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Heating seawater: the solution or the pipe dream of reverse osmosis electrical consumption

Sébastien Delagarde*, Sophie Bertrand

Degremont SA, 183 Avenue du 18 Juin 1940, 92 508 Rueil-Malmaison CEDEX, France,
emails: sebastien.delagarde@degremont.com (S. Delagarde); sophie.bertrand@degremont.com (S. Bertrand)

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ABSTRACT

The desalination market based on reverse osmosis is a growing market thanks to much lower energy consumption compared to thermal desalination. This leading position implies that a lot of efforts should be done to improve both its acceptability and cost to thwart its detractors. For those reasons, the further improvement of the energy consumption is a key factor and one of the main objectives of the desalination community. It is well known that temperature has an impact on membranes' feed pressure. For equivalent feed water quality and operational conditions, high temperature water will require less pressure to produce the same amount of permeate. Based on this reality, some projects are considering the opportunity to recover cooling waters from cooling towers or MSF/MED cooling system as seawater feed to RO plants to reduce electrical consumption, in particular on hybrid, IWPP, or co-location projects. But temperature has also an adverse effect on the permeate water quality that could result in increasing the 2nd Pass flow requirement or the use of tighter membranes. The present paper analyses the impact on electrical consumption and design of the complete RO plant using a heated seawater source. Through case studies based on typical middle east seawaters, 41 g/l and 45 g/l and two different permeate water quality targets, 200 mg/l and 500 mg/l TDS, it attempts to conclude if overall benefits can be identified in such conditions.

Keywords: Electrical consumption; Heating; Seawater; Reverse osmosis; Salt passage; Compaction; Hybrid

1. Introduction

Population growth and increased water scarcity has promoted, in a lot of countries, seawater desalination as a major solution to increase freshwater production capacity. Since the first desalination plant implementing reverse osmosis in 1974, the evolution of the technology has brought it to the first position in terms of alternative water sources in coastal areas, as its energy requirement is much lower than thermal technologies MSF or MED. Therefore, reverse osmosis desalination attracts a lot of public attention. For all the reverse osmosis desalination business, cost and

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*Corresponding author.

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environmental impact reduction are a must to further improve it acceptability.

With 30 to 50% of the desalinated water cost and up to 95% of the carbon footprint of reverse osmosis desalination plant [1], electricity is one of the main focuses.

The rapid decrease of electrical consumption in seawater desalination plants in the last 20 years has been possible mainly due to the improvement of reverse osmosis membranes, the use of energy recovery systems (with further improvement with the development of isobaric recovery systems), and the improvement of the pump efficiencies.

It's well documented that reverse osmosis feed pressure is impacted by the feed water temperature [2]. Therefore, as a first assumption, the choice of using heated water could improve the required feed pressure and lead to lower electrical consumption.

But the higher temperatures also lead to lower water quality, which is potentially requiring further treatment on the 2nd Pass or tighter membranes on the 1st Pass to achieve the required permeate quality.

Taking both effects into consideration, does a heated seawater source produce real gains for seawater reverse osmosis desalination?

2. Basic evolution of reverse osmosis performances

2.1. Effect on pressure

For reverse osmosis membranes the change in temperature results in the change of feed pressure (all other operating conditions remaining the same). This is due to the change in the rate of diffusion through the membranes.

This impact is clearly expressed in the formulas used for calculation of the permeate flow with the temperature correction factor [3] where:

Permeate Flow calculation formula:

$$Q_i = A_i \bar{\pi}_i S_E (\mathrm{TCF})(\mathrm{FF}) \left(P_{fi} - \frac{\Delta P_{fc\,i}}{2} - P_{pi} - \bar{\pi} + \pi_{pi} \right) \quad (1)$$

where:

Q_i	permeate flow of element i (m3/d).
$A_i \pi_i$	membrane permeability at 25° for Element i, a function of the average concentrate-side osmotic pressure ($m^3/d/bar$).
S_E	membrane surface area per element (m).
FF	membrane fouling factor.
P_{fi}	feed pressure of element i (bar).
$\Delta P_{cf\,i}$	concentrate-side pressure drop for element i (bar).
P_{pi}	permeate pressure of element i (bar).
π	average concentrate-side osmotic pressure (bar).
π_{pi}	permeate-side osmotic pressure of element i (bar).
TCF	temperature correction factor for membrane permeability.

Temperature correction factor (TCF):

$$\mathrm{TCF} = \exp\left(\mathrm{MembraneTempCoeff} \times \left(\frac{1}{298.16_{(25^\circ\mathrm{C})}} - \frac{1}{{}^\circ\mathrm{K}_{\mathrm{actual}}} \right) \right) \quad (2)$$

where MembraneTempCoeff is depending on membranes supplier and temperature range and °K is expressed in Kelvin.

As an example, for a salinity of 45,000 mg/l of TDS and a recovery of 42%, the required feed pressure can vary by more than 10% (Table 1).

2.2. Effect on salinity

The reverse effect of the feed water temperature increase is that when pressure is reduced the salt passage is increasing [3].

Salt Passage calculation formula:

$$C_{p\,j} = B(C_{fc\,j})(pf_i)(\mathrm{TCF}) \frac{S_E}{Q_i} \quad (3)$$

where:

C_{pj}	TDS concentration in permeate of element i (mg/l).
B	salt diffusion coefficient.
$C_{fc\,j}$	average concentrate-side concentration for Element i (mg/l).
pf_i	concentration polarization factor for element i.
TCF	temperature correction factor for membrane salt passage.
Q_i	permeate flow of element i (m^3/d).
S_E	membrane surface area per element (m^2).

This becomes more evident using the example of water having a salinity of 45,000 mg/l of TDS and a recovery of 42%, the permeate TDS is more than triple between 10 and 30℃ (Table 2).

Table 1
Example of membrane pressure evolution with temperature

Temperature	℃	10	15	20	25	30
Pressure	Bar	73.2	70.1	68.3	66.6	66.0

Table 2
Example of permeate TDS outlet evolution with temperature

Temperature	℃	10	15	20	25	30
Permeate TDS	mg/l	96	129	172	227	295

2.3. *Effect on pressure due to compaction*

During operation, the membranes are exposed to high pressure which tends to compact the membrane, increasing the membrane density [3]. As a result of this density increase the pressure required to process the same amount of water is increased.

This parameter is considered by the membrane supplier with the ageing of the membrane and the flux decline.

However, the compaction is increasing with the temperature (Table 3), this parameter is directly included in only one supplier simulation software but all suppliers are considering this effect either by modifying their flux decline per year or modifying their replacement rate (to compensate for extra flux decline).

3. Case studies

To have a better view of the interaction of those parameters, we will review 2 cases studies comparing the electrical consumption of the system with and without pre-heating of the water using an available cooling water source.

The co-location of the reverse osmosis plant with a MSF/MED plant or power plant could also have the Capex benefits by the reduction of the intake and discharge using cooling water feed [4]. The drawback is the use of continuously chlorinated water as feed to the membrane while known as inducing biofouling on the membranes.

The comparison, however, will be limited to the power requirement and water quality will be considered as unchanged: no salinity increase, no presence of chemical requiring special treatment, and the hot water does not induce a higher biological activity. The temperature is the only parameter considered modified by the use of this water.

For the 2 case studies, we considered that the temperature differential between the seawater and the heated water remains constant over the entire temperature range for simplification purposes.

For those 2 case studies, we will consider a desalination plant producing 100,000 m^3/d of permeate water, the design flux and recovery of the trains will remain unchanged, the type of membranes will be the only parameter modified for the exercise.

Table 3
Example of membrane feed pressure evolution with different maximum temperature

Temperature	℃	10	15	20	25	30
Feed pressure (without hysteresis)	Bar	73.2	70.1	68.3	66.6	66.0
Feed pressure (including hysteresis with T_{Max} 35℃)	Bar	78.7	73.7	70.4	68.1	66.7
Feed pressure (including hysteresis with T_{Max} 40℃)	Bar	80.3	75.3	71.7	69.1	67.5

3.1. *Case study 1*

This case study will consider that the desalination plant is located in the Arabian Gulf. Arabian Gulf waters are characterized by high TDS value and a wide range of temperature (Fig. 1).

Feed water TDS taken into consideration for the simulations is 45,000 mg/l at membrane feed (Table 4).

The water quality objective is limited to the TDS that should be less than 500 mg/l at the membrane outlet. Taking into account the safety factor on TDS of 1.35 the simulation targeted value is 370 mg/l.

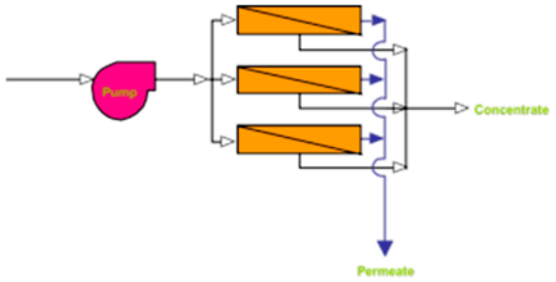

Fig. 1. Single pass plant design.

Table 4
Water analysis for Arabian Gulf water simulation

Parameters	Value	Parameters	Value
Ca^{2+}	510 (mg/l)	CO_3^{2-}	9 (mg/l)
Mg^{2+}	1,640 (mg/l)	HCO_3^-	165 (mg/l)
Na^+	13,850 (mg/l)	SO_4^{2-}	3,445 (mg/l)
K^+	500 (mg/l)	Cl^-	24,840 (mg/l)
Sr^{2+}	9.6 (mg/l)	F^-	1.5 (mg/l)
pH	7.8	B	5.5 (mg/l)

The seawater temperature range is from 15 to 35°C, taking into account that the cooling water temperature will be maintained 5°C above the seawater temperature, therefore, the range of design for the heated water will be 20 to 40°C.

To maintain the water quality at higher temperature the design required a tighter membrane (Table 5).

We can see that to keep the same permeate TDS outlet, in the case of the heated water we have to take tighter membranes. In addition to tighter membranes the compaction based on the maximum temperature of 40°C produces additional disadvantages to the heated water solution by increasing the compaction.

We can see that the heated water leads to an increase of pressure of about 2 bars on all range of operation (Fig. 2).

3.2. Case study 2

For the second case study we will consider that our desalination plant is located in the area of the Gulf of Oman (Fig. 3).

Feed water TDS taken into consideration for the simulations is 41,000 mg/l at membrane feed (Table 6).

The water quality objective is limited to the TDS that should be less than 200 mg/l at the membrane

Table 5
Design summary for Arabian Gulf Waters example

		Seawater design	Heated water design
TDS at max temperature	mg/l	370	
Recovery	%	40	
Flux	lmh	13.9	
Flow factor	–	0.8	
Temperature range	°C	15–**35**	20–**40**
Type of membranes	–	3 × SW30XHR + 4 × SW30XLE	6 × SW30XHR + 1 × SW30HRLE
Pressure at max temperature	Bar	63.7	65.9
Pressure at min temperature	Bar	71.2	74.0

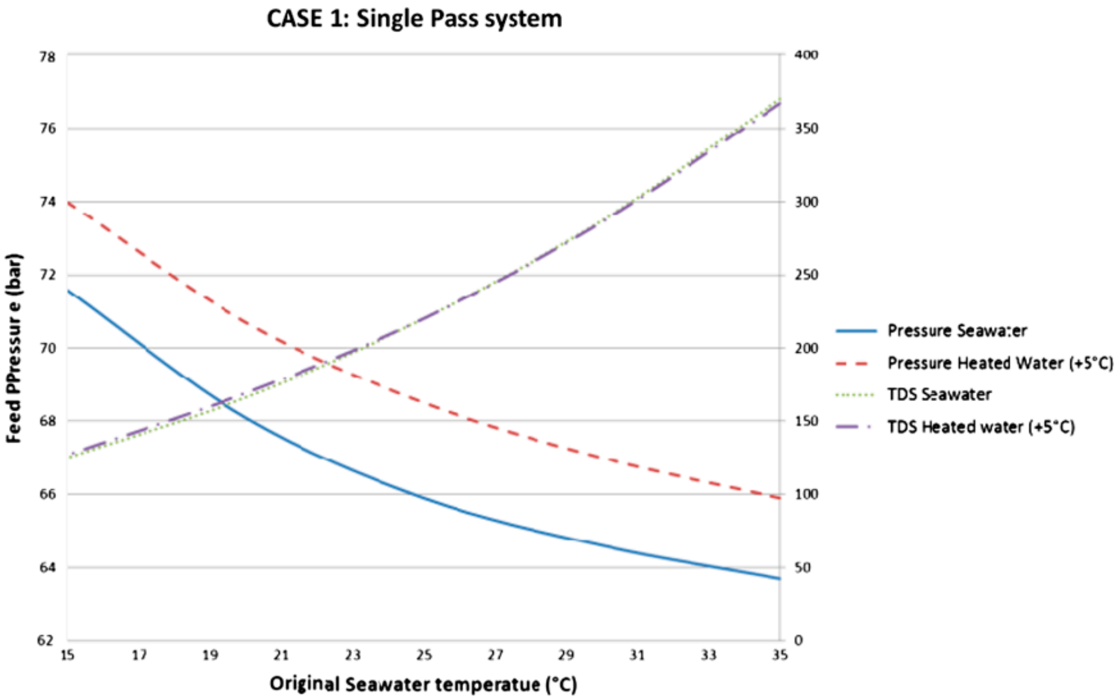

Fig. 2. Pressure and salinity comparison for Arabian Gulf example.

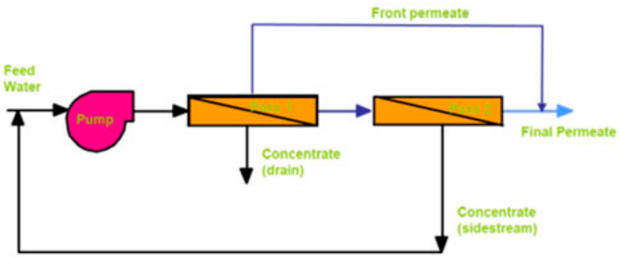

Fig. 3. Two pass split plant design.

Table 6
Water analysis for Oman Gulf water simulation

Parmeters	Value	Parmeters	Value
Ca^{2+}	465 (mg/l)	CO_3^{2-}	14 (mg/l)
Mg^{2+}	1,495 (mg/l)	HCO_3^-	150 (mg/l)
Na^+	12,610 (mg/l)	SO_4^{2-}	3,130 (mg/l)
K^+	460 (mg/l)	Cl^-	22,640 (mg/l)
Sr^{2+}	8.7 (mg/l)	F^-	1.4 (mg/l)
pH	7.8	B	5.0 (mg/l)

outlet, taking into account the safety factor on TDS of 1.35 the simulation targeted value is 150 mg/l.

The temperature for non-heated water is ranging from 22 to 33℃, taking into account that the cooling water temperature will be maintained at 5℃ above the seawater temperature therefore the range of design for the heated water ranges from 27 to 38℃.

To maintain the water quality at higher temperature, the split ratio is reduced to compensate for the water temperature.

We can see that the feed pressure on the First Pass is lower in the case of the heated water due to the higher temperature but at the same time the flow to the 2nd Pass is much higher. This induces a different design for the two solutions with more 2nd Pass membranes, in relation with flow difference (30%) (Table 7).

Normal seawater curve is passing by a minimum electrical consumption around 26℃ and increases at the same time as the temperature. At high temperature the increase of flow on the 2nd Pass overcomes the advantage of the reduction of pressure.

The heated water being 5℃ warmer than normal seawater, thus the curve is only the 2nd part where the increase of 2nd Pass flow is detrimental to the electrical consumption (Fig. 4).

The difference between the value of heated seawater at 22℃ and the normal seawater at 27℃ being the excess of compaction between that observed at 33 and 38℃.

4. How to make it interesting

From those 2 examples the interest of the heated water for RO seems limited as the sole source of water but the trends of simulation show that warm water could be of interest if limited to specific times and designs.

For single pass, the use of heated seawater is beneficial up to the maximum temperature of the seawater. For the maximum temperature the use of only seawater limits ability to not use tighter membranes. At low temperature we take the full benefit of heated water by reducing the required pressure of the membrane. The water can also be a mix of both waters allowing to get as close as possible to the maximum temperature without exceeding the maximum seawater temperature (Fig. 5).

For multiple pass systems the same arrangement could be used but in this case much more dependent on the design and the power curve shape to reveal any benefits.

Table 7
Design summary for Oman Gulf Waters example

		Seawater design		Heated water design	
TDS at max temperature	mg/l	150			
Recovery	%	45% (1st Pass)/90% (2nd Pass)			
Fux	lmh	13.7 (1st Pass)/<33 (2nd Pass)			
Flow factor	–	0.8 (1st Pass and 2nd Pass)			
Temperature range	℃	22–33		27–**38**	
Type of membranes	–	SW30HRLE/BW30HR		SW30HRLE/BW30HR	
		Max *T*	Min *T*	Max *T*	Min *T*
Pressure 1st Pass	Bar	61.2	64.6	61.1	63.3
Pressure 2nd Pass	Bar	9.5	8.1	10.4	9.5
Split ratio		70%	90%	61%	82%

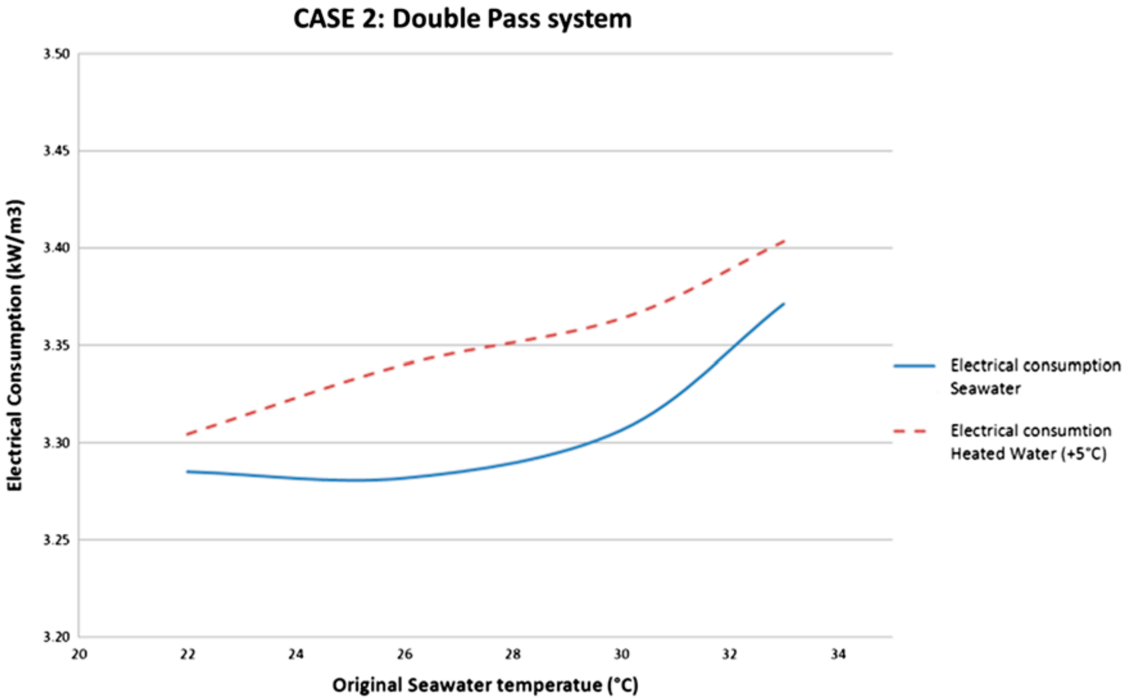

Fig. 4. Electrical consumption comparison for Oman Gulf example.

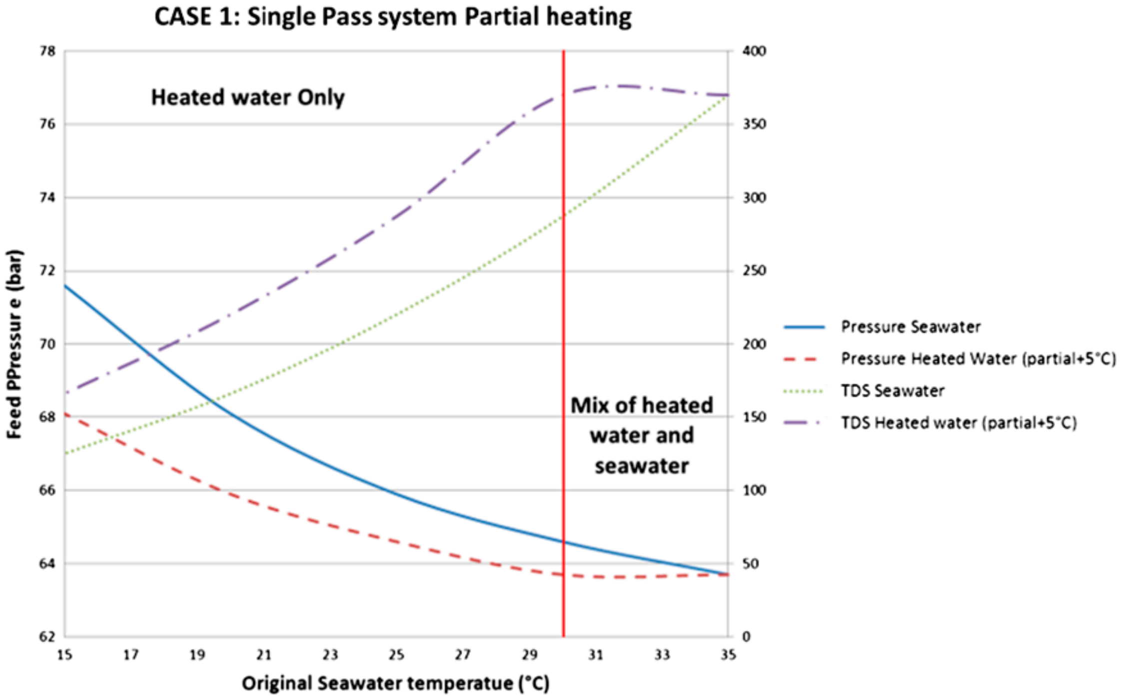

Fig. 5. Optimized use of heated water for single pass.

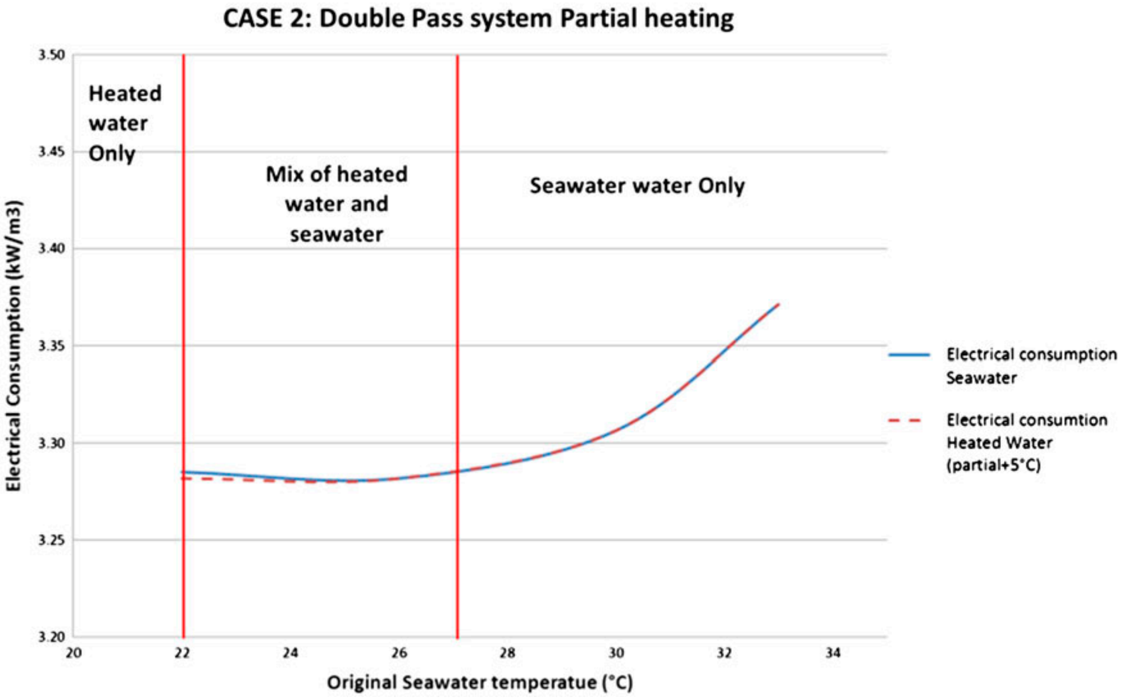

Fig. 6. Optimized use of heated water for double pass.

For a double pass system, the use of heated seawater is beneficial until the temperature of the seawater reaches the temperature of minimum electrical consumption. Above this temperature the use of only seawater produces improved electrical consumption (Fig. 6).

5. Conclusion

The benefits of heating seawater is limited when considered as a sole source of water for the energy purposes even so the Capex of the overall facility could be reduced by the simplification of the intake system and brine discharge.

The partial use of heated water (limited to period of the year when temperature is low) can be of interest. The final evaluation on the mixed water solution should be done comparing benefits (reduction of electrical consumption) and drawbacks (cost associated with the necessity to extract water from 2 different sources).

This study intentionally avoided the discussion on the water quality and the potential risk linked with utilizing a heated seawater source, as most of the time these cooling waters are continuously chlorinated to prevent biological growth in the cooling system. However, continuous chlorination/dechlorination is well known to induce biofouling on reverse osmosis membranes. The potential presence of other chemicals injected in the cooling system or discharged into the cooling water outfall could also be detrimental to RO membranes.

It also does not consider the advantage of the reduction of Capex linked with the removal of intake structure and discharge structure in some cases.

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