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Evaluation of Effectiveness of Cleaning-in-Place of Membranes and Optimum Period of Membrane Replacement on a Seawater Reverse Osmosis Plant

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ABSTRACT *Fouling reduces the performance of seawater reverse osmosis (SWRO) membranes by causing blockage, which leads to increased differential pressure across the membrane vessels. Over time, this can reduce efficiency and the quality of permeate. The lifespan of an RO membrane depends on the quality of the feed water, the flux the membranes are subjected to (which is influenced by the percentage recovery), and the extent of scaling/fouling the membranes accumulate. Cleaning-in-place (CIP) is a commonly carried-out practice on RO plants to counteract fouling within the membranes. This study evaluates the financial impact of membrane fouling by comparing the effect of membrane replacement and CIP on the specific energy consumption (SEC) of a SWRO plant operated in the Maldives by using operational data collected between January 2018 and January 2024. The water production and energy consumption of the plant were used to calculate the SEC. A life cycle cost analysis was carried out to determine the optimum membrane replacement period. The breakeven point for replacing every 4 years as compared to replacing them in every 5 years is 5 years. The breakeven of 4-year-period membrane replacement against a scenario where only CIP is done is 6.08 years. It was found that the SEC improves by 0.07 kWh/m³ on average after CIP. Replacing the membrane every 4 years results in the lowest energy consumption and consequently the lowest cumulative cost over a 12-year period.*

Keywords: Seawater reverse osmosis, Experimental, Cleaning-in-place, Specific energy consumption, Life cycle costs

Introduction

Background

The implementation and operation of seawater reverse osmosis (SWRO) membrane filtration systems are complex, with fouling presenting a significant challenge. Fouling is caused by the accumulation of precipitates, colloidal particles, bacteria, biofilm, and dissolved organic matter (Andes et al., 2013; Hydranautics, 2017; Muñoz et al., 2014). Typically SWRO membranes such as, Hydranautics SWC5-

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LD, have a life span of is typically 5-6 years (Hydranautics, 2013). However, fouling within the SWRO adversely impacts both the permeate production and membrane longevity. Despite advancements in feed water treatment, complete prevention of fouling remains unachievable (Alnajjar et al., 2021). To mitigate performance degradation, chemical and/or mechanical cleaning is employed, based on the specific type of fouling. However, these cleaning process necessitate careful implementation to avoid membrane damage, as repeated cycles of fouling and cleaning can further shorten the membrane lifespan (Muñoz et al., 2014).The specific energy consumption (SEC) of the SWRO process excluding pre-treatment and post-treatment in global desalination operates averages between 2.3–3.0 kWh/m³ (Kim et al., 2019; Kishizawa et al., 2015). SEC serves as an indicator of the energy required to produce one unit of desalinated water and is currently significantly higher than the thermodynamic energy requirement of 0.7 kWh/m³ (for 100% theoretical recovery) or the more practical 1.1 kW/m³ for 50% recovery (Voutchkov, 2018). A baseline test done at a state-of-the-art facility demonstrated an SEC of 1.58 kWh/m³ at 42% recovery employing a lower flux than MWSC's current operational practice (MacHarg et al., 2008). An internal energy audit at MWSC's Hulhumalé site revealed that the SEC of its plants ranged between 2.12 kWh/m³ and 2.92 kWh/m³ (Ibrahim & Sadiq, 2022).

Membrane fouling significantly impacts the SEC, leading to increased energy demand (Ruiz-García et al., 2023). Fouling or scaling causes blockages that degrade membrane performance, thereby raising energy consumption. This, in turn, increases the operating cost of the plant (Frans Knops et al., 2007; S. Pietsch, 2017).

Low pH cleaners, such as citric acid, are often used to target scale minerals and inorganic colloidal material, whereas high pH cleaners are applied to address organic fouling and biofouling (Andes et al., 2013). In cases of severe scaling, stronger chemicals, such as hydrochloric acid (HCl) may be employed. However, their use carries an increased risk of damaging the polyamide layer of the membrane. Biocides are also utilized to inhibit the bacterial growth. Mechanical methods, such as reverse flow cleaning are effective for removing foulants near the feed side of the membrane. This technique specifically targets biological fouling, particulates, and colloidal matter (Andes et al., 2013). High pH cleaners (pH of ~10), such as combinations of sodium tripolyphosphate and sodium salt of ethylenediaminetetraacetic acid (EDTA) (Hydranautics, 2017), or sodium hydroxide and sodium dodecyl sulfate, are particularly effective in mitigating fouling caused by biological matter (Al-Balushi et al., 2024; Hydranautics, 2017).

Cleaning-in-place (CIP) is one of the primary cleaning methods used in the industry. In this process, the plant is shut down, and a cleaning agent mixed with permeate water circulates through the pressure vessels for a set amount of time. CIP equipment is often integrated into the design of the RO plants, through hard piping, requiring only the operation of valves to initiate the cleaning cycle.

In industrial practice, membranes are discarded when their flow and quality drops more than 15% of the initial values (Eduardo Coutinho de Paula et al., 2017). However, membranes can only be discarded if cleaning fails to restore significant yield. The continued use of blocked membranes can result in increased operational costs, particularly energy costs, as greater pump power is required to maintain the desired flow rate (Frans Knops et al., 2007). Fouling is multi-faceted issue that requires a holistic approach, which is currently lacking in the cleaning practices of MWSC. While the impact of fouling on SEC is generally understood, and SEC is used as a performance indicator of, there is an insufficient consideration of the cost associated with ineffective cleaning. Membrane replacement is a significant expense; thus, it is essential to evaluate the costs accumulated by fouling against those of membrane replacement to draw comparisons in the context of current practices at MWSC to a more simplified approach to membrane cleaning and extended operations of plants with fouled membranes.

Objective

This study aims to evaluate the energy efficiency associated with CIP and identify the most cost-effective membrane replacement interval by analyzing data collected on an SWRO plant at MWSC's Hulhumalé Operations Site. Membrane replacement intervals of four years and five years were compared, along with a breakeven analysis of membrane replacement costs against the cumulative costs incurred when membranes are not replaced but only subjected to periodic cleaning.

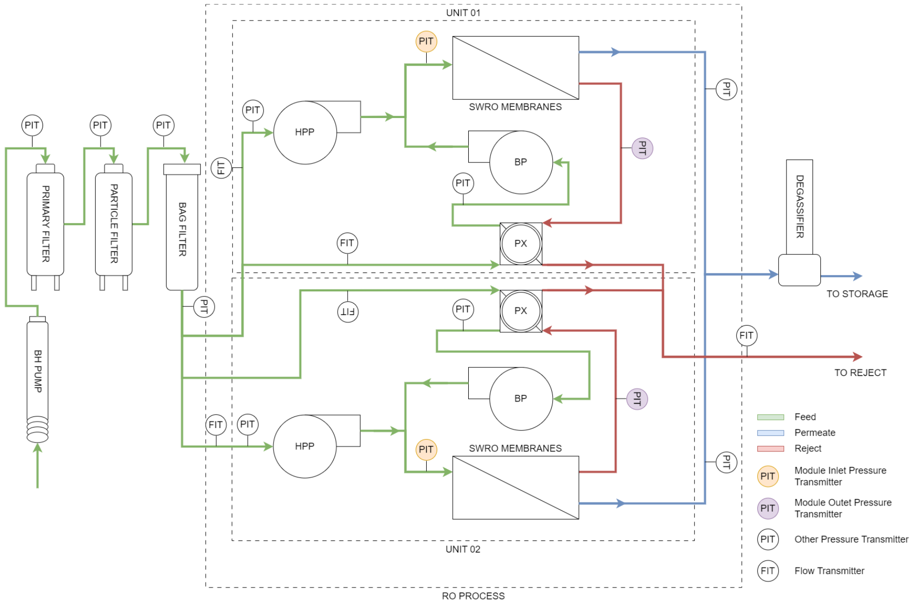
The impact of ineffective cleaning on the membrane lifespan and SEC of the plant are outlined in terms of energy demand and cumulative costs. Additionally, recommendations are provided to enhance the SEC and extend membrane lifespan.

Methodology

Research Design

Data for this study was collected from one of the RO plants at MWSC's operations centre. The SWRO plant has a production capacity of 3000 m^3/day, and consists of two units, each containing 18 pressure vessels (36 in total). Each pressure vessel houses six Hydranautic SWC5-LD spiral-wound composite polyamide SWRO membranes, resulting in a total of 216 membranes across the plant (with two units). Hydranautics SWC5-LD has a membrane surface area of 37.2 m^2 and is rated for a permeate flow of 34.1 m^3/day at 38.2 l/m^2h flux. At MWSC however, the membranes are operated at a lower flux range of 14-16 l/m^2h. This lower flux operation is intentionally maintained to reduce membrane fouling rates (Cornelissen et al., 2021). It is important to note that the SWRO plant is not a dedicated experimental setup, but an operational plant used for water production of Hulhumalé City. The plant was commissioned in late 2017 and fully operational by January 2018, marking the beginning of data collection for this study.

Figure 2.1: Overview of SWRO at MWSC.



The feed water for the SWRO process is drawn up from boreholes 30 – 50 meters deep using submersible pumps and filtered through the primary filter of 100 µm mesh size, particle filter of 50 µm mesh size, and bag filters of 5 µm pore size to remove particles that could clog up the membranes. No chemical pretreatment is currently applied, as water from deep boreholes is naturally well-filtered and contains minimal biological contaminants. The feed water entering the SWRO membranes has a turbidity of less than 1 NTU.

After filtration, the flow from the bag filter is split into two streams: with 30-35% of the flow being directed into the high-pressure pump while the remainder is sent into the pressure exchanger (PX) as illustrated in Figure 2.1. In the PX, the feed stream gets its pressure boosted from the reject stream exiting the SWRO modules at high pressure. The high-pressure feed stream from the PX gets a further pressure boost via the booster pump, to equalize both streams (feed from PX stream and feed from high-pressure stream) to the same pressure. It is at this high pressure that the feed streams converge and enters the SWRO membranes. The reject stream exiting the PX at low pressure is directed to the sump well, while the permeate is transferred through degassifiers into storage tanks. The water streams are consistently maintained at a temperature between 25° C and 27°C. Since this temperature variation is minimal, it is unlikely to significantly affect the processes involved.

The cleaning-in-place (CIP) procedure currently used by the MWSC involves the following steps (Aqua-Tech, 2009):

1. The pressure pipes are flushed with chlorine-free permeate water
2. A fresh batch of the cleaning solution is prepared in the tank using permeate
3. The cleaning solution is circulated through the plant for approximately five hours, specific to the plant under study.

4. The tank is drained and refilled with permeate water for rinsing.
5. Step 1 is repeated for a few minutes to ensure thorough flushing
6. The plant is operated in bypass mode until permeate flow is clear, free of foam and without residues (usually about 15-30 minutes).

Hydranautics does not recommend cleaning the membranes at extreme pH and temperature ranges for prolonged periods (Hydranautics, 2017). While cleaning at extremes can enhance the effectiveness of the cleaning procedure, it may adversely impact the membrane lifespan. Therefore, if cleaning at extreme pH or temperature ranges is necessary, reducing the contact time is recommended to minimize the potential damage. The recommended pH range for Hydranautics SWC5-LD membranes varies with temperature; pH 1 to 12 for temperatures ≤25°C, pH 1 to 12 for temperatures ≤35°C, and pH 2 to 11 for temperatures ≤45°C (Hydranautics, 2017). For continuous operations involving longer contact times, the acceptable pH range is narrower, between pH 3 to 10.5.

Currently MWSC employs only citric acid as a cleaning agent, for general untargeted cleaning. Citric acid effectively targets scale minerals and inorganic colloidal materials, and as a weak acid does not compromise membrane integrity (Andes et al., 2013). At times, caustic soda (sodium hydroxide) is used to adjust the pH of the cleaning solution.

Feed water currently is not pre-treated with antiscalants before being pumped into the polyamide membranes and citric acid serves as an effective cleaning agent to address scaling within the membranes. Biological fouling, however, is not addressed in the current cleaning regimen, as biofouling has not been identified as a significant issue on MWSC plants.

Data Collection

Water production data were obtained from totalizer values recorded by flowmeters installed on the permeate line of the plant, and the power consumption data were collected from the Variable Frequency Drives (VFD) of the high-pressure pump (HPP) and booster pump (BP) of the plant, as well as the plant's common control panel which also monitors other miscellaneous equipment such as valves. The Supervisory Control and Data Acquisition (SCADA) system enables plant operators to record and log data directly from their computer screens. During the study period of, operators manually recorded the values hourly, and subsequently compiled them into daily and weekly values for inclusions in monthly reports.

The flowrate meters installed on the plant's permeate lines provide the instantaneous water production value in m^3/h. The Variable Frequency Drives (VFD) of the HPPs and the BPs along with the common control system (which manages power for the miscellaneous equipment such as valves) supply plant's power consumption data. All these values essential for SEC calculations are accessible on the SCADA system.

The total water production and power consumption of the plant are calculated as monthly averages from the daily logged data.

Each time CIP is performed, the amount of citric acid consumed, and the volume of water used, are documented. The power consumption of the CIP pump is also recorded, and this data can be used to calculate the energy requirement of the operation. These variables collectively enable the calculation of the cost associated with performing CIP for each instance.

Data Analysis

The energy consumption and water production are used in equation 1 to calculate the corresponding SEC.

The Specific Energy Consumption (SEC) is calculated as follows:

$$SEC\ (kWh/m^3) = \frac{Energy\ consumed\ (kWh)}{Volume\ of\ water\ produced\ (m^3)} \qquad (1)$$

The Specific Fuel Consumption (SFC) is calculated using:

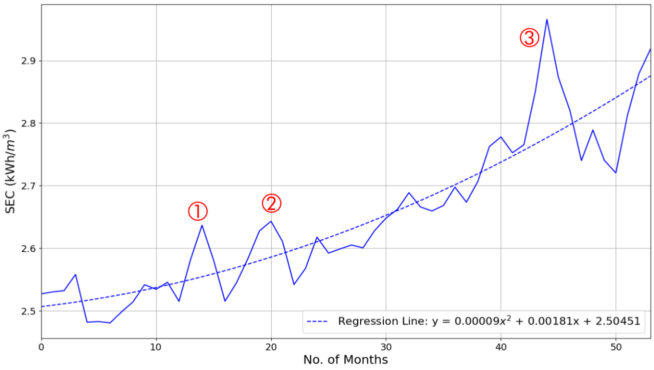
$$SFC\ (L/kWh) = \frac{Volume\ of\ fuel\ consumed\ (L)}{Energy\ produced\ (kWh)} \qquad (2)$$

Since SEC is a measure of energy efficiency (units of energy required to produce one unit of desalinated water), it can be used as an indicator for the loss of efficiency associated with membrane fouling (Ruiz-García & Ruiz-Saavedra, 2015). The energy required to maintain the pressure increases with increasing membrane blockage due to fouling (Shouman et al., 2024). This increase in energy requirement is reflected financially in the long term.

$$\begin{gathered} Change\ in\ cost\ (MVR) = \\ Change\ in\ SEC\ (kWh/m^3) \times Volume\ of\ water\ produced\ (m^3) \times SFC\ (L/kWh) \\ \times Price\ of\ fuel\ (MVR/L) \end{gathered} \qquad (3)$$

For change in SEC, the initial SEC with fresh membranes is used as the reference point. Hence, the calculation in Equation 3 yields the additional energy costs incurred due to membrane fouling. The cost of CIP is then added to these values to calculate the total cost. The cumulative total is then taken for each month until January 2024.

Figure 2.2: The SEC can be plotted against the number of months to yield the graph .



The equation of the line fit of the data points is as follows:

$$y = 0.00009x^2 + 0.00181x + 2.50451 \qquad (4)$$

Where y is SEC in kWh/m^3, and x is number of months. This equation was then used to forecast the SEC increase past January 2024. For these forecasts, the plant's average production of 83,350.08 m^3/month, was used. An annual inflation rate of 3.9% (Ministry of Finance, 2023) was applied to the fuel price and the cost of materials (for CIP and membranes) starting from January 2024. The resulting SEC was then used with Equation 3 to calculate the total variable cost for each of the corresponding months. During CIP procedure 100 kg of citric acid and 5 m^3 of water were used. The water is circulated for five hours, incurring an energy cost of MVR 475.2. The cost of 100 kg of citric acid is MVR 2,121.92, while the cost of water varies between MVR 34.60 and MVR 65.23 depending on the SEC of the RO plant. Consequently, the total cost of CIP varies between MVR 1,782.96 and MVR 3,973.48. Based on existing data the average interval between CIP procedure is 152 days. There are no records of CIP being done after December 2022 as the plant could not be shut down due to heightened water demand. Hence, the ideal scenario is a projection where CIP is done every 152 days, which is assumed to cause a 0.02 kWh/m^3 decrease in SEC (the minimum SEC reduction that is caused by CIP, historically). An annual inflation rate of 3.9% is applied to costs, to account for rising expenses. For the projections of this study, periodic membrane replacement assumes the replacement of all 216 membranes – or the number required to restore the desired/original performance of the plant. With new membranes, it is assumed that the increase in SEC caused by fouling will be 0 kWh/m^3; resulting a default SEC of 2.4 kWh/m^3 for the plant. This represents a significant reduction in energy consumption. For instance, in January 2022, the plant's SEC was 2.63 kWh/m^3. If the membranes had been replaced, the SEC would have been reduced to 2.4 kWh/m^3. This highlights the importance of evaluating the cumulative energy savings associated with membrane replacement accumulated over the time against the cost of the membrane replacement.

Hence, the costs are categorized into variable and fixed costs. Variable costs include energy expenses incurred from plant operation and other costs associated with CIP procedures, while the fixed costs comprise membrane replacement expenses. The cumulative cost over time is used to analyze to assess how these factors influence the total operational cost of the plant. This approach allows for the evaluation of long-term impacts under different scenarios.

Scenario 1 represents the current trajectory with inconsistent cleaning and no periodic membrane replacement. Scenario 2 reflects the current trajectory but accounts for consistent cleaning. Scenario 3 incorporate consistent cleaning alongside periodic membrane replacement every four years. Scenario 4 includes consistent cleaning with periodic membrane replacement every five years.

Currently, actual data is available from January 2018 to January 2024. The rest of the data points beyond this period extending until January 2030 are projections based on the calculations detailed earlier in this section.

Results and Discussion

SEC Data and Curve

During the data collection, the SEC ranged between 2.4 kWh/m³ and 2.92 kWh/m³. The increase of 0.52 kW/m³ is attributed to membrane fouling and aligns with fouling-related SEC increment reported in the industry (Ruiz-García et al., 2023). While SEC fluctuations may result from changes in pump efficiency and cost variations linked to engines performance, these factors are considered minor compared to the rising power demand caused by membrane fouling. At the end of the ideal 12- year trajectory, the cumulative CIP cost (of 12 years) is MVR 59,150.34. The small peaks 1 and 2 marked on Figure 2.2 are due to Unit 1 of the plant being gradually turned off for increasingly extended periods each month until it was fully offline in October 2020 (peak 1) for pump maintenance. This also resulted in disproportionately higher fouling within the membranes of Unit 2 due to its continued operation. The module inlet pressures of Unit 1 and Unit 2 in November 2020 were 55.26 bar and 59.58 bar, respectively. Performing CIP reduced these to 53.49 bar and 55.24 bar, respectively. The 3rd peak is attributed to rapid membrane fouling, which was mitigated by replacing membranes on the lead side of the vessels over three months.

Cleaning Costs

Considering the citric acid costs for various months, cleaning chemicals appear to account for most of the total cost, followed by the energy costs. The cost of water is relatively small, as shown in Table 3.1 below. It can be deduced that the cost of cleaning chemicals is the determining factor in the cost of CIP.

Table 3.1: Cost Distribution of CIP.

Cost Item	% of Total Cost
Citric Acid	71.4 – 86.8
Water	1.26 – 2.45
Energy	11.96 – 26.65

The cumulative cleaning costs over the study period account for only 0.28% of the total cumulative variable costs of Scenario 2 (with consistent cleaning), 0.38% of the total cumulative costs of Scenario 3 (membrane replacement every 4 years), and 0.4% of the total cumulative costs of Scenario 4 (membrane replacement every 5 years). This confirms that CIP costs are minor compared to the energy costs associated with the arising from the increased energy demand of fouled membranes.

Cumulative Costs Comparison

Figure 3.1: Cumulative costs of different scenarios across a period of 12 years.

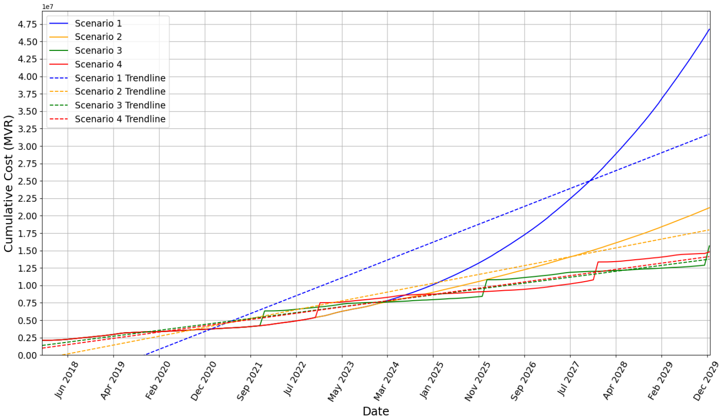
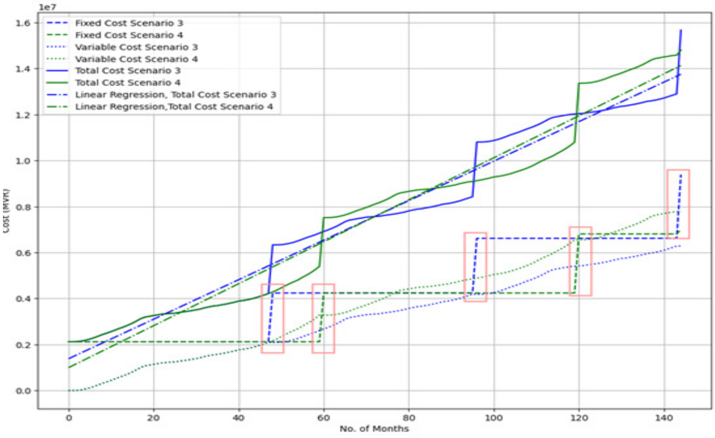


Figure 3.1 shows the cumulative costs of the four different scenarios mentioned in the previous section. The breakeven of Scenario 2 against Scenario 1 is 74 months (6 years and 2 months). The breakeven of Scenario 3 is 73 months (6 years and 1 month) against Scenario 1, 76 months (6 years and 4 months) against Scenario 2, and 60 months (five years) against Scenario 4.

Scenario 1 is the most expensive option in the long term, as the accelerated fouling of membranes significantly increases the system's energy costs. In comparison, Scenario 2 has a much flatter cost curve and with savings of MVR 25,620,359 over the 12-year period. This is owed to the SEC decrement due to the cleaning of the foulants in the membranes. Scenario 3 yields greater savings offering a savings of MVR 31,090,464.1 compared to Scenario 1, and MVR 5,470,105.08 compared to Scenario 2.

While the savings of Scenario 3 fluctuate compared to Scenario 4, Figure 3.2 shows that there is an overall increasing savings trend. The trend line of Scenario 3 is less steep than that of Scenario 4, as seen in Figure 3.1 and Figure 3.2. The primary savings here come from the variable savings, amounting to MVR 1,510,128.54. It is the fixed cost that is responsible for the fluctuations; with sudden increases observed in both fixed cost curves of both scenarios (highlighted in red rectangles on Figure 3.2) whenever membranes are replaced. For Scenario 3, the variable costs and fixed costs are 40% and 60% of the total cost, respectively. In the case of Scenario 4, they are 53% and 47%, respectively. There is, therefore, a strong case to be made that Scenario 3 is the more profitable route.

Figure 3.2: Fixed and variable cost trend of scenarios 3 and 4.



Energy Consumption Comparison

The energy savings from periodic cleaning and membrane replacement is apparent from the SEC comparison of the different Scenarios, shown in Figure 3.3. The current trajectory with minimal cleaning and no membrane replacement reaches an SEC of 4.24 kWh/m³ by January 2030, scenario 2 ends up with a maximum SEC of 3.01 kWh/m³, whereas scenario 3 sees the SEC reach a maximum of 2.68 kWh/m³ before membrane replacement, and the SEC in scenario 4 reaches 2.78 kWh/m³ before membrane replacement. In terms of energy in kWh, Scenario 2 has a savings of 3,703,290.76 kWh over Scenario 1. Scenario 3 has savings of 5,971,342.90 kWh over Scenario 1, 2,268,052.14 kWh over Scenario 2, and 245,335.69 kWh over Scenario 4.

Figure 3.3: SEC trend of different scenarios.

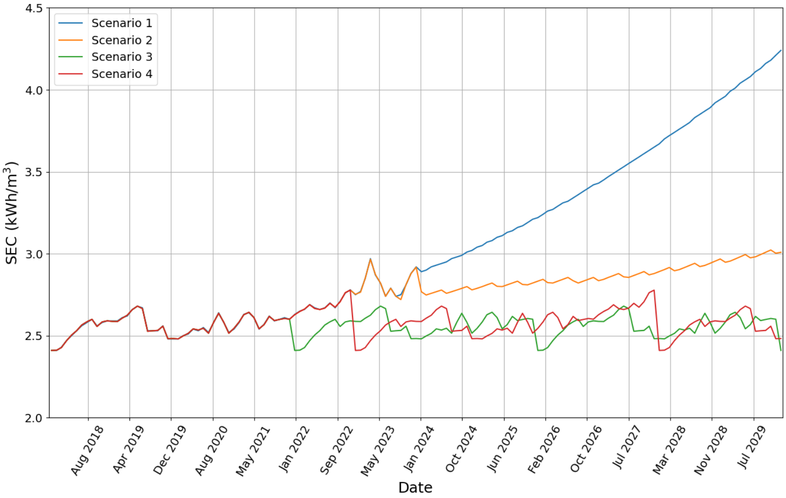


Figure 3.3 is important in characterizing the savings of Scenario 3 observed in Figure 3.1. It is shown that the reduction in energy consumption and the less time spent in higher-than-optimal SECs contribute towards a significant savings trend. Scenario 4 spends an extra year running the plant at an SEC higher than 2.6 kWh/m^3.

The maximum SEC of the RO process (excluding pre and post treatment) reached at a MWSC plant is 3.2 kWh/m^3. This is extremely dependent on the permeate production of the plant in addition to the module inlet pressure. Hence, it is possible for the SEC of a plant to increase beyond this value, if the membrane fouling can cause a larger decrement in permeate production even if the pump approaches its run-off point.

Further Discussions

It is abundantly clear that most of the energy savings of Scenario 3 come from the RO plant being operated at a lower SEC, which is made possible by periodic membrane cleaning. Shortening the membrane replacement period to 4 years – as implied by Scenario 3 being financially optimum – is not the solution; the membranes should only be replaced when their performance cannot be recovered by CIP procedures. Instead, it would be wiser to focus on implementing better cleaning practices. Membrane cleaning via CIP is scheduled when the differential pressure across the membrane increases past a certain point, causing the system to run for extended durations on high differential pressure to maintain permeate flow, leading to high power consumption (Ruiz-García et al., 2023). It is also important to understand that untargeted general cleaning with citric acid alone is insufficient to restore the performance of the membranes to full potential. This can be seen in Scenario 2 in Figure 3.1 and Figure 3.3, where the SEC increment, while mitigated, still remains prominent.

By conducting extensive membrane autopsies the nature of the foulants can be identified. The results can be used to either enhance pretreatment and/or develop specific cleaning regiments to target specific foulants. Effective cleaning can prolong membrane life and keep the energy costs of the RO process low (S. Pietsch, 2017). Predictive cleaning would also yield better results (Ruiz-García et al., 2023), for which SEC can be monitored live alongside differential pressure as markers of membrane fouling. In-situ detection of fouling via Electrical Impedance Spectroscopy (EIS) is a new technology that is currently being tested. It has proven to be more effective in providing early warning of biofouling compared to monitoring differential pressure (H. Komori et al., 2018). There is potential for EIS to be used to assess the biofouling potential of MWSC's feed water in the laboratory. Additionally, dedicating a plant to experimental studies would eliminate many uncontrollable variables, such as water demand that may require membrane replacement, and would provide higher quality data.

Limitations

There are limitations of this study that require elaboration, to frame the results in context where it is necessary. The values used in the SEC calculation are obtained from the monthly log sheets. The total production of each month is first calculated by subtracting the totalizer values of the permeate flowmeter, and then the total energy consumed by the plant is divided by this value. The resultant value is an average and less accurate than if the SEC is calculated live based on the permeate flowrate and instantaneous power consumption of the plant. This approach would increase the resolution of the data collected, thereby improving the accuracy of the resulting calculations.

Some membranes from the lead side of the plant were replaced during the period of this study due to rapid fouling and resultant SEC increment observed in the third peak in Figure 2.2. The effect on SEC was gradual, as the membrane replacement was done over the course of three months from April 2023 to July 2023. The resulting SEC decrement serves to balance the SEC increment due to the rapid fouling, in effect mitigating an anomaly. This activity was carried out to recover the plant's production in order to meet the city's water demand. However, this could have affected the recorded SEC, and such practices should be avoided in future data collection. It is recommended to dedicate a plant to experimental studies to avoid such issues. The SEC used in this study is SEC $_{\text{real}}$ (real SEC), as it is calculated from the total energy consumption of the plant. These values are taken from the VFDs of the high-pressure and booster pumps of the plant as well as the common control. The measurement of SEC $_{\text{real}}$ accounts for the mechanical and electrical efficiency of the pump and motor (Ruiz-García & Ruiz-Saavedra, 2015). This is more accurate as it is based on the actual energy consumption of the plant. However, SEC_{flow} (SEC calculated from pressure and flowrate as shown in Equation 5 below) could capture the SEC increment due to membrane fouling alone more effectively. The reason for this is that the efficiency of the pumps can be influenced by other factors that are not monitored or controlled in the duration of the study.

The SEC_{flow} can be calculated as follows:

$$SEC_{flow} = \frac{P_{fs}Q_f}{Q_{ps}}, \tag{5}$$

where P_{fs} is the feed pressure in Pa, Q_f is the raw water flow m^3/h, and Q_{ps} is the normalized permeate flow in m^3/h (Ruiz-García & Ruiz-Saavedra, 2015).

Conclusion

It is imperative to understand that membranes are replaced only when they are irreversibly damaged, that is, when the conductivity of the permeate increases or the permeate flow decreases and cannot be recovered by cleaning. Spiral-wound SWRO membranes, such as the Hydranautics SWC5-LD, typically last 5-6 years (Hydranautics, 2013), and this is true in the case of the plants being operated at MWSC. However, membrane fouling is a major issue that increases the energy demand of the SWRO process and drives up the variable costs of long-term plant operations. The results presented in this study arise from a situation that might be unique to the Maldivian islands; the increasing water demand, the lack of cleaning windows for CIP, and unidentified foulants in the feed water that might not be sufficiently removed during a cleaning regiment that employs citric acid alone, all compound to create a situation that, while still allowing for long membrane-life, has huge potential for cost savings in replacing the membranes every 4 years. However, the data discussed in the previous section elucidates that the savings of scenario 3 are owed to the plant being run at a lower SEC than scenario 4, which reinforces the fact that there are more energy savings to be had in a holistic approach to membrane cleaning. Hence, it is inaccurate to say that the shortened membrane replacement period found to be economical in this study can be generally applied to every other plant. The SEC-related findings are more prominent and applicable, and the study highlights the importance of effective membrane cleaning rather than promoting increasing the frequency of membrane replacement.

It is not recommended to replace the membranes every 4 years to save costs, rather it is recommended to focus on better cleaning strategies to save costs and prolong the life of the membranes in the process. The findings confirm that ineffective cleaning leads to increased energy costs and, subsequently, operational costs. Evidence suggests that the current cleaning practices are insufficient and leads to the accumulation of foulants within the membranes.

It is recommended to improve data collection via automated data logging to increase the accuracy of the data collected, and implement predictive cleaning based on live SEC monitoring alongside other variables such as differential pressure as markers of membrane fouling. And using SEC_{flow} instead of SEC_{real} might help eliminate additional factors that could affect the SEC value. Moreover, laboratory-scale experiments, such as those involving EIS, could be helpful in determining the fouling potential of MWSC's feedwater. Having a dedicated plant for experimental studies to eliminate uncontrolled variables and carrying out membrane autopsies to determine the nature of the foulants are also recommended.

There is a considerable gap in the research of the SWRO process limitations and solutions in the Republic of Maldives. Laboratory-scale studies on feed water's effects on membrane fouling are limited, and novel approaches to cleaning have not been developed as a result, despite the SWRO process in the Maldives being a result of multiple unique features of the country's geography and hydrology. Extensive research into the field is needed.

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Conflict of Interest

The authors of this paper are employees at Malé Water and Sewerage Company Pvt. Ltd.

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