TWO FULL SCALE DESALINATION PLANTS OPERATING SIDE-BY-SIDE: RESULTS & COMPARISON OF CONVENTIONAL VS NEW TECHNOLOGY

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Abstract

This paper shows the results of two desalination plants operating side-by-side, with a comparison between different aspects of the two systems. One of the desalination plants (Plant #1) consists of a conventional treatment, and the second and youngest plant (Plant #2) of new technologies for the production of demineralized water with less than 0,1 microS/cm, used to reduce NOx in a power generating turbine and for steam production for cogeneration. Both plants operated simultaneously therefore results and the comparison, are more reliable.

The comparison is focused on the pretreatment, the energy recovery devices and the polishing stage. The aspects included in the comparison are the operating cost (with a higher focus in energy consumption and chemical cleaning), as well as other aspects more difficult to quantify, such as availability of the system, robustness, and manpower.

The overall operating cost of the new plant was reduced by approximately 45%, mainly associated to a reduction on power consumption due to higher efficiency of the new Energy Recovery device. The frequency of the RO membrane chemical cleaning and replacement was drastically reduced: no chemical cleaning of the SWRO has been done after 20 months of operation, and no membranes have been replaced or are planned to be replaced in the near future. When compared to the cleaning frequency of the old plant (once / twice a month), the result is not only higher availability of the equipment for the production of DEMI water, but also a significant reduction in the cost of chemicals used for the cleaning. Finally, an important improvement of Plant #2 is associated to the selection of a second step of RO and CEDI as polishing stages, with lack of regeneration that translates into important savings as well as a simpler operation.

I. INTRODUCTION

The facility analyzed in this paper, Gas Atacama, operates a combined cycle thermal power plant in Mejillones, Chile, with an installed capacity of 780 MW. The plant uses seawater (SW) as the unique source of water and SW desalination through reverse osmosis (SWRO) is the primary technology used.

The purpose of this paper is to compare and analyze two SWRO plants, with their corresponding pre- and post-treatment, which are installed and have operated simultaneously. Each one of the two plants uses different technologies, so a comparison is made between them, including different aspects, mainly divided in: pretreatment, energy consumption and post-treatment.

1.1 General Background

The existing water intake was an Open intake, and seawater was used mainly for refrigeration, without any treatment. The flow of water used for this application was much greater than the flow of water needed to feed the desalination plant, and because of that, there was no need or advantage in changing the intake to a beach well.

Even when the plant produces electrical power, the cost associated to energy consumption is a key issue in the country, due to the high cost of electricity [1].

The feed water is characterized by seasonal variations in turbidity: during autumn and winter ranges from 1 to 5 NTU; during spring and summer it ranges from 3 to 35 NTU.

Water temperature ranges widely from 11 to 22 °C, resulting in a significant variation in RO operating pressure between winter and summer. It also affects the microbiological conditions of seawater: another important issue is the occasional presence of red ties, which are known to be a challenge for SWRO, responsible for causing bio-fouling on the RO membrane surface, requiring frequent chemical cleaning. They occur 1 to 3 times per year with a duration of up to a week.

1.2 Desalination Plants

The two plants are briefly described in this section.

1.2.1 – Plant # 1

Installed in 1995, it produces 50 m^3/h (0,3 MGD) of demineralized water reaching a conductivity of less than 0,1 microS/cm.

Main stages are:

- Conventional pre-treatment by Dissolved Air Flotation (DAF)
- Pressurized depth filters
- Seawater Reverse Osmosis (SWRO)
- Cation exchanger
- Degasifier
- Anion exchanger
- Mix Bed.

The energy recovery device is a Pelton Turbine.

1.2.2 – Plant # 2

Installed in 2010, it produces 108 m^3/h (0,7 MGD) of demineralized water reaching a conductivity of less than 0,1 microS/cm.

Main stages are:
- Ultrafiltration (UF)
- Seawater Reverse Osmosis (SWRO)
- Brackish Water Reverse Osmosis (BWRO)
- Continuous Electrodeionization (CEDI)

The energy recovery device is an ERI Pressure Exchanger.

1.2.3 – Summary of the plants

Table 1: Plants #1 and #2 summary

	Plant #1	Plant # 2
Raw Water	Seawater from the Pacific Ocean. TDS: 33000 mg/l, Turbidity: 10 NTU, SDI_5 : > 18 (or not measurable) Temperature: 11-22°C. Water Intake (existing): Open intake; 5 meters below medium sea level, and 3 meters above the ocean floor.	
Treated Water	Conductivity: 0,1 microS/cm	
Flow (seawater)	~130 m^3/h (0,8 MGD)	300 m^3/h (1,9 MGD)
Flow (Treated Water)	50 m^3/h (0,3 MGD)	108 m^3/h (0,7 MGD)
Pre-treatment	DAF Depth Filters Cartridge Filter	Self-cleaning Filter Ultrafiltration Cartridge Filter
Treatment	SWRO	SWRO
Post-treatment & Polishing Stage	Ion Exchange (IX) Mix Bed	BWRO CEDI

II. OPERATIONAL DATA

2.1.1 – Operational data of the Plants

The following data was provided by the end user of the plants and it includes all the values used for the comparison.

Table 2: Operational data from Plant #1

Plant #1	
RO Membrane replacement frequency	12% @ 18 months 20% @ 36 months (3 years) 33% @ 48 months (4 years) 100% @ 60 months (5 years) **TOTAL @ 5 years = 165%**
RO Chemical Cleaning	Once a month (winter) Once/twice a month (summer)
Energy Consumption	8 – 9 KWh/m^3 (for the complete plant)
Coagulant dose	25 ppm (used in the DAF)
5-micron cartridge filter replacement frequency	Once/twice a month (winter) Every 4 days (summer)
Pre-treatment footprint	12 x 25 m

Table 3: Operational data from Plant #2

Plant #1	
RO Membrane replacement frequency	None @ 20 months operation
RO Chemical Cleaning	None @ 20 months operation
Energy Consumption	5,4 KWh/m^3 (for the complete plant)
Coagulant dose	2 ppm (used in the UF)
5-micron cartridge filter replacement frequency	None @ 20 months operation
Pre-treatment footprint	12 x 20 m

2.1.2 – Operational cost calculation

Besides from the operational data collected from the client, other information was gather for the calculation, especially the equipment's design data (number of membranes, volume of resin, regeneration frequency, etc.). Were no data was available, conservative assumptions were made in order to compare the data.

Calculation includes the most important items that contribute to the operational cost, which are shown below [2,3]. The operational cost is expressed as $ (US dollars) per cubic meter of DEMI water.

Table 4: Operational cost calculation for Plant #1

TOTAL OPERATIONAL COST PLANT #1	**2,51**	**$/m³**	**NOTES**
SWRO MEMBRANES			
Quantity	211		According to planning stated in Table 2.
Price	850	$	
Duration	60	month	Planning period
Permeate volume	2160000	m^3	Considering 50 m^3/h of DEMI water

Cost	**0,083**	**$/m^3$**	
CARTRIDGE FILTERS			
Quantity	1944		According to Data from Table 2.
Price	20	$	
Duration	1	year	
Permeate volume	438000	m^3	Considering 50 m^3/h of DEMI water
Cost	**0,0888**	**$/m^3$**	
RO CHEMICAL CLEANING			
Quantity	18	annual	
Price	5000	$	Chemical cost
Permeate volume	438000	m^3	Considering 50 m^3/h of DEMI water
Cost	**0,205**	**$/m^3$**	
POWER			
Power consumption	8,5	KW.h/m^3	According to Data from Table 2.
Cost of electricity	0,18	$/KW.h	Market price in Chile
Cost	**1,530**	**$/m^3$**	
Coagulant (DAF)			
Dose	25	g/m^3	According to Data from Table 2.
Cost $FeCl_3$	0,001	$/g	
Recovery	45%		Includes SWRO and IX.
Cost	**0,055**	**$/m3**	
ANTISCALANT in OR			
Dose	5	g/m^3	
Cost	0,0075	$/g	
Recovery	43%		
Cost	**0,088**	**$/m^3$**	
CATION REGENERATION (H_2SO_4)			
Cationic resin volume	1755	liters	
Cost H2SO4 (98%)	0,22	$/kg	
Consumption	165	gr/l resin	
Run period	24	h	
Flow	50	m^3/h	Considering 50 m^3/h of DEMI water
Cost	**0,054**	**$/m^3$**	
ANION REGENERATION (NaOH)			
Anionic resin volume	2977	liters	
Cost NaOH (50%)	0,47	$/kg	
Consumption	170	g/l resin	
Run period	24	h	
Flow	50	m^3/h	Considering 50 m^3/h of DEMI water
Cost	**0,396**	**$/m^3$**	
MIX BED REGENERATION (H_2SO_4)			
Cationic resin volume	448	liters	
Cost H_2SO_4 (98%)	0,22	$/kg	
Consumption	165	g/l resin	
Run period	336	h	14 days

Flow	50	m^3/h	Considering 50 m^3/h of DEMI water
Cost	**0,001**	**$/m³**	
MIX BED REGENERATION (NaOH)			
Anionic resin volume	448	liters	
Cost NaOH (50%)	0,47	$/kg	
Consumption	170	gr/l resin	
Run period	336	h	14 days
Flow	50	m^3/h	Considering 50 m^3/h of DEMI water
Cost	**0,004**	**$/m³**	

Table 5: Operational cost calculation for Plant #2

TOTAL OPERATIONAL COST PLANT #2	**1,34**	**$/m³**	**NOTES**
UF MEMBRANES			
Quantity	144		
Price	2500	$	
Duration	5	years	
Permeate volume	4730400	m^3	Considering 108 m^3/h of DEMI water
Cost	**0,076**	**$/m³**	
SWRO MEMBRANES			
Quantity	240		
Price	850	$	
Duration	3	years	
Permeate volume	2838240	m^3	Considering 108 m^3/h of DEMI water
Cost	**0,072**	**$/m³**	
BWRO MEMBRANES			
Quantity	96		
Price	650	$	
Duration	5	years	
Permeate volume	4730400	m^3	Considering 108 m^3/h of DEMI water
Cost	**0,013**	**$/m³**	
CEDI MODULES			
Quantity	9		
Price	21000	$	
Duration	5	years	
Permeate volume	4730400	m^3	Considering 108 m^3/h of DEMI water
Cost	**0,040**	**$/m³**	
CARTRIDGE FILTERS			
Quantity	66		Considering 1 change @ 24 months
Price	20	$	
Duration	24	month	
Permeate volume	1866240	m^3	Considering 108 m^3/h of DEMI water
Cost	**0,0007**	**$/m³**	
RO CHEMICAL CLEANING			
Period	20	month	
Price	10000	$	Chemical cost

Permeate volume	1555200	m^3	Considering 108 m^3/h of DEMI water
Cost	**0,006**	**$/m^3$**	
POWER			
Power consumption	5,4	KW.h/m^3	According to Data from Table 3.
Cost of electricity	0,18	$/KW.h	Market price in Chile
Cost	**0,972**	**$/m^3$**	
Coagulant (UF)			
Dose	2	g/m^3	According to Data from Table 3.
Cost $FeCl_3$	0,001	$/g	
Recovery	38%		Includes UF, SWRO, BWRO and CEDI
Cost	**0,005**	**$/m^3$**	
NaOCl (ULTRAFILTRATED WATER)			(solution 150 g/l)
Dose	3	g/m^3	
Cost NaOCl	0,001	$/g	
Recovery	38%		Includes UF, SWRO, BWRO and CEDI
Cost	**0,003**	**$/m^3$**	
NaOCl (CEB)			
Dose	7	l/day	
Stock solution concentration	150	g/l	
Dose	1050	g/day	
Daily volume	6816	m^3	
Cost NaOCl	0,001	$/g	
Recovery	38%		Includes UF, SWRO, BWRO and CEDI
Cost	**0,0004**	**$/m^3$**	
H_2SO_4 (CEB)			
Dose	9,97	l/day	
Stock solution concentration	1800	g/l	
Dose	17946	g/day	
Daily volume	6816	m^3	
Cost H_2SO_4 (98%)	0,0022	$/g	
Recovery	38%		Includes UF, SWRO, BWRO and CEDI
Cost	**0,015**	**$/m^3$**	
NaOH (CEB)			
Dose	12,0	l/day	
Stock solution concentration	1022	g/l	
Dose	12250	g/day	
Daily volume	6816	m^3	
Cost NaOH (50%)	0,0047	$/g	
Recovery	38%		Includes UF, SWRO, BWRO and CEDI
Cost	**0,022**	**$/m^3$**	
ANTISCALANT in OR			
Dose	5	g/m^3	
Cost	0,0075	$/g	
Recovery	43%		Includes SWRO, BWRO and CEDI
Cost	**0,088**	**$/m^3$**	
MBSS in OR			
Dose	9	g/m^3	
Cost MBSS	0,0014	$/g	

Recovery	43%		Includes SWRO, BWRO and CEDI
Cost	**0,029**	**$/m^3**	

III. RESULTS AND ANALISIS

In this section the results of the comparison are analyzed. Figures 1 and 2 show the overall operational cost of each plant, as well as the percentage of each group of costs.

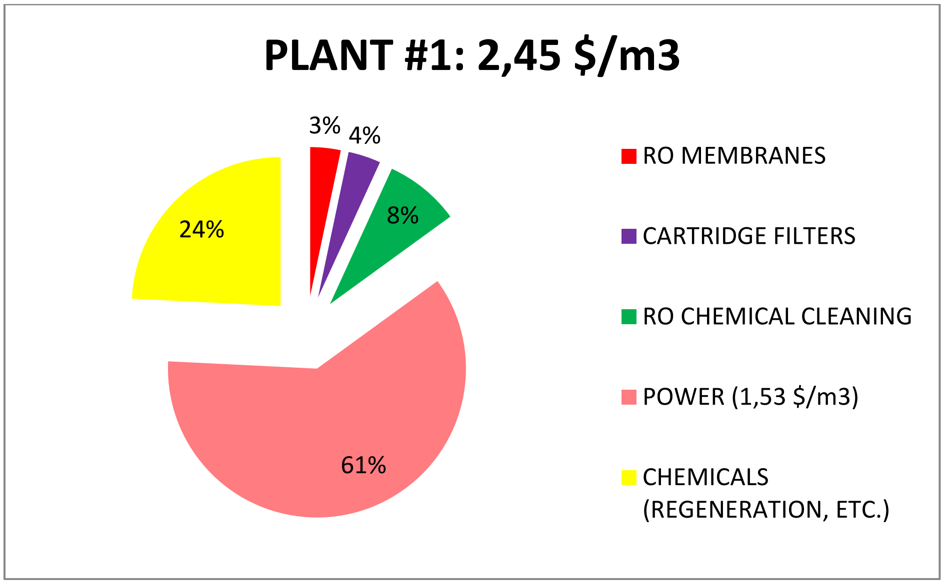

Figure 1 – Operational cost of Plant#1

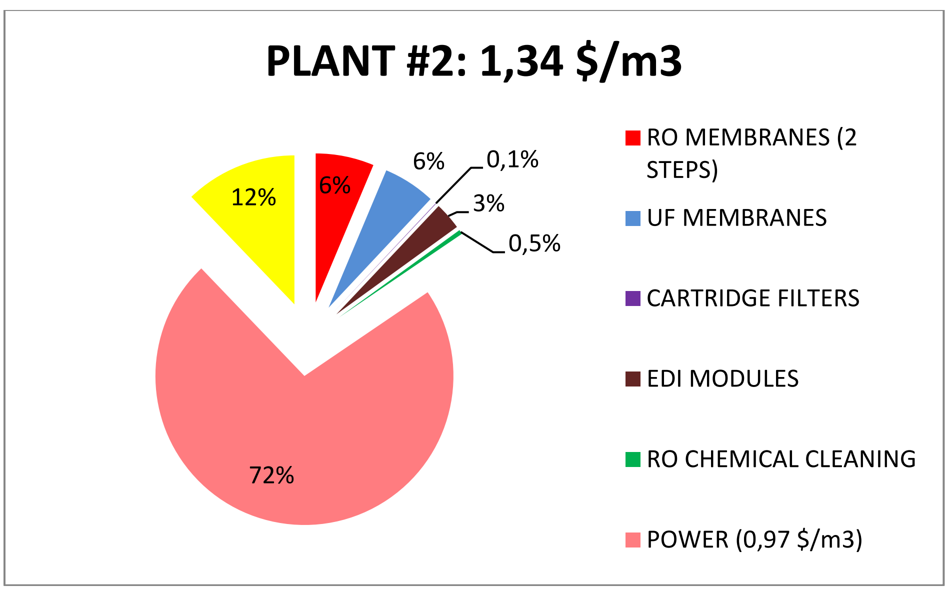

Figure 2 – Operational cost of Plant#2

3.1 Pre-treatment

The first aspect to be analyzed is the pre-treatment stage: the conventional pre-treatment compared to the Ultrafiltration stage. The main advantage of the UF is that since it is a barrier for suspended solids and turbidity, the treated water quality is independent of the raw water quality. The result is that, even when raw water quality fluctuates during the different seasons, treated water quality is much better than with conventional pre-treatment, which is shown in the SDI measurement of treated water.

Figure 3 shows the membranes used for the measurement of the SDI of Raw water [4], and figure 4 of ultrafiltrated water. Although not available, the SDI of the water treated with Plant #1 its implied to be higher than that of UF water (maintained 100% of the time below 3). This is assumed after analyzing the high replacement frequency of cartridge filters for Plant #1, as well as the number of chemical cleaning needed for the SWRO, which suggest a non-effective pre-treatment.

Figure 3 – Raw water SDI

Figure 4 – Ultrafiltrated water SDI

3.1.1 – Chemical cleaning of the SWRO membranes.

It was significantly reduced from once or twice a month, to none in 20 months. On the operational costs, one chemical cleaning every 20 months is considered for calculation, taking into account that that period has been reached already, but it should be considered as a conservative value, since the SWRO doesn't suggest that a cleaning might be required (no raise in operating pressure or reduction in water quality). This reduction equals to a 96% reduction in costs of chemicals for membrane cleaning.

3.1.2 – SWRO membrane replacement.

Since no chemical cleaning was performed, the SWRO membranes had not suffer from any degradation, so they are not expected to be replaced in the short-future. The 3 year period established for changing the whole set of membrane is even very conservative, since it's only 14% higher than scheduled for Plant #1, with poorer water quality. It is expected to last much longer and to provide a significant reduction in operating cost. As shown in Figure 1, the cost associated to SWRO membrane replacement for plant #1 is approximately 3% of the total operational cost (5% for Plant #2).

3.1.3 – Cartridge filters replacement.

Although it is not significant in the overall operational cost of either one of the plants (between 0,1% and 4%), the cartridge filter replacement was dramatically reduced. Actually, the 5-micron filters, prior to the SWRO of Plant #2, has not been changed since start-up, 20 months ago. As it was is expected, the 30 nm pore of the UF membrane removed virtually all solids, and the cartridge filters (that were installed as a final barrier in case solids would be present in the intermediate tank located between the UF and the SWRO) had shown no pressure drop, and therefore had not been changed.

As mentioned, the most significant improvement hasn't been the operational cost reduction, but the effect in manpower and availability. The time invested in filter replacement, as well as the manpower dedicated to that work, was virtually eliminated, which translates into a higher availability of the equipment, that is almost 100% of the time ready to produce water.

3.1.4 – Pre-treatment footprint.

Although not critical in this location, the footprint of the system was reduced by half, since both Plants occupy almost the same area, with Plant #2 producing twice as much water as Plant #1. This aspect is more significant with higher capacity, since modularity of the UF allows for a more efficient use of the space than conventional pre-treatment.

3.1.5 – Chemical consumption.

Observing the chemical consumption of the pre-treatment alone, it shows a reduction on the cost of chemical, mainly due to the reduction of the coagulant dose required for the suspended solids removal: the dose was reduced from 25 ppm at the DAF to 2 ppm at the UF. That reduction itself would account for a 92% reduction in net cost, but the use of chemicals for UF membrane cleaning is also considered, of course, and altogether translates into a 30% reduction in pre-treatment chemical costs.

Again, in both cases, the cost is just 3% of the overall cost, but it contributes to the overall cost reduction.

3.1.6 – Manpower.

A DAF is usually controlled by an experienced operator per shift, resulting in a manpower demanding treatment. The UF system is completely automatic, and it only requires an occasional supervision in case of failure and the load of chemicals for the CEB (fully automatic Chemically Enhanced Backwash), which is very simple and it's done twice a month.

3.1.7 – Sludge handling.

Although not mentioned before, the lack of sludge generation for the UF (UF reject containing suspended solids is returned to the ocean) is another aspect that is not quantified in the operational cost, but it should be taken into consideration. The DAF produces a large amount of sludge that has to be dewatered and disposed generating not only expenses associated to the treatment itself but to logistic and manpower.

3.2 Energy consumption

Since SWRO operates at high pressures and the reject accumulates energy in the form of pressure that is otherwise unused, energy recovery systems are usually installed in desalination plants. Both plants are equipped with an energy recovery device to reduce power consumption, which accounts for almost 50% of the operational cost. In this case, the energy recovery devices used for Plant#1 is a Pelton turbine, and for Plant #2 an ERI Pressure exchanger.

The first system uses the energy from the SWRO reject to move a wheel that transfers this energy to a shaft, which reduces the energy consumption of the high pressure pump. Due to the fact that the energy is transferred into the wheel, and then to the shaft, and then to the high pressure pump, the efficiency is subsequently reduced, due to losses in mechanical transfer of energy.

The second plant incorporates a modern energy recovery device, a Pressure Exchanger. This system is designed in a way that allows for a direct transfer of energy between the SWRO reject and the feed water. Since water is in direct contact, the efficiency is much higher than in the Pelton turbine, with only one disadvantage that is the mixing of the two flows of water. The mixing translates into a maximum raise of 2% in water TDS. The system is designed so that the high pressure pumps only pumps 50% of the flow, and the remaining 50% is pressurized with the Pressure Exchanger (PX). Since efficiency is not 100%, and the reject's pressure is lower than the feed water (due to losses in the membranes), the water pressurized with the PX needs a booster pump to compensate for those 2 or 3 bar of pressure lost.

Power consumption of an SWRO system usually contributes to 70% of the total cost of operation. In this case, two things had to be considered for the comparison: the power reduction due to the use of a higher efficiency energy recovery device and the power reduction associated to the DAF. Even when blowers contribute to the power consumption, how much they do is not quantified yet. However, the overall power consumption was reduced from 8,5 KW/h.m^3 (Plant#1) to 5,4 KW/h.m^3 (Plant#2), that is a 35% reduction (see Figures 1 and 2). It is important to mention that this value considers the energy consumption associated to all the stages (pretreatment, RO´s and polishing) and not only the high pressure pump, which is usually the data considered.

This 35% reduction in the power consumption, considering the cost of energy in Chile (0,18 \$/KWh) translates to a decrease in the overall cost of operation of 0,56 \$/m^3.

Another advantage associated to the energy recovery device is that the lack of moving parts provides for a long life of the system (around 20 years according to the manufacturer) so there are virtually no spare parts needed. Additionally, since the PX are modular, should a replacement be needed only one of the PX should be replaced, and not the whole system, reducing the cost as well as the time for replacement.

3.3 Post-treatment / Polishing

Due to the water quality requirement, 0,1 microS/cm, further treatment after the SWRO was needed and different technologies are used in each Plant.

Plant #1 uses a demineralization train, composed of a cation exchanger, followed by a degasifier, and an anion exchanger. Water is then further treated by a Mix Bed to achieve the required quality.

Plant #2, instead, uses a BWRO as a second step of reverse osmosis, and a continuous electrodeionization unit to produced ultrapure water.

3.3.1 – Demineralization train / BWRO

The first aspect analyzed is the operational cost of the two plants. When considered the chemical costs of the Plant #1, and the membrane replacement cost of the BWRO as well as the power associated to the high pressure pump, which are the most significant costs, a 44% reduction is observed from Plant #1 to Plant #2. Both costs represent 18-19% of the overall cost of each Plant, so this reduction equals to an 8% reduction in the global operational cost.

Another cost that is not as easy to quantify is associated to the chemical handling and storage of chemicals, as well as the safety hazard that they represent. Also, the instability of the price of chemicals is a risk for the operational cost, where membrane price (a commodity) and power cost (for a power plant) don't represent much of a risk.

It is not considered in the analysis the power consumption of this stage of Plant #1 (pumps, blower of the degasifier), but it will contribute further to the result: lower operational cost for Plant #2.

3.3.2 – Mix bed / CEDI

In this case, the operational cost of the polishing section for Plant #1 is lower than for Plant #2, when considering the chemical consumption for the mix bed, and the CEDI modules replacement. However, when the operational cost of the post-treatment and polishing stage is considered together, the operational cost for Plant #2 is lower than for Plant #1.

Nevertheless, an aspect that is not quantify and should be considered is not only the logistic and safety hazard of using chemicals, but the need of tanks for chemical storage. This affects not only the CAPEX, but the footprint and the risk of handling chemicals.

IV. CONCLUSIONS

From the results stated above the following conclusions can been reached:

- UF Pretreatment provides a better water quality than conventional pre-treatment (DAF + depth filters), with a reduction in operational costs, higher reliability and less manpower.
- The energy cost of the whole plant was reduced significantly due to two factors: the replacement of the DAF for a UF implicating the absence of a blower (associated to the DAF), and the use of an energy recovery device with higher efficiency (Pelton Turbine vs ERI Pressure Exchanger).

- The replacement of the post-treatment (IX) for a combination of RO + CEDI results in a simpler operation, with no chemical storage and handling and a reduction in operational costs.

V. REFERENCES

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