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Optimization of produced water quantity, quality, and cost

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Cartridge filter selection and replacement: Optimization of produced water quantity, quality, and cost

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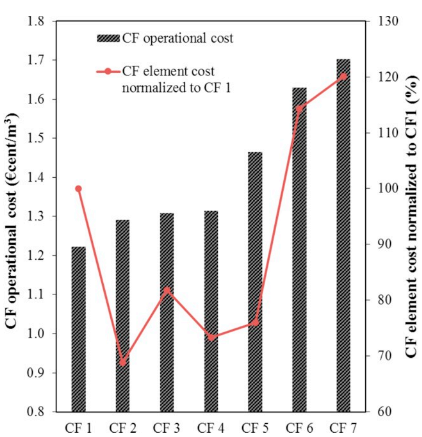
GRAPHICAL ABSTRACT



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ABSTRACT

In this study at a full-scale desalination installation seven types of commercially available cartridge filter (CF) elements were evaluated in terms of: (i) water production volume (m^3), (ii) produced water quality, and (iii) operational cost (€cent/m^3). The cost of optimal CF replacement time relative to increased CF pressure drop was determined for three electricity tariffs (0.05, 0.15, and 0.25 €/kWh) to assess further cost reduction. CF 1 was able to achieve the highest water production rate, the lowest produced water SDI, and the lowest cost of operation. The total costs of cartridge filtration varied between 1.22 and 1.70 €cents/m^3 produced water, depending on the CF type. Replacing the worst-performing CF type by the best-performing CF type would reduce operational CF costs by about 39.3%, enabling a cost saving of 0.48 €cents/m^3 produced water, emphasizing that selection of the right CF enables a large reduction of cartridge filtration costs. Moreover, depending on the electricity tariff an additional 2–16% cost reduction can be achieved by replacing CFs at an optimal time. At high energy cost, it may be more economical to replace cartridge elements more often to reduce the increased cost associated with the required higher pressure.

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1. Introduction

Reverse osmosis (RO) and nanofiltration (NF) membranes are used to produce high-quality drinking water from abundantly available brackish and seawater sources. The economic feasibility of membrane systems is crucially governed by the ability to sustain the required permeate production rates with minimum loss in performance [1]. Fouling occurrence is a major problem in membrane systems [2–6], resulting in increased cost of water production primarily due to losses in produced water quality and quantity, cleaning and related non-productive off-time [7,8], reduced lifetime of membrane modules due to cleaning, and finally increased costs caused by the generated waste treatment and disposal [9].

Different water sources require different levels of pre-treatment to lower the fouling tendency of the water in the RO membrane systems. Ideally, pre-treatment should target all foulant types present in the feed water. Pre-treatment is mainly categorized as chemical, physical or biological for removal of particulate, organic, inorganic fouling and biofouling [10–13]. Proper design and operation of pre-treatment should enable efficient removal of potential foulants from the RO feed water. Almost all conventional pre-treatment systems used in RO plants utilize low micron range cartridge filter (CF) units as a final protection barrier before the high-pressure pumps of the RO membranes. Standard CFs are operated in dead-end filtration mode in which all the water that enters the filter system passes through the filter while solids and components will be retained by the filter. CFs are normally rated with an absolute and nominal rating. Absolute rating of a filter is defined as the diameter of the largest spherical particle which will pass through the filter and reflects the pore opening size of the filter under specified test conditions [14]. Nominal rating indicates the filter's ability to prevent the passage of a minimum percentage of solid particles greater than the nominal rating's stated micron size. The nominal rating represents an efficiency or degree of filter rejection properties [14].

CFs are intended to act as a barrier against sand particles or other debris that may be released from the preceding media filters. In cases where the media filters are not performing as required, the CF stage will become a secondary filtration stage and will also be tasked with removing solids and reducing silt density index (SDI). As a result, a higher frequency of cartridge replacement would be required which increases cartridge purchases, costs of labor associated with cartridge replacement and plant downtime therefore ultimately increasing the water production cost. Moreover, the increase in differential pressure over the system as the CFs trap and accumulate solids leads to increased energy use and cost. Commonly, disposable CFs are used in RO and NF pre-treatment, typically used as woven, non-woven (spun) or pleated.

This study evaluated seven different types of commercially available pleated high flow CF elements in terms of product quantity and quality. Three ranking criteria (product quantity, quality, and cost of production) were used for CF evaluation. The objective is to highlight the importance of selecting the right CF for optimizing water treatment and reducing the costs associated with (i) CF replacement as well as with the (ii) average pressure differential across the CF installation. Moreover, cost analysis for optimal replacement time relative to CF pressure drop under three energy scenarios was performed and further potential savings were addressed.

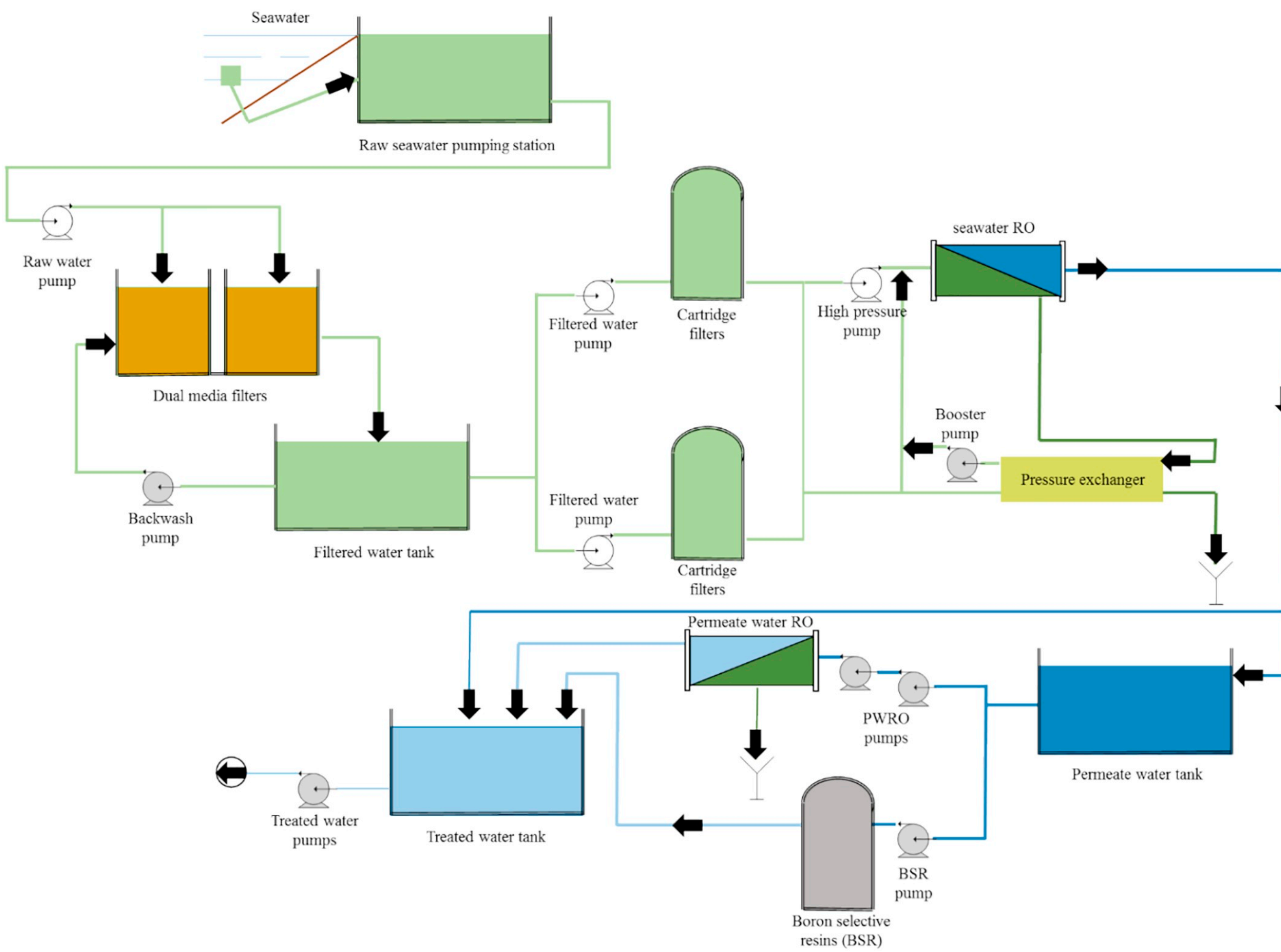

Fig. 1. Schematic diagram of the treatment train in the Dhekelia Desalination Plant, Cyprus.

2. Material and methods

2.1. Site description

The study was conducted in the Dhekelia Desalination Plant [15,16] which supplies 60,000 m^3/d of potable water to major districts (Famagusta, Larnaca and Nicosia Districts) in Cyprus. At the Dhekelia facility, the water is consecutively treated by ferric chloride dosage ($FeCl_3$), dual media filtration, antiscalant dosage, and 5 μm cartridge filtration before being fed to the RO system. The schematic diagram of the treatment train is shown in Fig. 1.

2.2. Cartridge elements

Seven commercially available pleated high flow CF types were compared as a 'safety stage' between the dual media filtration and reverse osmosis (RO) membranes in the Dhekelia seawater desalination plant over a testing period of one month from mid-August to mid-September 2018. Seven multi CF housings were tested in parallel, each housing containing 7 pleated CFs of the same type: in total 49 CFs were included in the study (Figs. S2 and S3 in supplementary material). All seven different types of high flow cartridge elements were tested at the same time. Table 1 shows the characteristics of the different CF types as obtained from the different manufacturers. The external dimensions of the CFs were 152 cm × 15 cm, with a total module length of 1.5 m. All CFs were operated inside out. The elements have been coded CF 1 to CF 7.

The flow was measured separately from each multi CF housing using a (Rosemount 3051SFC Compact) orifice plate flow meter. Each cartridge vessel had a regulating valve that was used to limit the flowrate to a maximum of 350 m^3/h. The flow from each cartridge vessel was regulated so that the production of the desalination plant was not disturbed. The pressure over the parallel cartridge vessels was recorded over the one month period (Cera bar, PMC51, Endress + Hauser, Switzerland). The pressure from the pressure indicator is only representative for the pressure drop over the vessel when the flow regulating valve was fully opened; when the flowrate is lower than 350 m^3/h.

2.3. SDI measurement

The silt density index (SDI) was measured daily for the produced water from the seven different high flow cartridge elements to monitor the produced water quality from the different filters and any changes that would occur in time. The SDI was measured according to the ASTM D4189 standard method. The SDI method can be used to indicate the quantity of particulate matter in water. The SDI was calculated using the following formula:

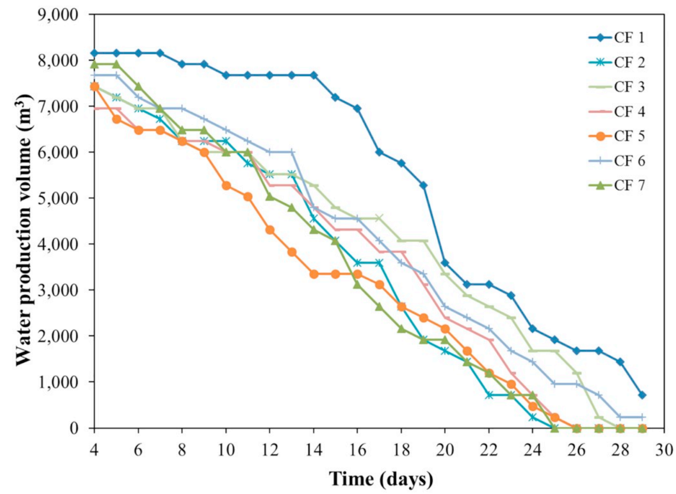

Fig. 2. Water production volume development (m^3) over the study period for the different CF types (coded).

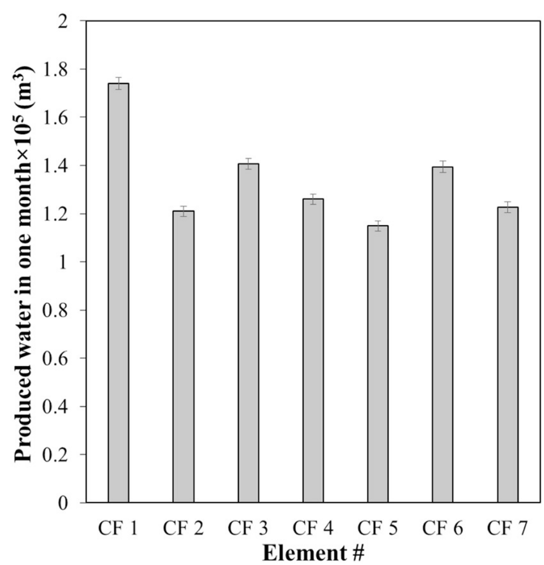

Fig. 3. Total amount of produced water (m^3) in one month for the different CF types, varying between 115,000 and 174,000 m^3.

$$SDI_T = \frac{\%P_{30}}{T} = \frac{\left(1 - \frac{t_i}{t_f}\right) \times 100}{T} \tag{1}$$

where SDI_T is the Silt Density Index (%/min), $\%P_{30}$ is the plugging ratio at 207 kPa (30 psi) feed pressure. T is the total elapsed flow time in

Table 1
Cartridge filter element code and characteristics (as per manufactures' data).

Element type	CF 1	CF 2	CF 3	CF 4	CF 5	CF 6	CF 7
Q (m^3/h)	57	57	50	50	50	65	60
Δp_{max} [a] (bar)	3.5	1.8–2.1	1.8–2.1	2.1	2.0	1.8–2.1	3.5
T_{max} [b] (°C)	82	70	70	80	70	70	82
Size (cm)	152 × 15	152 × 15	152 × 15	152 × 15	152 × 15	152 × 15	152 × 15
Particle removal efficiency (%)	98.36 (5 μm)	> 90	99.9	> 90	> 90	–	99
Area (m^2)	8.4	13.8	7.2	8.0	7.9	18.0	7.7
Number of layers	5	2	3	3	3	1	5

– Not available/not tested.
[a] Maximum Δp the element can withstand at an applied temperature (normally 25 °C).
[b] Maximum temperature the element can withstand for structural integrity.

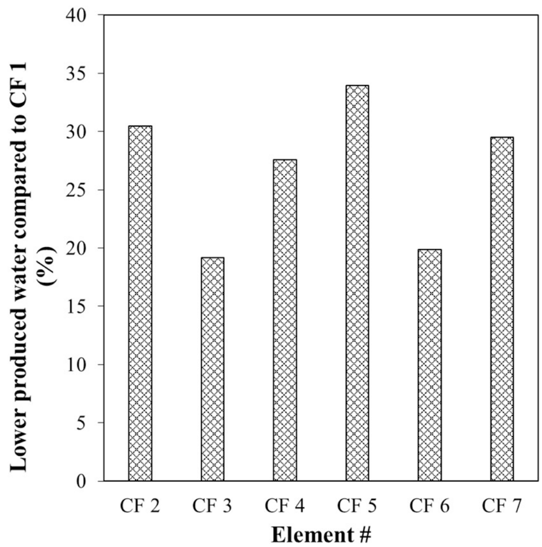

Fig. 4. Lower produced water amount (% percent) after 1 month for the six different CF types (CF 2 to CF 7) compared to CF 1.

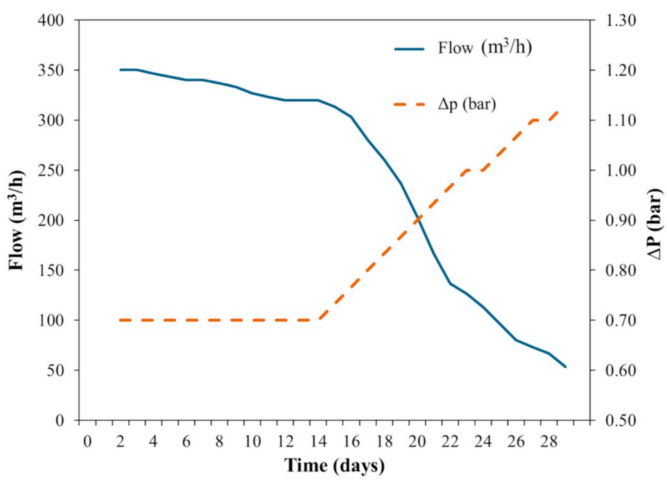

Fig. 5. Produced flow rate of CF 1 (m^3/h) and pressure drop increase, ΔP (bar) in time during one month period.

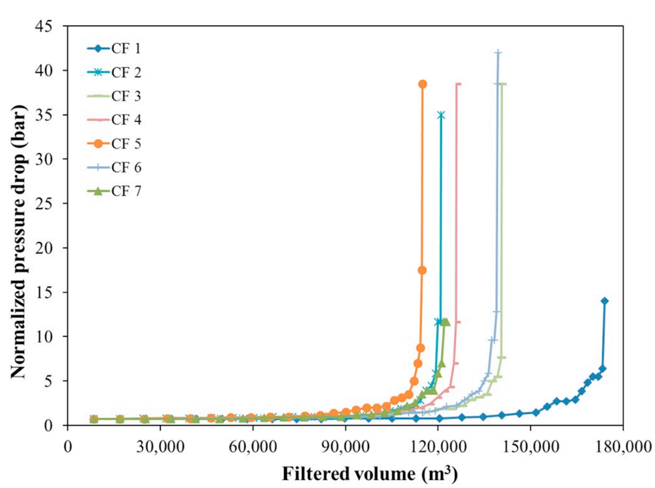

Fig. 6. Normalized pressure drop increase as the filtered water volume increase for all 7 types of CFs under constant flow operation.

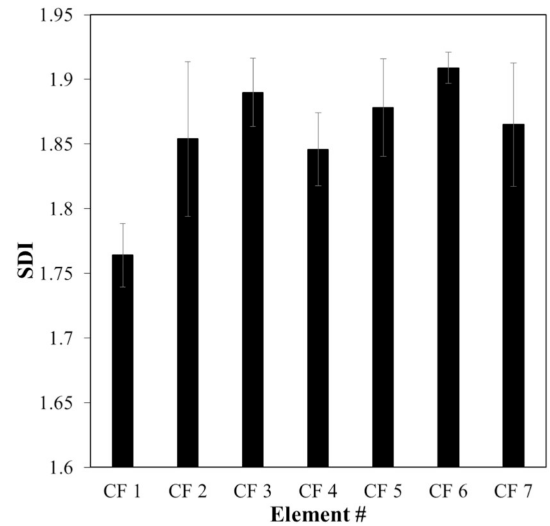

Fig. 7. Average SDI of water after the different CF types, varying between 1.76 and 1.91. Feed water SDI was 2.25 ± 0.10.

minutes (usually 15 min), t_i is the initial time required to collect 500 mL of sample (seconds), and t_f is the time required to collect 500 mL of sample after test time T (seconds). If the plugging ratio $\%P_{30}$ is exceeding 75% a shorter period T has to be taken, e.g. 10, 5 or 2 min. In this study the SDI with T = 15 min has been used, since the plugging in the test was in most cases < 75%. A 0.45-µm pore-sized membrane filter (47 mm in diameter) (Sterlitech, cellulose acetate membrane filters, CA04547100) was used in this study. The water temperature was monitored before and after the SDI measurement.

2.4. Cost assessment

The operational cost (€cents/m^3) of the different cartridge elements was calculated based on the replacement cost plus the energy cost of operation. The replacement cost is equal to the capital cost of the CF element divided by filtered volume. Therefore, the more water is filtered the lower the replacement cost. The energy cost was calculated based on the energy consumption according to the normalized pressure drop increase when CFs are operated with constant flow rate. Filtered volume was used instead of time as it better reflects how the CFs are used in most practices.

$$C_{operational} = C_{replacement} + C_{energy} \tag{2}$$

$$C_{replacement} = \frac{CF\ cost}{Filtered\ volume} \tag{3}$$

$$C_{energy} = electricity\ cost * \frac{sum\ of\ cumulative\ energy\ consumption}{Filtered\ volume} \tag{4}$$

The electricity tariff for Cyprus (0.15 €/kWh) was used for the cost calculations. The cost of optimal CF replacement time relative to increased CF pressure drop was determined for three electricity tariffs (0.05, 0.15 and 0.25 €/kWh) to assess further cost reduction. The electricity tariffs used for this calculation were selected after screening the range of electricity tariffs throughout the European countries.

3. Results

3.1. Produced water quantity and quality

In this study seven different industrial scale commercially-available pleated high-flow CF element types were evaluated. The produced water flow was measured separately from each cartridge vessel containing 7 CF elements of the same type for a period of one month. The

Table 2
Water production cost for the different cartridge elements.

Element type	CF 1	CF 2	CF 3	CF 4	CF 5	CF 6	CF 7
Element cost (%)	100	69	82	73	76	114	120
Total amount produced (m^3/month)	174,000	120,960	140,640	126,000	114,960	139,440	122,640
CF replacement cost (€cent/m^3)	0.59	0.58	0.60	0.60	0.68	0.84	1.00
CF energy cost (€cent/m^3)	0.63	0.71	0.71	0.72	0.79	0.79	0.70
Total CF operation cost (€cent/m^3)	1.22	1.29	1.31	1.32	1.46	1.63	1.70
Increase in CF operation cost compared to CF 1 (%)	0	5.7	7.0	7.6	19.8	33.4	39.3

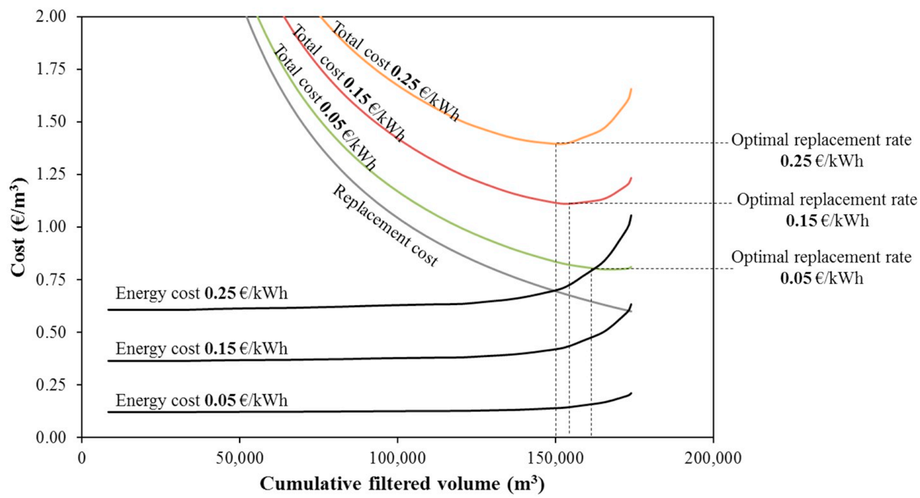

Fig. 8. Optimal CF replacement can reduce total economic costs of CF treatment. Balancing cost of earlier CF replacement relative to increased CF pressure drop for three electricity tariffs (0.05, 0.15 and 0.25 €/kWh).

flow was regulated to a maximum of 350 m^3/h using a regulating valve and once the valve was fully open the flow rate started to decline. Fig. 2 shows the water production volume development in time for the different elements, where a major decline in produced water is observed at the end of the 30 day period with complete clogging of some CFs even at day 24. The total amount of produced water by the different CFs in one month varied between 115,000 m^3 for CF 5 and 174,000 m^3 for CF 1 (Fig. 3). Results reveal that improper selection of a cartridge element can decrease the produced water amount by 19–33% (Fig. 4). The applied pressure can be seen in Fig. 5.

The pressure drop increase in time during the operation of the cartridge elements is shown in Fig. 5. The pressure drop increase (Fig. 5) due to CF clogging will result in an increase in the energy requirements to produce water.

CFs normally operate with a set flowrate and variable pressure, rather than set pressure and variable flowrate (otherwise, the production rate of the entire desalination plant would be reduced by fouling of the cartridge filters). Therefore, a normalized pressure drop was calculated (Fig. 6) indicating the pressure-drop that would be required to maintain the flowrate constant at 350 m^3/h.

The silt density index (SDI) was measured daily for the produced water from the seven different CF elements to monitor the produced water quality from the different filters and any changes that would occur in time. CF 1 which produced the highest water amount also showed the lowest SDI throughout the experimental period (Fig. 7).

3.2. Cost assessment

Selection of the CF type is governed by the quantity and quality of produced water compared to the cost. CF 1 that was able to produce better quality water (Fig. 7) with the highest cumulative quantity during 1 month (Figs. 2–4) was used as a reference. All cartridge element purchase costs were normalized to the cost of CF 1 (Table 2) to reflect on the ranking of purchase cost compared to performance. Table 2 demonstrates that the most expensive filter was not the best performing and the cheapest CF was not the worst performing. Afterwards, an operational cost parameter (€cent/m^3) was calculated. The operational cost was calculated based on constant flowrate operation of the CFs where the pressure drop was normalized so as a constant flowrate of 350 m^3/h is produced as shown in Fig. 6. CF 1 had the lowest operational cost closely followed by CFs 2, 3, and 4. CFs 2, 3, and 4 produced less water compared to CF 1 therefore the selection of these CFs will result in more frequent cartridge replacement compared CF 1 further increasing the water cost due to higher labor cost and longer plant downtime. The total costs of cartridge filtration varied between 1.22 and 1.70 €cent/m^3 produced water. Table 2 shows that replacing the worst performing CF (CF 7) by the best performing CF 1 type would reduce the CF operational cost by ≈ 39.3% and enable a cost saving of 0.48 €cent/m^3 of produced water.

Even for the best performing CF (CF 1) optimizing the CF replacement moment shows to have a significant additional reduction of the cost (Fig. 8). The optimal replacement time in each total cost graph (Fig. 8) is at the point of minimum cost. When the energy cost is high (Table 3) earlier cartridge replacement can reduce 16% of the total CF operation cost.

4. Discussion

4.1. Cartridge filtration: a significant cost in large scale treatment plants

In recent years, reducing the cost of water produced through membrane-based desalination has been a major focus [17–19]. Energy consumption has always been highlighted as the most important economic aspect in the cost of reverse osmosis desalination plants. Other costs that are highly significant include membrane and CF replacement costs [20]. Therefore, cost optimization of cartridge filtration, a

Table 3
Reduction in CF 1 (best performing) operational cost due to earlier replacement under high, medium and low energy cost scenario.

Energy scenario		Total amount produced (m^3/month)	ΔP (bar)	CF replacement cost (€cent/m^3)	CF energy cost (€cent/m^3)	Total CF operation cost (€cent/m^3)	Cost reduction (%)
0.25 €/kWh	Optimal replacement time (20 days)	151,680	0.90	0.68	0.71	1.38	16
	End of life replacement (30 days)	174,000	1.20	0.59	1.06	1.64	
0.15 €/kWh	Optimal replacement time (21 days)	155,280	0.90	0.66	0.44	1.10	10
	End of life replacement (30 days)	174,000	1.20	0.59	0.63	1.22	
0.05 €/kWh	Optimal replacement time (25 days)	166,560	1.00	0.61	0.17	0.79	2
	End of life replacement (30 days)	174,000	1.20	0.59	0.21	0.80	

necessary step in all desalination plants, will result in significant cost savings. Cartridge replacement frequency determines cartridge purchases, costs of labor associated with cartridge replacement and plant downtime [21]. A secondary cost of increased dependence on the cartridge filtration stage is increased energy costs due to pressure differential over the system as the CFs trap and accumulate solids.

In this study, the evaluation of seven commercially available pleated high flow CFs was intended to estimate the possible reduction in water production cost. CF 1 showed the best performance in terms of produced water quality and quantity in this location/application (Figs. 2–6). Calculation of water production cost for each cartridge element revealed that three CFs had a closely similar water production cost as CF 1 which had the lowest cost. The total costs of cartridge filtration varied between 1.22 and 1.70 €cents/m^3 produced water, depending on the CF type. The higher amount of water produced by CF 1 before the need for replacement remains CF 1 superior over the other CFs tested. The selection of the right CF has significant cost savings on industrial scale treatment plants. Results from this study demonstrate that a 0.48 €cents/m^3 of produced water can be saved just by selecting the best CF element (Table 2). Therefore, the potential savings over various treatment plant sizes (60,000–700,000 m^3/d) can range between 100,000 to > 1,000,000 euros per year.

Monitoring the development of differential pressure over the cartridge elements in time aids in determining the optimal moment of replacement of the CFs. The cost of replacement (operational cost) decreases in time as more water is filtered through the CF, however, the cost of energy increases due to increase in differential pressure along the CF. It would be more feasible to replace the CF at the time when the total CF operation cost is minimum (Fig. 8). In Dhekelia Desalination Plant replacing the CF when the operation cost is minimum has the potential in further reducing the cost by 10% since their electricity tariff is 0.15 €/kWh (Table 3). The location energy cost (€/kWh) is the determining factor as to when the minimum CF operation cost occurs in time and dictates whether early or later replacement is more viable. In regions where the electricity cost is high it would be more economical to replace the CFs earlier before a significant pressure drop increase is observed (Fig. 8). Only when the energy cost is very low, operating the CF longer at a higher pressure drop is economic.

4.2. Further research

This work aimed to illustrate the importance of cartridge filters in the overall economic performance of a desalination plant and present a methodology on how to find the optimal CF replacement rate. Capital expenditure (CAPEX), for example the costs of the filter housings, was not included in this work as the number of filter housings was not a variable, and therefore, the observed results were not influenced by CAPEX. However, determining the optimal number of filter housings is also interesting. A possible scenario for further cost reduction would be oversizing the cartridge filtration step and operating at a lower flowrate. Operation at a lower flow rate will reduce pressure drop increase in time. As a result, the reduction in energy cost increase (operational cost) in time as well as lower CF replacement frequency should be outweighed against the capital cost of additional cartridge vessels.

5. Conclusions

In this study, seven different types of commercially-available pleated high-flow CF elements were evaluated at a full scale installation in terms of: (i) water production rate, (ii) produced water quality (measured as silt density index, SDI), and (iii) CF operational cost. The main study findings can be summarized by:

- Large differences were found in the operating costs between the 7 different CFs types tested.
- The best CF element resulted in 34% higher water production

volume with better water quality compared to worst CF element.

- Selecting the right cartridge element can reduce up to 39.3% of cartridge filtration cost, enabling a cost saving of 0.48 €cents/m^3 produced water.
- Higher differential pressure across the cartridge elements results in higher energy consumption.
- Depending on the energy cost an additional 2–16% cost reduction can be achieved by replacing CFs at an optimal time.
- When the energy cost is high, it is more economical to replace CF elements earlier.

Declaration of competing interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.desal.2019.114172.

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