

Summary

Water scarcity is one of the most severe challenges faced nowadays by the world's population. With nearly two billion people living in water-stressed regions, the number of urban centers with access to clean, affordable water is rapidly diminishing. This situation directly leads to health and poverty issues, and translates into the need for efficient, effective, sustainable and affordable solutions for safe water supply, wastewater management, and water reuse. In this context, increasing the water supply is largely dependent on desalination and water reuse strategies. However, the energy demands of these technological solutions limit their worldwide adoption and applicability. To complete this figure, the strong interconnection between water and energy, known as water-energy nexus, significantly complicates the issue, as water is essential in most energy production operations, and energy is necessary to extract, purify, deliver, and reclaim water.

To address these challenges, emerging water treatment technologies that can handle complex water sources and recover water even from challenging environments are crucial. Among them, membrane distillation systems are specially promising for the desalination of hypersaline water streams (salinity > 70‰). However, some bottlenecks currently limit their adoption beyond pilot-scale applications. This thesis aims to explore ways to overcome these limitations, especially focusing on promoting the transition of membrane distillation towards efficient real-scale applications.

The research encompasses three main chapters. In Chapter 2, the energy behavior of membrane distillation modules and systems is comprehensively presented and discussed, with emphasis on unveiling real energy consumption for heating, cooling, and electrical operation. In addition, a methodology to evaluate the net energy consumption, considering available energy sources and heat sinks, is presented and applied to pilot-scale data. Findings reveal that heating demands approximately $130 \text{ kWh}\cdot\text{m}^{-3}$, while a thermal energy extraction of approximately $80 \text{ kWh}\cdot\text{m}^{-3}$ is necessary for cooling. These values translate into

net energy consumption values spanning from $0.6 \text{ kWh}\cdot\text{m}^{-3}$ to $200 \text{ kWh}\cdot\text{m}^{-3}$, depending on the presence/absence of energy sources and heat sinks. These insights highlight the importance of a fair energy evaluation prior to economic analyses.

Chapter 3 examines the performance of one of the largest active area membrane distillation modules available nowadays. A pilot-scale vacuum assisted air gap membrane distillation system was tested under near-real operating conditions to determine productivity, selectivity, and energy consumption. Also, as a consequence of the large membrane active area ($\sim 25 \text{ m}^2$), low specific productivity values were recorded ($< 2.5 \text{ L}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$). However, the relative specific thermal energy consumption values ranged promisingly from approximately $50 \text{ kWh}/\text{m}^3$ to $500 \text{ kWh}/\text{m}^3$. In addition, the salt rejection ranged from 2-log to 4.5-log removal values. In summary, the results support air-gap membrane distillation as a possible solution for the desalination of hypersaline water streams, especially when powered by renewable or low-grade heat sources, and/or when heat sinks are available.

Lastly, Chapter 4 explores the adaptability of membrane distillation for specific applications, such as the concentration of temperature-sensitive, highly valuable substances from diluted water streams. Using a draw agent on the distillate side of a direct contact membrane distillation unit, this process, known as osmotic membrane distillation, was modeled starting from physical equations, and then validated by an experimental campaign. Results shown that under certain conditions, the productivity increased by around 50% and consequently allowed substantial energy savings due to the reduction of feed stream temperatures. Tests with phycocyanin and spent coffee ground extracts demonstrated the potential of this approach, with the concentration of phycocyanin achieved at feed stream temperature $\leq 35^\circ\text{C}$. This last chapter demonstrates the possibility of adapting membrane distillation to specific applications and target scenarios.

Overall, this thesis contributes to advancing membrane distillation technology by addressing key challenges and evaluating its application under diverse configurations and conditions. These findings support the transition towards efficient, large-scale use of membrane distillation for water recovery and resource management.