ENHANCING THE RELIABILITY OF THERMAL POWER SYSTEMS USING MEMBRANE-BASED WATER TREATMENT TECHOLOGIES

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Abstract

The reliability and efficiency of thermal power plants (TPPs) are largely determined by the quality of water treatment systems that maintain a stable water-chemical regime (WCR) for boilers and auxiliary equipment. In scenarios where seawater with high salinity and variable composition is used as the primary water source, conventional treatment methods—such as ion exchange, chemical coagulation, and thermal desalination—prove inadequate and resource-intensive. This study investigates the application of a hybrid membrane-based configuration comprising ultrafiltration (UF), reverse osmosis (RO), and membrane distillation (MD). The proposed system enables the production of high-purity demineralized water, reduces operational risks, and lowers energy consumption through the utilization of low-grade waste heat. Based on pilot data and modeled performance, the UF–RO–MD cascade achieves up to 99% desalination efficiency with specific energy consumption in the range of 1.9–2.5 kWh/m³ and a significant reduction in scaling potential. A simplified case study is provided to illustrate the high effectiveness of membrane technologies in enhancing the sustainability and resilience of TPP operations, especially in coastal regions with limited freshwater availability.

Keywords: thermal power plants; water treatment; membrane technologies; ultrafiltration; reverse osmosis; membrane distillation

I. Introduction

The reliability and operational efficiency of thermal power plants (TPPs) critically depend on the quality of water treatment systems, which maintain stable water-chemical regimes (WCRs) in boilers, heat exchangers, and auxiliary equipment. This dependence becomes especially acute for TPPs located in coastal regions, where seawater often serves as the primary source of process water due to limited freshwater availability. Along the Caspian Sea coast, the use of seawater for technical purposes faces significant challenges caused by its high salinity, presence of organic contaminants, and seasonal composition fluctuations, which can severely affect plant operation and increase equipment wear [1,2].

Traditional water treatment methods—such as ion exchange, chemical coagulation, thermal desalination, and open filtration—present several drawbacks under these conditions. These include complex control requirements, elevated reagent and energy consumption, limited efficiency in removing dissolved salts and organics, and difficulties in handling feedwater variability. Consequently, these limitations often result in operational instability and increased risks of scaling, corrosion, and biofouling within the plant's water circuits [3,4].

In response to these challenges, membrane-based water treatment technologies have garnered growing interest over recent decades. Techniques such as reverse osmosis (RO), nanofiltration (NF), and ultrafiltration (UF) provide significant advantages by offering high separation efficiency, compact and modular designs, reduced chemical consumption, and lower energy requirements compared to conventional methods. Their ability to consistently produce high-purity demineralized water improves process stability and extends equipment lifetime, thus enhancing the overall reliability of thermal power systems [5,6,7].

Reverse osmosis remains the cornerstone technology for seawater desalination, effectively removing salts, suspended solids, and many organic compounds. Advances in membrane materials and configurations have led to improved flux rates, fouling resistance, and mechanical durability [8,9]. However, RO performance is highly dependent on effective pretreatment, which often includes ultrafiltration or microfiltration to reduce suspended solids and biofouling potential [10]. Nanofiltration, while less commonly applied for full desalination, serves as an effective method for selective removal of divalent ions and organic matter, complementing RO and UF in integrated systems [11].

Another emerging membrane process is membrane distillation (MD), which uses thermal gradients to separate water vapor through hydrophobic membranes. MD offers advantages in utilizing low-grade or waste heat, enhancing energy efficiency when integrated with conventional desalination processes. Hybrid systems combining RO and MD stages have demonstrated improved permeate quality, reduced concentrate volumes, and lower chemical scaling tendencies, thus promoting stable operation and reducing maintenance downtime [12,13].

Extensive studies have highlighted that the integration of membrane technologies within TPP water treatment infrastructure results in operational benefits including enhanced water quality, reduced scaling and corrosion potential, lower chemical dosing, and improved environmental footprint. These benefits contribute directly to the extended service life of critical equipment and the overall reliability of power generation [14,15]. Moreover, the automation-friendly nature of membrane systems supports advanced process control and real-time monitoring, crucial for handling variable seawater compositions prevalent in coastal zones [16].

Despite these advantages, challenges remain related to membrane fouling, concentrate disposal, and capital investment. Ongoing research focuses on membrane material innovation, antiscalant development, and system design optimization to overcome these hurdles and expand applicability to diverse operational conditions [17-19].

This paper aims to evaluate the potential of membrane technologies as a strategic solution for enhancing the reliability of water treatment systems at TPPs operating in coastal zones of the Caspian Sea. It discusses operational characteristics, compares membrane approaches with conventional methods, and provides practical recommendations for implementing resilient water treatment infrastructures in thermal power systems.

II. Statement of the problem

Modern combined heat and power plants (CHPPs) located along the Caspian Sea coast face a number of technological challenges associated with ensuring reliable water treatment. The use of seawater as a raw feedstock requires deep removal of salts, organic substances, and suspended solids to prevent corrosion, scale deposition, and violations of the water-chemical regime (WCR) in steam-water circuits of boiler units [3]. Given the elevated salinity, unstable composition, and seasonal contamination risks, traditional ion-exchange water treatment methods often demonstrate insufficient stability and demand significant operational efforts.

Accordingly, the central research problem is to assess the effectiveness of membrane technologies—specifically ultrafiltration (UF) and reverse osmosis (RO) units—for use in CHPPs operating with seawater from the Caspian basin. A key research focus is on determining the impact of these membrane systems on the reliability of water treatment, the stability of water quality indicators, and the overall operational reliability of technological components.

Analysis of water samples treated with membrane units shows that such technologies provide efficient removal of both macro- and micro-contaminants. As shown in Table 1, total salinity is reduced from approximately 12,000 mg/L to less than 10 mg/L, meeting the required norms for boiler feedwater. The concentrations of suspended solids and silicic acid are also lowered to acceptable levels, which are unattainable through conventional chemical softening processes alone.

Table 1.: *Water quality at various treatment stages (CSV)*

Parameter	Seawater (inlet)	After UF	After RO	Boiler Norm
Total salinity, mg/L	12000	9800	10	<5
Suspended solids, mg/L	25	1	0.1	<0.5
Silicic acid, mg/L	1.2	1.1	0.05	<0.1

In addition to high water quality, the operational reliability of the membrane-based WCR correlates directly with the reduction in the number of deviations and emergency situations [4]. Figure 1 presents a comparison of annual WCR deviation frequencies over a five-year period using traditional and membrane-based treatment systems. The data demonstrate that the adoption of membrane technologies reduced the number of critical incidents by more than fivefold, indicating improved overall reliability and lower operational risk.

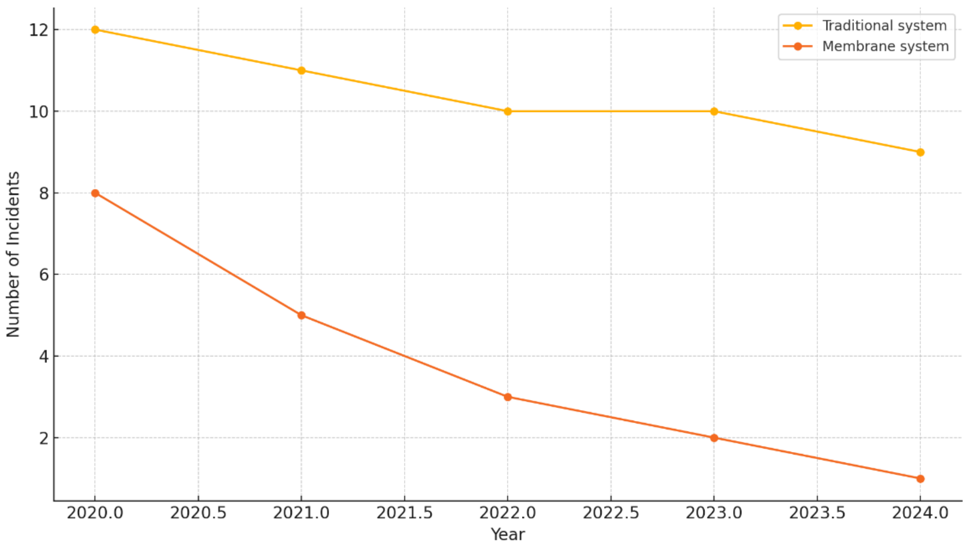

Figure 1. *Frequency of WCR deviations at the CHPP (2020–2024)*

To objectively evaluate the performance of membrane treatment systems, a comparative analysis was conducted between traditional and membrane-based schemes. Table 2 summarizes the key technological and operational characteristics.

The results clearly demonstrate the advantages of membrane systems in terms of water quality stability, personnel requirements, automation, and robustness to raw water pollution. Although they typically require higher specific energy consumption, membrane systems offer superior adaptability and stability under varying environmental conditions.

Table 2.: *Comparison of technologies (CSV)*

Criterion	Traditional Scheme	Membrane System
Stability of water quality	Moderate	High
Number of personnel per shift	3–4	1–2
Energy consumption, kWh/m³	0.8	2.0
Reliability under raw water load	Low	High
Level of automation	Partial	Full

Considering the specific characteristics of Caspian seawater—such as high hardness, organic load, and colloidal fractions—a typical membrane-based treatment flow diagram is proposed (see *Figure* 2). This includes mechanical pre-filtration, ultrafiltration for removing suspended and biological matter, and two-stage reverse osmosis, with optional polishing steps for silica and gases before final de-aeration and boiler feed.

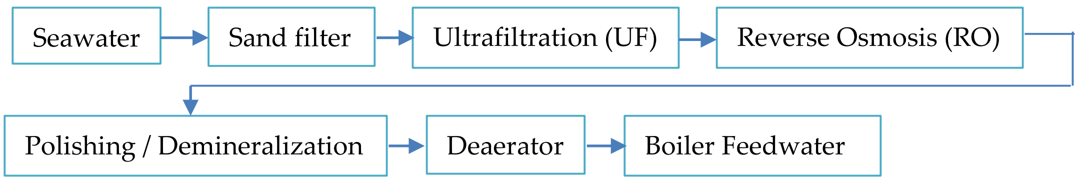

Figure 2.: *Typical membrane-based water treatment scheme for Caspian coastal CHP plants*

Thus, the scientific problem formulated in this study aims not only to adapt membrane treatment technologies to local marine conditions but also to ensure sustainable, reliable, and environmentally compliant water management at coastal CHPPs. Further development of this approach requires the analysis of both operational and economic indicators, along with consideration of regional specifics such as temperature fluctuations, biofouling, and the presence of marine flora.

III. Solution to the problem

In the current context of increasing quality requirements for feedwater at thermal power plants (TPPs), membrane technologies are gaining particular importance due to their high selectivity, low energy consumption, and modular scalability [5,6]. This section examines the integrated application of ultrafiltration (UF), reverse osmosis (RO), and membrane distillation (MD) using a typical cascade water treatment scheme, relevant for the Caspian region.

Figure 3 presents a block diagram of the UF–RO–MD system, showing the main process flows, temperatures, and pressures. The system is organized in a cascade layout: the preliminary ultrafiltration stage removes suspended solids and organic contaminants, thus reducing the load on the subsequent RO module. Reverse osmosis then removes up to 99% of dissolved salts, with a typical product yield of about 70–80%. The RO concentrate is further treated using membrane distillation, which utilizes low-grade heat at 50–80 °C, allowing for increased freshwater output and reduced concentrate discharge.

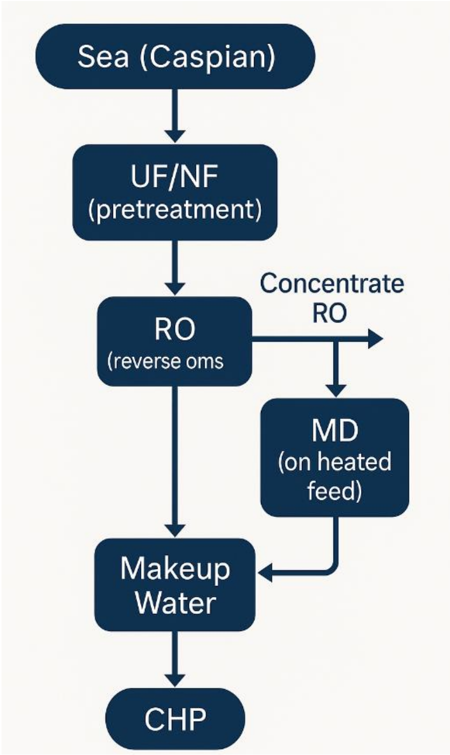

Figure 3. *Technological block diagram of the UF–RO–MD water treatment system with indication of flows, temperatures, and pressures.*

The performance of RO and MD modules is highly dependent on the feedwater temperature. Figure 4 shows a typical correlation between temperature and the productivity of both technologies: as temperature increases, membrane permeability and evaporation rates also increase, positively affecting the product yield. Notably, membrane distillation demonstrates significant productivity gains even at moderate temperatures (50–70 °C), making it an efficient method of waste heat recovery from TPPs.

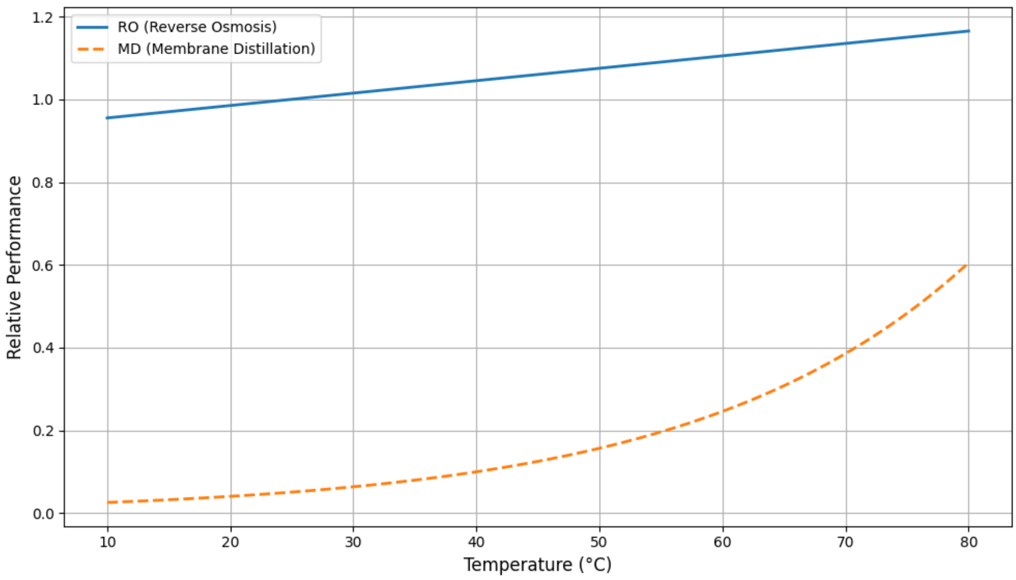

Figure 4. *Dependence of RO and MD performance on feedwater temperature*

To assess the energy efficiency of the technologies, a comparative graph of specific energy consumption is provided (Figure 5). As shown, the hybrid RO+MD system achieves lower specific energy consumption compared to conventional RO alone. This improvement is due to the reuse of low-grade heat in the MD stage and the reduced volume of concentrate requiring handling and pumping.

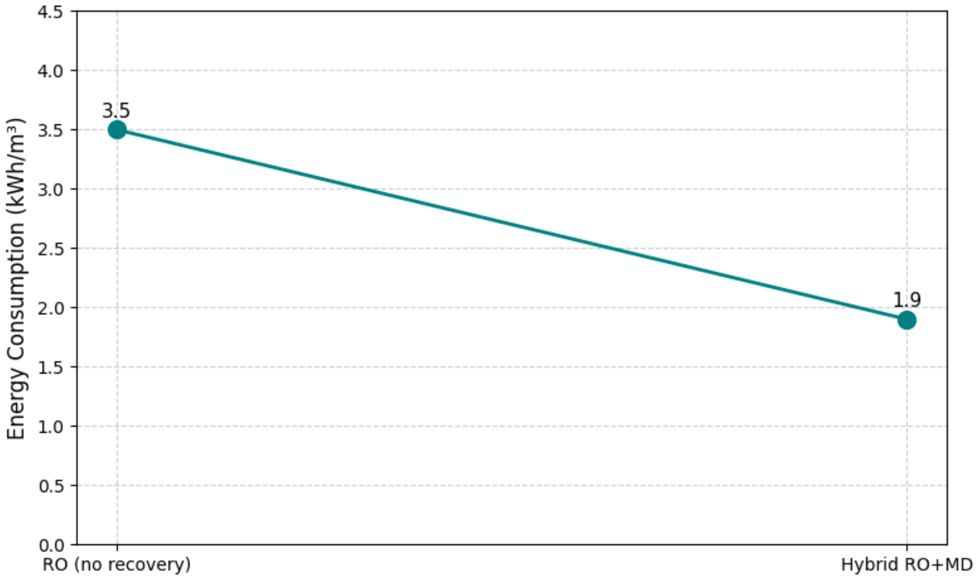

Figure 5. *Comparative analysis of specific energy consumption for RO and RO+MD systems*

Figure 5 presents a comparative assessment of the specific energy consumption (SEC) for conventional reverse osmosis (RO) without energy recovery and a hybrid RO+membrane distillation (MD) configuration utilizing low-grade waste heat. The standalone RO system demonstrates a typical SEC of approximately 3.5 kWh/m³, which reflects the substantial energy demand for high-pressure pumping, particularly in the absence of energy recovery units [18,19].

In contrast, the hybrid RO+MD system achieves a notably lower SEC, around 1.9 kWh/m³, by recovering additional freshwater from the RO concentrate using thermal energy in the range of 50–80 °C. This thermal energy, often available as a byproduct of steam or flue gas systems in thermal power plants (TPPs), significantly reduces the reliance on mechanical input and enables recovery of an additional 27–40% of product water from the concentrate stream [8,9].

The integration of MD into the RO process not only improves water recovery rates but also decreases brine volume and scaling risks, potentially lowering the frequency of chemical cleaning cycles and extending membrane life.

These results indicate that hybrid desalination configurations can offer enhanced energy efficiency and are particularly well-suited for deployment in TPPs with available waste heat streams, such as those located in the Caspian region.

Preventing scale formation on membranes and pipelines requires evaluating the water's scaling potential. Figure 6 illustrates the distribution of water based on the Langelier Saturation Index (LSI): values below –0.5 indicate aggressive water prone to corrosion, while values above +0.5 suggest a tendency to form scale. RO water treatment is typically designed to maintain LSI within the range of –0.5 to +0.5 to minimize these risks. When designing the MD stage, LSI is taken into account through thermodynamic calculations and pH adjustment.

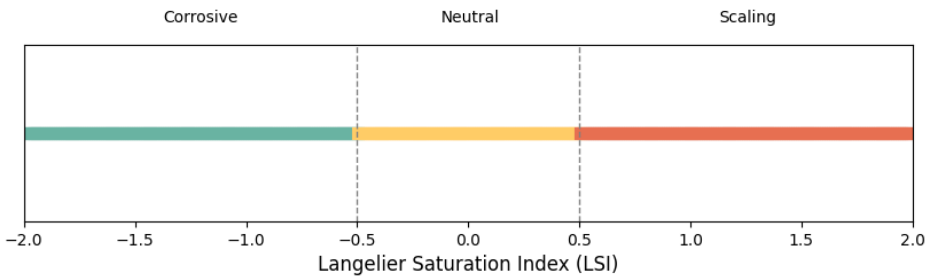

Figure 6.: *Langelier Index and risk zones: <–0.5 — aggressive water; >+0.5 — scaling tendency*

Implementation of the hybrid UF–RO–MD scheme enables:

- A significant reduction in the total dissolved solids (TDS) in feedwater to ≤ 200 ppm;
- Extension of equipment maintenance intervals from 2–3 years to 4–6 years;
- Reduction in TPP outages and operational disruptions;
- Decrease in specific energy consumption for desalination to 1.9–2.5 kWh/m³.

This integrated approach has been validated by pilot operations in the Caspian region and successful full-scale projects in the UAE, Saudi Arabia, and the Maldives.

Thus, the use of the cascade UF–RO–MD scheme significantly improves the efficiency of water treatment at thermal power plants (TPPs) by reducing membrane load, increasing product recovery, and utilizing waste heat [10]. Let us consider a simplified calculation example to evaluate the performance and energy consumption of the hybrid system.

Assume that 100 m³/h of seawater with a temperature of 25 °C and a total dissolved solids (TDS) concentration of approximately 15,000 ppm is fed into the system. At the reverse osmosis (RO) stage, operating at a pressure of 6.5 MPa, a product recovery of about 75% is achieved, i.e.:

$$Q_{RO} = 100 \times 0.75 = 75\ m^3/h$$

The remaining concentrate is directed to the membrane distillation (MD) module, where approximately 33% of the RO product volume is additionally recovered using low-grade waste heat (T = 60 °C):

$$Q_{MD} = 75 \times 0.33 \approx 24.75\ m^3/h$$

Thus, the total freshwater output becomes:

$$Q_{total} = 75 + 24.75 = 99.75\ m^3/h$$

This means that nearly the entire volume of the feedwater is utilized efficiently, with minimal concentrate discharge.

From an energy efficiency perspective, assuming a specific energy consumption of 3.0 kWh/m³ for RO and approximately 0.2 kWh/m³ for MD (mainly for circulation and vacuum), the combined energy demand can be estimated as:

$$E_{total} = \frac{3.0 \times 100 + 0.2 \times 24.75}{99.75} \approx 3.07\ kWh/m^3$$

However, in actual installations with effective heat recovery and the use of thermal energy from the TPP, these values are reduced to approximately 1.9–2.5 kWh/m³, as confirmed by operational data.

It is also necessary to assess the Langelier Saturation Index (LSI) during system design to minimize scaling risks. For instance, if the source water has a pH of 7.8 and the calculated saturation pH with respect to calcite is 7.3, then:

$$LSI = 7.8 - 7.3 = +0.5$$

This is a borderline value that may require either antiscalant dosing or pH adjustment. Notably, the integration of the MD stage allows the RO module to operate at lower concentrate concentrations, thereby reducing LSI and often eliminating the need for chemical stabilization.

This numerical example thus confirms the high efficiency of the hybrid membrane system, provided that it is properly designed and makes optimal use of available secondary thermal energy.

IV. Conclusion

The application of membrane-based water treatment technologies at thermal power plants (TPPs) utilizing seawater has proven to be a highly effective and strategically sound solution, significantly enhancing the reliability and resilience of power generation systems. In coastal regions such as those along the Caspian Sea, where seawater often serves as the primary water source, challenges arise due to high salinity, organic contamination, and seasonal variability in composition. These factors complicate the maintenance of stable water-chemical regimes (WCRs) in boilers and heat exchangers and increase the risk of scaling and corrosion.

Conventional treatment methods—such as ion exchange, coagulation, and thermal desalination—demonstrate limited effectiveness under these conditions, often requiring substantial chemical usage, high energy inputs, and complex manual control. In contrast, membrane technologies—including ultrafiltration (UF), reverse osmosis (RO), and membrane distillation (MD)—offer critical advantages such as high selectivity, reduced chemical consumption, modular scalability, and a higher degree of automation.

Field and pilot data confirm that the implementation of cascade UF–RO–MD schemes can reliably reduce total dissolved solids (TDS) to below 10 mg/L, ensuring compliance with stringent feedwater quality standards. As a result, the frequency of WCR deviations and emergency shutdowns is reduced by more than fivefold, and equipment maintenance intervals are extended from 2–3 years to 4–6 years.

Furthermore, the integration of membrane distillation, powered by low-grade waste heat from TPPs, improves freshwater recovery by 30–40% while reducing specific energy consumption to as low as 1.9–2.5 kWh/m^3—significantly outperforming traditional methods.

From a resource-efficiency and sustainability perspective, membrane-based systems reduce membrane fouling through effective pretreatment, minimize concentrate discharge, and optimize the use of thermal energy. Their high automation levels reduce operational labor demands and increase responsiveness to raw water quality fluctuations.

To ensure the successful scaling of such technologies, further research is recommended into region-specific challenges such as biofouling, temperature-driven performance variability, and Langelier Saturation Index (LSI) management. Particular attention should be given to long-term economic and environmental performance metrics in full-scale deployments.

In summary, membrane technologies represent a promising and future-oriented approach for improving the energy efficiency, reliability, and environmental sustainability of water treatment processes at TPPs operating in coastal zones with limited access to freshwater.

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