Optimizing the energy performance of a demineralization unit using an energy recovery device: application to the Moroccan context

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Abstract. The demineralization of brackish water through reverse osmosis (RO) represents a strategic and sustainable solution to meet the increasing water demands in the southeastern regions of Morocco, particularly in arid areas such as Zagora. Despite its effectiveness, the RO process remains highly energy-intensive, primarily due to the operation of high-pressure pumps, which account for 40% to 55% of total operating costs. Furthermore, a substantial amount of hydraulic energy is lost when the concentrated brine is discharged at atmospheric pressure, highlighting a major inefficiency. To address this challenge, the present study investigates the integration of an isobaric Pressure Exchanger (PX) as an energy recovery device to enhance the energy performance of a reverse osmosis unit. Using real operational data collected from the Zagora demineralization plant specifically pressure and flow rate readings from the OS1 and OS2 reject lines a detailed numerical simulation was conducted to quantify the recoverable hydraulic energy and analyze its variation over time. The results emphasize the critical role of energy recovery technologies in improving the sustainability, efficiency, and environmental footprint of desalination plants in Morocco. Integrating such systems aligns with the country's strategic goals for resource optimization and the energy transition in water infrastructure.

Keywords *:* Reverse osmosis (RO); Brackish water; Energy recovery; Pressure Exchanger (PX); Hydraulic energy; Desalination; Energy efficiency; Numerical simulation; Sustainable water treatment.

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1 Introduction

Water lies at the core of human existence it is one of the planet's most vital and irreplaceable resources. Although nearly 75% of the Earth's surface is covered by water, approximately 97% of it is saline, contained in the oceans, leaving only about 3% as freshwater suitable for human use [1,2]. Unfortunately, while the global population continues to grow, the demand for freshwater is increasing at twice that rate, whereas freshwater availability remains stagnant or even declines in many regions [3,4]. Currently, water consumption mirrors our societal priorities: agriculture alone consumes around 70% of global freshwater resources, industry accounts for 20%, and only 10% is used for domestic purposes [5,6]. This imbalance, coupled with rapid urbanization and increased industrial activity, places tremendous stress on conventional water sources.To address this challenge, industries and governments are increasingly turning to non-conventional water sources, such as the treatment of brackish water and seawater, to meet the growing demand [7,8]. However, desalination and demineralization processes are highly energy-intensive, relying predominantly on fossil fuels a dependency that not only escalates operational costs but also significantly contributes to greenhouse gas emissions [9,10,11]. As a response, integrating renewable energy into water treatment systems is no longer just a trend it is a necessity. This transition offers a more sustainable solution, particularly for arid and semi-arid regions where water scarcity is most severe [12]. Aligned with this context, the present study investigates the energy challenges associated with desalination. Specifically, it explores ways to optimize the energy efficiency of such processes particularly by recovering hydraulic energy from the reject streams of reverse osmosis units, a resource often overlooked yet rich in potential.

The main objective of this study is to evaluate the potential for hydraulic energy recovery in a brackish water reverse osmosis (RO) desalination system using real operational data from the Zagora plant in southeastern Morocco. Specifically, the study aims to: (i) quantify the recoverable energy from the brine reject streams (OS1 and OS2); (ii) assess the temporal evolution of this energy potential; and (iii) investigate the benefits of integrating an isobaric Pressure Exchanger (PX) to enhance the system's energy efficiency. Through numerical simulation and performance analysis, the study seeks to provide practical insights into improving the sustainability and economic viability of inland desalination facilities in arid regions (see Figure.1).

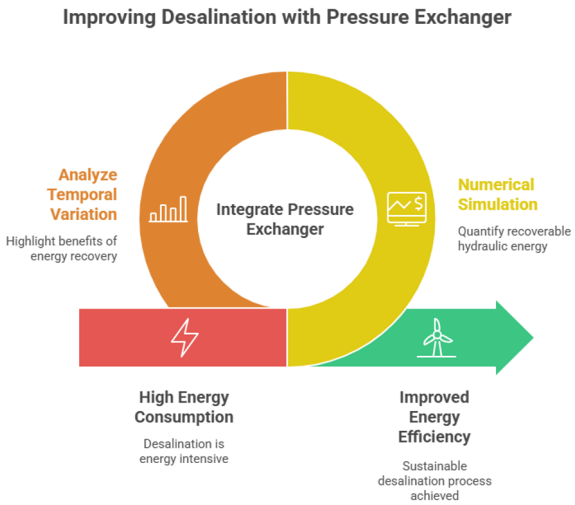

Figure 1 : Improving desalination with adding pressure exchanger

2 Materials and methods

The methodology adopted in this study follows a structured approach combining field data collection, hydraulic analysis, and numerical modeling.
The first step consists of describing the physical and operational characteristics of the Zagora plant, which provides the experimental framework of this work. Subsequently, the pumping and pretreatment systems are detailed to highlight the main hydraulic parameters influencing energy performance.
Finally, a computational procedure is developed to estimate the recoverable hydraulic power and to evaluate the impact of integrating an isobaric pressure exchanger.

2.1. Zagora plant description

The brackish water demineralization plant of Zagora is located at the geographic coordinates 27°03′23.14″N latitude and 13°25′29.73″W longitude. It is situated in southern Morocco, specifically in the Drâa-Tafilalet region, as illustrated in Fig. 1(a). The facility, shown in Fig. 1(b), is equipped with two parallel production lines referred to as Line A and Line B both utilizing reverse osmosis (RO) technology to produce up to 600 m^3 of freshwater per day. Two storage tanks, each with a capacity of approximately 400 m^3, are located about 200 meters from the demineralization unit.

2.2. Pumping system

Following the intake of brackish water, the Zagora demineralization plant uses two primary pumps to supply the feed water to the treatment unit. Each of these pumps has a flow rate of 250 m^3/h and a power rating of 45 kW, drawing water from the collection pond to the facility. A third pump is available as a backup and can substitute either of the main pumps, when necessary, thereby ensuring operational continuity and system reliability.

2.3. Pretreatment unit

The pretreatment step is necessary for maximizing efficiency, operation, and lifetime of a reverse osmosis system. It cleanses raw brackish water from a variety of contaminants, including reducing turbidity, killing microorganisms, removing colloidal particles, dissolved organic and inorganic substances, total dissolved solids (TDS), and chemical contaminants. Considered an essential index during this phase, the Silt Density Index (SDI) essentially evaluates the fouling potential of feed water. A higher index means that particulate matter is present in an amount that could clog membranes, lessen system performance, and raise the cost of maintenance. Henceforth, an optimum SDI has to be maintained to protect the RO membranes, improve efficiency, and increase the system's life.

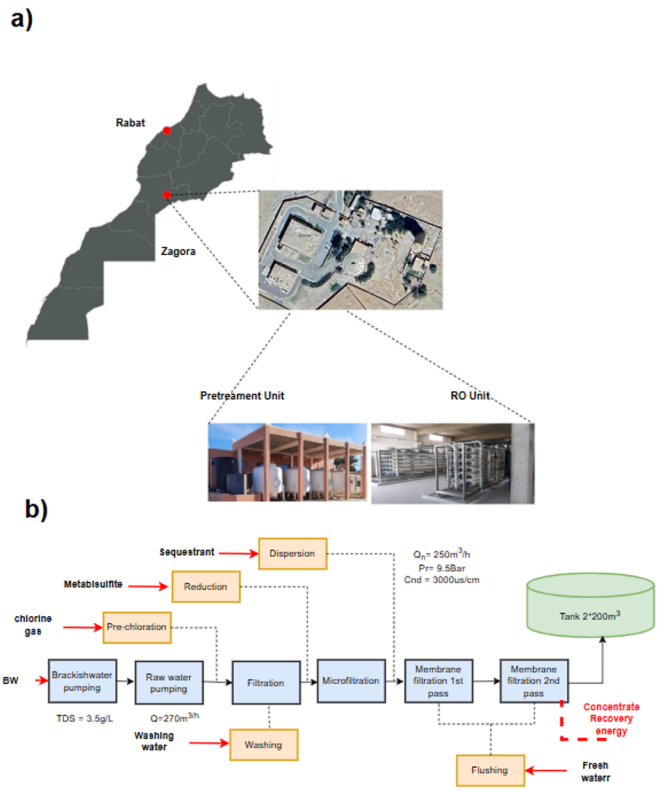

Figure 2 : Zagora plant description

3 Results and discussion

After defining the plant configuration, the next step focuses on the energy performance evaluation based on operational data.

3.1 Visualization of brine pressure in the system

The theoretical hydraulic power available in the reject streams from the reverse osmosis lines OS1 and OS2, as shown in **Fig. 2**, were evaluated in this study. The goal was to evaluate the energy potential presently being lost during the discharge of brine, based on actual operations' pressure and flow measurements. Understanding this potential energy source is crucial to exploring options for improving overall energy efficiency of the process by implementing viable energy recovery systems.

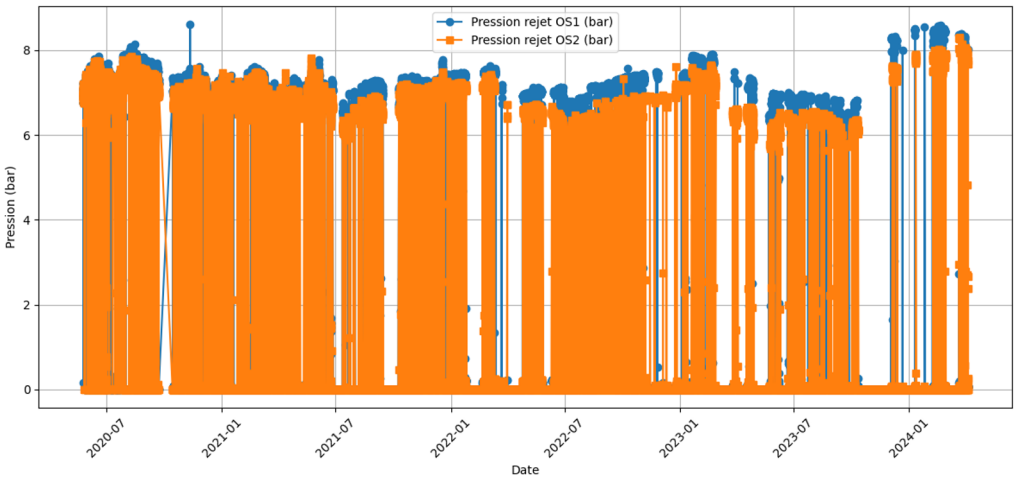

Figure 3: Visualization of a pressure of brine in the system

3.2 Calculation and analysis of hydraulic power from brine reject streams (OS1 and OS2)

Real-time operation data at the Zagora demineralization plant is used for this purpose of evaluation. Actual values of outlet pressure from the first-stage membrane of each of the reverse-osmosis lines (OS1 and OS2) as well as that of reject flows associated therewith were considered. These parameters were drawn from the monitoring and control system of the plant, giving credentials on the fact that they were accurate values, representative of genuine operational cases. Therefore, using the theoretical formula as follows, the theoretical hydraulic power (P) related to these reject streams is computed:

$$P = \rho \cdot g \cdot Q \cdot h \quad (1)$$

where

ρ: is the **density of water** (1000 kg/m³);
g: is the **gravitational acceleration** (9.81 m/s²) ;
Q: is the **volumetric flow rate** (in m³/s),
h: is the **hydraulic head**, derived from the reject pressure converted using:

This allowed the estimation of any recoverable hydraulic energy in the pressurized brine reject streams; indeed, any such energy would be wasted since no energy recovery scheme exists presently. Applying the respective pressure and flow rate values, the power theoretically harness able was calculated from these streams under actual operating conditions. In order to understand better the dynamism of the energy potential, the results were plotted as time series curves showing the temporal evolution of hydraulic power in the

two lines, OS1 and OS2. These curves, shown in **Fig. 3**, give insights into the recoverable energy's stability and variation along the plant operation cycles and serve as a starting point for assessing the feasibility and advantages of installing an energy recovery device.

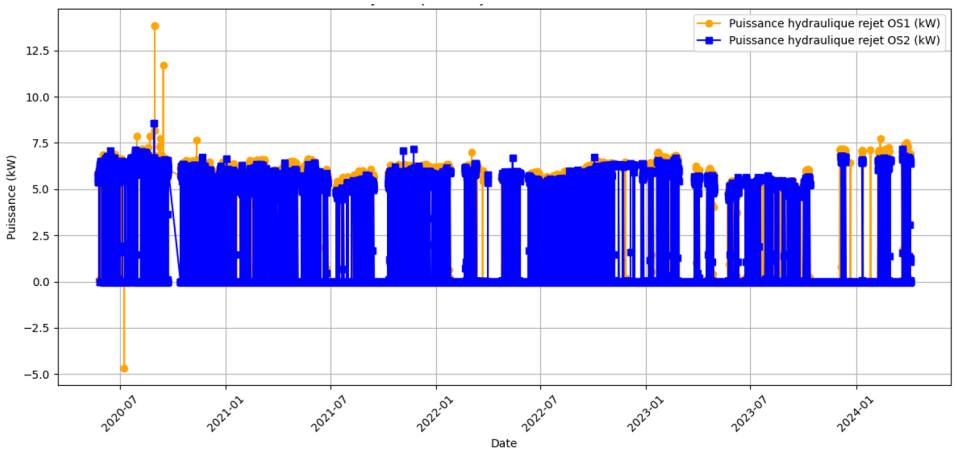

Figure 4 : Calculation and Analysis of the Hydraulic Power of the Brine Reject (OS1 and OS2)

3.3 Integration of a pressure exchanger into the system

The pressure exchanger illustrated in **Fig. 4** is an isobaric energy recovery device specifically designed to transfer hydraulic pressure from a high-pressure fluid stream (typically the brine reject) to a low-pressure incoming feed stream, without converting the energy into mechanical or electrical form. This direct pressure transfer mechanism significantly reduces the energy demand of the high-pressure pump, thereby improving the overall energy efficiency of the reverse osmosis (RO) system. Such systems are widely adopted in modern desalination and demineralization facilities, particularly in high-pressure applications, due to their high efficiency (often exceeding 95%) and low maintenance requirements. By recovering energy from the reject stream and using it to pre-pressurize the feed water, pressure exchangers contribute to substantial reductions in operational costs and environmental impact, making them a cornerstone of energy-optimized RO plant design.

Figure 5: Pressure exchanger schema

For an approximation of energy efficiency:

$$\text{Recover Energy}\left(\frac{\text{kWh}}{\text{m3}}\right) = \eta \text{ x } \frac{\text{Preject x Qrject}}{\rho \text{ .g}} \quad (2)$$

where:
η : PX effeciency ;
Preject : Reject pressure ;
Qreject : Reject flow ;
ρ : density (kg/m^3)
g : gravity (m/s^2)

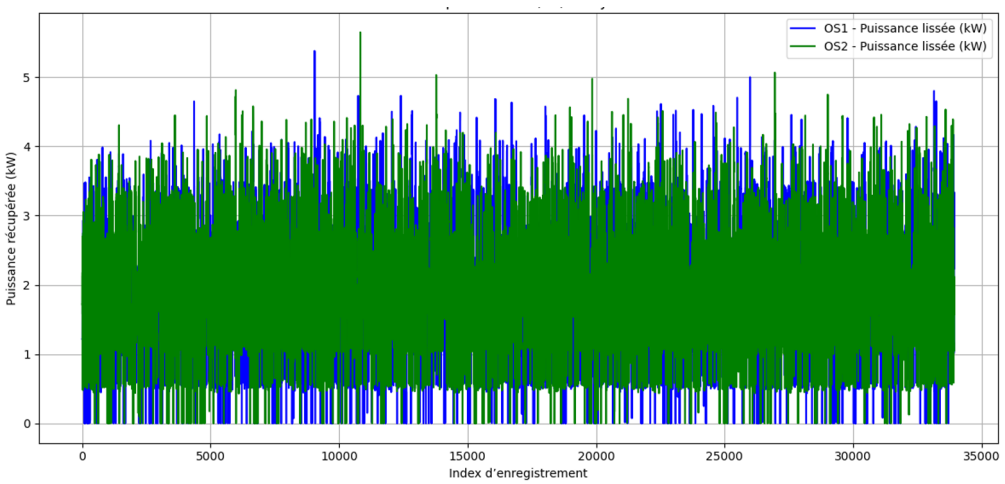

Figure 6: The total recoverable hydraulic energy from the reverse osmosis rejects streams (OS1 and OS2)

Over the monitoring period, the total recoverable hydraulic energy from the reverse osmosis reject streams (OS1 and OS2) was estimated under the assumption of one data measurement per minute, as shown in Fig. 5. The analysis revealed that approximately 1014.55 kWh could be recovered from OS1 and 1049.46 kWh from OS2, resulting in a combined energy recovery potential of 2064.01 kWh. From a financial perspective, this recoverable energy translates into an estimated savings of 2476.81 MAD (approximately 250.18 USD), calculated using a standard electricity tariff of 1.2 MAD/kWh and a conversion rate of 1 USD ≈ 9.9 MAD. Beyond economic benefits, the environmental implications are equally significant. The recovery of this energy would prevent the emission of nearly 1238.41 kg of CO_2, which is equivalent to driving more than 1200 kilometers in a conventional petrol-powered vehicle. These findings highlight the considerable potential for energy savings and carbon emission reduction through the integration of an energy recovery device such as a pressure exchanger. Notably, the recovered energy over the monitoring period corresponds to the average monthly electricity consumption of more than two typical Moroccan households, demonstrating the real-world impact and scalability of this approach in similar desalination contexts.

Conclusion

This study highlighted the considerable potential of hydraulic energy recovery in reverse osmosis (RO) demineralization processes, using the Zagora desalination station as a representative case study. Through the analysis of real operational data specifically the reject pressure and flow rates from the OS1 and OS2 lines we accurately quantified the recoverable hydraulic power and examined its temporal evolution throughout the monitoring period. The results demonstrated that integrating an isobaric Pressure Exchanger (PX) into the system could enable the recovery of over 2064 kWh of energy annually. This would translate into a financial saving of approximately 2476 MAD (≈ 250 USD) and prevent the emission of more than 1200 kg of CO_2, equivalent to the environmental impact of driving over 1200 kilometers in a conventional vehicle. Furthermore, the smoothed power curves revealed a consistent and stable recovery potential, thereby reinforcing the technical feasibility and reliability of PX implementation in such inland water treatment facilities.

These findings strongly advocate for the integration of energy recovery devices in brackish water desalination units, especially in arid regions like southeastern Morocco. Such a strategy not only contributes to improving the energy efficiency and cost-effectiveness of water production, but also aligns with national objectives related to sustainable resource management, climate change mitigation, and the broader energy transition in the water sector.

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