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Experience with integrated ultrafiltration/reverse osmosis systems in industrial applications in Spain

Javier Suárez*, Javier Villa, Blanca Salgado

Dow Water & Process Solutions—Dow Chemical Ibérica S.L.
Email: jsuarezmartin@dow.com

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ABSTRACT

While fresh water resources are increasingly limited, efforts are taken aiming at a more efficient use of those resources and the value of water reuse, not only due to environmental but also due to economic aspects. This is especially true for the industrial sector, with a high potential to save water by reuse. This is expected to be even more critical in the coming future as the price of the water increases and the access to good quality water sources near the industries decreases. Reverse osmosis (RO) technology has been used in the industrial sector for decades for various purposes such as softening, ultra pure water production, or water reuse. But like in other applications such as desalination, in industrial applications, membrane fouling remains as one of the main causes for poor RO plant performance. This implies frequent downtime for cleaning and maintenance and shorter membrane life time, leading to significant operational costs. Therefore, the selection of a proper pretreatment is essential to produce a high quality feed water for the RO system in order to ensure a more sustainable and reliable operation. In the past decades, ultrafiltration (UF) has become more popular for RO pretreatment in the municipal and lately in the industrial sector too. Ultrafiltrate water is virtually free of particles, colloids, and suspended solids. Therefore, plugging of RO feed channels is minimized and the RO cleaning frequency can be noticeably reduced. In comparison with conventional filtration (e.g. sand filtration), UF requires significantly lower footprint, produces a higher and more consistent water quality regardless of variations in the feed quality, and usually needs less power and chemicals. This paper will review the design and operational data of a number of successful full-scale integrated membrane systems (UF followed by RO) installed in different types of industries and treating diverse water sources.

Keywords: Ultrafiltration; RO pretreatment; Integrated membrane systems; Reuse; Industrial water treatment

1. Introduction

The concern for a more efficient use of water in industrial applications has considerably increased worldwide, due to not only environmental but also economic factors, and it will grow even more in the future as the price of water increases and the access to good quality water in proximity to factories decreases.

According to published studies, industrial applications in Spain accounts for up to 19% of total water withdrawal (i.e. 6.60 km^3/yr in year 2000). The

*Corresponding author.

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average price of water for industrial use in Spain is 1.81 €/m^3, of which around 62% (i.e. 1.12 €/m^3) is charged for the water supply and the rest for sewerage and treatment. A 26% of the industries get the water from the network, 56% from surface, and 15% from underground own sources [1,2].

Reverse osmosis (RO) technology has already been successfully applied for water treatment in industrial applications for many decades, treating a wide range of water sources such as tap water, groundwater, surface water, or waste water or the treatment of the domestic industrial effluents for internal reuse or for compliance with the existing discharge regulations. The water use in the industry is broad, such as cleaning of raw material, main ingredient of the final product, cleaning of the premises, cooling towers and boilers feed, etc.

However, an appropriate pretreatment is the most critical factor to warrant the successful performance of these RO systems. In recent years, hollow fiber ultrafiltration (UF) technology has gained acceptance in the treatment of waters with high contamination levels, among other benefits, due to its higher efficiency—compared to other conventional filtration technologies—in the removal of suspended solids, microorganisms, and colloidal and organic matter, which are usually the main cause for the operational problems experienced in the RO membranes installed downstream.

Unlike conventional filtration systems, the UF technology produces a higher and more consistent filtrate water quality regardless of upsets in the feed water quality or in the hydraulic conditions. This operational advantage makes UF systems an appealing technology for the pretreatment of RO plants.

There are several reasons to consider UF pretreatment instead of conventional pretreatment [3,4]:

(1) *Ability to cope with variable feed quality*: UF membranes are a physical barrier against suspended matter, colloids, bacteria, and viruses, producing an excellent water quality to feed the RO system downstream independently of variations in the UF influent quality. More particularly, outside feed UF fibers can cope better with highly loaded feeds, as the risk of fiber plugging is eliminated.

(2) *Better product quality*: Due to their fine pores, UF membranes provide a very high quality filtrate with a typical ultrafiltrate turbidity below 0.1 NTU and silt density index (SDI) below 2%/min. UF membranes can reject by size exclusion pathogens that are immune to chlorination techniques (e.g. Gryptosporidium and Giardia parasites).

(3) *Reliability*: High value is given to the reliability to maintain the plant capacity and product water quality, more critically in industrial plants where the cost of downtime due to lack of water is more significant than the water production cost.

(4) *Lower plant footprint*: UF pretreatment systems generally require lower foot print and weight than media filtration systems, although this depends on the complexity of the conventional filtration scheme.

(5) Modules *Integrity Tests* can be done easily online to detect potential leakages without significant plant downtime.

(6) *Membrane modules can be individually isolated* for repair, maintenance, or replacement without compromising the plant output.

(7) *Ease of design and operation*: Despite requiring more focus on sustained permeability and productivity, UF systems provide much more stable water quality than a multimedia filtration system, without the need to monitor filter ripening time or breakthrough, or the need of ensuring appropriate layering of multimedia after backwash. Therefore, the process design and control is more automated than with conventional pretreatment.

(8) *Lower environmental impact*: The lower chemical consumption in general, and particularly the limited usage of coagulant in the UF process compared to conventional treatments leads to lesser environmental concerns for waste water disposal.

(9) *Lower RO stage cost*: The potential for lower downstream cost, based on better and more consistent water quality achieved by the UF system, is a key aspect. UF as pretreatment also allows higher design flux in the RO stage, as well as lower requirements for membrane cleaning and ultimately lower replacement rates, by enabling RO feed water with lower fouling tendency.

2. DOW™ UF membranes description

DOW™ UF technology is based on double-wall Hydrophilic Polyvinylidene Fluoride (H-PVDF) hollow fibers. The hydrophilic nature of this material reduces its tendency to organic contamination, which is the characteristic of other materials that are more hydrophobic. The double wall renders more sturdiness to the fiber and less tendency to rupture. PVDF is known as one of the most attractive polymer materials in the membrane industry. It provides, extraordinary mechanical properties, excellent resistance to oxidants, high thermal stability, and very good membrane forming properties, reasons that make it an ideal material for challenging water treatment applications.

DOW™ UF hollow fibers have an interior diameter of 0.70 mm and an exterior diameter of 1.30 mm and are arranged in bundles of thousands of fibers which are introduced into U-PVC cylindrical containers in a vertical configuration, obtaining a very compact module which achieves high production in little space.

The membrane features a pore size of 0.030 nominal microns, which achieves a great removal of contaminants such as micro-organisms (including virus), particles, suspended solids, or colloidal matter, obtaining a high quality filtration and, more importantly, with consistent characteristics, independently from the fluctuation in the inlet water quality.

In addition, it allows cleaning through an air scour that sweeps the fibers' external surface, which reduces the use of water and chemical products during cleaning process. Table 1 shows the main features of the DOW™ UF membrane [5,6].

3. Case study 1: food additives industry—well water

In this first example, DOW™ UF technology is used in a food additives production plant. Within the production process, water has two main applications: steam generation and process water. In order to operate the manufacturing process at full capacity, it is essential to secure a production of RO water of 2.400 m^3/day with salinity below 30 mg/L.

The plant has its own underground water wells available and the treatment plant's original scheme included sand filtration, cartridge filtration, and RO system. However, with the existing configuration a significant variability was noticed in the SDI of the RO feed water, mainly due to the presence of colloidal iron, which generated a progressive increase of pressure drop in the RO system. This fouling resulted in a higher cleaning frequency of the membranes leading to a reduction of net water production, a higher consumption of chemicals and energy, and a higher cost of membrane replacement.

Once the problem was identified and characterized, different alternatives were evaluated and it was decided to carry out a pilot test using a DOW™ UF SFP-2860 UF module. The pilot trial results confirmed the UF's suitability as a technology capable of providing a high and constant quality filtrate to feed the RO unit. Fig. 1 shows the SDI15 filter before (immeasurable) and after the UF system (SDI15 < 1%/min).

The UF system, in operation since February 2009, consists of four skids, each of them designed to treat from 60 to 90 m^3/h. The selected UF model was DOW™ UF SFP-2860, which has 51 m^2 of active membrane surface. The UF system reduced more than 50% the RO pretreatment footprint compared to the sand filters formerly installed.

The UF filtrate water is subsequently stored in a tank, where it is chlorinated (since part of this filtration goes to the plant's internal network) at

Table 1
DOW™ UF membrane features

UF module configuration	Pressurized vertical module
Membrane configuration	Double-wall hollow fiber
Hollow fiber diameter	Int. $D = 0.70$ mm/Ext. $D = 1.30$ mm
Membrane material	Hydrophilic PVDF
Nominal pore size	0.030 μm
Membrane surface per UF module	Model DOW™ UF SFP/SFD-2660: 33 m^2 Model DOW™ UF SFP/SFD-2860: 51 m^2 Model DOW™ UF SFP/SFD-2880: 77 m^2
Flow direction	Outside-in
Typical filtration flux range	40–120 L/m^2h
Typical backwash flux range	100–150 L/m^2h
Typical TMP	0.3–0.6 bar
Maximum TMP	2.1 bar
Typical chlorine concentration for cleaning	1,000 ppm NaOCI
Typical UF filtrate turbidity	<0.1 NTU
Typical virus removal	>4 LRV
Typical UF filtrate SDI	<2

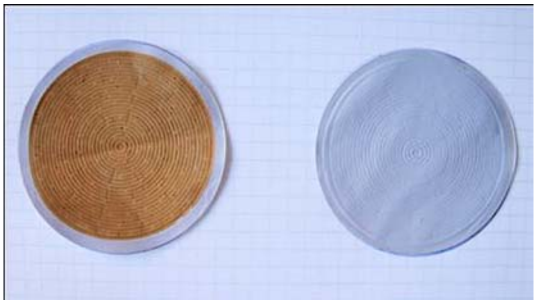

Fig. 1. SDI filter UF feed (left) and UF filtrate (right).

0.3–0.5 ppm of NaOCl, and after passing through the safety cartridge filters, it feeds two RO lines, each producing 100 m^3/h, working at 75% recovery (see Fig. 2 and Table 2). Prior to the RO system, sodium bisulfite is dosed to eliminate residual chlorine as well as a scaling inhibitor. Each RO line has two stages, with 10 pressure vessels in the first stage and five pressure vessels in the second stage, with six elements in each vessel. A final polishing step with ion exchange resins yields water suitable for steam generation.

The UF plant does not require online chemical cleaning procedures, but only offline chemical cleanings are carried out (i.e. "Cleaning in Place" or CIP) when needed, typically with citric or oxalic acid for iron fouling control. Fig. 3 shows the UF transmembrane pressure (TMP) evolution before and after a CIP with oxalic acid for iron fouling removal.

After the start-up of the UF system, the RO system CIP frequency has been reduced from every 3–6 months (when the sand filters were in operation) to only around once per year with DOW™ UF as pretreatment.

4. Case study 2: mining industry—surface water

In this case, a DOW™ UF system is followed by a two-pass RO system with DOW FILMTEC™ elements in a mining industry. The feed to the UF system is river water and the product water has different uses depending on its quality (UF filtrate water, first pass RO water, and second pass RO water), including service water for internal use and boiler feed water and process water for equipment cooling. The UF plant has been in operation since May 2010 and replaced sand filters, achieving a reduction of footprint around 40%.

The UF plant pretreatment consists of a safety filter of 150 µm, to prevent big sized particles from reaching and damaging the UF fibers. Even though raw water quality can reach up to 50–60 NTU of turbidity and 40–50 mg/L of suspended solids, at the outlet of the UF system the SDI15 mean value keeps below 1.3%/min.

The UF system consists of two skids, each with 11 DOW™ UF SFP-2880 modules (this model has 77 m^2 of active membrane surface per element), to produce a total UF net filtrate flow of 80–90 m^3/h, which feeds the first pass of the RO (see Fig. 4). The RO first pass consists of a two-stage system with eight pressure \vessels in the first stage and four in the second stage (six RO elements per vessel). The second RO pass consists of five vessels in the first stage and three in the second stage (five RO elements per vessel) (see Table 3). The final RO water has conductivity below 5 µm/cm.

5. Case study 3: soft drinks industry—well water

In this application, a DOW integrated system of UF and RO membranes treats well water after it has

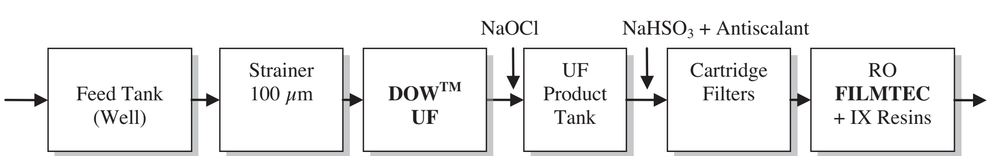

Fig. 2. Process flow diagram of the UF/RO system at the food industry.

Table 2
Design parameters of UF and RO plants installed in the food additives industry

Unit	Capacity (m^3/h)	Recovery (%)	Number of lines	Total number of installed elements	Membrane model
UF	240–360	>95	4	80	DOW™ UF SFP-2860
OI	2 × 100	75	2	180	DOW FILMTEC™ LE-440i and BW30LE-440

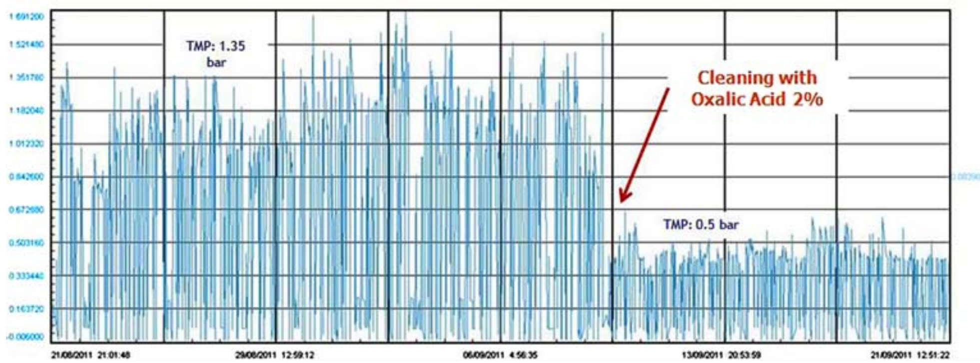

Fig. 3. UF system TMP evolution.

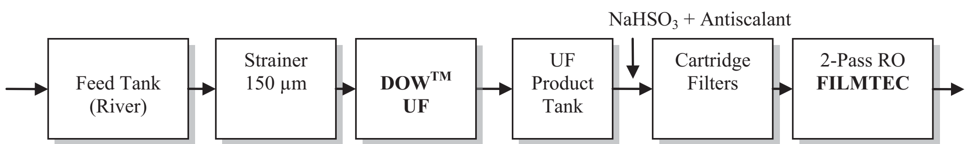

Fig. 4. Process flow diagram of the UF/RO system at the minning industry.

Table 3
Design parameters of UF and RO plants installed in the mining industry

Unit	Capacity (m^3/h)	Recovery (%)	Number of lines	Total number of installed elements	Membrane model
UF	90	>90	2	22	DOW™ UF SFP-2880
OI first pass	75	80	1	72	DOW FILMTEC™ LE-400
OI second pass	40	80	1	40	DOW FILMTEC™ BW30-400

passed through a safety filter of 100 µm. The UF system feed water is of relatively good quality, usually under 2 NTU of turbidity, less than 5 mg/L of total organic carbon, and less than 5 mg/L of suspended matter. Nevertheless, it was deemed appropriate to install an UF system prior to the RO in order to ensure a constant high quality RO feed water and reduce operational costs. The product water, having gone through the RO system and a final refinement by means of activated carbon filters, is used in the soft drinks manufacturing process. The plant has been in operation since June 2010 and replaced sand filters.

The DOW™ UF system consists of three lines, each with 15 DOW UF SFD-2880 elements (77 m^2 of active membrane surface per element), to generate a total flow of 200 m^3/h. The UF system feed water goes through continuous chlorination inline (ClO_2 is used to minimize formation of disinfection by-products) to keep the membranes disinfected in order to control biological contamination, taking advantage of the UF fibers material (PVDF) great tolerance to oxidizing agents. Then, the UF filtrate is accumulated in a regulation tank and subsequently, chlorine is reduced through the addition of sodium bisulfite to prevent the oxidation of the RO membranes installed downstream (see Fig. 5).

The UF filtrate has an average turbidity below 0.05 NTU (100% below 0.1 NTU) and SDI15 < 0.5%/min, which makes it suitable to feed the RO plant. The UF system operates with a TMP in the range of 0.4–0.6 bar (see data for more than one year operation in Fig. 6), remaining stable simply by means of periodic backwashing with water (it does not need online chemical washes or chemically enhanced backwashes [CEB]). It is worth mentioning that during the first year of operation only one offline chemical cleaning (CIP) had to be carried out in the UF system (currently, it is every 4–6 months) and the RO system CIP

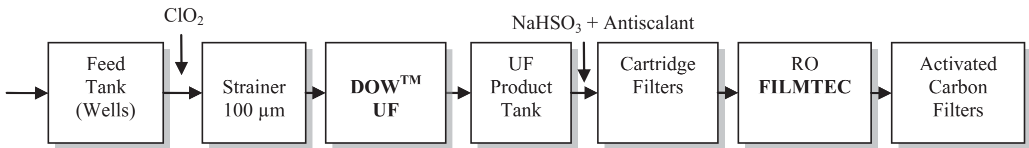

Fig. 5. Process flow diagram of the UF/RO system at the soft drinks factory.

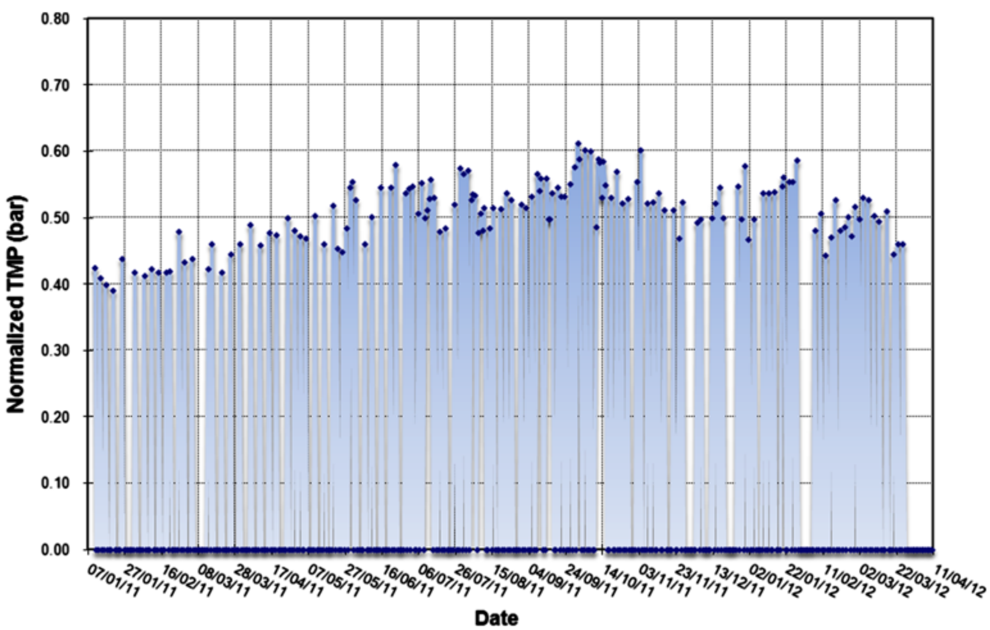

Fig. 6. UF system TMP evolution.

frequency has been reduced from every 4–6 months, when it was pretreated by the sand filters to none after more than two years of operation with DOW™ UF as pretreatment.

Table 4 shows the main design parameters of UF and RO plants installed in this industry.

6. Case study 4: beverage industry—rinse water reuse

This industry represents a clear example of the efficient use and conservation of water resources and minimization of wastewater discharge. The plant takes its raw material from natural water springs to manufacture the final product. However, in the production process, large volumes of water are required for equipment refrigeration and washing of the final product containers. Using the spring water source for these purposes would not be cost efficient or environmentally friendly. To solve this problem, an integrated system of UF and RO has been installed to treat and reuse the wastewater generated from the washing of containers, storage tanks, and facilities, as well as cooling towers blowdown.

A sand filter precedes the UF plant, which consists of two lines, each with seven DOW™ UF SFP-2860 elements, to generate a total net UF flow of approximately 20 m^3/h with an average turbidity under 0.1 NTU. The UF filtrate water partially feeds a RO plant

Table 4
Design parameters of UF and RO plants installed in the soft drinks industry

Unit	Capacity (m^3/h)	Recovery (%)	Number of lines	Total number of installed elements	Membrane model
UF	200	>95	3	45	DOW™ UF SFD-2880
OI	100	75	1	108	DOW FILMTEC™ BW30LE-440

Table 5
Design parameters of UF and RO plants installed in the beverage industry

Unit	Capacity (m^3/h)	Recovery (%)	Number of lines	Total number of installed elements	Membrane model
UF	20	>85	2	14	DOW™ UF SFP-2860
OI	10	65	1	18	DOW FILMTEC™ BW30FR-365

in two stages, with 2:1 array, with six low fouling zelements per pressure vessel. The final product is utilized for the cleaning of containers and also as cooling water make-up and boiler feed water. Table 5 shows the main design parameters of UF and RO plants installed in this industry, which has been in operation since October 2010.

7. Case study 5: power industry (biomass)—waste water reuse

In this last example, an integrated system with DOW™ UF and DOW FILMTEC™ RO membranes treats municipal secondary effluent of up to 50 mg/L of suspended solids. Optionally, depending on the influent water quality, the raw water passes through a previous silex filter. A two-month UF pilot trial preceded the final design and execution of the full-scale plant.

This system is installed in an industry that uses biomass for power generation. The ultrafiltrate typically with a turbidity below 0.1 NTU and SDI less than 1.5%/min is mixed with the permeate of a first pass RO system to produce water suitable to feed the cooling towers. The second pass RO product is used as boilers feed water. The full-scale plant was started to run in May 2011.

The DOW™ UF system consists of two lines with nine DOW™ UF SFP-2880 elements each (77 m^2 of active membrane surface per element), to generate a total flow up to 80 m^3/h (design flow is 60 m^3/h). Then, the UF filtrate is accumulated in a regulation tank and feeds the 2-pass RO membranes installed downstream, with BW30XFR-400/34i elements (see Fig. 7).

The DOW™ UF system operates with a TMP of around 0.4 bar when membranes are clean and up to 1.1 bar in fouled condition. CEB are regularly carried out to keep stable operation and TMP under control. It is important to emphasize that only one intensive CIP cleaning has been done after 10 months of operation.

An important fact about this plant is that in spite of the lack of standardization of the different UF products present in the market today, in this particular case there was an existing membrane microfiltration plant from another manufacturer based on a different fiber material that was replaced by the DOW™ UF system. The main reason for this change was the higher tolerance of DOW UF's PVDF material to chlorination vs. previous material, which is an advantage of special importance in such an application of municipal waste water treatment. Besides, most of the original auxiliary equipments such as tanks, piping, or feed, backwash, and chemical dosing pumps, remained the same, therefore reducing significantly the system retrofit cost. It is interesting to note that the RO system CIP frequency was reduced from every 1–2 weeks with the former membrane pretreatment to a more sustainable frequency of every 3–4 months with DOW™ UF as pretreatment.

8. Cost analysis

Table 6 shows estimated figures for the installation and operating cost of the five DOW™ UF systems presented in this article (note that this refers to the cost of the UF part only, not the whole water treatment process, e.g. RO part).

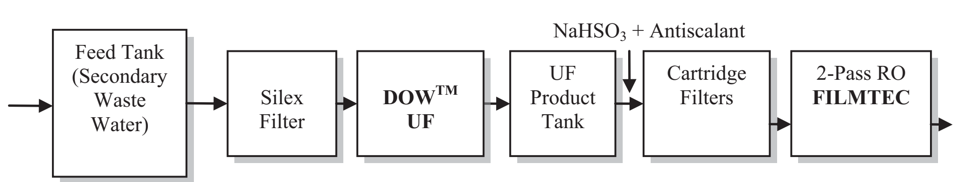

Fig. 7. Process flow diagram of the UF/RO system at the power industry.

Table 6
Estimated installation and operating costs for the five DOW™ UF plants described (UF part only)

	Case 1: food additives industry (well water)	Case 2: mining industry (surface water)	Case 3: soft drinks industry (well water)	Case 4: beverage industry (industrial effluent)	Case 5: power industry (municipal waste water)
Energy	0.010	0.012	0.010	0.015	0.010
Chemicals	0.001	0.009	0.001	0.027	0.009
UF membrane replacement	0.009	0.018	0.010	0.050	0.028
Labor/personnel	0.008	0.021	0.008	0.059	0.024
Maintenance spares	0.005	0.007	0.005	0.007	0.003
Amortization of capital	0.012	0.011	0.010	0.016	0.002
Overhead	0.001	0.002	0.001	0.005	0.002
Total operating cost (€/m^3 of UF filtrate produced)	0.047	0.080	0.044	0.179	0.077
Installation cost (€/m^3/day of installed capacity)	70.5	73.5	64.7	115.0	40.5

For this analysis, the energy consumption calculation has been based on a price of 0.10 €/kWh. Chemical cost includes products used in backwash, CEB, and CIP cleanings as well as UF feed disinfection inline, when used. As per the cost of the UF membrane replacement, different element life spans have been considered depending on the application and using a conservative approach (i.e. seven years of UF membrane life for well water treatment, five years for surface water treatment, and three years for industrial or municipal waste water treatment).

Amortization cost is based on 20 years of plant life span and 7% annual interest, and includes the cost of the UF skids plus the auxiliary equipment (e.g. strainer, tanks, pumps, chemical cleaning systems, instrumentation, etc.and civil works excluded) but not the UF membranes, which are included in the membrane replacement cost section. Note that the amortization cost of Case 5 is significantly lower than the rest as in this case only the UF skid was needed, while all the auxiliary systems remained from the existing UF plant, as described above in this document. Finally, the maintenance spares cost has been estimated as 3% per year over installation cost and overhead has been estimated as 3% of total operating cost.

Note that this cost analysis does not take into account the above-mentioned cost reduction associated to the benefits of the UF technology installed upstream the RO system, such as lower footprint compared to sand filtration, lower frequency of RO chemical cleanings due to the more suitable feed, longer RO membrane life, higher plant availability, or lower replacement rate of cartridge filters, which all added can be significant.

9. Summary

9.1. Reliability

An appropriate pretreatment is the most critical factor to warrant a stable and cost-effective performance of the RO systems. UF technology based on hollow fibers has gained acceptance in recent years as a reliable technology for the treatment of waters with high fouling indexes, since it produces a high quality filtrate by removing suspended solids, colloids, and micro-organisms, and most importantly, with a constant quality independent of the feed water fluctuations.

9.2. Versatility

This article has presented four cases of UF and RO integrated systems successfully operating in Spain's industrial sector, for very different applications (from soft drink production to reuse of industrial effluents) and with different origins and feed water quality (underground well water, river water, and wastewater). In addition, both technologies (UF and RO) are supplied by the same manufacturer (DOW), which enormously simplifies the interaction between the system integrator and the end user with the supplier.

This aspect is especially important in applications such as the ones hereby presented, given that the success of the operation is driven by the good coupling between both technologies.

9.3. Competitiveness

Among the benefits offered by that treatment scheme, apart from the mentioned better UF quality compared to conventional systems, it is worth mentioning the cost reduction was derived from the fouling reduction of the RO membranes. Lower chemical consumption for membrane cleaning and longer lifetime lead to lower operational and capital expenses. In addition, less downtime for maintenance is required, which allows the plants to achieve a higher recovery, availability, and plant throughput.

9.4. Feasibility

Lastly, it is worth pointing out that in four out of the five case studies presented, UF pilot tests were carried out on site prior to defining the project. These tests, although not always essential, are highly advisable to determine the optimal operational parameters, avoid false expectations, and optimize the plant design and therefore the investment. The need/value for pilot testing increases when there is greater overall CAPEX (e.g. large projects) or there is more uncertainty on the process design (raw water quality and novel dosing schemes).

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