Effect of temperature on energy consumption and recovery rate of the reverse osmosis brackish systems in a different arrangement

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Abstract

One of the first water treatment technologies that used by humans is reverse osmosis. It has become a sustainable alternative solution to the concern of water scarcity in the current conditions of the world. In this research, the effect of temperature and pH on efficiency, energy consumption, and outlet water quality from simple single-stage reverse osmosis systems, single-stage hybrid, simple two-stage, and two-stage hybrid are investigated with reverse osmosis software. The results depicted that at all temperatures, the two-stage reverse osmosis system is more efficient in terms of efficiency, and the hybrid two-stage system has the best performance in terms of energy consumption. Also, the pH of the water entering the system has no effect on the efficiency and energy consumption of desalination plants. In terms of water quality, all four desalination plants have reduced the concentration of harmful ions to the desired level, but single-stage systems performed better than two-stage systems. In terms of corrosion index, two-stage systems performed better than single-stage systems. Also, the corrosion rate of water can be significantly reduced by increasing the temperature and adding sodium hydroxide. Also, obtained results showed that by increasing the temperature, the operating pressure in the RO system is decreasing.

Keywords: Reverse osmosis; Temperature effect; ISD; Energy saving; Membrane efficiency analysis;

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1. Introduction

Today, the human need for fresh water is obvious. Many people around the world encounter the challenge of fresh water. In many parts of the world, due to global warming and industrial development, especially in developing countries, they encounter water shortage or polluted water problems [1, 2]. Meanwhile, the Middle East and central regions of the Iranian plateau have worse conditions than other regions due to drought and lack of adequate rainfall [3-5]. In recent years due to lack of rainfall, successive droughts, and uncontrolled increasing water consumption, the need for rational and long-term solutions to address the problem of fresh water shortage has been raised as a new concern and challenge [6, 7]. Seawater and other saline waters are not suitable for direct human consumption, agricultural and industrial purposes [8, 9]. According to the World Health Organization (WHO) standards, the maximum allowable total dissolved solids (TDS) in water are about 500 ppm. However, these materials in saline water have TDS in the range of 10000-45000 ppm. Therefore, fresh water shortage in many areas is met by the desalination of saline water [10, 11].

Nowadays, desalination of seawater and brackish are useful processes against the shortage of freshwater resources on a global scale [12,13]. Water desalination has become a life-saving technology, especially in the Middle East and Africa, where rainfall is insufficient [14, 15]. According to technological advances and cost trends, the most popular commercial desalination processes are multi-effect distillation (MED), multi-stage flash distillation (MSF), vapor compression (VC), reverse osmosis (RO), and electrodialysis (ED) [16, 17]. It has been found that almost all the energy consumption of conventional desalination units was obtained from the combustion of fossil fuels [16-20]. Consumption of fossil fuels contributes to global warming and acid rain by emitting greenhouse gases (GHG) and other harmful emissions [21].

Other emerging low-consumption desalination technologies are still in research and development and have not been scaled for commercialization. These technologies include membrane distillation (MD),
forward osmosis (FO), capacitive deionization (CDI), reverse pressure osmosis (PRO), and adsorption desalination (AD) [22-24]. According to the World Water Organization (GWI) DesalData, a total of $ 93700 million will be spent on water desalination projects over the next four years [25]. Approximately $ 51600 million is allocated just for operating expenses. As demonstrated in Fig. 1, approximately 50% of operating costs spent on thermal and electrical energy [25, 26].

The amount of energy required for the desalination process depends upon the quality of the feed water, the level of water treatment, the treatment technology used by the center, and the capacity of the unit [27]. Table 1 shows the different energies required to obtain one cubic meter of drinking water when purifying water from different sources. The dependence of water treatment on energy, as well as the significant amount of energy consumption for drinking water supply, is quite clear. In 2019, the amount of water treatment in newly established desalination units was almost twice as much as units built in 2018 [25, 28]. This continuous increasing trend in water treatment by desalination plants leads to increased energy consumption and costs. Therefore, the need for research and development to reduce energy consumption and achieve higher efficiency in industrial systems is essential [29].

In general, desalination technologies consist of thermal and membrane separation processes. Both thermal and membrane-based processes are essential for fresh water supply, therefore reducing their energy demand through research advances is significant for both [30]. Thermal desalination technologies require higher energy and costs maintenance, which make them less attractive [31]. In some parts of the world, such as the Persian Gulf, the use of thermal desalination plants is still expected due to high access to oil for energy supply. However, interest in RO-based desalination has increased in recent years in the Persian Gulf region due to significant technological advances [32, 33]. One of the most economical industrial methods of water desalination is the RO system, according to Fig. 2, approximately 69% of water desalination are fulfilled in this way [34]. In the RO systems, high-pressure pumps are commonly used, which leads to high energy consumption, so achieving an optimal amount of energy in such systems is essential. It is worth noting that in marine systems, the amount of
energy consumption is much higher [35]. Due to the difficulties in high recovery processes for single-stage RO systems, the hybrid and multi-stage systems have recently been proposed as suitable designs for the RO process [36, 37].

Agashichev et al. investigated temperature parameters and several hydrodynamic parameters on the efficiency of treated water and energy consumption in RO systems. The results have represented that increasing temperature has increased efficiency and reduced energy consumption [38]. Goosen et al. investigated the effect of temperature on water treatment in polymer membranes. Their results showed that polymer membranes are susceptible to temperature changes. Their results also demonstrated that by increasing temperature from 20 °C to 40 °C, the rate of purified water flux increased to 60%. Zhao Jin et al. experimentally and theoretically modeled the effect of temperatures of 15, 25, and 35 °C on the rate of filtered water, yield, mass transfer, and sediment level in both types of brackish membranes. Their results depicted that increasing the temperature increases the amount of treated water and reduces energy consumption [39]. Their results demonstrated that increasing the temperature has increased the amount of water treatment and reduced energy consumption [40]. Molina et al. tested two low-energy and high-efficiency marine membranes from Dow, FILMTEC, designed with ISD in four different geographical areas. They demonstrated that ISD systems caused less energy consumption, increased flux, and higher efficiency. They also depicted that these designs resulted in dimensional optimization of the RO system, pre-treatment system, and inlet feed pressure [41].

Mustaqimah et al. reported a single and two-stage RO system modeling. The findings depicted that by increasing feed pressure, the TDS of the product water has increased. The amount of water produced and recovered by two-stages TDS was more considerable than single-stage [42]. Peñate et al. reported a hybrid membrane design in the entering stage, which was a new method for the RO system. The results depicted that HID \(\text{(hybrid Inter design)}\) could increase the capacity of the RO system plants [43].
Hong et al. designed a new single-stage split partial single-pass structure. They mixed the output water from the downstream membranes in the pressure vessel (PV) with the input feed water. They showed that the highest energy efficiency is when the water leaving the last membranes is returned and mixed with the feed water. They also depicted that this design has 15% better water quality than conventional single-pass RO systems with uniform flux distribution, less sedimentation rate, and high operating conditions concerning the marine RO system [44]. Kim et al. used a hybrid marine RO system to improve water quality and energy efficiency. They designed various hybrids with three different types of commercial membranes to achieve a cost-effective relationship between energy consumption and purified water quality [1].

Karabelas et al. investigated the effect of temperature at range 15-40 °C on energy consumption. The obtained results showed that energy consumption was decreased in the RO brackish. Also, in the seawater system, increasing the temperature causes osmosis pressure to increase. So, energy consumption just decreased in the 30°C. Furthermore, by increasing the temperature, salt rejection decreases in the Brackish and seawater system [45]. Mujtaba et al. investigated energy recovery devices (ERD) on the energy consumption of APC via gPROMS software. The obtained results showed that energy consumption at the low feed flow rate, low pressure, and also high temperature decreased [46]. Alanezi et al. investigated the effect of energy recovery devices and pretreatment on the RO system. The obtained results showed that the RO system with ERD could be useful in the high feed flow and low recovery value [47].

Hong et al. represented a novel concept that coupling membrane capacitive deionization (MCDI) and reverse electrodialysis (RED) with two-pass reverse osmosis (RO) to treat for BWRO. Under optimized operation conditions, the obtained results showed that the energy consumption of this RO-MCDI-RED hybrid system was declined by 39.0%. Also, the energy
consumption decreased to 16.8% compared to conventional two-pass RO systems without and with RED [48]. Diallo et al. presented an energy-efficient hybrid desalination process for high salinity brackish water. This novel design integrates flow capacitive deionization (FCDI) with nanofiltration (NF). The experiments and energy calculations showed that the energy consumption of the new FCDI-NF unit was lower by 16–20% than the best-reported energy consumption. Also, the obtained results showed 1-stage practical minimum energy consumption of the brackish water reverse osmosis (BWRO) unit treating the same feed at 70% water recovery, at the final total dissolved solids (TDS) were in the drinking water range [49]. Gao et al. proposed a hybrid RED/ED system for simultaneous osmotic energy recovery and complete desalination in the phenol-containing wastewater treatment process. Comparing obtained results with artificial seawater showed more power generation was produced by using phenol-containing wastewater as the high-salinity stream. Their finding suggested that average power generation and limiting wastewater treatment capacity would provide insightful guidelines for the design and improvement of the hybrid system [50]. Elimelech et al. proposed system-scale models to analyze the energy consumption and energy efficiency of Capacitive deionization (CDI) and RO at a wide range of material properties and operating conditions. The results showed that at higher salinity feed streams and higher salt rejection values, RO was significantly more efficient than CDI. Furthermore, brackish water with a salt concentration of 2000 mg L$^{-1}$, with an average water flux of 10 L m$^{-2}$ h$^{-1}$, achieved 50% water recovery and 75% salt rejection, respectively. Also, CDI required significantly specific energy consumption more than eight times than the RO [51]. Hong et al. investigated high specific energy consumption (SEC) of seawater reverse osmosis
(SWRO). The analysis presented the increasing number of large-size SWRO plants, the SEC reduced by isobaric energy recovery devices (ERDs). The obtained result showed that high salinity increased energy demand, whereas energy consumption was not affected by the temperature entirely clear. Also, High-efficiency ERDs and pumps could reduce SEC, but overall SEC, could not be examined by these factors alone. Furthermore, SEC was affected by target water quality and quantity [32]. Chong et al. presented a numerical model for the 1-2 EERO process and validated it with the data obtained from commercial RO projection software. The obtained results showed that under the optimized conditions, the energy-efficient reverse osmosis (EERO) process demonstrated not only greater energy efficiency (3–25%) but also conventional SSRO (single-stage reverse osmosis). Also, (EERO) process achieved lower concentration polarization (CP) and potentials of membrane fouling than conventional SSRO (single-stage reverse osmosis) for ≥55% overall recoveries [52].

Despite various studies, the high energy consumption of RO systems at sea scale as well as surface water is still a controversial concern and challenge for using this technology. The aim of this research is to study the optimization of RO systems using a hybrid design (ISD), the evaluation of the temperature effect on efficiency, and comparing energy consumption and efficiency in simple, multi-stage, and hybrid designs in the RO system. In the end, the analysis of membranes, the effect of temperature, Langjiller index, and the amount of chlorine and nitrate ions in purified water are examined.

2. Materials and simulation methods

2.1. Experimental data
Simulation of 300 m³/day RO system was evaluated in the south of Tehran. The purpose of desalination was to achieve fresh water with the relevant standards. The raw water extracted from wells from the south of Tehran and ions analysis are shown in Table 2 [4].

2.2. Simulation method

RO software was used for simulation. In the plant design, 12 numbers of 8*40 inch Membrane and three and four-element PVs were used in different designs, including single-stage, two-stage, single-stage hybrid, and two-stage hybrid with two classes of BW 400 ES and BW 400 R. Figure 3 depicts a different design for an RO system.

3. Results and Discussion

3.1. Temperature effect

The effect of temperature on the Langelier index for the design of single-stage simple, hybrid RO systems, two simple, and hybrid stages has been shown in Figure 4. As can be seen in Fig. 4(a), by increasing the temperature, the Langelier index for different RO systems has been increased. Figure 4(b) also depicts the addition of a sodium hydroxide solution with pH = 9.2 to these systems. In Figures 4(a) and 4(b), it is clear that the treated output water moves away from the corrosive state by increasing the temperature. Increasing the temperature has increased the output efficiency of the membranes, which ultimately increased the number of ions in the water, and causes the system to move away from corrosion [37, 44].

Figure 4(b) also shows that adding the sodium hydroxide to desalination caused the system to move away from corrosion quickly. Figure 5 shows that increasing the temperature due to increasing kinetic energy and decreasing the viscosity of water molecules increased the passage of water molecules through the membranes and increased the process efficiency. The efficiency of two-stage systems was much higher than the single-stage systems. Simple systems also produced higher efficiencies than hybrid systems [42]. Therefore, the best desalination system was simple system in terms of efficiency,
which even at 15 °C had higher efficiency than 35 °C in the two-stage hybrid system. This phenomenon is due to the decrease in NDP and the increase in TDS in the water entering the BW 400 R membranes, which has caused the efficiency of the BW 400 R membranes to decrease compared to the two BW 400 ES membranes. Therefore, this reduction in membranes efficiency resulted in a decrease in the overall efficiency of the RO system in two-stage hybrid designs compared to the system with simple designs.

Figures 6 (a) to 6 (f) depict 3D graphs of the effect of temperature on single- and two-stage simple and hybrid efficiencies in terms of membrane number and the order in which they are placed in the PV in RO systems. Figure 6 (a) represents that in a simple single-stage system, by increasing the number of membranes in the design, the efficiency of the membranes increased [37]. In Fig. 6, the hybrid single-stage system shows that the recovery rate increased in membranes 1 and 2, but the membrane efficiency decreased in membranes number 3 at high pressure. Since the ISD in this type of design used a class of membranes with a higher percentage of solute removal at the beginning of the input to the pressure vessel (PV), in other words, upstream. Also, membranes with a higher percentage of flux were used at the end of the pressure vessel (PV), in other words, downstream. Another reason, as mentioned, is due to the decrease in NDP and the increase in TDS in the water entering the BW 400 R membranes, which has caused the efficiency of the BW 400 R membranes to decrease compared to the two BW 400 ES membranes.

Figures 6 (c) and 6d demonstrate the simple two-step systems. These figures depict that in the first and second stages, by increasing the temperature and the number of membranes in simple two-stage systems, the efficiency increased. Figures 6 (e) and 6 (f) show the two-stage hybrid system. In the first and second stages of the two-stage hybrid system, the efficiency of the membranes increased by increasing the temperature and the number of membranes. Because by increasing temperature, the kinetic energy and chemical potential of water molecules increased. This increase in chemical potential caused more driving force to be generated in the membrane and NDP high-pressure cell system than in
the simple state system. Another reason is that as the temperature increases, the viscosity of the water decreases.

In other words, by increasing the temperature, the viscosity and stickiness of water, and the flux passing through the membranes have increased, and consequently, the efficiency have increased. Therefore, by increasing the temperature, the efficiency has increased for both systems. In the simple and hybrid two-stage systems, it has been shown that the highest percentage of salt removal has been implemented in the first stage of the two-stage system. It is probably due to the increase in TDS feed in the second stage and the decrease in the pressure gradient for water molecules to pass through the membranes. As shown in Table 3, when the temperature increases, the efficiency of different systems becomes closer. The efficiency ratio at low temperatures was higher than at high temperatures, indicating that increasing the temperature in systems with lower efficiency caused more upgrades. The single-stage hybrid system compared to the simple single-stage system at best condition, depicting a 2% reduction inefficiency and the two-stage hybrid system compared to the simple two-stage system at 35 °C, depicting an 8.9% reduction in efficiency. Therefore, choosing a high-temperature system for hybrid systems may be more appropriate than simple systems. In general, if only higher efficiency is considered in the RO process, the best option is to use a simple two-stage RO system. And the worst option is to use a single-stage hybrid RO system.

Figure 7 represents the effect of temperature on the energy consumption of single and multi-stage RO systems of simple and hybrid systems. As can be seen in this figure, by increasing the temperature, energy consumption has reduced in the RO system [37]. Since, increasing the temperature reduced the viscosity of water and increased the kinetic energy of the molecules; as a result, the flow of output water of the membrane pores increased. Therefore, much water can leave from membranes than the constant temperature, and a certain pressure is removed from the membranes and reduced the energy consumption in the RO system. It can also be seen that the energy consumption of the two-stage hybrid system had the lowest energy consumption compared to the simple single-stage and two-stage
mode [1]. Since the hybrid systems had less sediment potential, therefore less energy and washing processes were required, and the lifespan of the membranes become longer. Any increase in temperature has had the greatest impact on the simple single-stage RO system and the least impact on the two-stage hybrid system. In designing a desalination plant for the studied system, the best choice in terms of energy consumption is a two-stage hybrid RO system.

2.3. Energy optimization

Figure 8 shows the energy saving of a single and two-stage simple and hybrid RO system. As depicted in this figure, two-stage hybrid systems (ISD) have more energy saving than simple two-stage and single-stage hybrid systems [1]. From Table 4, it can be deduced that the energy saving of a two-stage system, two-stage hybrid system, and single-stage hybrid system compared to simple one-stage systems had the least of 29.2%, 41.8%, and 21.8%, respectively. The table also depicts that two-stage hybrid systems had 1.43 times more energy savings than simple two-stage systems and two-stage hybrid systems had 1.92 times more energy savings than single-stage hybrid systems in similar situations. Also, the systems in this table clearly show that the two-stage hybrid system had less energy consumption than other designs. Figures 9 (a) and 9 (b) examine the levels of dangerous and toxic ions of chlorine and nitrate in purified water, respectively. According to the figures, it can be seen that the simple and hybrid single-stage systems had better conditions than two-stage systems in the removal of chlorine and nitrate ions. Since in the second stage, two-stage systems produced more TDS. Therefore, the sum of TDS in the first and second stages increased the TDS of the output product [41]. And, the amount of chlorine and nitrate ions in simple and hybrid two-stage systems were more than simple and single-stage hybrid systems. Also, by increasing the temperature, the concentration of chlorine and nitrate ions have increased for all four systems [44]. These figures show that the performance of simple single-stage RO systems and hybrid single-stage was almost similar due to the relative overall efficiency.
However, the two-stage hybrid RO system performed better than the simple two-stage removal of chlorine and nitrate ions. In other words, in hybrid systems, the percentage of removal was higher, and the water quality was better, with lower efficiency [1]. This phenomenon was due to the reduction of NDP of the second stage membranes compared to the first stage, which reduced the efficiency of the second stage of the hybrid system compared to the efficiency of the second stage of the simple two-stage system. Therefore, the overall efficiency of the two-stage hybrid system was reduced compared to the two simple stages; as a result, the amount of chlorine and nitrate output was also decreased.

3.3. Effect of water pH

Figures 10(a) and 10(b) show the effect of the pH of the water entering the desalination system on the energy consumption and efficiency of different RO systems. As can be seen from this figure, any changes in pH of the given feed had little effect on the efficiency and energy consumption of RO systems, and the addition of substances such as sodium hydroxide or acid to the system did not change the system energy consumption or overall process efficiency.

3.4. Effect of operating pressure

Operating pressure values in the Brackish RO system is depicted in Fig. 11. This figure showed that with increasing temperature, operating pressure deceased. Also, RO system with different membranes have lower operating pressure than the simple system.

4. Conclusion

In this study, the effect of the temperature, which is an essential parameter in different design parameters, such as efficiency, the energy consumption of the RO system, the number of harmful ions in the product water, and the Langelier index was investigated. The simulation results have depicted that by increasing the temperature and PH, the Langgiller index for single, two-stage simple and hybrid RO systems in simple mode has increased. The simulation results also depicted that by increasing the temperature of the water, due to more significant chemical potential (NDP) and decreasing the viscosity of water in the membranes, the flux of water, leaving the membrane pores and the overall efficiency
were increased. Analysis of BW 400 ES and BW 400 R membranes in different designs represented that in two-stage, two-stage hybrid and simple single-stage systems by increasing the number of membranes and putting in the pressure vessel, the efficiency of the membranes in each design phase increased by increasing temperature. In terms of energy saving, hybrid systems had better performance than similar simple systems, but in terms of efficiency, simple RO systems performed better than similar hybrid modes. The findings also showed that the pH of water entering the RO system did not affect the efficiency and energy consumption. And, also the removal of nitrate and chlorine ions in single and two-stage hybrid (ISD) design has been higher than RO systems with simple single and two-stage designs.

**Data availability statement**

Data for the case study provided in this manuscript can be accessed from Rosa Use Plan for the RO System. Data associated with this paper can be found in the published data set at [https://doi.org/10.5004/dwt.2009.770](https://doi.org/10.5004/dwt.2009.770).

**References**


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**List of Figures:**

**Figure 1:** Operating costs in desalination plants

**Figure 2:** Distribution of desalination methods all over the world

**Figure 3:** Schematic of the RO system in design for, a) simple single-stage, b) single-stage hybrid, c) simple two-stage, d) two-stage hybrid

**Figure 4:** The effect of temperature on the Langelier index to design a single-stage simple, hybrid RO system, and two simple and hybrid stages (a) without addition of sodium hydroxide. (b) After addition of sodium hydroxide solution

**Figure 5:** The effect of temperature on the efficiency of simple single-stage, single-stage hybrid, simple two-stage, and two-stage hybrid systems in RO

**Figure 6:** 3D graphs of the effect of temperature on simple and hybrid single-stage efficiency, simple and hybrid two-stage in RO systems for, a) Single-stage hybrid, b) Single stage, c) two stage-first stage d) two stage hybrid-first stage, e) two stage hybrid-second stage, f) Two stage-second stage

**Figure 7:** The effect of temperature on the energy consumption of single and double phase simple and hybrid systems

**Figure 8:** The energy-saving rate of single and double stage simple and hybrid RO system

**Figure 9:** The effect of temperature on the number of ions of output product in single, two-stage simple and hybrid RO system for, a) chlorine, and b) nitrate

**Figure 10:** The effect of input water pH on, a) energy consumption, and b) efficiency of different RO systems

**Figure 11:** The effect of temperature on the operating pressure in single and double stage simple and hybrid RO system
List of Tables:

Table 1. The required energy for one cubic meter of drinking water with different water sources
Table 2: Desalination feed compositions
Table 3: The amount of efficiency changes in different designs compared to the single-stage system
Table 4: The amount of energy-savings of different designs compared to a simple single-stage system

Figure 1: Operating costs in desalination plants [24].

Figure 2: Distribution of desalination methods all over the world [33].
Figure 3: Schematic of the RO system in design for, a) simple single-stage, b) single-stage hybrid, c) simple two-stage, d) two-stage hybrid.
Figure 4: The effect of temperature on the Langelier index to design a single-stage simple, hybrid RO system, and two simple and hybrid stages (a) without addition of sodium hydroxide. (b) After addition of sodium hydroxide solution.
Figure 5: The effect of temperature on the efficiency of simple single-stage, single-stage hybrid, simple two-stage, and two-stage hybrid systems in RO.

Figure 6: 3D graphs of the effect of temperature on simple and hybrid single-stage efficiency, simple and hybrid two-stage in RO systems for, a) Single-stage hybrid, b) Single stage, c) two stage-first stage d) two stage hybrid-first stage, e) two stage hybrid-second stage, f) Two stage-second stage.
**Figure 7:** The effect of temperature on the energy consumption of single and double phase simple and hybrid systems.
Figure 8: The energy-saving rate of single and double stage simple and hybrid RO system.
Figure 9: The effect of temperature on the number of ions of output product in single, two-stage simple and hybrid RO system for, a) chlorine, and b) nitrate.
Figure 10: The effect of input water pH on, a) energy consumption, and b) efficiency of different RO systems.
Figure 11: The effect of temperature on the operating pressure in single and double stage simple and hybrid RO system.

![Operating pressure vs temperature graph]

Table 1. The required energy for one cubic meter of drinking water with different water sources [25, 28].

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<tr>
<th>Source type</th>
<th>Energy consumption (kWh/m³)</th>
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<tr>
<td>Surface water (Rivers or lakes)</td>
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<td>Groundwater</td>
<td>0.48</td>
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<td>Purified wastewater</td>
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<td>Recycled effluent water</td>
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Table 2: Desalination feed compositions [4].

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<th>TDS (ppm)</th>
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<th>Ca</th>
<th>Mg</th>
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<th>K</th>
<th>NH₄</th>
<th>SO₄</th>
<th>Cl</th>
<th>NO₃</th>
<th>SiO₂</th>
<th>Ba</th>
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<td>1592</td>
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<td>138.4</td>
<td>89.76</td>
<td>350</td>
<td>2</td>
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<td>525</td>
<td>355</td>
<td>18.7</td>
<td>30</td>
<td>0.06</td>
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Table 3: The amount of efficiency changes in different designs compared to the single-stage system.

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<th>Temperature (°C)</th>
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<th>25</th>
<th>30</th>
<th>35</th>
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<tbody>
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<td>-5</td>
<td>-2</td>
<td>-2</td>
<td>-2</td>
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<tr>
<td>Two stage hybrid vs. single stage</td>
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<td>+50</td>
<td>+50</td>
<td>+44.7</td>
<td>+44.8</td>
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<td>Two stag hybrid vs. two stage</td>
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<td>-10</td>
<td>-10.8</td>
<td>-10.5</td>
<td>-8.9</td>
</tr>
</tbody>
</table>

Table 4: The amount of energy-savings of different designs compared to a simple single-stage system.

<table>
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<tr>
<th>Temperature (°C)</th>
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<th>20</th>
<th>25</th>
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<td>Single stage hybrid vs. single stage</td>
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