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Energy efficiency solutions for RO desalination plant

Naveen Bhutani[a], Amit Purohit[a], Vasudeva Kumar Mantravadi[a,*], Srinivas Mekapati[a], Senthilmurugan Subbaiah[b]

[a]*ABB Corporate Research, Bangalore, Karnataka, India*
Email: vasudeva.m@in.abb.com
[b]*ABB Water ISI, Bangalore, Karnataka, India*

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ABSTRACT

Asea Brown Boveri (ABB) provides a portfolio of energy efficiency solutions for reverse osmosis (RO) based desalination plant. ABB has developed: (1) Energy and carbon footprint assessment tool in order to identify the opportunities for energy efficiency improvements and quantify them into economic benefits, (2) Membrane Performance (MP) tool to monitor and optimize the operations in RO plant, and (3) Decision Support System (DSS) to help the engineer while planning the membrane maintenance and production activities. In this study, the energy assessment was first performed on a RO plant to identify the opportunities for improvement. Subsequently, the identified opportunities are evaluated using MP tool on the plant data. Further, the benefits associated with DSS are also discussed using the simulated data.

Keywords: Energy efficiency; Energy assessment; Desalination; Reverse osmosis; Cost benefit; Membrane performance monitoring; Decision Support System

1. Introduction

Desalination plants have emerged as a leading technology for producing potable water. These plants are typically run sub-optimally and thus, present major opportunities to improve energy efficiency, plant production and profitability [1] that can be transformed into business by means of best practices, process automation, and application of advanced control and optimization solutions. There are limited solutions on energy efficiency improvements, optimal scheduling, and load distribution in the desalination industry [2]. Therefore, a comprehensive tool is desired that can systematically conduct energy assessment in desalination plants with minimal effort, identify opportunities and quantify them into realizable benefits, and help the service engineers in master plan development and application of advanced solutions to improve performance, productivity, and profit.

Though RO-based desalination is relatively simple in operation and less energy intensive than conventional thermal technologies, the savings potential from energy efficiency is huge due to high production volume. Moreover, the performance of RO desalination plant is strongly influenced by the RO membrane fouling which also impacts the energy efficiency. Therefore, the use of advanced automation solutions

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*Corresponding author.

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for energy efficiency such as membrane performance (MP) monitoring, energy/production optimization, and optimal scheduling of membrane maintenance activities becomes important.

2. Case study

In this study, a comprehensive energy assessment was performed for a RO desalination plant using Asea Brown Boveri's (ABB's) energy and carbon footprint assessment (ECA) tool. The study is conducted for RO section of the plant which consists of several RO trains in parallel. Each RO train consists of high pressure (HP) pump, membranes, and an energy recovery device (ERD) as shown in the schematic (Fig. 1).

As shown in Fig. 1, the pretreated feed water from the pre-treatment section is pressurized by HP pump, and is fed to the RO membranes where it is separated into product water and brine reject. In general, RO membranes are contained in pressure vessels which are stacked in parallel. Each pressure vessel consists of several membrane elements in series. The product water is adequate for drinking as it has low concentration of salts. The brine reject is highly concentrated but has HP energy. This pressure energy is recovered by means of ERD. In this case it is Pelton Wheel type ERD. The Pelton Wheel ERD transforms the pressure energy of brine into power, which is then supplied to the HP pump. In general, the main energy consumers in a RO train are membranes and pumps, whereas some energy losses are expected in energy recovery in ERD. The plant consists of two lines of which each line has 13 RO trains. The study is conducted on one of the RO lines, based on the availability of data.

The energy assessment was performed on above configuration (Fig. 1) using ECA tool and the findings are shown in Fig. 2. The variables on the x-axis are dimensionless flow rates. Some of the important findings of the energy assessment study were: (1) the specific electricity consumption for all major pumps in the trains were decreasing with the increase in plant load (Fig. 2). Multiple profiles (Pareto) were seen because the number of RO trains that were operating at a given time were different, (2) energy efficiency of all major equipment could be improved by increasing the production load. As an example, the efficiency of ERD for Train 1 evaluated in combination with its HP pump for a train revealed that energy efficiency was improved by ~5% (from 71 to 76%) with 15% increase in load (Fig. 2(c)). Note that, coupled efficiency was evaluated, due to unavailability of measurement of power supplied from ERD to HP pump. Similarly, the RO Train 1 efficiency was also improved by 2% (from 30 to 32%) with an increase in its load by 15% (Fig. 2(d)), (3) the production load for RO plant was scattered over wide range (Fig. 2(b)) which revealed that the resources (RO trains in operation) in RO section were underutilized. It was also identified that the product from RO plant was not meeting the quality and the overall product quality was maintained by mixing the RO desalination plant product water with high quality product obtained from multi-stage flash (MSF) based desalination plant. This indicated an opportunity for optimal production management plan/policy between MSF and RO plants.

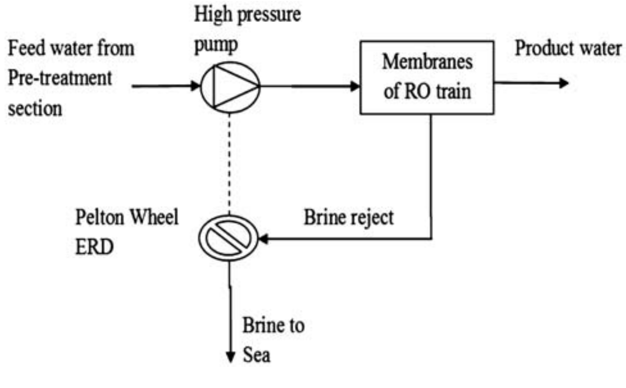

Fig. 1. Schematic of a RO train in the RO section of the plant.

Further, an equipment level assessment was also performed using ECA tool to evaluate the efficiency, operating load and fouling status of individual trains. The mutual comparison of these trains (Table 1) revealed that

(1) Train 1 had lower operating load factor, higher than allowable membrane pressure drop and high specific electricity consumption. Therefore, it was identified as the first candidate to be taken offline from production and sent for cleaning.
(2) Train 7 was operating at high efficiency with high load distribution, least specific electricity consumption, low membrane pressure drop (below design differential pressure), and good product recovery.
(3) The load factor for Trains 1, 3, 5, 6, and 8 could not be increased further as the membrane pressure drop for these trains was already higher than the allowable differential pressure. Increasing load factor to these trains could lead to increase in electricity consumption.

The above analysis showed that energy efficiency and/or production could be improved by optimal operation (i.e. production load distribution between

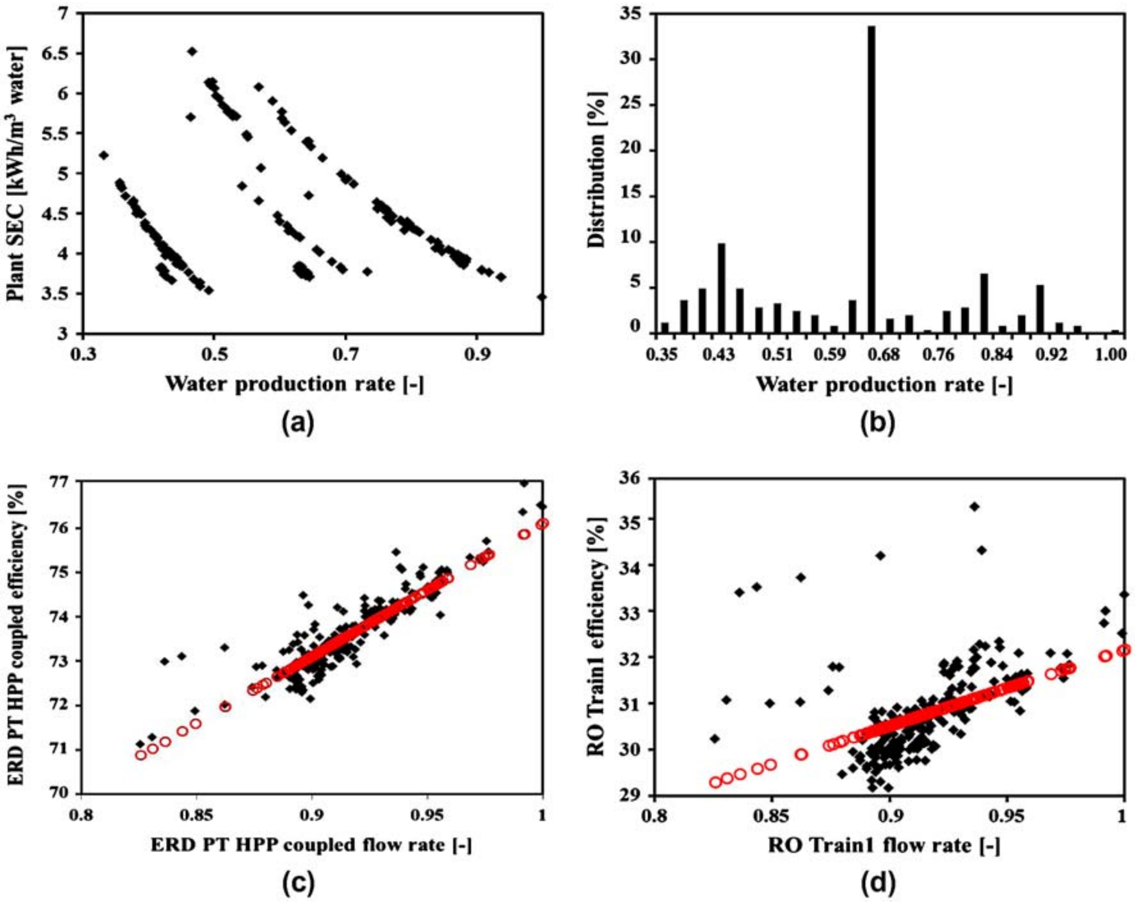

Fig. 2. Results from energy efficiency assessment (a) plant specific energy consumption, (b) % distribution of the product load, (c) ERD and HP pump coupled efficiency, and (d) RO Train 1 efficiency in RO section. Note that the red colored circles indicate the best fit of black colored actual operating points.

Table 1
Average KPIs for RO trains

KPI	Train 1	Train 2	Train 3	Train 4	Train 5	Train 6	Train 7	Train 8	Train 9
Specific electricity consumption, kWh/m^3	3.94	3.78	3.78	3.75	3.67	3.36	3.61	3.79	3.75
Specific operating cost, \$/m^3	0.39	0.38	0.38	0.38	0.367	0.34	0.36	0.38	0.37
Membrane pressure drop, barg	2.01	0.59	1.41	0.27	1.29	1.80	0.84	1.98	0.11
Allowable pressure drop, barg	0.92	1.20	1.18	1.12	1.15	1.10	1.20	1.19	1.09
Load factor	0.93	0.99	0.99	0.98	0.99	0.95	0.99	0.99	0.97
% Load distribution	15.53	16.82	8.98	4.40	12.21	1.86	17.78	11.56	10.86
Product recovery, %	42.98	42.99	42.98	43.06	42.97	42.01	42.97	42.77	42.75

RO trains considering number of trains in operation). This can be realized by means of a Decision Support System (DSS).

The following are some of the recommendations that were derived based on energy assessment:

- Optimally operate the plant/train at maximum feasible load.
- Optimally distribute the production load between RO trains based on their fouling status while meeting the product quality constraints and required production.

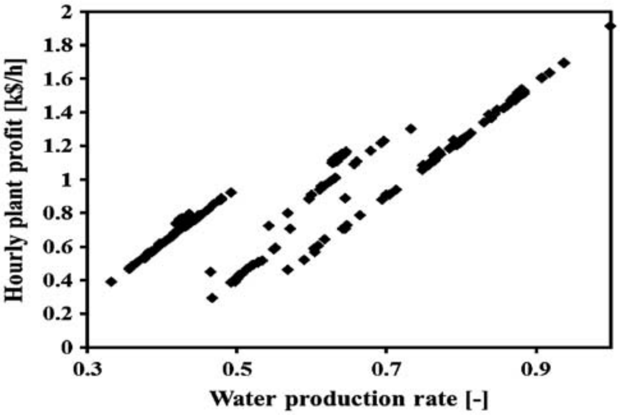

Fig. 3. Plant hourly profit for RO section.

- Continuously monitor KPIs, such as energy consumption and condition of membrane. Evaluate energy efficiency and important KPIs of key equipment. Track their operating performance, set benchmarks, and target improvements for achieving economic benefits.

The economic analysis (Fig. 3) showed that the hourly plant profit could be increased from ~0.1 up to ~1.8 kUSD/h by two-fold increase in production (for an approximated electricity cost of $0.06/kWh and product water cost of $0.5/m^3). The hourly plant profit is defined as Product flow × [Product cost − electricity cost]. The approximate total cost saving for RO plant was estimated as ~600 kUSD/year.

Based on the above preliminary energy assessment and economic analysis, a master plan was developed and the application of following advanced solutions was studied on customer plant data before implementation:

2.1. *OPTIMAX® MP tool*

The OPTIMAX® MP [3] was first used to tune the membrane model with the plant data obtained

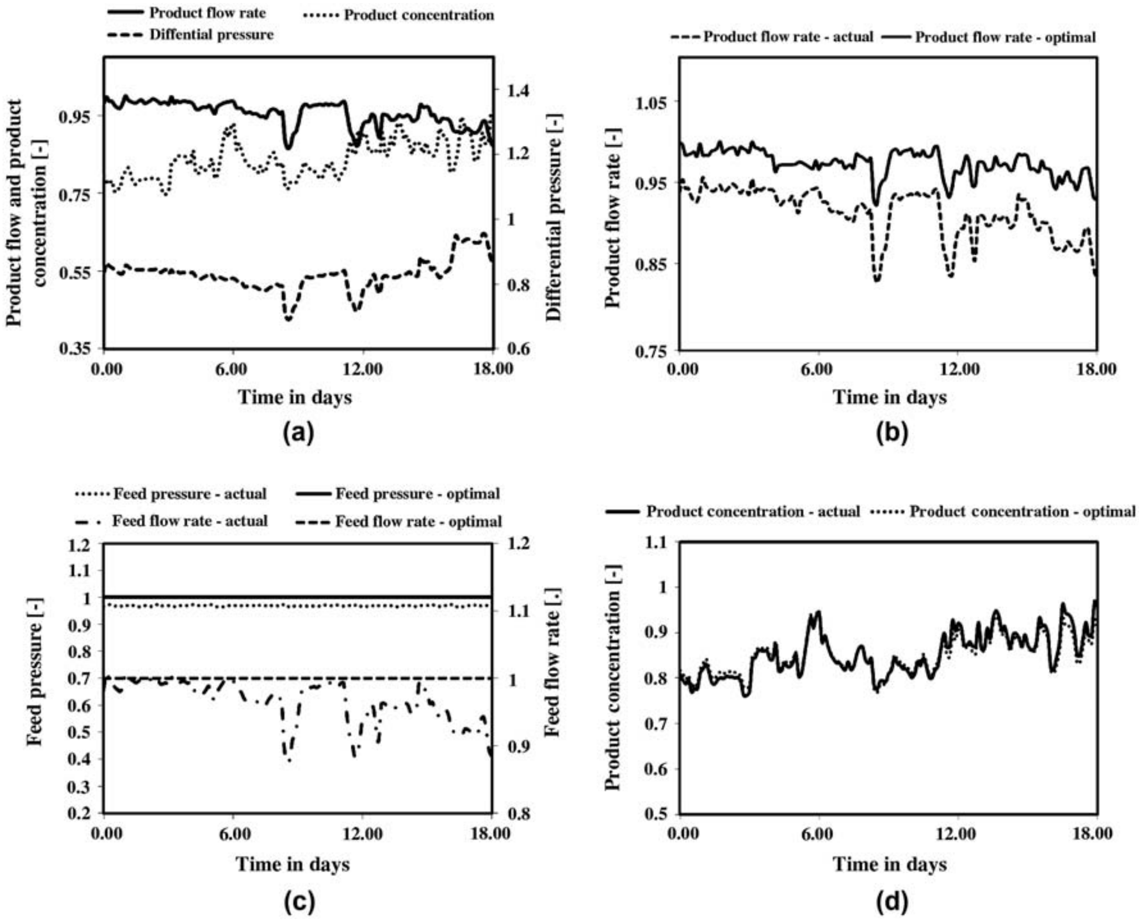

Fig. 4. Results from MP tool (a) effect of membrane fouling, (b) actual and optimal product flow rates, (c) actual and optimal feed flow and pressure, and (d) actual and optimal product concentration.

from step test experiments. Membrane fouling condition was then monitored for ~18 days of operation, and the optimal operating conditions were estimated to improve production. The membrane condition monitoring (Fig. 4(a)) revealed an increase of ~10% in differential pressure, a decrease of ~10% in product flow rate, and an increase of 18% in product concentration due to membrane fouling with time. The sharp drop in the values of these process variables at certain time instants were due to membrane flushing activity.

In the next step, the product flow rate was optimized considering the current membrane fouling status with constraints on product quality and membrane life. It was found that the product flow rate for both optimal and actual case was decreasing with time due to membrane fouling. Further, the optimal case showed that on an average, ~3% increase in product flow rate (Fig. 4(b)) was feasible.

The corresponding optimal feed flow and feed pressure of the membrane (Fig. 4(c)), showed that the feed pressure could be increased by ~4%, while the feed flow could be increased by ~3% on an average to improve the product flow rate. Further, it could be seen that the product quality (i.e. product concentration) at an optimal operating condition was maintained almost equal to its actual operating value before solution implementation (Fig. 4(d)).

An overall benefit of 820 kUSD/year was estimated, based on the excess water production at the rate of 0.5 USD/m^3 water. However, since most of trains (~50%) were standby due to limited demand, under pessimistic scenario, these benefits were reduced to ~400 kUSD/year.

2.2. DSS for RO desalination plants

Based on one of the identified opportunities, the DSS will be ideal to schedule the membrane cleaning/maintenance activities, and also to optimally distribute the production load between RO trains based on their fouling status. The DSS offered by ABB consists of several functionalities, namely, scheduler and load distributor. The scheduler provides the optimal schedules for membrane maintenance activities, such as chemical cleaning and membrane replacements, while

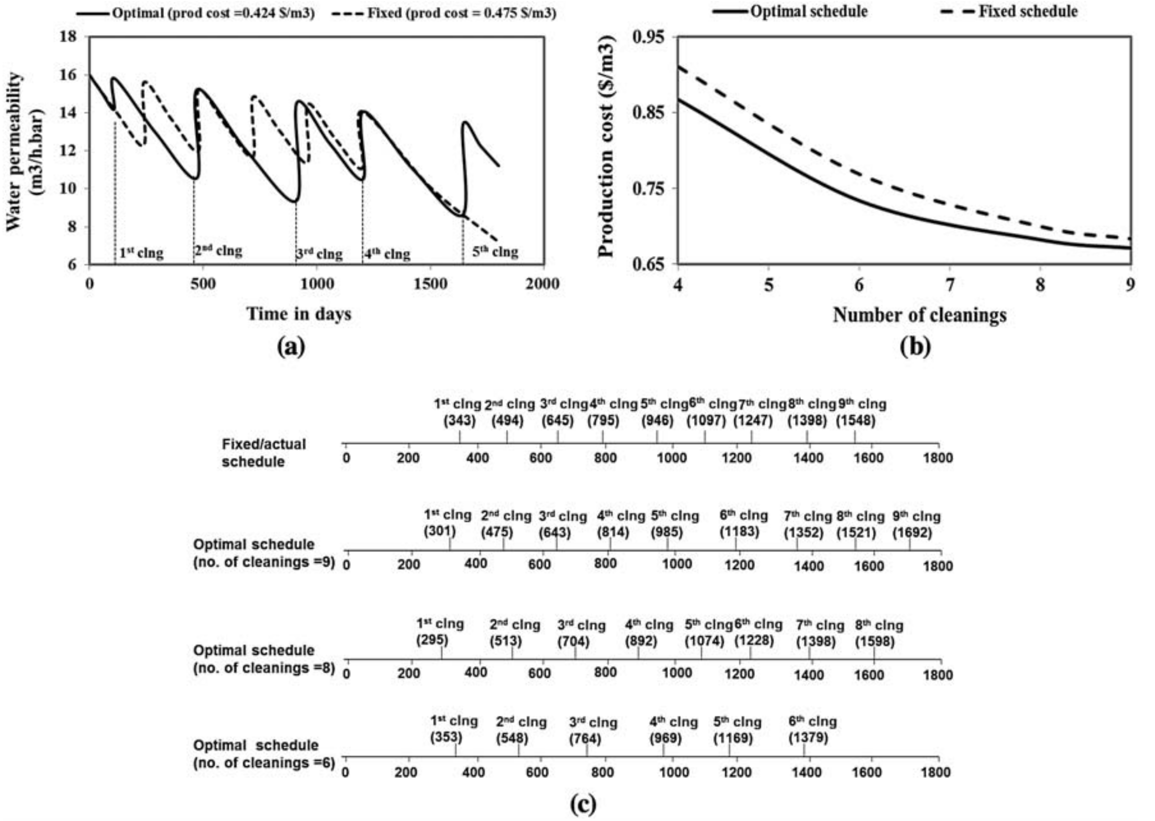

Fig. 5. Results from DSS tool (a) typical optimal schedule from scheduler, (b) comparison of production cost for optimal and fixed schedules, and (c) sensitivity of optimal schedules with number of cleanings.

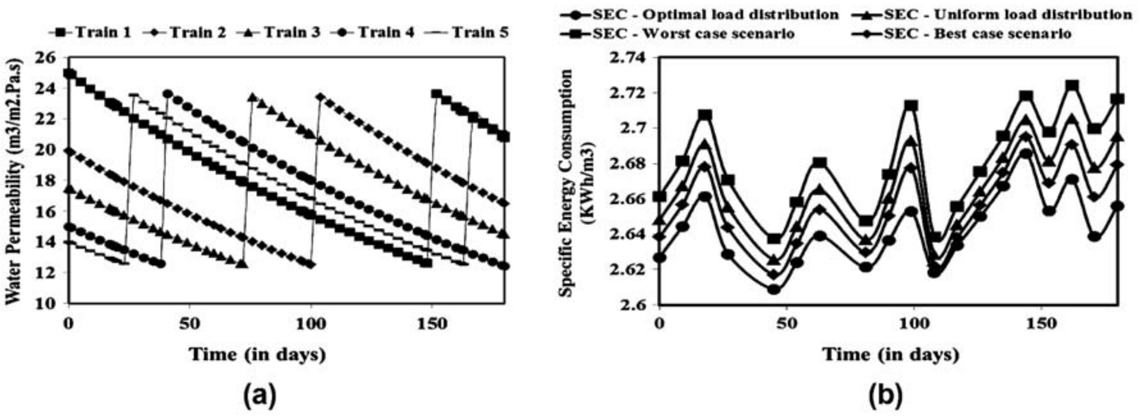

Fig. 6. Results from DSS tool (a) water permeability profiles for several RO trains in a RO section and (b) comparison of energy consumption–optimal distribution versus different scenarios.

the load distributor provides optimal production load distribution among RO trains.

The scheduler aims at minimizing the overall production cost while the load distributor targets at minimizing the energy consumption of the RO section. The typical optimal schedule generated by scheduler over a time horizon of 1,800 days is given in Fig. 5(a). Scheduler distributed the membrane cleanings in an optimal fashion over the time horizon to minimize the production cost.

Subsequently, the sensitivity of the optimal schedules with respect to number of membrane cleanings is given in Fig. 5(c). With increase in number of cleanings, the optimal schedule is coming close to actual/fixed schedule, since the scheduling time horizon is constant. The fixed schedule here refers to membrane cleaning at fixed interval of five months. Further, the production cost comparison of optimal schedule vs. fixed schedule with respect to the number of cleanings is given in Fig. 5(b). The result shows that optimal schedule is giving lower production cost (~6% on an average) compared to fixed schedules for different number of membrane cleanings.

Load distributor provides the optimal distribution of production loads across RO trains in the plant to minimize the energy consumption of the RO section. In general, fouling condition of the membranes in each of the RO trains is different, which results in different throughputs for the given operating conditions. The simulated water permeability of several RO trains over a period of ~6 months is shown in Fig. 6(a). Water permeability decreases with time due to fouling, and regains its value close to its initial value (at time = 0) when it gets cleaned with chemicals (for example, on 100th day for Train 2). In this study, load distributor is tested for a case consisting of five RO trains over the time horizon of ~6 months. The energy consumption corresponding to optimal load distribution and several other scenarios is given in Fig. 6(b). The scenarios considered for comparison are: (1) best case scenario where the operator distributes more load to the less fouled RO train and vice versa, (2) uniform distribution scenario in which the production load across all the RO trains are same, and (3) worst case scenario in which the operator gives more load to the more fouled RO train, and vice versa. The results (Fig. 6(b)) show that optimal distribution results in less energy consumption with a savings of 1.32, 1.61 and 2.00% when compared to best case, uniform distribution and worst case scenarios, respectively.

3. Conclusions

The ECA tool is used to evaluate KPIs like efficiency, load distribution, and fouling status of individual trains which indicated their performance. The tool identifies significant opportunities for energy efficiency improvements. Subsequently, based on the identified opportunities, advanced solutions like MP and DSS tools are evaluated. MP tool is successful in monitoring membrane fouling and calculating optimal operating conditions. Results of MP tool show that there is a scope to improve productivity by ~3%. Further, DSS tool which comprises of Scheduler and Load distributor functionalities is used to obtain optimal maintenance schedules, and production load distributions for RO trains. The results show that optimal cleaning and replacement schedules can reduce production cost by ~6%. In addition, optimal load distribution results in energy savings of ~1.6%.

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