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Analysis of High Recovery Brackish Water Desalination Processes using Fuel Cells

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Abstract: The production and supply of potable water and the disposal of wastewater are among the major challenges of the 21st century. Inadequate supply of potable water, coupled with increasing water demand in developing countries due to rapid population growth and industrialization are among the major reasons for the worsening water situation (1). Desalination of brackish water by reverse osmosis (RO) and nanofiltration (NF) are the leading technologies used in supplying potable water. Typically, these plants operate at 75% product water recovery so that 25% of RO feed water is wasted as concentrated brine. However, the recovery can be increased by processing the primary RO reject water with the aid of selective membrane processes such as a secondary RO or NF unit. Hybrid RO/NF processes were modeled using the membrane manufacturer's software for various membranes and for two specific brackish waters studied (total dissolved solids, TDS = 1700 and 3700 mg/1). The analyses show that 90% product water recovery is achieved for the low TDS feed water and 88% recovery is achieved for the high TDS feed water using simple, state-of-the-art hybrid membrane systems, and with minimal feed water chemical pre-treatment. It is also shown that the specific energy consumption of the RO system is reduced when it is powered by a stand-alone, on-site fuel cell power plant.

Keywords: Brackish water, desalination, fuel cells, high recovery, reclamation, RO/NF

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INTRODUCTION

Reverse osmosis (RO) membrane plants are used extensively for brackish water desalination and industrial water purification. The operating range of these plants – single-pass primary RO – is 60–80% product water recovery depending on the quality of raw water and feed water pretreatment. Typically, these plants operate at 75% recovery so that 25% of feed water is wasted as concentrated brine (2). For example, in the state of Texas, brine wastewater is generated @ 40,000 m^3/day from 100 brackish water desalination plants producing 160,000 m^3/day potable water. The disposal of brine streams containing high concentration of salts is becoming an environmental problem. Increasingly, RO plant owners are required to minimize brine discharge in order to obtain plant operating licenses from their local governments, and to reduce the high costs of disposing brine (3). Hence, modified membrane process designs are required to increase product water recovery to >90% (4,5). The functioning of a high recovery energy efficient membrane desalination system powered by a biogas fuel cell stand-alone power plant for maximizing potable water production, especially in rural areas of developing countries, is analyzed in this paper.

The performance of RO and NF membrane processes is typically determined by two key parameters, recovery and rejection defined below:

$$\%\text{Recovery, PWR} = \frac{\text{Product flow rate}}{\text{Feed flow rate}} \times 100$$

$$\%\ \text{Rejection, R} = \frac{\text{Feed solute concentration} - \text{Product solute concentration}}{\text{Feed solute concentration}} \times 100$$

Another useful expression for membrane rejection is (6)

$$\%\text{R} = [1 - (\rho.\ \text{B})/\text{A}(\Delta\text{p} - \Delta\pi)] \times 100$$

where, ρ is the density of water, g/cm^3, B is the salt permeability constant, A is the membrane permeability constant, Δp is the pressure difference across the membrane, and $\Delta\pi$ is the osmotic pressure differential across the membrane. The value of A is in the range of $3(10^{-3})$–$6(10^{-5})$ $m^3/m^2 \cdot$hr. bar for RO membranes and higher for looser NF membranes [$3(10^{-3})$–$2(10^{-2})$ $m^3/m^2 \cdot hr \cdot bar$]. The value of B is in the range of $5(10^{-3})$–$1(10^{-4})$ m^3/m^2 hr for RO membranes with NaCl as the solute (2).

The amount of product water (permeate) recovered is generally dependent on:

a. Total surface area of membrane within each vessel;
b. Membrane pressure supplied by the high pressure pump(s);
c. Reject flow rate; and
d. Feed water quality (2).

The recovery in each element is controlled by the concentration of rejected species to prevent the precipitation of sparingly soluble salts of calcium, magnesium, barium, strontium, and silica in the brine channel. Thus, when the product recovery is 50%, the salt concentration in the reject stream is doubled, whereas the salt concentration increases four-fold when the recovery is 75%. The salt concentration at the membrane surface is higher due to concentration polarization. Specifically, the β factor must be <1.2 where β = salt concentration at the membrane surface/salt concentration in the brine channel. The scaling potential due to these sparingly soluble salts is usually the highest in the last elements of the final stage. In brackish and hard waters, $CaCO_3$ and gypsum ($CaSO_4 \cdot 2H_2O$) are the most common scalants. Scaling is controlled by adding acid to lower the Langelier Saturation Index (LSI) to <0, by softening the water to remove calcium and magnesium ions, and/or by adding an anti-scalant. In order to prevent fouling, the Silt Density Index of RO feed water must be <4 and the turbidity must be <1.0 NTU, which requires raw feed water filtration.

RO membrane plants can be quite energy intensive; hence operation at a high product water recovery is desirable so that the high energy costs can be compensated by higher productivity. The specific energy consumption for brackish water RO plants operating at 70–75% recovery is $<0.75\,kWh/m^3$ whereas for seawater RO plants operating at 35–45% recovery is $2.9–3.7\,kWh/m^3$ (7,8). Because of high energy consumption and scarcity of water in many remote areas of the world, renewable energy based desalination systems such as solar stills have been built (9), and wind power as well as photovoltaic solar energy integrated RO plants have been investigated and commissioned (10–12). The largest wind powered seawater RO desalination plant with a capacity of 140,000 m^3/day was commissioned in Perth, Australia in 2007 (13).

In a recent study, the benefits of on-site distributed fuel cell systems integrated with membrane desalination systems were analyzed (7). The fuel cell system provided power to the desalination plant, and the fuel cell stack low-grade heat was used to preheat RO feed water and reduce RO system energy consumption.

Fuel cells are electrochemical engines that convert the available chemical free energy in a fuel, usually hydrogen and oxygen, to electrical energy directly without going through the heat-exchange process. Gaseous fuel is fed continuously to the anode where it gets oxidized and the oxidant—air or oxygen—is fed continuously to the cathode where it gets reduced. Electrochemical reactions take place at the electrodes to produce an electric current in the external circuit. The electrolyte separating the anode from the cathode conducts ions between the electrodes completing the electric circuit. The overall reaction of the electrochemical process with water and heat as the only byproducts is: $H_2 + \frac{1}{2}O_2 = H_2O + \text{Heat}$. Fuel cells operate at nearly constant efficiency (40–50%) independent of size; small plants are nearly as efficient as large ones.

A typical fuel cell power plant (14) consists of a fuel processor that reforms the fuel, e.g. natural gas or methanol to hydrogen, a multi-cell fuel cell stack (5 to 500 kW), a power conditioner that converts fuel cell d.c. power output to a.c. power, and a heat exchanger (for heating during startup and for removing heat due to irreversible losses). Since, fuel cell systems are modular on-site distributed power plants, they not only eliminate the costly installation of hundreds of miles of transmission lines but also mitigate extremely high losses (30%) incurred during transmission in developing countries. On-site desalination units have the added benefit of eliminating or reducing water losses due to leaks in transmission over long distances.

SYSTEM DESIGN BASIS

A schematic process flow diagram of a high recovery membrane system powered by a fuel cell system is shown in Fig. 1. A typical 200-kW phosphoric acid fuel cell (PAFC) unit generates enough power to supply electricity to nearly 150 households, and 226,800 kcal/hr of usable heat at 60°C (15) that is sufficient to heat 22.5 m^3/hr of RO plant feed water from 20°C to 30°C. The membrane system consists of a primary RO (PRO) unit and a brine recovery unit, which purifies the reject water from the PRO unit to provide additional purified water. The brine unit is either a secondary RO or a NF unit. The reject from the PRO unit is typically high in hardness ions. Low pressure nanofiltration is often used for water softening and seawater pre-treatment because the NF membranes have a high rejection of divalent ions and is less susceptible to fouling (16,17).

The membrane processes were modeled using Hydranautics Membrane Solutions Design Software v. 2007 for a low TDS brackish well water (south-east USA) and a high TDS brackish groundwater

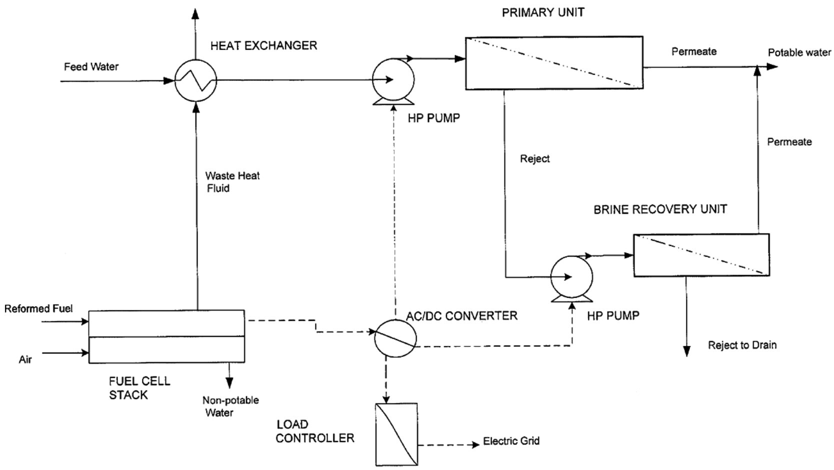

Figure 1. Schematic of a high recovery membrane desalination system. The primary RO unit operates at 75% recovery. The brine recovery unit operates at 50–60% recovery. Brackish feed water with TDS between 1500 and 4000 ppm is pre-heated and pre-treated. The fuel cell stack is rated for 200 kW, and is fed with reformed biogas fuel (hydrogen).

(south-west USA) given in Table 1. The performance projection data was based on membrane performance after 3 years run time. The RO and NF membranes were spiral-wound polyamide thin-film composite (TFC) elements. Feed water treatment was kept to a minimum; anti-scalant addition to maintain the Langelier Saturation Index (LSI) <1.8, and pH adjustment with acid to 6.7–7.0. Based on the membrane manufacturer's recommendations, the saturation limits with anti-scalants are as follows: $BaSO_4 = 6000\%$, $SrSO_4 = 800\%$ and $CaSO_4 = 230\%$. Silica solubility is increased to 300 ppm in the presence of a dendrimer anti-scalant (Professional Water Technologies, Vista, California). These saturation limits define the maximum product water recovery achievable depending on raw feed water quality and feed water pre-treatment (2).

Low TDS Brackish Water Systems Design Conditions

The Primary RO (PRO) System Design was based on the Following Conditions:

- Feed water flow rate = 22.5 m^3/hr
- Feed water total dissolved solids (TDS) = 1695 mg/1
- Feed water temperature = 20, 25, and 30°C

Table 1. Brackish water analysis*

	Low TDS Water		High TDS Water	
Ion	PRO Feed, mg/l	Brine unit feed, mg/l	BW-PRO Feed, mg/l	Brine unit feed, mg/l
Ca	140	557	204	809
Mg	10	39.8	92	365
Na	394	1541	896	3437
Sr	–	–	3.1	12.3
CO_3	0.2	0.7	0.2	0.8
HCO_3	232	896	327	1223
SO_4	350	1393	902	3574
Cl	521	2043	1156	4450
F	0.8	3.1	–	–
NO_3	1.0	3.5	–	–
B	0.8	0.8	–	–
SiO_2	10	39.4	32	124
TDS	1695	6655	3613	13997
pH	7.0	7.5	6.7	7.2

*Brine feed data is PRO/BW-PRO concentrate at 75% recovery based on Hydranautics membrane projections.

- Product water recovery = 75%
- Product water flux same for each temperature sub-set
- Hydranautics CPA2 membranes (20 cm diameter elements)

The Brine Recovery SRO System Design was based on the Following Conditions

- Feed water flow rate = 5.7 m^3/hr
- Feed water total dissolved solids (TDS) = 6655 mg/1
- Feed water temperature = 25°C
- Product water recovery = 50 and 60%
- Hydranautics CPA2-4040 membranes (10 cm diameter elements).

The feed water source was the reject stream from the PRO system operating at 30°C. The SRO feed water temperature was assumed to be 25°C accounting for heat losses. The SRO(I) unit is a single-pass, 3:2 two-stage membrane array designed for 50% product water recovery, and the SRO(II) unit is a single-pass, 4:2 two-stage membrane array when the recovery is 60%.

Brine Recovery SNF System Design

The design was based on the same conditions as the SRO case discussed above except the membrane elements were ESNA1-LF-4S (10 cm diameter). The feed water source as before was the reject stream from the PRO system operating at 30°C. The brine NF feed water temperature was assumed to be 25°C accounting for heat losses. The SNF unit was a single-pass, 4:2 two-stage membrane array designed for 60% recovery as in the case of SRO.

High TDS Brackish Water Systems Design Conditions

The Primary RO (BW-PRO) System Design was based on the Following Conditions

- Feed water flow rate = 22.5 m^3/hr
- Feed water total dissolved solids (TDS) = 3613 mg/1
- Feed water temperature = 20, 25, and 30°C
- Product water recovery = 75%
- Product water flux same for each temperature sub-set
- Hydranautics CPA2 membranes (20 cm diameter elements).

The membrane array design was identical to the lower TDS case discussed earlier. In all cases, the BW-PRO unit was a single-pass, two-stage membrane array (3:2).

The Brine Recovery BW-SRO System Design was based on the Following Conditions

- Feed water flow rate = 5.7 m^3/hr
- Feed water total dissolved solids (TDS) = 13,997 mg/1
- Feed water temperature = 25°C
- Product water recovery $<$50%
- Hydranautics CPA2-4040 and ESPA1-4040 (10 cm diameter membrane elements).

The feed water source was the reject stream from the BW-PRO system operating at 30°C. The BW-SRO feed water temperature was assumed to be 25°C accounting for heat losses. The BW-SRO unit is a single-pass, 3:2 two-stage array using CPA2-4040 membrane elements, and is a 4:0 single-stage array using ESPA1-4040 membrane elements.

RESULTS AND DISCUSSION

Primary RO System

The design and performance data are presented in Table 2. In all cases, the PRO unit was a single-pass, two-stage membrane array (3:2). The product water flow rate is $17\,m^3/hr$ at 75% recovery. The product water TDS increased 41% from 41 ppm to 58 ppm with increase in feed water temperature from 20°C to 30°C. Product water quality decreases (higher solute concentration in permeate or lower solute rejection) with rise in temperature due to higher osmotic pressure, and because solute flow has a higher activation energy than water flow (2,6). For solutions of predominantly NaCl, a rule of thumb is that the osmotic pressure is 0.69 bar per 1000 mg/1 concentration, e.g. the osmotic pressure of seawater (35,000 mg/1) is 23.1 bar.

The feed pressure and net energy required decreased by 18% when the feed water temperature increased from 20°C to 30°C at the same product water flux. The specific energy consumption decreased from $0.58\,kWh/m^3$ at 20°C to $0.48\,kWh/m^3$ at 30°C. The RO pump and motor efficiencies were 80% and 90%, respectively.

Brine Recovery SRO System

The design and performance data are presented in Table 2. The brine recovery system produced $2.8\,m^3/hr$ at 50% recovery and $3.4\,m^3/hr$ at 60% recovery, resulting in an overall (PRO + SRO) product water flow rate of $19.8\,m^3/hr$ and $20.4\,m^3/hr$, respectively corresponding to an overall product water recovery of 88% and 90%. The product water TDS increased 11% from 253 ppm to 281 ppm with increase in product water recovery due to higher concentration polarization when operating at the same flux. The concentration polarization coefficient, the β factor, increased from 1.1 to 1.16 where β = solute concentration at the membrane surface/solute concentration in the bulk fluid, and must be <1.2. The blended (PRO + SRO) product water TDS was between 86 ppm and 95 ppm.

The SRO feed pressure increased from 14.9 bar g to 15.4 bar g as the membrane array size increased at higher recovery. The SRO specific energy consumption, however, decreased from $1.18\,kWh/m^3$ at 50% recovery to $1.0\,kWh/m^3$ at 60% recovery due to higher product water throughput consistent with previous data (18). The combined (PRO + SRO) specific energy consumption at 90% overall product recovery was $0.56\,kWh/m^3$ compared to $0.58\,kWh/m^3$ for the PRO case at 75% recovery and 20°C. Thus, the PRO-SRO high recovery system is a substantial

Table 2. High recovery membrane system design and performance data

Case#	Membrane type**/ Membrane array^	Feed temp °C	Feed flow m^3/hr	Product flow m^3/hr	PWR %	Avg. flux $L/m^2.hr$	System overall PWR %	Feed TDS+ mg/l	Product TDS mg/l	Salt Rej. %	Blended product TDS mg/l	Feed press. bar g	RO/NF Motor power kW	Net power kW	Total@ specific energy kWh/m^3
PRO (I)	CPA2/3:2(A)	20	22.5	17	75	16.8	75	1695	41	97.6	n/a	11.4	9.9	9.9	0.58
PRO (II)	CPA2/3:2(A)	25	22.5	17	75	16.8	75	1695	49	97	n/a	10.3	8.9	8.9	0.52
PRO (III)	CPA2/3:2(A)	30	22.5	17	75	16.8	75	1695	58	96.6	n/a	9.3	8.1	8.1	0.48
SRO* (I)	CPA2-4040/3:2(B)	25	5.7	2.8	50	17.9	88***	6655*	253	96	86	14.9	3.3	11.4$	0.58
SRO* (II)	CPA2-4040/4:2(B)	25	5.7	3.4	60	17.9	90	6655*	281	95.8	95	15.4	3.4	11.5$	0.56
SNF*	ESNA1-LF-4S/4:2(B)	25	5.7	3.4	60	17.9	90	6655*	2167	67	410	10.3	2.3	10.4$	0.51
BW-PRO (I)	CPA2/3:2(A)	20	22.5	17	75	16.8	75	3613	106	97	n/a	14	12.2	12.2	0.72
BW-PRO (II)	CPA2/3:2 (A)	25	22.5	17	75	16.8	75	3613	127	96.5	n/a	13	11.3	11.3	0.66
BW-PRO (III)	CPA2/3:2 (A)	30	22.5	17	75	16.8	75	3613	152	95.8	n/a	12.2	10.6	10.6	0.62
BW-SRO* (I)	CPA2–4040/3:2(B)	25	5.7	2.6	46	16.5	87	13997*	529	96	202	21	4.6	15.2$$	0.78
BW-SRO* (II)	ESPA1–4040/4:0(C)	25	5.7	2.6	46	13.9	87	13997*	1443	90	324	17.2	3.8	14.4$$	0.73

#PRO = Primary RO; SRO = Brine recovery RO; SNF = Brine recovery NF.

*SRO/SNF feed is PRO (III) reject. BW-SRO feed is BW-PRO (III) reject.

**Hydranautics TFC membranes. Membrane age = 3 years.

^Two-stage array: (A) Six (20 cm dia) spiral-wound modules/vessel; (B) Four (10 cm dia) spiral-wound modules/vessel.

Single-stage array: (C) Six (10 cm dia) spiral-wound modules/vessel.

&PWR = Product water recovery.

***__System Overall PWR__ = [PRO product flow rate + SRO product flow rate]/PRO feed flow rate, e.g. (17 + 2.8)/22.5 = 88%.

+Total dissolved solids.

$Net power is PRO (III) + SRO, or PRO (III) + SNF.

$$Net power is BW-PRO (III) + BW-SRO. RO pump motor $\eta = 90\%$ and RO pump $\eta = 80\%$.

@Specific energy consumption = Net power/Product flow rate.

improvement over the standard primary RO case providing 20% more potable water at 3.5% less specific energy consumption.

Brine Recovery SNF System

The design and performance data are presented in Table 2. The product water TDS was 2167 ppm (rejection = 67%), which was substantially higher than the SRO case. The blended product water (PRO + SNF) TDS was 410 ppm compared to the PRO + SRO blended product water TDS = 95 ppm. The SNF feed pressure, however, was 33% less than SRO feed pressure at 60% recovery. The inferior blended product water quality, though within the US EPA's limit of 500 ppm, was compensated by lower specific energy consumption; 0.51 kWh/m^3 for the PRO-SNF system versus 0.56 kWh/m^3 at 30°C for the PRO-SRO system at the same productivity (20.4 m^3/hr) and product water recovery (90%). The high recovery PRO-SNF system is, thus, a substantial improvement over the standard PRO design at 20°C providing 20% more potable water at 12% less specific energy consumption.

Primary RO (BW-PRO) System

The design and performance data are presented in Table 2. The product water flow rate is 17 m^3/hr at 75% recovery. The feed pressure was higher than in the PRO case discussed in the previous section because of higher feed water TDS. The product water TDS increased 43% from 106 ppm to 152 ppm with increase in feed water temperature from 20°C to 30°C for reasons discussed in the previous section.

The feed pressure and net energy required decreased by 14% when the feed water temperature increased from 20°C to 30°C at the same product water flux. The decrease was less than the low PRO case discussed earlier possibly due to higher osmotic pressure. The specific energy consumption decreased from 0.72 kWh/m^3 at 20°C to 0.62 kWh/m^3 at 30°C. The RO pump and motor efficiencies were 80% and 90%, respectively.

Brine Recovery BW-SRO System

The design and performance data are presented in Table 2. The feed pressure decreased from 21 bar g to 17.2 bar g as the membrane array size decreased, and because of energy saving membranes ESPA1. The brine recovery system produced 2.6 m^3/hr at 46% recovery. Higher recovery was not possible due to calcium sulfate concentration in the reject exceeding the solubility limit. The overall (BWPRO + BWSRO) product water flow rate was 19.6 m^3/hr corresponding to an overall product water recovery of 87%. The product water TDS increased from 529 ppm to 1443 ppm when the standard CPA2 membrane was replaced with the lower rejection ESPA1 membrane elements. However, the blended (BWPRO + BWSRO) product water TDS was between 202 ppm and 324 ppm.

The combined (BWPRO + BWSRO) specific energy consumption was 0.78 kWh/m^3 when the brine recovery unit was a two-stage unit as compared to 0.73 kWh/m^3 for the single-stage unit with low energy ESPA1 membranes. The high recovery system is a substantial improvement over the standard primary RO (BWPRO) operation at 20°C providing 15% more potable water at comparable specific energy consumption in spite of very high BWSRO feed TDS.

Hybrid Membrane Plant Fuel Cell System Output and Application

As discussed above, energy required to heat 22.5 m^3/hr RO feed water is 226,800 kcal/hr. This requires one 200 kW PAFC system (15). Typically, 10–12% of fuel cell power is required for PAFC system parasitic needs (14). Hence, net fuel cell power available is 176 kW.

Low TDS Brackish Water Desalination System

For an RO system operating at 90% recovery [PRO(III) + SRO(II), Table 2], 12 kW is consumed by the RO high-pressure pumps. In addition, up to 16 kW is required to power raw feed water and product water pumps, other ancillary equipment, and general community needs. Thus, about 148 kW of net fuel cell power is available for a community of 100 households or ~1.5 kW per household. At 90% recovery, the membrane system is rated for 20.4 m^3/hr of desalinated water with a TDS of 95 mg/l. Assuming 10% of potable water is reserved for plant maintenance such as membrane cleaning and 50% is required for community needs, the remaining 40% would be available for personal household needs or about 490 liters per day per household assuming the membrane plant is in operation 6 hours per day.

High TDS Brackish Water Desalination System

For an RO system operating at 87% recovery [BWPRO(III) + BWSRO(I), Table 2], 16 kW is consumed by the RO high-pressure pumps. In addition, up to 16 kW is required to power raw feed water and product water pumps, other ancillary equipment and general community needs. Thus, about 144 kW of net fuel cell power is available for a community of 100 households or ~1.4 kW per household. At 87% recovery, the membrane system is rated for 19.6 m^3/hr of desalinated water with a TDS of 202 mg/l. Assuming 10% of potable water is reserved for plant maintenance such as membrane cleaning and 50% is required for community needs, the remaining 40% would be available for personal household needs or about 450 liters per day per household assuming the membrane plant is in operation 6 hours per day.

SUMMARY AND CONCLUSIONS

The design of high recovery membrane processes for brackish water desalination plants is presented. The analysis illustrates that high recovery membrane systems are capable of maximizing potable water production and, thus, reducing costly and environmentally unacceptable brine disposal problems. The desalting plant powered by a biogas powered stand-alone fuel cell power plant is an added advantage when operating water purification plants in developing countries. The results of several high recovery brackish water membrane systems design and analysis are summarized below:

1. The brine recovery membrane system raises the overall product water recovery from 75% without brine recovery to 87–90% with brine recovery.
2. The product water recovery of the brine system is in the 50–60% range for the lower TDS brackish water (1695 ppm primary RO feed) and <50% for the higher TDS brackish water (3613 ppm primary RO feed).
3. The brine system recovery is controlled by the concentration of silica and/or sulfate ions.
4. The brine stream volume is reduced by >50% when the brine system is deployed with minimal penalty vis-à-vis energy consumption. Consequently, the brine disposal problem is minimized substantially.
5. The PRO net power required decreases by 14–18% for the two brackish water cases when the feed water temperature is raised from 20°C to 30°C with waste heat from the on-site fuel cell power plant.
6. The specific energy consumption decreases with increase in feed water temperature when operating at the same flux because the feed pressure decreases.

7. The specific energy consumption decreases as the product water recovery increases from 50% to 60% recovery.
8. The specific energy consumption is lower with NF membranes for brine recovery albeit with a substantial increase in blended product water TDS equal to 410 ppm.
9. The specific energy consumption at 30°C increased by 6% for low TDS feed water and 17% for high TDS feed water when the brine recovery system is also in operation. However, this is compensated by an increase in product water flow of 15–20%.
10. The PRO product water TDS increases by 40–45% (the salt rejection decreases) with an increase in feed water temperature as expected. However, the penalty is inconsequential.
11. The high recovery system blended product water TDS varies between 86 ppm and 410 ppm when the brine system feed water TDS is 6615 ppm. The 410 ppm TDS potable water is produced when NF membranes are used. The high TDS product water is, however, within the EPA's drinking water guidelines of <500 ppm.
12. The high recovery system blended product water TDS varies between 202 ppm and 324 ppm when the brine system feed water TDS is 13,997 ppm. The higher TDS (324 ppm) potable water is a result of using lower rejection RO membranes.

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