Water Conservation & Management (WCM)

DOI: http://doi.org/10.26480/wcm.01.2025.81.85

ISSN: 2523-5664 (Print)
ISSN: 2523-5672 (Online)
CODEN: WCMABD

RESEARCH ARTICLE

THE IMPACT OF OPERATING TEMPERATURE ON ENERGY EFFICIENCY IN BRACKISH AND SEAWATER TREATMENT: WATER PRODUCTION AND ENVIRONMENTAL PROTECTION

Reda Askouri*[a], Mohamed Moussetad[a], Kamal Abderrafi[a], Asmaa Drighil[b], Bouchra Ifegous[a], Touria Lachhab[a], R'hma Adhiri[a]

[a]Laboratory of Engineering and Materials, Faculty of Science Ben M'Sick, Hassan II University of Casablanca, B.P.7955 Casablanca, Morocco.
[b]LTI Laboratory, Faculty of Science Ben M'Sick, Hassan II University of Casablanca, B.P.7955 Casablanca, Morocco.
**Corresponding Email Author : askouri.reda.univh2c@gmail.com*

ARTICLE DETAILS

Article History:

Received 18 October 2024
Revised 20 November 2024
Accepted 19 December 2024
Available online 29 January 2025

ABSTRACT

Specific energy consumption (SEC) is an important parameter for designing and operating reverse osmosis desalination units, which treat different types of supply water. The primary aim is to improve the accuracy of the theoretical model used to calculate the SEC, while the second goal is to present the effect of supply water temperature (T_s) on the efficiency of a reverse osmosis process operating at a constant recovery rate and including an energy recovery device system (ERD). The study focuses on the SEC for brackish and seawater desalination, considering the effect of temperature on membrane performance. In general, improving the accuracy of the theoretical model minimises the relative errors between the improved model and the experimental-specific energy consumption (SEC_{exp}). Increasing the T_s reduces the SEC for brackish water treatment in the temperature range of approximately 10 to 45°C. However, for high seawater salinity, a significant increase in osmotic pressure with increasing T_s tends to neutralise the other positive effects, thus minimising SEC at approximately 45°C. Finally, high T_s for brackish and seawater negatively impact membrane performance, which needs to be considered in the optimisation study.

KEYWORDS

Energy consumption, Desalination process, Reverse osmosis, Water supply temperature, Environmental impact.

1. INTRODUCTION

Reverse osmosis (RO) is a widely used water separation technology crucial for providing clean drinking water, treating wastewater, and desalinating (Shah Abedi et al., 2022; Mehrizi et al., 2024. It employs a semi-permeable membrane to remove contaminants and impurities from the water, leaving behind purified water (Alam et al., 2023). A significant aspect of RO systems is their specific energy consumption (SEC), which refers to the energy required to produce a specific volume of purified water (Beithou et al., 2024; Karabelas et al., 2018). Understanding and optimising SEC is vital for enhancing the efficiency and sustainability of RO systems, as it directly impacts operational costs, energy usage, and environmental considerations (Yagnambhatt et al., 2024; Sohrabiet al., 2024). Therefore, exploring the importance of SEC in RO processes is essential for achieving more sustainable water treatment solutions (Bin Darwish et al., 2024).

Several parameters influence the SEC in RO processes, ultimately affecting the efficiency and cost-effectiveness of water treatment (Kim et al., 2019). Firstly, feed water characteristics such as temperature, salinity, and total dissolved solids (TDS) significantly impact SEC (Koutsou et al., 2020). Higher salinity and TDS levels typically require more energy to overcome osmotic pressure and drive water through the membrane. Additionally, variations in supply water temperature (T_s) affect fluid viscosity and membrane permeability, influencing energy requirements (Wang et al., 2019). Moreover, operating conditions such as feed flow, recovery rate, and system pressure also play an important role (Alanezi et al., 2020). Furthermore, membrane fouling, scaling, and degradation over time can adversely affect system performance, leading to reduced permeate flux and increased energy consumption. To maintain the required water production rate, the system operates less efficiently (Delpla et al., 2023). Overall, understanding and optimising these parameters are essential for minimising SEC in RO, improving efficiency and reducing operating costs.

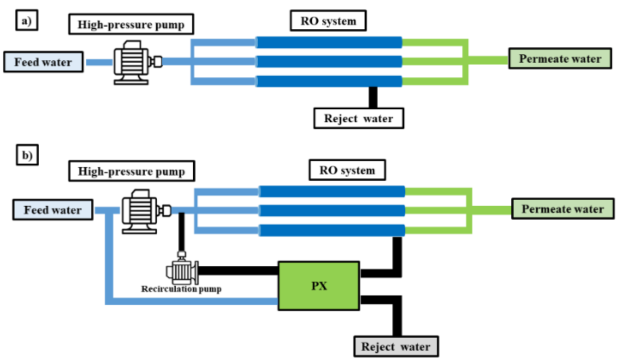

Figure 1: Diagram representation of the reverse osmosis unit in the absence/presence of ERD.

Temperature impacts the efficiency of the high-pressure pump (HPP) and system recovery (ERD). As temperature increases, the efficiency of these devices tends to decrease, primarily due to minimising water viscosity and increased friction losses which also lead to higher leakage in ERD systems (Wu et al., 2017; Whillier, 1968). Extensive research has focused on different types of ERD_s, examining their characteristics and efficiency concerning the energy consumption of desalination processes. That

Quick Response Code | Access this article online

Website: www.watconman.org

DOI: 10.26480/wcm.01.2025.81.85

studied the efficiency of various ERDs, such as turbochargers, and Pelton and Francis turbines, comparing their efficiencies under different conditions and their impact on overall energy consumption, including losses in the HPP and the main seawater reverse osmosis unit (Farooque et al., 2008). The study also estimated the average efficiency of the recovery system, using other parameter values appropriate for the SEC of the reverse osmosis process. Furthermore, a theoretical model developed investigated how temperature impacts energy consumption and water recovery (Agashichev et al., 2003). This model considers factors such as pump energy consumption, energy recovery system, and pressure drop within the RO unit as functions of temperature and permeate recovery. They noted that higher temperatures improved permeate recovery, thus reducing energy consumption. The analysis conducted a thermodynamic evaluation to assess the energy consumption of a standard RO process using different types of ERD_s. Their findings underline the essential role of ERD integration, particularly in the case of high supply water salinity (Al-Zahrani et al., 2012). The SEC has been shown to vary with supply salinity, which increases almost linearly with the pressure applied at low supply salinities. That analysed the operating efficiency of a desalination unit equipped with a Pelton turbine, examining different salinity levels (El-Emam et al., 2014). The economic and thermodynamic analyses revealed that rising temperatures considerably reduced the performance of HPP and Pelton turbines. Using numerical analysis, investigated the operation of RO desalination units, considering variations in feed pressure, temperature and ERD such as turbine and PX (Atab et al., 2016). The study illustrated the advantages of using an ERD and the impact of temperature increase on energy savings, despite lower salt rejection rates in the latter scenario. This literature review leads to the conclusion that, although progress has been made in addressing related issues such as energy recovery performance, HPP, and RO efficiency, there is still a need for a comprehensive study that systematically takes into account the influences of T_s. It has been observed that, until recently, the major membrane producers had not fully considered the effects of Ts on seawater desalination. Furthermore, the corresponding analyses did not take ERD_s into account.

A comprehensive study is presented herein to examine the effect of T_s on the SEC of brackish water and seawater in the presence of an isobaric exchanger (PX), depicted in figure 1 as a simple block diagram of a single-stage reverse osmosis unit, comprising pressure tubes and several spiral-wound SWC4-LD membranes. The SWC4-LD RO membrane is a large-format (37.1 m^2) spiral-wound cartridge membrane manufactured by Hydranautics Nitto Group. It is characterised by a high NaCl rejection rate of ≥99.7%, making it suitable for desalination applications requiring levels of purity. This membrane has a wide operating pH range of 2 to 11, offering flexibility in process design, and a maximum applied pressure of 1200 psig, allowing for efficient operation even under high feed water salinity conditions. Taking into account the effect of T_s on the osmotic pressure, feed pressure, permeate concentration and SEC in both types of water, based on the comprehensive IMS Design software tool. This paper also presents an improvement in the precision of specific energy consumption predictions, validated by experimental data. The results are presented and discussed in the following sections.

2. Improve the Accuracy of a Specific Energy Consumption Model

Table 1 provides the input parameters used to improve the theoretical model accuracy for calculating the specific energy consumption (SEC_i) mentioned in eq. (1). The values of these parameters are cited from the experimental study referenced in (Qiu et al., 2015). For the simulation, Table 2 lists the necessary conditions, such as the supply water characteristics mentioned in and operational parameters, including the supply flow rate and conversion rate (Karabelas et al., 2018).

Table 1: The parameters used in the improvement of the theoretical model.

Before improving accuracy			
Feed concentration	2g/l	3g/l	4g/l
Supply flow	13.01 l/min	11.24 l/min	11.12 l/min
Feed pressure	883.4 KPa	1026.8 KPa	1232.8 KPa
Recovery rate	0 .7944	0.7939	0.7941
Pump efficiency Recirculation pump energy	0.587 0.054 KWh/m^3	0.612 0.058 KWh/m^3	0.623 0.060 KWh/m^3

Table 2: The operating data used in this study.

Characteristics of the supply water	Seawater	Brackish water
Salinity	40,000 ppm	2000 ppm
Parameters of operation		
supply Flow	35 m^3/h	35 m^3/h
Recovery rate R	30%	55%
Membrane design		
Type of membrane	SWC4-LD	SWC4-LD
Membrane polymer	Composite polyamide	Composite polyamide
Membrane active area, S	37,1 m^2	37,1 m^2
Numbers of envelopes, N	18	18

In this work, we considered an existing model in the literature for calculating the SEC of reverse osmosis units. The objective is to improve the accuracy of this model to align with SEC_{exp} cited in the literature (Youcef et al., 2022). The model that predicts the SEC_i based on a high-pressure pump of RO before improving accuracy is:

$$SEC_i = \frac{P_{HHP}}{e_{HHP} \times R \times 36{,}6} \quad \text{(1) (Youcef et al., 2022)}$$

$$SEC = CPF \times SEC_{ideal} + SEC_{re-pump} \quad \text{(2)(Qiu and Davies, 2015)}$$

The rejected water from the system was evacuated without being reused by the recirculation pumps. However, the model cited in eq. (1) cannot provide highly accurate predictions of the SEC_{exp} of units using recirculation pumps.

It is assumed that the recirculation pump's SEC will increase linearly with respect to the supply flow rate. This implies that as the flow rate increases, the $SEC_{re-pump}$ will proportionally rise as well. This assumption provides a basis for predicting the energy requirements of the recirculation pump in correlation with variations in the flow rate, allowing for better planning and optimisation of the overall system efficiency (Qiu and Davies, 2015).

$$SEC_{ideal} = \frac{P_{os}}{R} \times \ln\left(\frac{1}{1-R}\right) \quad \text{(3) (Youcef, et al., 2022)}$$

For this study, the $SEC_{re-pump}$ expression in eq. (2) serves as the improvement term for the SEC_f refined in this work. The overall expression after improvement is presented as follows:

$$SEC_f = SEC_i + SEC_{re-pump} \quad (4)$$

3. Results

Figure 2 shows the effect of the accuracy term on the SEC_f mentioned in eq. (4). For different concentrations, the SEC_f closely aligns SEC_{exp}. This indicates that the improvement added to the theoretical model significantly enhances the accuracy of specific energy consumption. This alignment is evident in figure 3 through the relative error calculation, which shows an average error of 0.88% between the SEC_{exp} and the SEC_i, and 8.47% between the SEC_{exp} and the SEC_i.

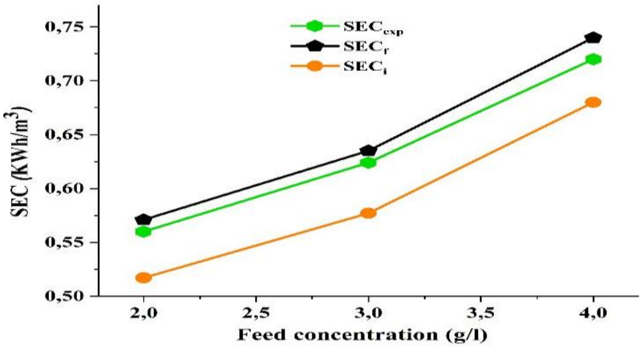

Figure 2: Effect of the improvement term on the theoretical model.

Cite The Article: Reda Askouri, Mohamed Moussetad, Kamal Abderrafi, Asmaa Drighil, Bouchra Ifegous, Touria Lachhab, Rhma Adhiri (2025). The Impact of Operating Temperature on Energy Efficiency in Brackish and Seawater Treatment: Water Production and Environmental Protection. *Water Conservation & Management, 9(1): 81-85.*

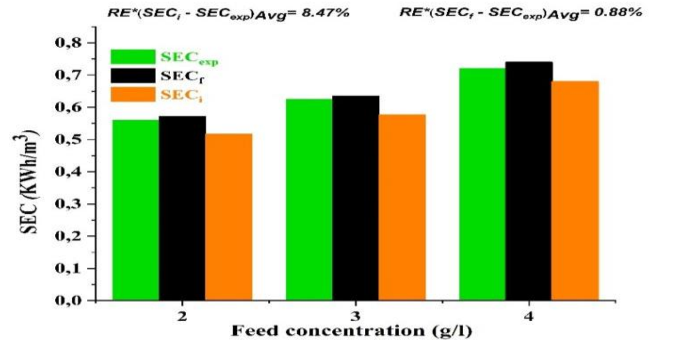

Figure 3: Relative errors between experimental and theoretical models.

Figure 4 illustrates the effect of temperature on the osmotic pressure of brackish and seawater. In Figure 4. a, as the T_s increases, the osmotic pressure of brackish water changes in steps across the temperature range. In contrast, figure 4b shows that the osmotic pressure of seawater increases linearly with temperature. Furthermore, figure 5 depicts the decrease in SEC for brackish water and seawater, reaching a minimum at 45°C. Additionally, figure 5. a show that the SEC for brackish water is lower than that for seawater, as presented in figure 5. b. The introduction of an ERD, as illustrated in figure 6, results in a continuous decrease in energy consumption across the entire temperature range for both brackish and seawater, reaching 0.57 kWh/m^3 (figure 6. a) and 1.97 kWh/m^3 (figure 6. b), respectively.

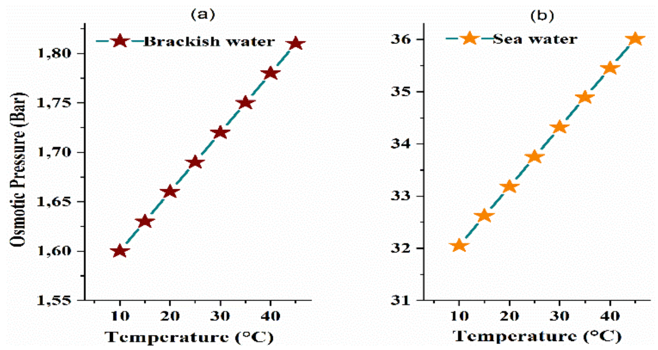

Figure 4: Temperature effect on osmotic pressure in brackish and seawater.

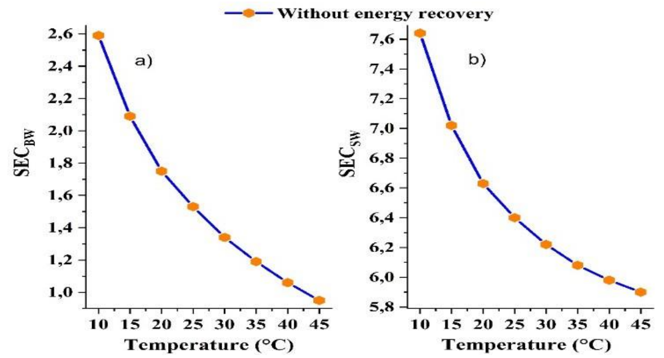

Figure 5: Evolution of energy consumption as a function of temperature without energy recovery.

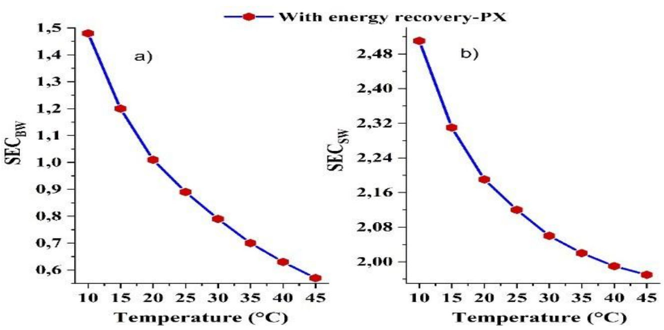

Figure 6: Evolution of energy consumption as a function of temperature with energy recovery.

Figure 7 illustrates the effect of temperature on the variation in pressure and permeate concentration for the RO unit. At 25°C, the SWC4-LD membrane achieves of 3.52 mg/L for brackish water and 156.66 mg/L for seawater. This performance is attributed to the membrane's efficiency in removing Na^+ and Cl^- ions.

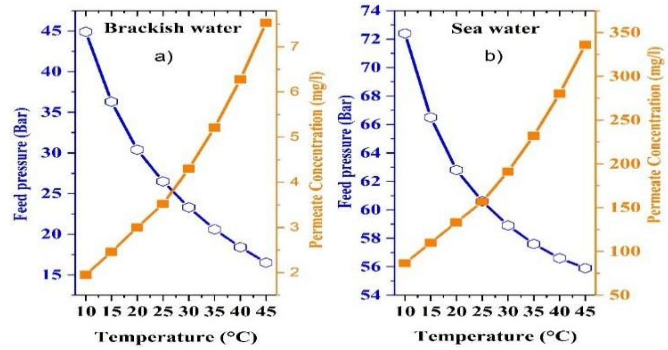

Figure 7: Influence of water temperature on feed pressure and permeate concentration in brackish and seawater.

4. Discussion

This paper focuses on the study of SEC in the RO system; Figure 2 illustrates the close correspondence between SEC f and SEC exp, attributed to the inclusion of the SEC re-pump term, allowing the model to predict experimental values with high accuracy; an increase in feed concentration necessitates a rise in SEC, reflecting the additional pressure required by the system to overcome osmotic pressure and enable water to pass through the SWC4-LD membrane (Essa et al., 2023); in Figure 4, the increase in osmotic pressure in brackish and seawater is attributed to the enhanced mobility of Na+ and Cl- ions, necessitating that the RO system consumes more energy for seawater compared to brackish water, evident in Figure 5. a and b, which shows the RO unit without an ERD for seawater consumes over 60% more energy for seawater than for brackish water; simultaneously, increasing the temperature minimises the SEC as the viscosity of the water passing through the SWC4-LD membrane decreases; the use of other membranes also results in a significant reduction, with Al Obaidi et al. reporting an energy reduction of 9.3% within the same temperature range using the ECO PRO 400 membrane (Al-Obaidi et al., 2023); the presence of an ERD in the RO unit minimises SEC, and Figure 6 shows that as T s increases, SEC decreases for both brackish and seawater (Figure 6. a and b), attributed to the efficiency of the ERD and temperature (Kim et al., 2019); additionally, the temperature also affects PX efficiency, and in this study, the efficiency of the ERD was set at 95%, while the effect of temperature on ERD was not considered.

Notably, the ERD does not significantly affect the changes in permeate pressure and concentration across the temperature range. Despite the pressure reduction shown in figures 7. a & b, it is crucial to consider for the quality of permeate concentration, especially in units that require a specific level of quality. Additionally, the efficiency of the SWC4-LD membrane in removing Na^+ and Cl^- ions from brackish and seawater is 99.86% and 99.7%, respectively. The impact of temperature on membrane integrity is of significant importance, particularly in RO and nanofiltration systems. Certainly, as temperature increases, the occurrence of salts with reversed solubility, such as calcium ions and other divalent ions, can decrease, resulting in an enhanced membrane potential (Nthunya et. al., 2022). conducted experiments on low-salinity waters and found that higher temperatures yielded favourable results for desalination (Nthunya et al., 2022). However, temperatures rising above 25°C need particular attention due to the potential for membrane degradation. For this study, we focus solely on the quality of permeable from brackish and seawater at 25°C, despite the SWC4-LD membrane's ability to withstand higher temperatures, and consider the production costs for both brackish and seawater.

Although this issue falls outside the scope of the current paper, it is appropriate to make a few remarks. In the context of the circular economy, which offers solutions to reduce the negative impacts of human activities on the environment, we highlight the effect of high salinity on the environment (Borowski et al., 2021). Using high salinity in water can have detrimental effects on aquatic life (Velasco et al., 2019;Borowski et al., 2021). When this highly saline brine is discharged into natural water bodies, it can significantly increase the salinity of the local environment.

Many aquatic organisms, particularly freshwater species, are sensitive to changes in salinity and may experience osmotic stress, which can lead to dehydration, impaired physiological functions, and eventually death (Dugan and Arnott, 2023). For marine ecosystems, the introduction of concentrated brine can disrupt the balance of marine flora and fauna (Röthig et al., 2023). Species not adapted to such high salinity levels may struggle to survive, leading to a decline in biodiversity. Moreover, the chemical composition of the brine, which may include residual agents and other pollutants from the RO process, contributes to these negative impacts (Nurjanah et al., 2024). These substances can be toxic to marine life, causing further harm beyond the effects of salinity alone.

5. Conclusion

Based on the findings presented in this paper, it is evident that SEC plays a critical role in RO units for different types of water. The primary objective of the study to improve the accuracy of the theoretical model used to calculate SEC has been successfully achieved, as evidenced by the significant reduction in relative error from 8.47% to 0.88% following the enhancement. The study observed a consistent decrease in SEC with increasing T_s across the range of 10°C to 45°C for both brackish and seawater. This finding underscores the importance of considering T_s as a factor in optimising energy efficiency in water processes. Furthermore, the presence of an ERD was found to contribute to maintaining this decrease in SEC, indicating the potential for implementing energy-efficient solutions in water treatment facilities The significant impact of the SWC4-LD membrane on water quality, as evidenced by the permeate concentrations achieved, underscores its effectiveness in producing high-quality water suitable for various applications. Additionally, the quality of seawater permeate allows for its use in irrigation and other application field, provided adjustments are made to meet standard norms. Another important point is that seawater rejected by the unit has a high salinity level. At 25°C, the salinity reaches 58,000.00 mg/l, which impact on the environment due to its high concentration.

Therefore, we suggest using evaporation ponds as an additional method to generate salt. This strategy complements our approach to resource utilisation and diversifies the production methods. The analysis of production costs also highlights the economic viability of using brackish and seawater resources for water production. In conclusion, the study's thorough methodology and reliable results offer valuable insights for optimising energy efficiency and water quality in reverse osmosis water treatment processes. The findings suggest potential applications in various sectors, underlining the importance of continued research and implementation of sustainable solutions for water treatment. The results presented in this study lay the foundation for further discussion and exploration in subsequent sections.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Agashichev, S. P., and Lootahb, K. N., 2003.Influence of temperature and permeate recovery on energy consumption of a reverse osmosis system , Desalination, vol. 154, no 3, Pp. 253-266, mai 2003, doi: 10.1016/S0011-9164(03)80041-3.

Alam, J., Daoud, O. A., Shukla, A. K., Ali, F. A. A., and Alhoshan, M., 2023.Simulation of a Solar-Powered Reverse Osmosis System Integrated with Vacuum Membrane Distillation for Desalination Brine Treatment, Arab. J. Sci. Eng., vol. 48, no 12, p. 16343-16357, déc. 2023, doi: 10.1007/s13369-023-08212-x.

Alanezi, A. A., Altaee, A., and Sharif, A. O., 2020. The effect of energy recovery device and feed flow rate on the energy efficiency of reverse osmosis process, Chem. Eng. Res. Des., vol. 158, p. 12-23, juin 2020, doi: 10.1016/j.cherd.2020.03.018.

Al-Obaidi, M. A., Alsarayreh, A. A., Bdour, A., Jassam, S. H., Rashid, F. L., and Mujtaba, I. M., 2023.Simulation and optimisation of a medium scale reverse osmosis brackish water desalination system under variable feed quality: Energy saving and maintenance opportunity, Desalination, vol. 565, Pp. 116831, nov. 2023, doi: 10.1016/j.desal.2023.116831.

Al-Zahrani, A., Orfi, J., Al-Suhaibani, Z., Salim, B., and Al-Ansary, H., 2012. Thermodynamic Analysis of a Reverse Osmosis Desalination Unit with Energy Recovery System », Procedia Eng., vol. 33, Pp. 404-414, janv. 2012, doi: 10.1016/j.proeng.2012.01.1220.

Atab, M. S., Smallbone, A. J., and Roskilly, A. P., 2016. An operational and economic study of a reverse osmosis desalination system for potable water and land irrigation, Desalination, vol. 397, Pp. 174-184, nov. 2016, doi: 10.1016/j.desal.2016.06.020.

Beithou, N., Khalid, M. B., As'ad, S., Alsaqoor, S., Borowski, G., Alshabatat, N., and Andruszkiewicz, A., 2024. Atmospheric Water Harvesting Technology: Review and Future Prospects , J. Ecol. Eng., vol. 25, no 3, Pp. 291-302, mars 2024, doi: 10.12911/22998993/182814.

Bin Darwish, N., Alalawi, A., and Alotaibi, N., 2024.Evaluation of Single and Mixed Draw Solutions on Forward Osmosis Process Performance, Arab. J. Sci. Eng., janv. 2024, doi: 10.1007/s13369-023-08662-3.

Borowski, G., Alsaqoor, S., and Alahmer, A., 2021.Using Agglomeration Techniques for Coal and Ash Waste Management in the Circular Economy », Adv. Sci. Technol. Res. J., vol. Vol. 15, no no 3, 2021, doi: 10.12913/22998624/140784.

Delpla, I., Bouchard, C., Dorea, C., and Rodriguez, M. J., 2023.Assessment of rain event effects on source water quality degradation and subsequent water treatment operations », Sci. Total Environ., vol. 866, Pp. 161085, mars 2023, doi: 10.1016/j.scitotenv.2022.161085.

Dugan, H. A., and Arnott, S. E., 2023. The ecosystem implications of road salt as a pollutant of freshwaters, WIREs Water, vol. 10, no 2, p. e1629, 2023, doi: 10.1002/wat2.1629.

El-Emam, R. S., and Dincer, I., 2014. Thermodynamic and thermoeconomic analyses of seawater reverse osmosis desalination plant with energy recovery », Energy, vol. 64, Pp. 154-163, janv. 2014, doi: 10.1016/j.energy.2013.11.037.

Essa, F. A., Selim, F., and El-Sebaey, M. S., 2023.Performance and control of a reverse osmosis unit integrated with Pelton Wheel to supply emergency electric loads under various operating conditions, Sustain. Environ. Res., vol. 33, no 1, Pp. 22, août 2023, doi: 10.1186/s42834-023-00183-w.

Farooque, A. M., Jamaluddin, A. T. M., Al-Reweli, A. R., Jalaluddin, P. A. M., Al-Marwani, S. M., Al-Mobayed, A. A., and Qasim, A. H., 2008.Parametric analyses of energy consumption and losses in SWCC SWRO plants utilizing energy recovery devices », Desalination, vol. 219, no 1, Pp. 137-159, janv. 2008, doi: 10.1016/j.desal.2007.06.004.

Karabelas, A. J., Koutsou, C. P., Kostoglou, M., and Sioutopoulos, D. C., 2018.Analysis of specific energy consumption in reverse osmosis desalination processes », Desalination, vol. 431, Pp. 15-21, avr. 2018, doi: 10.1016/j.desal.2017.04.006.

Kim, J., Park, K., Yang, D. R., and Hong, S., 2019. A comprehensive review of energy consumption of seawater reverse osmosis desalination plants, Appl. Energy, vol. 254, Pp. 113652, nov. 2019, doi: 10.1016/j.apenergy.2019.113652.

Koutsou, C. P., Kritikos, E. M., Karabelas, A. J., and Kostoglou, M., 2020. Analysis of temperature effects on the specific energy consumption in reverse osmosis desalination processes , Desalination, vol. 476, Pp. 114213, févr. 2020, doi: 10.1016/j.desal.2019.114213.

Mehrizi, R. A., Mirbagheri, S. A., and Shams, A., 2024.Development of a generalized mathematical model for two-stage reverse osmosis desalination systems , Comput. Chem. Eng., vol. 182, p. 108562, mars 2024, doi: 10.1016/j.compchemeng.2023.108562.

Nthunya, L. N., Bopape, M. F., Mahlangu, O. T., Mamba, B. B., Van der Bruggen, B., Quist-Jensen, C. A., and Richards, H., 2022. Fouling, performance and cost analysis of membrane-based water desalination technologies: A critical review, J. Environ. Manage., vol. 301, p. 113922, janv. 2022, doi: 10.1016/j.jenvman.2021.113922.

Nurjanah, I., Chang, T. T., You, S. J., Huang, C. Y., and Sean, W. Y., 2024.Reverse osmosis integrated with renewable energy as sustainable technology: A review », Desalination, vol. 581, Pp. 117590, juill. 2024, doi: 10.1016/j.desal.2024.117590.

Qiu, T. Y., and Davies, P. A., 2015. Concentration polarization model of spiral-wound membrane modules with application to batch-mode RO desalination of brackish water, Desalination, vol. 368, Pp. 36-47, juill. 2015, doi: 10.1016/j.desal.2014.12.048.

Röthig, T., Trevathan-Tackett, S. M., Voolstra, C. R., Ross, C., Chaffron, S., Durack, P. J., and Sweet, M., 2023. Human-induced salinity changes impact marine organisms and ecosystems, Glob. Change Biol., vol. 29, no 17, Pp. 4731-4749, 2023, doi: 10.1111/gcb.16859.

Shah Abedi, M., Hashemi, S. H., Fazeli, M., 2022.Feasibility of Increasing Water Recovery of Inland Reverse Osmosis Systems and the Use of Reject Brine », Arab. J. Sci. Eng., vol. 47, no 5, Pp. 6525-6534, mai 2022, doi: 10.1007/s13369-021-06451-4.

Sohrabi, A., Meratizaman, M., and Liu, S., 2024.Comparative analysis of integrating standalone renewable energy sources with brackish water reverse osmosis plants: Technical and economic perspectives, Desalination, vol. 571, Pp. 117106, févr. 2024, doi: 10.1016/j.desal.2023.117106.

Velasco, J., Gutiérrez-Cánovas, C., Botella-Cruz, M., Sánchez-Fernández, D., Arribas, P., Carbonell, J. A., and Pallarés, S., 2019. Effects of salinity changes on aquatic organisms in a multiple stressor context », Philos. Trans. R. Soc. B Biol. Sci., vol. 374, no 1764, p. 20180011, déc. 2018, doi: 10.1098/rstb.2018.0011.

Wang, Q., Zhou, Z., Li, J., Tang, Q., and Hu, Y., 2019.Investigation of the reduced specific energy consumption of the RO-PRO hybrid system based on temperature-enhanced pressure retarded osmosis, J. Membr. Sci., vol. 581, p. 439-452, juill. 2019, doi: 10.1016/j.memsci.2019.03.079.

Whillier, A., 1968. Pump Efficiency Determination in Chemical Plant from Temperature Measurements », Ind. Eng. Chem. Process Des. Dev., vol. 7, no 2, Pp. 194-196, avr. 1968, doi: 10.1021/i260026a007.

Wu, J., Jin, Q., Wang, Y., and Tandon, P., 2017.Theoretical analysis and auxiliary experiment of the optimization of energy recovery efficiency of a rotary energy recovery device », Desalination, vol. 415, p. 1-7, août 2017, doi: 10.1016/j.desal.2017.03.038.

Yagnambhatt, S., Khanmohammadi, S., and Maisonneuve, J., 2024.Reducing the specific energy use of seawater desalination with thermally enhanced reverse osmosis, Desalination,

Youcef, R., Sabba, N., Benhadji, A., Djelal, H., Fakhfakh, N., and Taleb Ahmed, M., 2022. Nanofiltration Treatment of Industrial Wastewater Doped with Organic Dye: A Study of Hydrodynamics and Specific Energy », Processes, vol. 10, no 11, p. 2277, 2022.