chemical reagents and the floating particles on the brine it is recommended to use, as mentioned before, a pH meter and a decanter for said floating particles.

8) Energetic Consumption Cost:

To end with the costs analysis involved in the reverse osmosis desalination plants, the cost of the energy consumption is studied, which is the most influential parameter in the total cost.

From the moment the water is pumped off the sea into the plant up to the moment the consumer receives it at home, the energetic consumption is involved in different phases, to be described further on.

Each of said phases is represented by the necessary generated power in kW and by the generated consumption in kWh/m^3.

The studied phases correspond to the boost pump, the reverse osmosis process, the intermediate processes of the plant, the environmental cost and the boost for consumers.

Having data from the power to hire, called term power and total consumption, which is what we call from now energy term is necessary to provide conditions rates peak periods (P1), plain (P2) and valley (P3), corresponding to the terms of power and energy (see Table 3)

TABLE 3 POWER AND ENERGY TERMS PRICES IN AT [27]

	Tariff Period 1	**Tariff Period 2**	**Tariff Period 3**
Tp €/kWh año	24.493015	15.104184	3.463562
Te en DH3 €/kWh	0.134025	0.116987	0.081679

After this, the energy cost calculation, based on the above said terms, will be the summary of the power term, energy term, electricity tax, measure equipment hiring cost, local tax I.G.I.C. 3% (reduced) and the local tax I.G.I.C. 7% which only affects the measure equipment.

IV. APPLIED METHODOLOGY AND CALCULATIONS FOR A MATHEMATICAL SIMULATION

A. Applied Methodology

To conclude the investigation of this paper, the obtained results are studied so that the mathematical model which will define our investigation can be found. Data are represented graphically. Therefore, the program SPSS version 20 [28] is used, which is a software tool to represent statistical functions. For each cost the results in a bar diagram, dispersión diagram and box and mustache diagram are represented, obtaining some data which are important for the study and for posible elimination of certain values.

To study the possible values that can be anomalous for our model, in addition to the information obtained above, there are some graphics for each cost control to ensure that those values will be removed from study.

As a result of the material studied in the previous sections, the three most representative types of costs (depreciation, personnel and energy) were selected at a rate that ranges from 5000 to 15000 m^3/day.

To said costs, previously defined as Fundamentals, we make the Kolmogórov-Smirnovy 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 during the whole process, as well as the total cost. Below factor analysis was performed with the Bartlett test and the Kaiser-Meyer-Olkin. After this, we analyzed the possible mathematical models.

B. Calculations for the Mathematical Model

Once reached this point, using SPSS version 20, possible models within our research were discussed, on the basis that the total cost is a variable dependent on 8 other independent variables. So based on the comments the mathematical model corresponds to a univariate model had to study, describe, calculate and define.

C. Analysis of the 'Uni-variable' Model

TABLE 4 TESTS OF BETWEEN-SUBJECTS EFFECTS

Depending variable : totals

Origin	Sum of squares	gl	Mean Square	F	Sig.
Corrected model	17491,744[a]	8	2186,468	161571,620	,000
Intersection	,003	1	,003	,245	,636
Amortization	,009	1	,009	,642	,449
Reagents	,001	1	,001	,096	,766
Filtres	,027	1	,027	2,004	,200
Membranes	,016	1	,016	1,174	,314
Staff	9,482	1	9,482	700,717	,000
Maintenance	,088	1	,088	6,535	,038
Environmental	,097	1	,097	7,161	,032
Energetic	,071	1	,071	5,248	,056
Error	,095	7	,014		
Total	**140335,079**	**16**			
Total corrected	**17491,838**	**15**			

TABLE 5 GRAND AVERAGE

Dependent variable: total

Mean	Error típ.	confidence interval 95%	
		lower limit	Upper limit
87,623[a]	,029	87,554	87,691

TABLE 6 TEST OF INTERSUBJECT EFFETCS

Dependent variable: total

Origin	Sum of squares	gl	Mean Square	F	Sig.	Partial Eta squared	Parameter noncentrality	Observed power[b]
Corrected model	17491,744[a]	8	2186,468	161571,620	,000	1,000	1292572,963	1,000
Intersection	,003	1	,003	,245	,636	,034	,245	,072
Amortization	,009	1	,009	,642	,449	,084	,642	,107
Reagents	,001	1	,001	,096	,766	,013	,096	,058
Filtres	,027	1	,027	2,004	,200	,223	2,004	,232
Membranes	,016	1	,016	1,174	,314	,144	1,174	,156
Staff	9,482	1	9,482	700,717	,000	,990	700,717	1,000
Maintenance	,088	1	,088	6,535	,038	,483	6,535	,595
Environmental	,097	1	,097	7,161	,032	,506	7,161	,634
Energetic	,071	1	,071	5,248	,056	,428	5,248	,506
Error	,095	7	,014					
Total	**140335,079**	**16**						
Total corrected	**17491,838**	**15**						

TABLE 7 PARAMETERS ESTIMATIONS

Dependent variable: total

Parameter	B	Error típ.	t	Sig.	confidence interval 95%		Partial Eta squared	Parameter noncentrality	Observed power[b]
					lower limit	lower limit			
Intersection	10,613	21,442	,495	,636	-40,091	61,316	,034	,495	,072
Amortization	,317	,395	,801	,449	-,618	1,252	,084	,801	,107
Reagents	,715	1,971	-,309	,766	-5,271	4,051	,013	,309	,058
Filtres	20,886	14,754	1,416	,200	-14,001	55,773	,223	1,416	,232
Membranes	,674	,622	1,084	,314	-,797	2,146	,144	1,084	,156
Staff	,962	,036	26,471	,000	,876	1,048	,990	26,471	1,000
Maintenance	,890	,866	2,556	,038	,166	4,263	,483	2,556	,595
Environmental	1,427	,533	2,676	,032	,166	2,688	,506	2,676	,634
Energetic	,825	,360	2,291	,056	-,027	1,676	,428	2,291	,506

TABLE 8 TESTS FOR ADJUSTMENTS FAULTS

Dependent variable: total

Origin	Sum of squares	gl	Mean Square	F	Sig.	Partial Eta squared	Parameter non centrality	Observed power[b]
Adjustement fault	,095	7	,014	.	.	1,000	.	.
Pure error	,000	0	.					

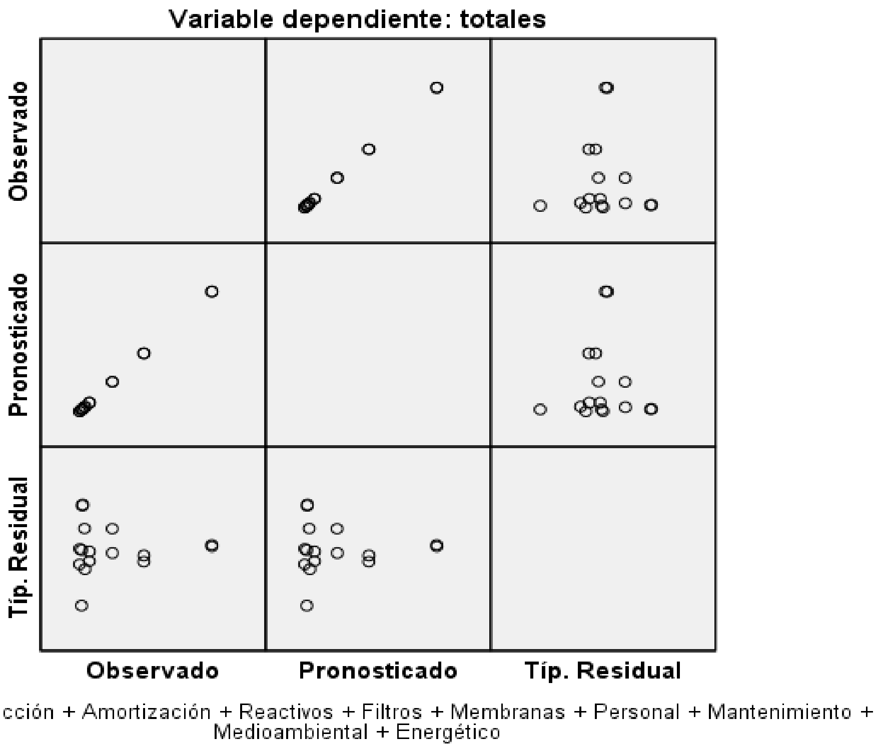

Fig. 5 Dependent variables: Observed, predicted and residual

V. RESULTS

As a result, the work done first presents the graphs obtained in the study. At first basic energy costs were obtained, without introducing taxes on the Canary Islands, for temperatures of 19, 20 and 21ºC and the fouling factor of 0.85 and 1. Figures 6 and 7 represent a conversion factor of 42% and 45%.

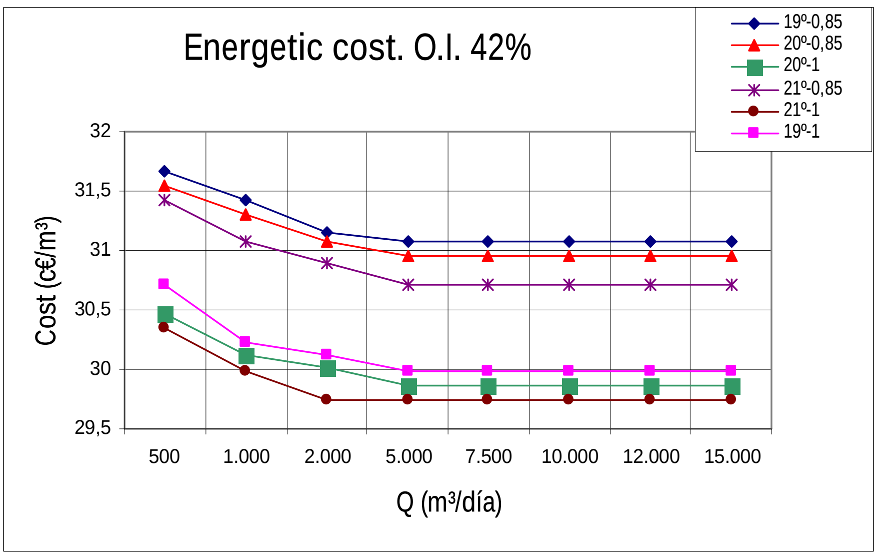

Fig. 6 Energetic cost influenced by temperature and fouling factor 42%

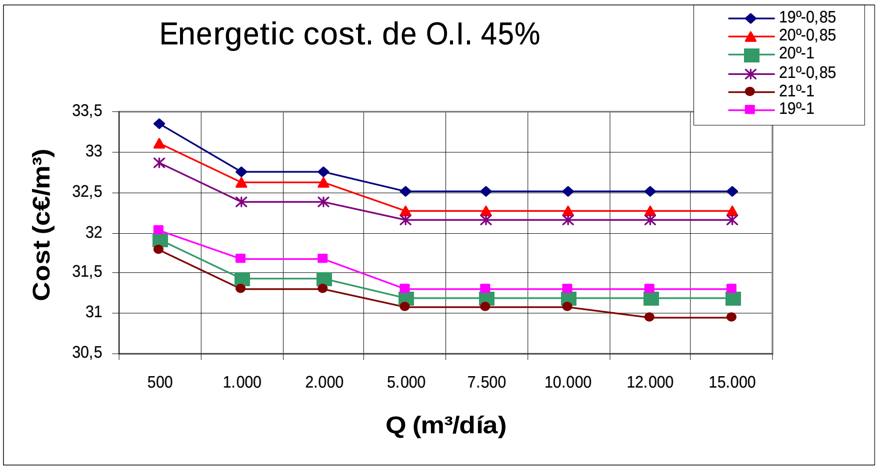

Fig. 7 Energetic cost influenced by temperature and fouling factor 45%

In these second figures the values are obtained for the rest of the costs for the same conversión factors.

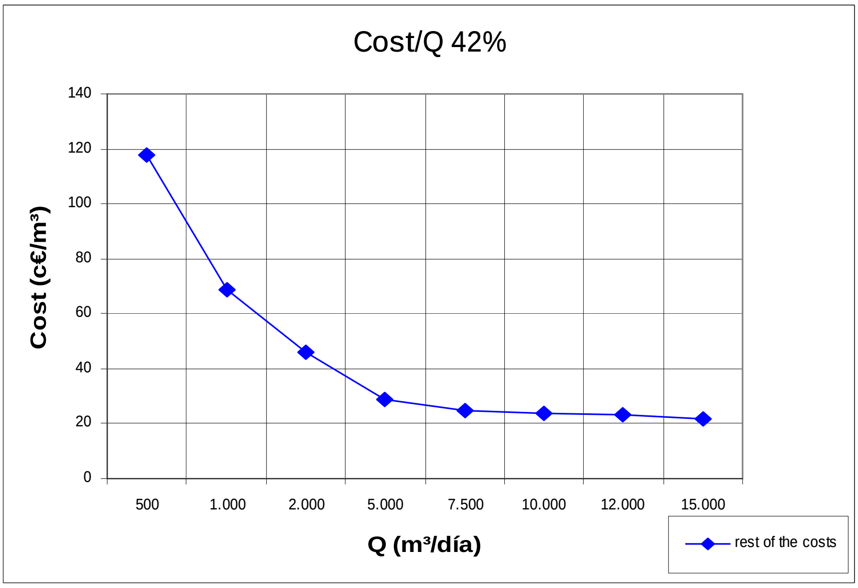

Fig. 8 Different costs for conversion factor of 42%

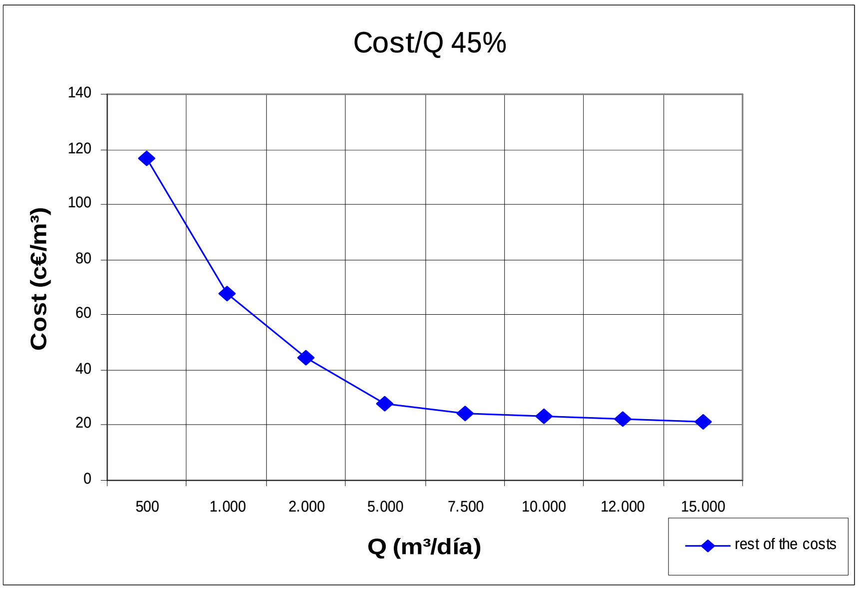

Fig. 9 Different costs for conversion factor of 45%

The Figure 10 presents the total cost results, for a conversion factor of 42 and 45%.

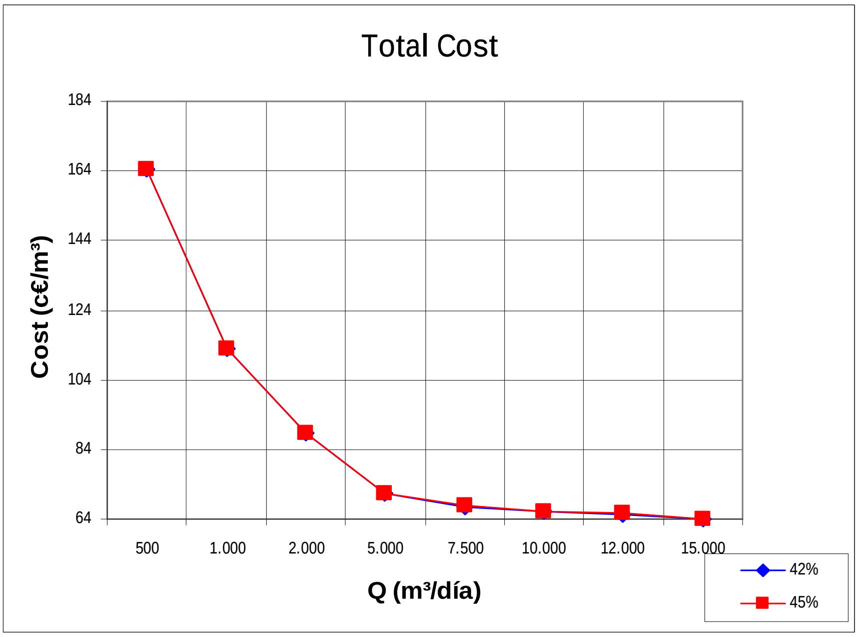

Fig. 10 Total cost results

Secondly present as a result of this work, the expression that defines the mathematical model and that is:

Cost Function= 10,613 + 0,317A + 0,715R + 20,886F + 0,674M+ 0,962P + 0,890MO + 1,427MA + 0,825E

Where, the coefficients correspond to amortization values, reagents consumption, filtres replacement, membrans replacement, staff, maintenance, environmental and energetic consumption.

VI. CONCLUSIONS

1) The figures show that there is a stabilization in the energetic consumption after a production of 5,000 m^3/day and that best values correspond to a temperature of 21ºC with a fouling factor of 1.

2) As a result of the figures, it can be observed that the value of the different costs begin to stabilize for a flow of 5000 m^3/day and that differences based on conversion factor are minimal.

3) The temperature and the fouling factor are fundamental, observing that there is a saving of 0.3 €/m^3.

4) In the figures, in the initial study, the values up to 2000 m^3/day were high due to the amortization of the initial capital and staff cost. There arises the need for these plants with the initial capital investment support as well as the automation of the plant in order to reduce the staff costs.

5) The most efficient production line for reverse osmosis desalination plants in the range of 500 to 15,000 m^3/day correspond to a production of 5,000 m^3/day, with a conversion factor of 45% at 21ºC of temperature and with a fouling factor of 1.

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