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Solving the Energy Consumption Barrier in Brackish Water Reverse Osmosis Desalination Plants: A Genetic Algorithm and Energy Recovery Approach

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Abstract: Reverse osmosis desalination is an effective technology for supplying potable water to regions facing water stress. However, this process consumes a significant amount of energy, limiting its widespread adoption globally. This study aims to analyze the variations in specific energy consumption (SEC) in the reverse osmosis desalination process for brackish water at a plant in Morocco, considering the feed water parameters. Additionally, the study examines energy consumption with and without the implementation of energy recovery devices at this plant, which produces 10 million cubic meters of water annually. A genetic algorithm is utilized to identify the optimal combination of design and operational parameters to achieve the lowest SEC. The findings indicate that incorporating energy recovery devices in the future design of the plant could reduce the SEC by up to 30%.

Keywords: desalination, brackish water, reverse osmosis, energy recovery

1. INTRODUCTION

At present, increases in the global population, coupled with drought and desertifcation due to climate change, will undoubtedly aggravate water security [1]. Desalination technologies have been emerged to supply water from unconventional water sources, and reverse osmosis systems account for a large share of desalination facilities [2]. Reverse osmosis (RO) process is an important filtration process that is used extensively for the desalination of sea and brackish water all over the world [3]. Reverse osmosis is generating growing interest due to its energy efficiency and versatility compared to other desalination technologies. The need to supply drinking water to populations in regions suffering from water shortages has made the development of this technology essential. [4]. Reducing the Specific Energy Consumption (SEC) poses a significant challenge, driving technological innovation and research in the desalination industry. The energy cost of the desalination process (RO) can account for up to half of the total cost of producing one cubic metre of drinking water. [5]. Nevertheless, compared with other desalination technologies, such as multi-stage flash (MSF) [7], [8], multiple-effect distillation (MED) [9], membrane distillation (MD) [[10], [11], [12], [13],and electrodialysis (ED) [15], the RO process consumes relatively little energy. Consequently, most large-scale seawater and brackish water desalination plants have been designed to use the RO method.
According to several research studies, the SWRO process consumes between 2 and 5 kWh/m³ depending on the feed characteristics [24]. On the other hand, the total energy consumption of the BWRO process, including electrical energy, is between 1.5 and 2.5 kWh/m³ [20].
Many researchers and engineers have dedicated significant effort to finding innovative ways

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to reduce the energy consumption of the reverse osmosis process. They have focused on several key areas and methods to achieve this objective, including the following:

- **Improvement of RO membranes**: Developing and utilizing high-performance membranes to enhance filtration efficiency and reduce energy requirements.
- **Reduction of membrane fouling**: Implementing prevention and cleaning techniques to decrease membrane fouling, maintaining optimal efficiency and lowering energy consumption.
- **Efficiency of energy-consuming equipment**: Enhancing the efficiency of pumps and other energy-intensive equipment to minimize energy use.
- **Energy recovery devices (ERDs)**: Using energy recovery devices to capture and reuse energy, thereby reducing the overall energy demand.
- **Innovative membrane module designs**: Introducing new membrane module configurations to reduce pressure drops in the membrane channel, thus improving energy efficiency.
- **Process optimization**: Applying optimization algorithms to dynamically adjust operational parameters and maximize energy efficiency in real-time.
- **Integration of renewable energy**: Utilizing renewable energy sources, such as solar or wind power, to supply desalination plants, reducing reliance on traditional energy sources.

First, advances in RO membranes have contributed to energy savings. High-performance reverse osmosis membranes, characterized by increased water flow and salt rejection rates, mitigate the excess pressure required above the osmotic pressure of seawater. Researchers have successfully developed an efficient RO system for low SEC water desalination by adjusting membrane type and size [25] and [26], respectively.

Furthermore, low fouling propensity is critical for lowering energy consumption in the SWRO process because membrane fouling reduces water permeability, which requires higher operating pressure. Surface modification has been used to develop fouling-resistant RO membranes by improving hydrophilicity, reducing surface roughness, and decreasing concentration polarization at the membrane's surface [16] and [17] .

Moreover, to achieve an optimal combination for a reverse osmosis system with the lowest SEC, some researchers are focusing on the design of single-stage or two-stage RO systems. They analyze the performance of these systems with varying feed parameters, membrane permeabilities, and recovery rates. ([1, 27–30]). Two-stage reverse osmosis can achieve a recovery rate of over 50% ([31]).Mingheng [32]. It has been demonstrated that, without inter-stage booster pumps, single-stage is more energy efficient than two-stage in BWRO due to lower retentate pressure drop. Li et al. [33] investigated the validation of a model-based optimization for BWRO operations.

In addition, energy-intensive equipment such as high-pressure pumps (HPPs), booster pumps (BPs), and ERDs have been developed and improved to reduce the overall energy consumption of the SWRO process. The efficiency of HPP has increased by about 90%, which is a practical limit for centrifugal pump efficiency. Large pumps are recommended for improving HPP efficiency, with pump efficiency in a large-scale desalination plant reaching up to 85% [18], [22].

In other areas, the integration of photovoltaic (PV) and wind power in desalination processes has been evaluated, with promising results in regions with high solar and wind potential. For example, Yahiaoui et al. optimized a PV-diesel generator-battery hybrid system for the city of Djanet, Algeria, using the Grey Wolf optimizer [23]. In the last 20 years, advancements in ERD have played a significant role in reducing the energy consumption of the SWRO process. The development of ERD equipment, including Francis turbines (FTs) and pressure exchangers (PXs), has significantly reduced energy consumption [18], [19]. The efficiency of PX can exceed 95% [18]. As a result, advancements in energy-consuming units have nearly

reached their practical limits.
Many research investigations have been conducted to compare ERDs for saline waters. Alexander et al. analyzed the choice between two types of ERD (turbocharger and isobaric ERD) for brackish water in his study [35], taking into account the conversion rate parameter and the Life Cycle Cost analysis. In addition to its efficiency of between 94 and 98 percent for a discharge rate of up to 110 m3 per hour, which is close to the discharge rate of the plant in this case study, (Alexander et al. concluded that the isobaric ERD is more energy efficient than the turbocharger, particularly at a conversion rate of 75 to 81 percent, which is also the case for the plant in this study. As a result, the isobaric ERD will be considered an energy recovery system for the RO process used in this plant, which lacks ERD.
Furthermore, because the organization intends to expand this plant by adding more RO trains, an analysis of the SEC with and without ERD will be conducted to justify the feasibility of implementing this ERD at this plant.

This analysis will determine whether implementing an energy recovery device (ERD) in the expanded plant is a viable option. To achieve this, a genetic algorithm will be applied to identify the optimal ERD configuration, maximizing energy efficiency while considering the specific parameters of the reverse osmosis process. The genetic algorithm, known for its ability to solve complex optimization problems, will help explore a wide range of possible solutions and converge on the best configuration.

2. DESCRIPTION OF BWRO DESALINATION PLANT

The BWRO desalination plant consists of three production lines, as depicted in Fig 2.1. Each production line is structured in two stages. In this setup, the concentrate from the first stage serves as the feed water for the subsequent stage, allowing for additional permeate production. The permeate collected from the first stage is combined with the permeate from the second stage. The HPP increases the pressure of the pre-treated brackish water to a suitable value for

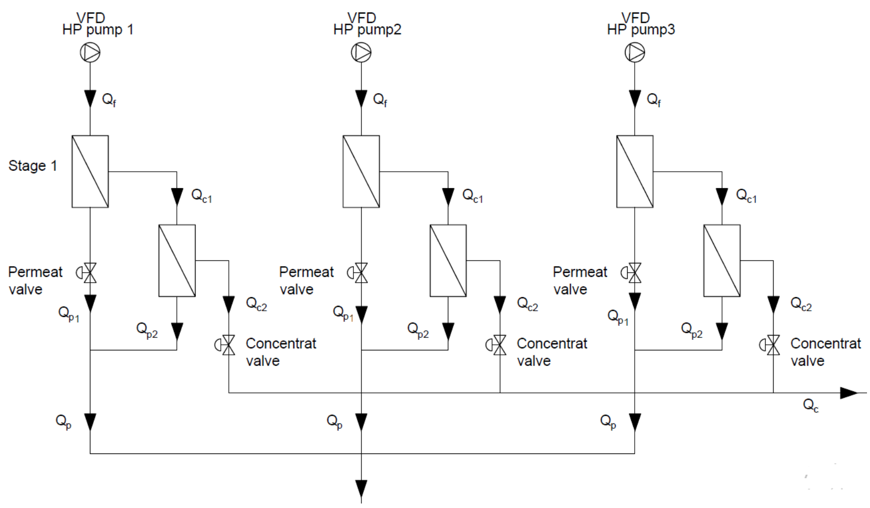

Fig. 2.1. Schematic Diagram

the membrane. The pressure required depends on the concentration and temperature of the feed water.

Osmotic pressure increases with concentration, so the operating pressure must be higher than the osmotic pressure corresponding to the concentration of the rejected brine flow rate at the membrane rack outlet, as well as membrane fouling. This plant's feed water concentration varies from 1g/l to 3g/l throughout the year, as does its temperature, which ranges from

Table 2.1. Equipment characteristics

Number of production line	3
Number of membrane by line	600
Membrane Sectional area	$35m^2$
Nominal Flow of HP pump	$550m^3/h$
Nominal Pressure of HP pump	20 bar
Nominal Speed of HP pump	3000 rpm

7C° to 32C°. To manage the changing characteristics of brackish water and keep within the operating range of this plant, the recommended conversion rate for each production line with its two stages is 75%, with a production flow rate of about 390 m3/h. To ensure that the above instructions are followed, each HP feed pump is equipped with a VFD that allows the pump speed to be varied, which changes both the flow rate and the pressure of the membrane feed water. The article [36] used fuzzy logic to effectively control these parameters in the station object of this study. Table 2.1 shows the equipment used in this station's RO process.

3. MATERIELS AND METHODS

Before evaluating the specific energy consumption (SEC) of the (RO) process implemented in this station, it is essential to first model the RO process and develop a simulation model. This initial step was thoroughly addressed in the work presented in article [37].Using Matlab/Simulink software tools, a numerical model was developed and validated against real plant values, as well as against the model used by Arun-Joseph and Vasanthi Damodaran in

Table 3.1. RO Process Equations

Definition	Equation	
Osmotic Perssure (bar)	$\pi = i.C_f.R.T$	(3.1)
Permeate flux ($m{\cdot}s^{-1}$)	$J_w = A_w(\Delta P - \Delta\pi)$	(3.2)
Solvent permeability ($m{\cdot}s^{-1}.Pa^{-1}$)	$A_w = A_0 exp(6.433 - \frac{1885}{T})$	(3.3)
Permeat flow (m^3/h)	$Q_p = S.J_W$	(3.4)
Drop Pressure Across Membrane (bar)	$\Delta P = (\frac{P_f + P_c}{2} - P_p)$	(3.5)
	$\Delta P = \Delta\pi + (\frac{Q_p}{S.A_w})$	(3.6)
Conversion rate	$Y = \frac{Q_p}{Q_f}$	(3.7)

their study [38]. The equations used for this modeling are summarized in Table 3.1. With this model in place, the current SEC of the RO process can be evaluated both with and without an energy recovery device (ERD). This comparison will demonstrate the potential benefits of installing an ERD in the plant. Following the conclusion to install the ERD, it is necessary to determine the optimal parameters for the RO process, taking into account the parameters of the ERD, which will also be modeled using equations. This optimization will be carried out using a genetic algorithm to ensure the most efficient operation of the expanded plant.

4. EVALUATION OF SEC AT BWRO

Electricity consumption is a major obstacle in the development of the RO process, with High-Pressure Pumps (HPPs) being the primary energy consumers. These pumps need substantial energy to overcome the osmotic pressure of saline water. Optimizing energy use involves lowering the feed's osmotic pressure and selecting the most efficient pump. HPPs account for about 75% of total specific energy consumption, with the remainder coming from membrane operations [26]. This study, therefore, focuses on the energy consumption of HPPs in the RO process for freshwater production. The equation below shows a mathematical method for estimating the SEC of the RO membrane without the need for an ERD system:

$$E_s = \frac{P_f.Q_f}{Q_p.\eta} \tag{4.1}$$

The model generated in Matlab/Simulink to evaluate the fluctuation of SEC in the station under study can be used to get an understanding of the predicted energy consumption and losses at the discharge. Three additional scenarios are added to the three cases given in the article [37] to study the energy fluctuation, as shown in Table 4.1. Furthermore, the energy assumed to be lost during discharge can be calculated by adding the flow rate and pressure of the concentrates. Given that the organization intends to expand this station with more trains, and based on the results, which show that the energy lost to create a cubic meter of permeate can average 0.3 kwh, a ERD for the new entity must be installed.

5. MODELING ERD

As previously mentioned, an isobaric Energy Recovery Device (ERD) will be utilized for the RO process implemented in this plant. Rotary isobaric devices use a small rotor to recover hydraulic energy from the concentrate stream. The rotor contains ducts that alternately fill with high-pressure brine and low-pressure feed water. As the rotor turns, these ducts are exposed to high- and low-pressure zones alternately, effectively replacing the high-pressure brine with saltwater on a 1-to-1 basis. The timing of the water exchange ensures that the chamber is never completely empty, creating a static water piston that prevents the two streams from mixing. [39].

The equations presented below are used to determine the best design for the RO process with an ERD. The installation of an ERD in an existing RO process necessitates knowledge of its operating parameters. Figure 5.1 shows the ERD system's inputs and outputs.

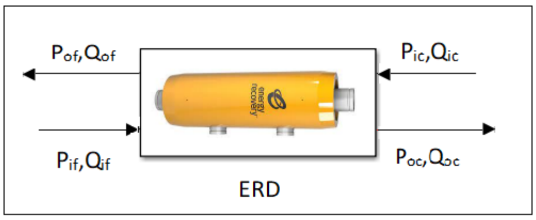

Fig. 5.1. The ERD system's inputs and outputs

5.1. Flow Calculation

The ERD requires for its adequate choice the preknowledge of the inlet flows(Q_{ic}, Q_{if}) and outlet flows (Q_{oc},Q_{of}) of this equipment. Water flows from the concentrate of RO process and the low pressure pumps are the two types of water flows that enter the ERD. Q_{ic} can be determined as is defined, the concentrate flow rate, Q_c which is a function of the RO process feed flow Q_f and its conversion rate Y :

$$Q_{ic} = Q_f.(1-Y)\ Where:\ Q_f = \frac{Q_p}{Y} = Q_c + Q_p \tag{5.1}$$

Each ERD is is characterised by Brine flow loss or Leak (L) and Overflush (Of) [34] where : Q_{if}, Q_{of} and Q_{oc} can be defined using the following equations:
Flow balance:

$$Q_{ic} + Q_{if} = Q_{of} + Q_{oc} \tag{5.2}$$

Overflush (Of): Overflush range is provided by isobaric ERDs manufactures:

$$O_f = \frac{Q_{if} - Q_{o_f}}{Q_{of}} \tag{5.3}$$

Table 4.1. Simulation values and actual values comparaison

Cnd	Unit	case1			case2			case3		
T	C°	20			13,5			24		
C_f	g/l	2			1.6			1.26		
	Pa	ST*	Mb**	Er %	ST	Mb	Er %	ST	Mb	Er %
P_f	bar	15,9	15,2	4,4	18,1	17,8	1,65	12,9	14,1	9,3
P_{c1}	bar	13,9	13,2	5,03	15,2	15,7	3,28	10,5	12,1	15,2
P_{c2}	bar	11,9	11,2	5,88	12,9	13,7	6,2	8,95	10,1	12,84
Q_{p1}	m^3/h	305,4	299,04	2,1	296,9	323	8,7	298,9	287,3	3,88
Q_{p2}	m^3/h	76,05	74,4	2,16	91,3	80,4	11,9	80	71,5	10,6
Q_{c1}	m^3/h	230,45	225,6	2,1	215	243	13	226,6	216,6	4,4
Q_{c2}	m^3/h	154,4	151,15	2,1	140,2	163,1	16,33	146,6	145.1	1
C_{p1}	g/l	0,04	0,02	50	0,01	0,01	0	0,02	0,02	0
C_{p2}	g/l	0,09	0,06	33,3	0,02	0,03	50	0,06	0,04	33,3
Y	%	71,2	72,7	2,1	73,5	71,1	3,2	72,1	71,2	1,2
Es	kwh/m^3	0,8	0,76	5	0,85	0,89	4,4	0.68	0.71	4,4
E_c	kwh/m^3	0,17	0,15	7,5	0,16	0,2	23,5	0,15	0,16	6
Cnd	Unit	case4			case5			case6		
T	C°	24			10			12		
C_f	g/l	1			2			1.2		
	Pa	ST*	Mb**	Er %	ST	Mb	Er %	ST	Mb	Er %
P_f	bar	13,4	13,95	4,1	19,1	19,55	2,35	17,8	18,09	1,6
P_{c1}	bar	11,6	11,95	3	17,7	17,55	1,1	15,9	16,09	1,1
P_{c2}	bar	10,2	9,95	2,4	15,9	15,5	2,5	14,3	14,09	1,4
Q_{p1}	m^3/h	291,04	285,62	1,8	345,2	338,1	2	330,2	325,28	1,4
Q_{p2}	m^3/h	72,05	71,11	1,3	96,3	84,17	12,5	82,1	80,98	1,3
Q_{c1}	m^3/h	220,45	215,47	2,2	257,2	255,07	0,8	243,6	245,39	0,7
Q_{c2}	m^3/h	149,4	144,36	3,3	173,2	170,9	1,3	167,6	164,41	1,9
C_{p1}	g/l	0,04	0,02	50	0,05	0,04	20	0,02	0,02	0
C_{p2}	g/l	0,07	0,05	28,5	0,11	0,09	18,1	0,07	0,06	14,2
Y	%	71,19	72,1	1,2	71,1	71,1	0	72,1	71,2	1,2
Es	kwh/m^3	0,66	0,69	4,5	0,92	0,98	6,5	0,88	0,91	3,4
E_c	kwh/m^3	0.15	0,13	13,3	0,25	0,24	4	0,22	0,21	3

Brine flow loss or Leak (L): is provided by isobaric ERDs manufactures as a function of temperature and brine input flow per isobaric ERDs unit [40]:

$$L = \frac{Q_{ic} - Q_{of}}{Q_{ic}} \tag{5.4}$$

Therefore the output flow rate from the side of feed membranes Q_{of} can be expressed as :

$$Q_{of} = Q_{ic}.(1 - L) \tag{5.5}$$

And Q_{if}:

$$Q_{if} = (Of + 1).Q_{of} \tag{5.6}$$

Finally by using Flow balance:

$$Q_{ic} + Q_{if} = Q_{oc} + Q_{of} \tag{5.7}$$

The output flow rate from ERD to the rejection can be expressed as :

$$Q_{oc} = Q_{ic} + Q_{if} - Q_{of} \tag{5.8}$$

5.2. Salinity Calculation

After defining the inlet and outlet flows of the ERD system, the salinity of the flows in the ERD sides can be determined. $C_{ic}$is the salinity of the concentrate of the RO process C_c and C_{if} is the salinity of feed water with low-pressure flow which is equal to the salinity C_f. It remains to determine the concentration of outflows from the ERD system C_{oc} and C_{of} which are respectively the salinity of reject flow and the salinity of pressured flow by the ERD. Each isobaric ERD has its own mixing M_x ratio [41] which is the ratio of the volume of brine that transfers into a volume feed water and can be calculated with the following equation independent of the pressure exchanger high and low pressure flow balance:

$$M_x = \frac{C_{of} - C_{if}}{C_{ic} - C_{if}} \tag{5.9}$$

Using the equation (5.9) C_{of} can be expressed as a function of the previously known parameters:

$$C_{of} = M_x(C_{ic} - C_{if}) + C_{if} \tag{5.10}$$

According to the salinity balance :

$$Q_{ic}.C_{ic} + Q_{if}.C_{if} = Q_{oc}.C_{oc} + Q_{of}.C_{of} \tag{5.11}$$

C_{oc} can be expressed as:

$$C_{ic} = \frac{(Q_{ic}.C_{ic} + Q_{if}.C_{if}) - Q_{of}}{Q_{oc}} \tag{5.12}$$

5.3. Pressure Calculation

The ERD's input pressures P_{ic} and P_{if} are respectively, the one of the from the concentrate flow rate of the RO process P_c, and the second is the pressure of low pressure flow rate coming from the low pressure pump, which is generally the circulation water pressure taken at approximately 2 bar. Moreover, the ERD outlet pressure may be estimated as follows: The output pressure recovered by ERD P_{of}:

$$P_{of} = P_{ic} - \Delta p1 \tag{5.13}$$

The pressure of the discharge from the ERD P_{oc}:

$$P_{oc} = P_{if} - \Delta p2 \tag{5.14}$$

Where : $\Delta p1$ and $\Delta p2$ are the losses across the isobaric ERD.

6. BOOSTER PUMP

A multi-stage brackish system without an interstage boost can be designed in a similar manner to a single-stage system. In this scenario, the previous stage's concentrate is used to pressurize a feedwater stream for the first stage. The circulation pump compensates for pressure losses in the membrane stages, pipework, and ERD. Because the brackish and seawater RO processes are not the same, the implementation of isobaric ERDs in brackish water RO systems must be handled differently. The small amount of pressure loss caused by membranes, friction in the ERD, and the piping circuit necessitates the use of a booster pump in isobaric ERD. This pump is used as the ERD's output in single-stage seawater systems. The ERD booster pump, on the other hand, can play two important roles in a two-stage brackish water system by being installed between stages one and two. The ERD booster pump acts as an inter-stage booster pump in this configuration, lowering the required pressure from the main high-pressure feed pump and balancing flux between stages 1 and 2 [35]. In this study, the booster pump will function as a circulation pump to recover pressure lost in the circuit (membranes, ERD, and pipes).

7. THE SEC OF BWRO WITH ERD

In order to evaluate the SEC by a BWRO equiped with a ERD, firstly it is necessary to express the energy recovered in the concentrate part of the process, which is function of the RO brine pressure P_c , flow rate of the concentrate Q_c, and the ERD efficiency η_{erd} as shown :

$$E_{erd} = P_c.Q_c.\eta_{erd} \tag{7.1}$$

by introducing a booster pump (BP) with efficiency η_{BP} , the energy consumed by this pump must be considered in order to evaluate the energy saving envisaged in the new design. In fact, this pump takes the water flow Q_{of} coming from the ERD with the pressure P_{of} in order to achieve the required pressure at the RO process inletP_f, therfore, the energy consumed by(BoP) can be expressed as follows:

$$E_{BP} = \frac{(P_f - P_{of})Q_{of}}{\eta_{BP}} \tag{7.2}$$

The pressure provided by the booster pump P_{BP}:

$$P_{BP} = P_f - P_{of} \tag{7.3}$$

The SEC by the BWRO with a ERD will be the combined energy consumed by the HP pump and the Booster pump [**?**]:

$$SEC = \frac{(Q_f - Q_{of}).P_f}{\eta_{HP}.Q_p} + \frac{P_{BP}.Q_{of}}{\eta_{BP}.Q_p} \tag{7.4}$$

8. RESULTS AND DISCUSSIONS

The Matlab/Simulink model developed in the article [37] and validated by the real values of the studied station makes it possible to evaluate the SEC by the process RO and especially the HP pumps. Furthermore, the values considered in the above study are taken at the start of exploitation of the said plant. However, after two years of operation, it was discovered that feed pressure values had increased for the same feedwater properties (salinity and temperature). This is due to membrane fouling and its life span. Following the development of the operating parameters of the RO process in this plant, it was observed that feed pressure and concentrate pressure rise by 2 to 3 bars. As a result, the SEC increases, proving the significance of the current study.

Using the ERD modeling equations and the RO model developed in Matlab/Simulink, the ERD has been implemented into this model while taking into account the inclusion of a booster pump, which is essential for an RO process with an ERD. The proposed design is illustrated in Figure 8.3.

Then, the Specific Energy Consumption (SEC) of the three reverse osmosis (RO) trains implemented in the plant under study is evaluated by considering various states of the saltwater feed, specifically by varying its salinity and temperature. These two parameters have a direct impact on the SEC of an RO process, as indicated in several studies ([6,20,21]), regardless of the system's design and structure. The graphs below illustrate the evolution of SEC for the RO process in this plant with and without Energy Recovery Device (ERD). When the feed water salinity is set at 1.85 g/L and its temperature is varied within the recorded range at the station, the SEC of the RO process with ERD decreases from 2.1 kWh/m³ to 1.45 kWh/m³ as the feed water temperature increases (Figure 8.1). In contrast, the SEC for the current design without ERD decreases from 3.05 kWh/m³ to 2.15 kWh/m³ under the same conditions (Figure 8.2).

In the same way, the feed water temperature was set to 22°C, and the salinity was adjusted within the station's operating range. The SEC with an ERD ranges from 1.55 kwh/m3 to 1.72 kwh/m3 (Figure 8.5), while the SEC without an ERD ranges from 2.27 kwh/m3 to 2.53 kwh/m3. Implementing the ERD at this station can reduce the SEC by an average of 30%, even with the installation of a booster pump, according to the study's findings. In addition, the SEC formula (7.4) takes into account the energy used by this pump. To evaluate the SEC

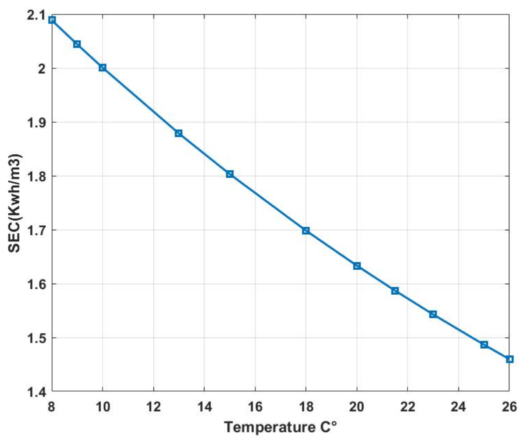

Fig. 8.1. SEC with T(with ERD)

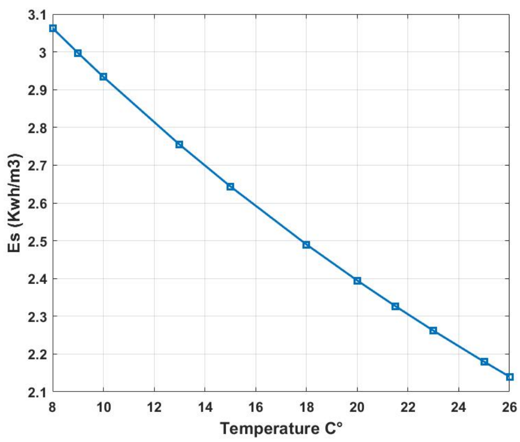

Fig. 8.2. SEC with T(without ERD)

Table 8.1. Algorithm Genetic parameters

Parameter	Number of Variables	Population size	Mutation	Migration	Crossover	Iteration
Value	6	50 for five	0,71	0,41	0,7	155
		Definition of variables				
X_i	X_1	X_2	X_3	X_4	X_5	X_6
Variable	Y	L	Q_{if}	O_f	Q_f	Q_p
Lower value L_b	0.7	0.003	136	0	490	370
Upper value U_b	0.75	0.013	162	0.05	550	400

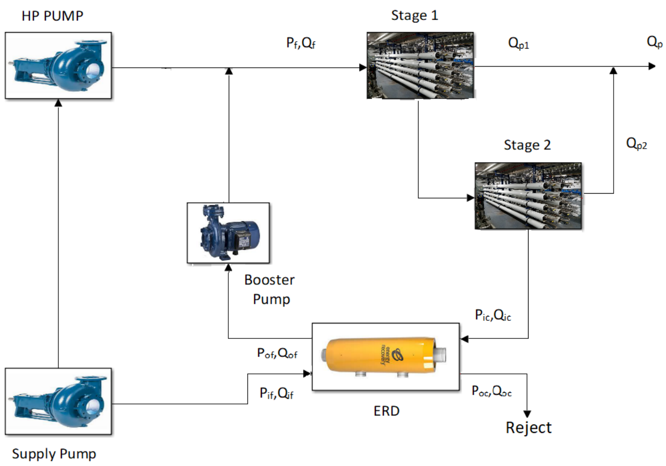

Fig. 8.3. The proposed Design

provided by the RO process in the three production lines, several salt water scenarios that closely resemble reality were captured and then simulated on the Matlab platform. It is clear that the inclusion of an ERD has an important effect on energy saving, and according to the 3D multivariate representation (Figure 8.6 and Figure 8.7), it can be observed that the temperature variation has a significant effect on the SEC more than the salinity variation

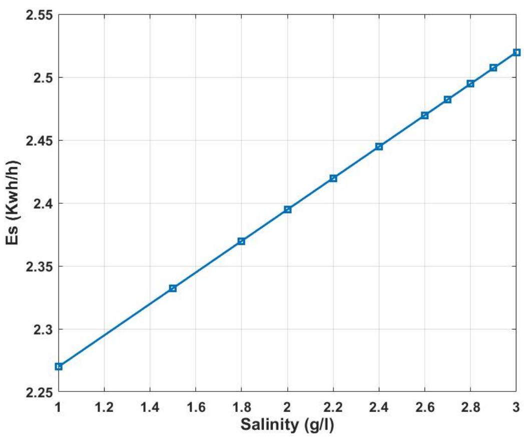

Fig. 8.4. SEC with C_f (without ERD)

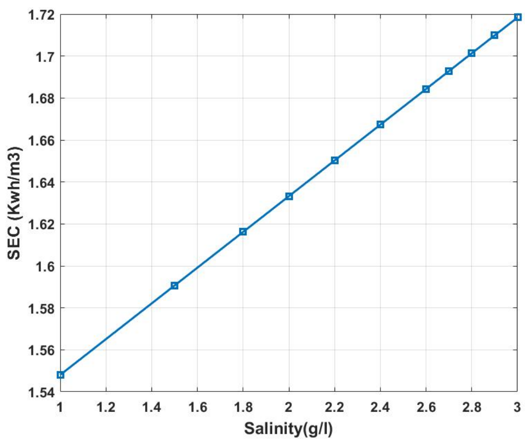

Fig. 8.5. SEC with C_f(with ERD)

Table 8.2. Results of Genetic Algorithm

Pressure (bar)	10	14	17	20	22	25
SEC($Kwh/m3$)	1,07	1,45	1,73	2,01	2,29	2,48
Y	0,7	0,7	0,7	0,7	0,7	0,7
L	0,03	0,03	0,03	0,03	0,03	0,03
$Q_{if}(m3/h)$	136,64	136,92	136,16	136,66	136,99	136,65
$o_f(m3/h)$	0,04	0,04	0,04	0,04	0,04	0,04
$Q_f(m3/h)$	549,54	549,88	549,85	549,45	549,99	549,58
$Q_p(m3/h)$	412,99	412,95	412,68	412,78	412,99	412,93

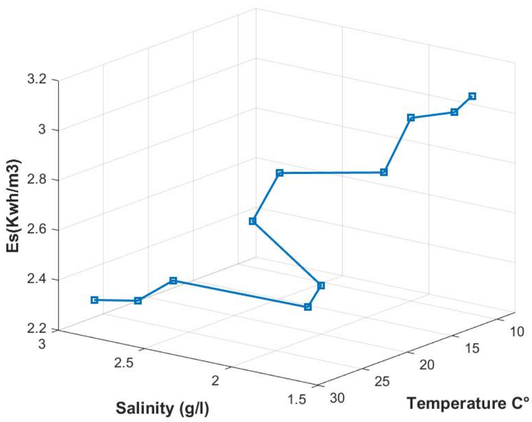

Fig. 8.6. SEC without ERD

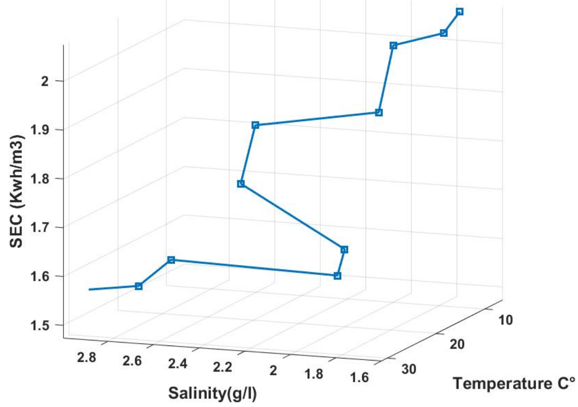

Fig. 8.7. SEC with ERD

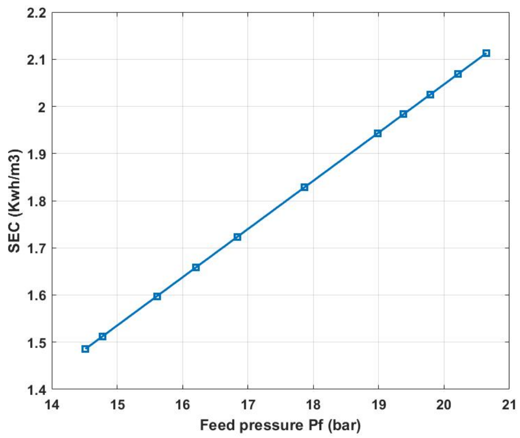

Fig. 8.8. SEC compared to P_f

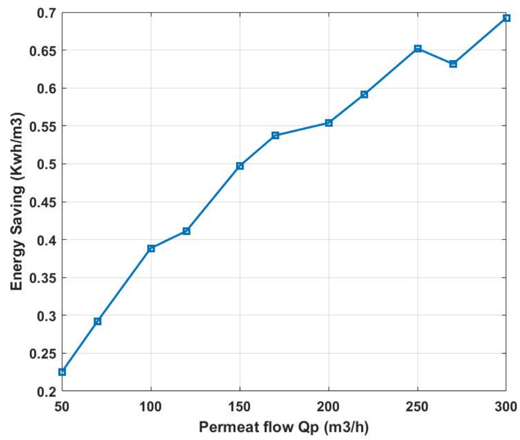

Fig. 8.9. Energy saving and Q_p

because its range of variation in this station is limited.

As concluded in various studies, including the article [37], changes in saltwater parameters (temperature and salinity) cause variations in the feed pressure. The relationship between SEC and feed pressure is illustrated in Figure 8.8, which shows that SEC increases with rising feed pressure. Figure 8.9 depicts the energy savings, defined as the difference in SEC between the RO process with ERD and the process without ERD. The curve indicates that energy savings increase with the produced flow (permeate flow). The reduction rate of SEC with the ERD remains approximately 30%, regardless of changes in permeate flow. Therefore, deploying the ERD is beneficial for RO stations with high energy consumption, especially for saline water within the same variable range of salinity and temperature. This advantage can be further supported by a techno-economic analysis.

By incorporating the genetic algorithm-based optimization approach, significant improvements in energy efficiency can be achieved for the RO process in water desalination plants. The observed 30% reduction in the SEC by adding an ERD in the RO process highlights the potential benefits of using this approach. Additionally, the genetic algorithm-based optimization can identify the most suitable ERD configuration based on the specific parameters of the RO process, leading to further improvement in energy efficiency. The

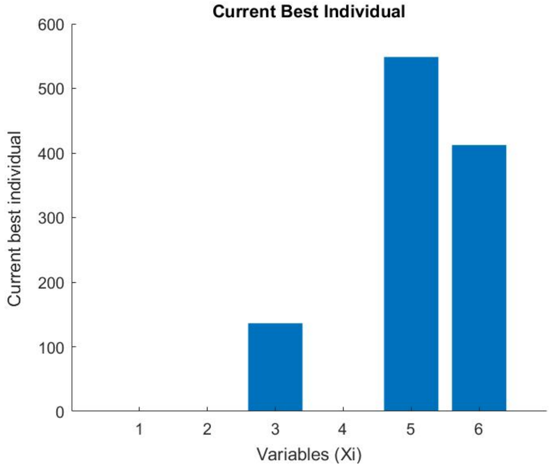

Fig. 8.10. Best individual

combination of ERD deployment and genetic algorithm-based optimization could provide a more sustainable and cost-effective approach to water desalination.

In order to optimize the specific energy consumption (SEC) of the RO process using a genetic algorithm, the formula (7.4)for SEC it's developed as a function of the parameters that contribute to the choice of the ERD(overflush: OF and leak: L). The equation can be expressed as follows:

$$SEC = \frac{(1-(1-Y)(1-L)).P_f.Q_f}{\eta_{HP}.Q_p} + \frac{P_{BP}.Q_{if}}{(O_f+1).\eta_{BP}.Q_p} \tag{8.1}$$

The optimal values of the SEC were obtained by using the Genetic Algorithm on the given formula, considering the feed pressure values ranging from 7 to 25 bar. It is important to note that the feed pressure values were calculated based on the salinity and temperature of the water. The parameters of the applied genetic algorithm are detailed in Table 8.1 and the obtained optimization results are presented in Table 8.2.

Upon analyzing the values obtained through the genetic algorithm, it can be concluded that the specific energy consumption (SEC) of the implemented RO process in the studied station ranges from 0,73 to 2,3. This means that, at the maximum feed pressure values considered in this station, energy consumption can be reduced by over 40%.

Table 8.2 summarizes the optimal values of the variables xi required for the operation of the RO process in this station, taking into account the parameters that characterize the ERD. For the process to function optimally, an appropriate ERD should have an overflush value of 0,04 and a leak value of 0,03.

The Figure 8.10 shows that variables X_3,X_5 and X_6 are the parameters that have the most influence on energy optimization in this RO process.

9. CONCLUSIONS

The analysis of specific energy consumption (SEC) in the Moroccan plant's reverse osmosis desalination process for brackish water reveals significant potential for energy savings. The study shows that by using a genetic algorithm to optimize design and operational parameters, the incorporation of energy recovery devices can reduce SEC by up to 30%. These findings highlight the significance of energy optimization in increasing the feasibility and sustainability of reverse osmosis desalination. Implementing these technologies can make the process more cost-effective and environmentally friendly, encouraging widespread adoption in water-scarce regions. Future research will focus on implementing intelligent control systems for the operating parameters to ensure consistent production under optimal conditions. This approach aims to maintain the desired output quality while adapting to varying feed water characteristics, thus ensuring the process remains efficient and reliable.

10. ABBREVIATIONS

[ERD]	Energy Recoverey Device
[RO]	Reverse Osmosis
[HP]	High Pressure
[BW]	Brackish Water
[BWRO]	Brackish Water Reverse Osmosis
[SWRO]	Sea Water Reverse Osmosis
[HPP]	High Pressure Pump
[BP]	Booster Pump
[LPP]	Low Pressure Pump
[VFD]	Variable Frequency Drive
[SEC]	Specific Energy Consumed (kwh/m^3)
[P_f]	Feed Pressure (bar)
[P_c]	Concentrate Pressure (bar)
[P_p]	Permeat Pressure (bar)
[Q_f]	Feed flow rate (m^3/h)
[Q_c]	Concentrate flow rate (m^3/h)
[Q_p]	Permeat flow rate (m^3/h)
[C_f]	Feed water salinity (g/l)
[C_c]	Concentrate salinity (g/l)
[C_p]	Permeat salinity (g/l)
[T]	Temperature (C°)
[E_s]	Specific energy consumed without ERD (kwh/m^3)
[E_c]	Energy lost on the rejection (kwh)
[E_{erd}]	Energy recovered by ERD (kwh)
[E_{BP}]	Energy consumed by BP (kwh)
[η_{HP}]	HPP efficiency
[η_{BP}]	BP efficiency
[η_{erd}]	ERD efficiency
[P_{if}]	ERD input Pressure from LPP (bar)
[P_{ic}]	ERD input Pressure from the concentrate (bar)
[P_{of}]	ERD output Pressure from ERD to BP (bar)
[P_{oc}]	ERD output Pressure from ERD to the rejection (bar)
[Q_{if}]	ERD input flow rate from LPP (m^3/h)
[Q_{ic}]	ERD input flow rate from the concentrate (m^3/h)
[Q_{of}]	ERD output flow rate from ERD to BP (m^3/h)
[Q_{oc}]	ERD output flow rate from ERD to the rejection (m^3/h)
[C_{if}]	ERD input salinity of flow rate from LPP (g/l)
[C_{ic}]	ERD input salinity of flow rate from the concentrate (g/l)
[C_{of}]	ERD output salinity of flow rate from ERD to BP(g/l)
[C_{oc}]	ERD output salinity of flow rate from ERD to the rejection (g/l)
[L]	ERD Flow Loss
[O_f]	ERD over flush range

$[M_x]$	Mixing Ratio
$[*ST]$	Station Values
$[**Mb]$	Matlab/Simulink Values
$[Er]$	Margin of error between ST and Mb
$[i]$	Number of ions dissociated in the case of an electrolyte
$[R]$	Ideal gas constant R = 8.314 $(J{\cdot}mol^{-1}.k^{-1})$
$[S]$	Surface of the membrane (m^2)

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