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Techno-Economic Assessment (TEA) of a Minimal Liquid Discharge (MLD) Membrane-Based System for the Treatment of Desalination Brine

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Abstract

Desalination plays a critical role in addressing global water scarcity, yet brine disposal remains a significant environmental challenge. This study evaluates a minimal liquid discharge (MLD) membrane-based system integrating high-pressure reverse osmosis (HPRO) and membrane distillation (MD) for brine treatment, with a focus on the Eastern Mediterranean. A techno-economic assessment (TEA) was conducted to analyze the system's feasibility, water recovery performance, energy consumption, and cost-effectiveness. The results indicate that the hybrid HPRO-MD system achieves a high water recovery rate of 78.65%, with 39.65 m^3/day recovered from MD and 39 m^3/day from HPRO. The specific energy consumption is 23.2 kWh/m^3, with MD accounting for 89% of the demand. The system's cost is USD 0.99/m^3, generating daily revenues of USD 228 in Cyprus and USD 157 in Greece. Compared to conventional brine disposal methods, MLD proves more cost-effective, particularly when considering evaporation ponds. While MLD offers a sustainable alternative for brine management, challenges remain regarding energy consumption and the disposal of concentrated waste streams. Future research should focus on renewable energy integration, advanced membrane technologies, and resource recovery through brine mining. The findings highlight the HPRO-MD MLD system as a promising approach for sustainable desalination and circular water resource management.

Keywords: minimal liquid discharge (MLD); zero liquid discharge (ZLD); resource recovery; desalination; brine; desalination brine; Eastern Mediterranean; brine management; brine treatment; membrane-based separation

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1. Introduction

Water occupies an important position in sustainable development, as the revitalization of ecosystems, the provision of energy, and social development are all inextricably tied to its availability [1,2]. The nations of the Eastern Mediterranean, exemplified by the Hellenic Republic (i.e., Greece) and the Republic of Cyprus (i.e., Cyprus), are peculiarly prone to water scarcity due to their characterization as highly susceptible regions to climatic fluctuations [3,4]. A novel approach to addressing the global challenge of water scarcity is unfolding, as desalination technology seeks to tap into the virtually boundless resources of the world's oceans [5–9].

The global desalination industry currently comprises over 21,000 operational facilities, which collectively yield nearly 140 million m^3 of potable water every day [10]. While desalination processes provide a consistent source of freshwater, they also generate a secondary

product (i.e., by-product), namely brine, concentrate, or reject, which is characterized as saline wastewater [11]. The brine in question presents substantial ecological concerns due to its elevated salinity (Table 1) and the likelihood of the presence of potential hazardous substances resulting from the residues of pretreatment processes. The salinity of brine hinges on a spectrum of several ions (Na^+, Ca^{2+}, Mg^{2+}, Cl^-, HCO_3^-, etc.) [12–16].

Brine effluent management necessitates the deployment of diverse disposal strategies by desalination facilities, encompassing the utilization of evaporation ponds, deep-well injection, conveyance to sewage systems, oceanic or surface water disposal, and terrestrial practices [17–20]. Regrettably, these disposal methods are accompanied by detrimental consequences for local ecosystems [21,22].

In recent years, environmental concerns surrounding saline wastewater discharge have driven the development of innovative approaches. Zero liquid discharge (ZLD) represents a paradigmatic approach to saline water valorization/treatment, which seeks to entirely eliminate wastewater discharge from facilities, thereby enabling the recovery of significant volumes of water for reuse and ensuring the responsible management/valorization of co-generated solid salt. Notably, nearly all freshwater is reclaimed through ZLD systems, wherein the resulting solid salt(s) can be valorized or disposed of in a significantly more environmentally friendly manner [23–27]. From a long-term perspective grounded in sustainability, the ZLD concept exhibits remarkable congruence with the fundamental tenets of the circular economy (CE) paradigm, rendering it an apt framework for the furtherance of desalination and brine management [28–33].

It is pertinent to note that the notion of minimal liquid discharge (MLD) also warrants consideration, as it shares a similar objective with ZLD, namely, to extract water while reducing the volume of effluent brine. However, there exist distinct differences between the two approaches. For instance, MLD exclusively relies on membrane-based technologies, which, in turn, result in a greater quantity of brine. The MLD approach, having garnered significant attention of late, has been found to necessitate substantially reduced energy and operational expenditure while concurrently achieving a remarkably high target for freshwater recovery [11,34].

In hybrid MLD systems, multiple desalination processes are consolidated, mirroring the configuration employed in ZLD systems. Notably, the reliance solely on membrane-based technologies in MLD systems yields notable benefits. In particular, the reduced energy and cost requirements of MLD systems can be ascribed to the fact that they predominantly employ membrane-based technologies, unlike ZLD schemes, which integrate both membrane- and thermal-based processes [10,35].

Membrane-based technologies encompass a diverse array of methods, including electrodialysis reversal (EDR), forward osmosis (FO), reverse osmosis (RO), membrane distillation (MD), and high-pressure RO (HPRO), amongst others [36–40]. The MLD framework operates within the paradigm of the circular economy model, a paradigm endorsed by the European Union (EU). This notion of sustainable development, as championed by the EU, suggests a departure from traditional linear practices, instead embracing a regenerative approach that favors recycling and reusing resources.

Regarding the desalination technologies, a small variety of technologies has been adopted. Notably, approximately 74% of the global desalination facilities employ RO technology due to its demonstrated energy efficiency. The existing generation of RO membranes and modules possesses the capacity to withstand pressures < 82 bar and tolerate salinities of up to 70 g/L [41]. Nevertheless, RO technology is not ideally suited for treatment of extremely saline streams. Advances in membrane technology have facilitated the creation of HPRO, a system capable of functioning at pressures of up to 160 bar, thereby allowing it to be effectively utilized for the desalination of brackish water/seawater as

well as the treatment of brine. However, it should be mentioned that the standard RO membranes are not suitable for HPRO applications. Under the extreme hydraulic pressures of HPRO, these membranes undergo severe and irreversible compaction. This deformation leads to a densification of the membrane's support and polyamide selective layers, resulting in a significant decline in water permeability and a potential loss of salt rejection due to the formation of defects on the selective layer. Therefore, HPRO requires specially engineered membranes with enhanced mechanical strength and structural integrity to withstand these harsh operating conditions and maintain performance [42–45].

Another membrane-based technology, MD, has emerged as a cutting-edge approach to desalination, leveraging the unique properties of hydrophobic membranes to transform saline water into treated water. By exploiting the thermodynamic gradient generated across the membrane, water vapor is translocated from the salty, hotter side to the more diluted, cooler side, thereby effecting the separation of water from its inorganic and organic impurities. A particularly attractive feature of MD is its energy efficiency, which enables operation at lower pressures/temperatures in comparison to traditional methods, such as RO. This technology has demonstrated exceptional efficacy in treating seawater and brine, which are inherently high-salinity sources, thereby rendering it a pragmatically viable solution to addressing global water scarcity. Furthermore, the modular design of MD facilitates effortless scalability, allowing it to cater to a wide range of desalination requirements, from large-scale industrial applications to localized village settings [46–49].

Despite the pervasive importance of brine treatment, a substantial amount of theoretical and empirical knowledge remains to be explored in regard to these topics. The existing corpus of research primarily centers on assessing the efficacy of MLD/ZLD systems that integrate conventional and well-established technologies. This research study introduces a novel approach by integrating HPRO and MD technologies within a MLD framework for the first time. This article represents a significant contribution to the peer-reviewed literature, as it explores the combination of HPRO and MD for effective brine valorization/treatment and resource extraction. Additionally, the computational study evaluates the feasibility and performance of this HPRO-MD hybrid system, focusing on brine management strategies. It also investigates the potential for implementing this MLD system in Eastern Mediterranean countries, specifically Greece and Cyprus. To achieve these goals, the techno-economic viability of the HPRO-MD MLD system is thoroughly analyzed for its effectiveness in treating and utilizing seawater brine. The selection of HPRO and MD for this MLD system is based on their complementary operational capabilities for treating hypersaline brines. While both technologies can be energy-intensive, their combination offers a strategic advantage. HPRO is one of the few membrane technologies capable of handling the high osmotic pressure of desalination brine to achieve significant initial water recovery [50]. The resulting HPRO reject, which is too saline for further pressure-driven membrane treatment, is an ideal feed for MD. MD is a thermally-driven process that is not limited by osmotic pressure and can treat brines to very high concentrations [46,51]. This synergy allows the hybrid system to achieve much higher overall water recovery than either technology could alone, which is the primary objective of an MLD strategy.

Table 1. Composition of brines from several industrial sectors [52].

Industrial Sector	Total Dissolved Solids (TDS) (mg/L)
Petrochemical industry	20,000–85,000
Desalination industry	50,000–82,000
Aquaculture industry	12,000–47,000
Textile industry	1500–50,000
Pharmaceutical industry	20,000–50,000

2. Materials and Methods

2.1. System Configuration

This study outlines a methodology designed to optimize water extraction, achieve MLD conditions, and manage brine generated from a desalination plant. The MLD treatment framework integrates two primary technologies, namely HPRO and MD. Figure 1 depicts the operational layout of the MLD system, highlighting the sequential progression of processes. Within this framework, seawater is initially introduced into the HPRO unit, where desalination occurs, yielding two outputs, namely brine and permeate. The permeate is reclaimed as freshwater, whereas the brine is conveyed to the MD unit. In the MD unit, both the desalted liquid (permeate) and the brine are collected. The combined freshwater output consists of HPRO permeate and MD permeate. A significant advantage of this system is its capacity to process saline water/wastewater, gradually reducing its volume, thus minimizing environmental impact while producing precious resources, such as drinking water. From a structural standpoint, the HPRO unit is placed as the first step in the MLD system due to its ability to handle feedwater with lower salinity levels compared to the MD unit. It is crucial to highlight that Figure 1 illustrates a conceptual process flow diagram for a computational model, not a schematic of a physical component. The techno-economic assessment methodology section that follows provides specifics on the technical factors that define this model, including operational pressures, flow rates, etc. This modeling technique, which is used for feasibility studies, enables the assessment of a system's potential before it is physically constructed, which requires significant financial investment.

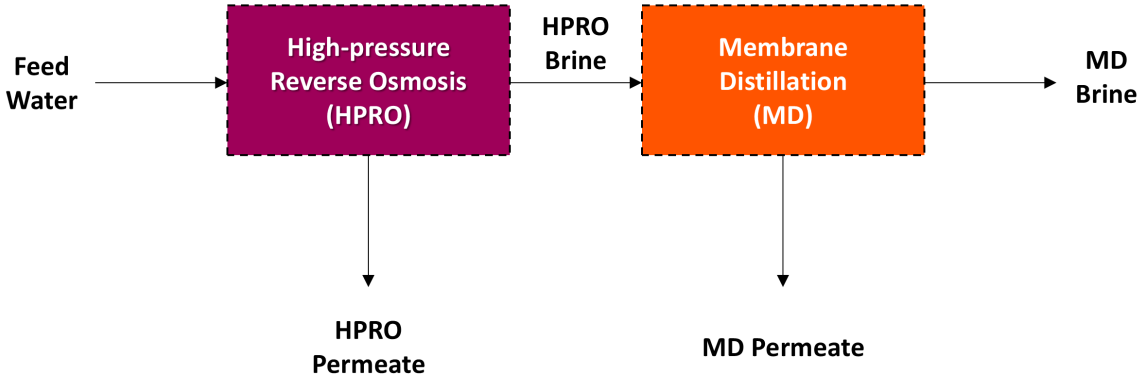


Figure 1. A visual representation showing the configuration of the MLD system, particularly the HPRO-MD process.

2.2. Techno-Economic Assessment (TEA) Methodology

This study conducts a detailed techno-economic assessment (TEA) and feasibility analysis to evaluate the technical/commercial potential of implementing the MLD system for seawater treatment. The research explores scalability prospects for deployment across the Eastern Mediterranean, specifically in Greece and Cyprus. A representative feedwater flow rate of 100 m^3/day (ambient temperature and pressure) and salinity of 38.000 mg/L—consistent with regional seawater characteristics—were selected as baseline parameters [53]. A feedwater flow rate of 100 m^3/day was selected as a representative baseline for a small-scale decentralized treatment facility, allowing for a scalable analysis applicable to various contexts. The HPRO operating pressure of 120 bar was chosen as it represents a realistic and challenging condition for treating hypersaline seawater RO brine, consistent with the upper operational limits of commercially available HPRO systems. For desalination plants to operate as efficiently as possible, the simulation is predicated on continuous operation. While the MD unit is modeled with a feed–permeate temperature differential of 40 °C

(i.e., 60 °C feed, 20 °C permeate), which is a common working condition, the HPRO unit is designed to run at a pressure of up to 120 bar, a typical parameter for high-salinity applications. These predetermined parameters serve as the foundation for the reported performance results and are essential to the simulation's integrity. Financial assumptions include a 5% interest rate and a 30-year operational lifespan to align with long-term infrastructure investments. Economic data on equipment and operational costs were compiled through vendor quotations, peer-reviewed publications, industry reports, and authoritative databases. Analytical methodologies and equations underpinning the assessment are summarized in Table S1 (Supplementary Material), while Table 2 delineates cost estimates, technical specifications, and assumptions derived from prior studies and verified sources. The fact that this study is a computational techno-economic evaluation must be denoted. Instead of constructing or operating a physical pilot system, the methodology focuses on developing a comprehensive model. The performance (such as energy consumption and water recovery) and cost of the suggested HPRO-MD system are simulated by this model under a specific set of assumptions. To make sure that the simulation offers a realistic and reliable assessment of the system's viability, the data, equations, and parameters are carefully taken from the peer-reviewed literature, technical datasheets from equipment manufacturers, manufacturers' offers, and well-known industry cost databases [24,53–56].

Table 2. The information and assumptions applied in the techno-economic assessment (TEA) conducted in this study.

Item	Value	References
Projected operational duration of the facility	30 years	assumption
Interest rate imposed	5%	assumption
Charge for water in Cyprus	USD 3.9 per cubic meter	[53]
Storage unit for the feed solution	USD 93.6 per cubic meter	[53]
Storage tank for freshwater	USD 75.53 per cubic meter	[53]
Rate of flow for the feed solution	100 cubic meters per day	assumption
Level of salinity in the feed solution	38 g per liter	[53]
Chemical consumption expenses	USD 0.0176 per cubic meter	[53]
Utility service charges	USD 41.04 per cubic meter per day	[53]
Monetary outlay for pretreatment processes	USD 79.26 per cubic meter per day	[53]
Expenditure for maintenance and replacement parts	USD 0.019 per cubic meter	[53]
Cost of electricity usage	USD 0.064 per kilowatt-hour	[53]
Workforce-related expenditures	USD 0.0315 per cubic meter	[53]
Land development and site preparation expenses	USD 25.33 per cubic meter per day	[53]
Cost for miscellaneous expenditures	USD 83.2 per cubic meter per day	[53]
Determining factor for plant availability	90%	assumption
Cost of water in Greece	USD 3 per cubic meter	[55]
Feed solution composition	Ca^{2+} (417 mg/L), Mg^{2+} (1401 mg/L), Cl^{-} (22,661 mg/L), Na^{+} (11,853 mg/L), K^{+} (454 mg/L), SO_4^{2-} (1182 mg/L), and HCO_3^{-} (46 mg/L)	[53]
Membrane material	HPRO: thin-film composite (TFC) membrane with a polyamide layer; MD: hydrophobic polyvinylidene fluoride (PVDF) membrane	[24,54]
Grid emission factor for the Eastern Mediterranean region (Greece)	0.256 kg CO_2-eq/kWh	[56]

3. Results and Discussion

3.1. Water Recovery

In the desalination sector, the enhancement of water reclamation is crucial, as it allows for the recovery of larger quantities of potable water while simultaneously reducing wastewater disposal. Water recovery is calculated by dividing the volume of produced water by the total volume of feed water. The MLD system achieves an impressive water re-

covery rate of 78.65%, which is significantly valuable in relation to the maximum threshold in the MLD approach. In particular, the recovery rate is composed of 39.65 m^3/day from MD and 39 m^3/day from HPRO, with each technology contributing 50% to the overall recovery (Figure 2).

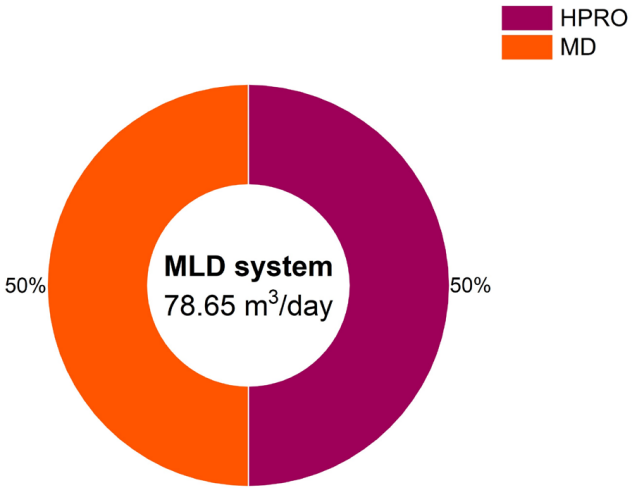


Figure 2. The impact of HPRO and MD processes on water recovery, declared as a percentage.

The water produced by this system meets potable water criteria, exhibiting TDS below 500 mg/L. A detailed ionic composition of the permeate is provided in the Supplementary Material. The MD unit, which operates on thermal principles, generates pure water (TDS < 50 mg/L). This substantial decrease in TDS is accomplished through the evaporation and condensation processes utilized in this technology. The availability of such pure water is particularly valuable in industrial sectors, like pharmaceuticals, where strict requirements necessitate minimal salinity levels.

In contrast, HPRO produces water with an increased TDS that can range from 450 mg/L to over 1000 mg/L [42]. The TDS of the HPRO permeate is principally determined by the membrane's salt rejection capability [42,57–59]. Although HPRO demonstrates salt rejection of over 95%, various factors, such as fouling or extended operational periods, may reduce its efficiency, leading to a decrease in water purity. The extent of efficiency reduction in HPRO can vary based on specific conditions and the severity of encountered challenges. Observations indicate that this efficiency decline can vary from 2% to 10%. It is essential to recognize that it is a generic estimate, and the loss in the efficiency could vary [35,60–63].

Additionally, the replacement of the membranes is affected by water quality, effectiveness of pretreatment, conditions of the operation, and membrane integrity. Increased fouling issues or inadequate pretreatment can speed up degradation, necessitating more regular replacements. As a rule of thumb, the membrane replacement rate for the HPRO is estimated to range from 2% to 5% annually. This range (i.e., 2–5%) is widely accepted in techno-economic analyses of brackish water and seawater RO desalination plants and is substantiated by long-term operational data from full-scale facilities, which report on membrane longevity and replacement cycles under various feedwater qualities and pretreatment regimes [59,64,65]. Nevertheless, it is crucial to emphasize that the HPRO water quality is within a satisfactory range. The volume breakdowns of the MLD system's end-product indicate that the permeate volumes from the HPRO unit (39 m^3/day) and the MD unit (39.65 m^3/day) are comparable, with each contributing roughly half of the total recovered water.

3.2. Energy and Cost Demands

In addition to the water recovery, energy demands represent a crucial factor when assessing the performance of MLD systems. The energy consumption of the hybrid MLD system is 23.2 kWh/m^3, a competitive value that underscores the advantage of integrating HPRO and MD. This hybrid configuration strategically balances electrical and thermal energy inputs to optimize efficiency, thereby enhancing the overall sustainability of the system. The integration of these two technologies not only improves energy utilization but also contributes to reducing operational costs over time. Figure 3 illustrates the breakdown of energy demands across each MLD process, with the MD unit accounting for the majority at 89%, while the HPRO unit represents the lowest energy requirement at 11%. This significant disparity highlights the importance of optimizing the MD process to further enhance energy efficiency and reduce costs associated with energy consumption. Understanding these energy dynamics is essential for future advancements in MLD technology and for making informed decisions regarding system design and operation. Furthermore, it is important to include a preliminary analysis of the system's carbon. Given the total specific energy consumption of 23.2 kWh/m^3 and using a grid emission factor for the Eastern Mediterranean region (i.e., 0.256 kg CO_2-eq/kWh for Greece) the estimated GHG emissions are 5.94 kg CO_2-eq/m^3 of produced water [56]. This analysis underscores the significant environmental benefit of integrating renewable energy sources to power the MLD system, a point that is now discussed in greater detail.

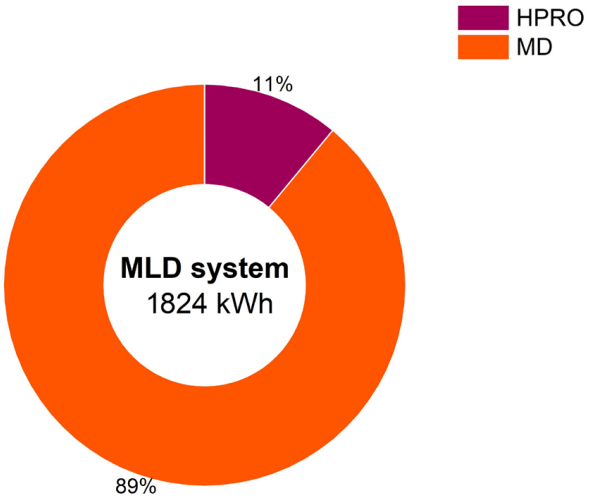


Figure 3. The impact of HPRO and MD processes on energy demands, declared as a percentage.

The assessment of costs is of paramount significance in the execution of desalination initiatives, serving as a vital element in the TEA. The cost of the MLD system is documented at USD 0.99/m^3, a reasonable figure given the hybridization of two distinct technologies within the hybrid framework. To gain additional insight into the cost breakdown across the MLD processes, Figure 4 delineates the percentage breakdown of each technology. The MD process emerges as the most expensive element, accounting for 60% of the total cost demands, whereas the HPRO process represents a lesser expense, contributing 40%.

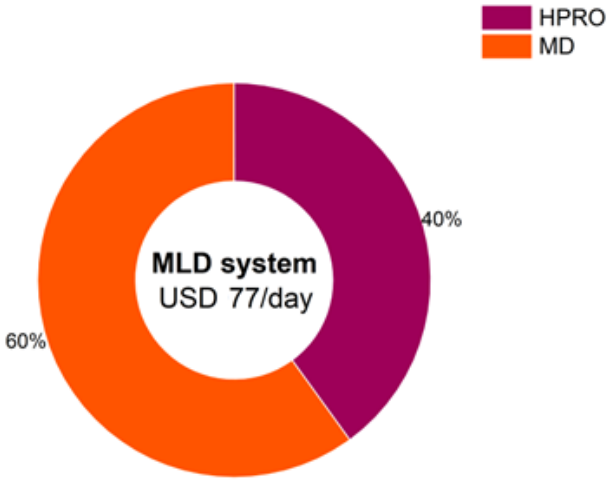


Figure 4. The impact of HPRO and MD processes on cost demands, declared as a percentage.

The MLD system presents numerous opportunities for the utilization of its output. The freshwater generated by this system can be applied in various residential and commercial contexts. Figure 5 provides an analysis of net revenue, which evaluates the economic viability and potential benefits of the MLD system. Notably, the MLD system generates the highest revenue in Cyprus, amounting to USD 228 per day, whereas Greece sees the lowest revenue at USD 157 per day. This variation in earnings can be credited to differences in water sale prices between the two countries. These valorization techniques are crucial from a techno-economic perspective because they offer prospective sources of income that could partially cover the brine treatment's operating expenses. For instance, the recovery of valuable minerals turns brine from a liability that needs to be disposed of at great expense into an asset, increasing the MLD system's overall viability and encouraging a desalination process that is genuinely circular.

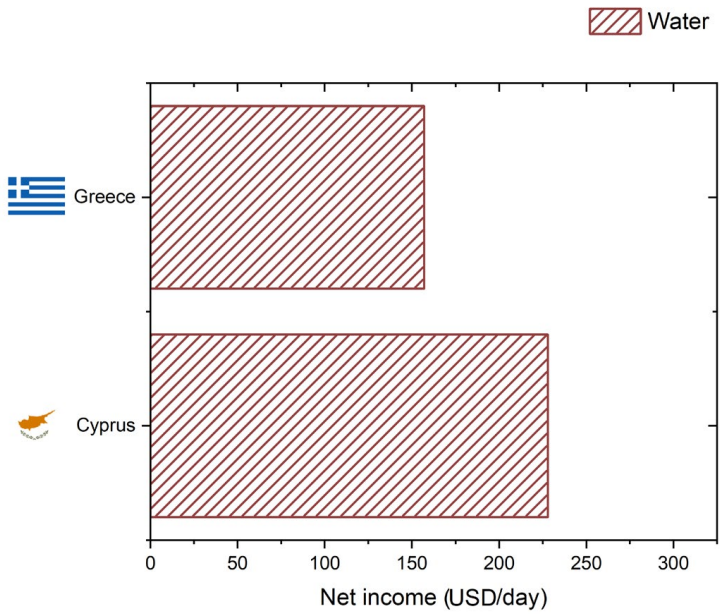


Figure 5. The profitability of the MLD system utilizing HPRO and MD processes in Greece and Cyprus.

3.3. Cost Comparison and Profitability

Figure 6 illustrates a comparative evaluation of the costs related to the MLD system and those associated with traditional water sources. The analysis reveals that water ob-

tained from surface water sources demonstrates a cost reduction of at least 42.3% relative to the expenditures of the MLD system. In contrast, the financial outlay for water extracted from subsurface sources is nearly equivalent to that of the MLD system. It is worth noting that the costs of subsurface water extraction can exceed those of the MLD system, especially in scenarios where substantial well depths require considerable energy consumption for pumping activities. Furthermore, the expenses tied to subsurface water sources are influenced by various factors, such as permit requirements, distribution infrastructure, compliance with environmental regulations, and transportation systems. By offering water prices comparable to those of subsurface sources, MLD systems provide additional water resources and contribute to mitigating water scarcity. This is particularly beneficial for nations in the Mediterranean region, including Greece, where roughly one-quater of water supplies are sourced from subsurface [66,67].

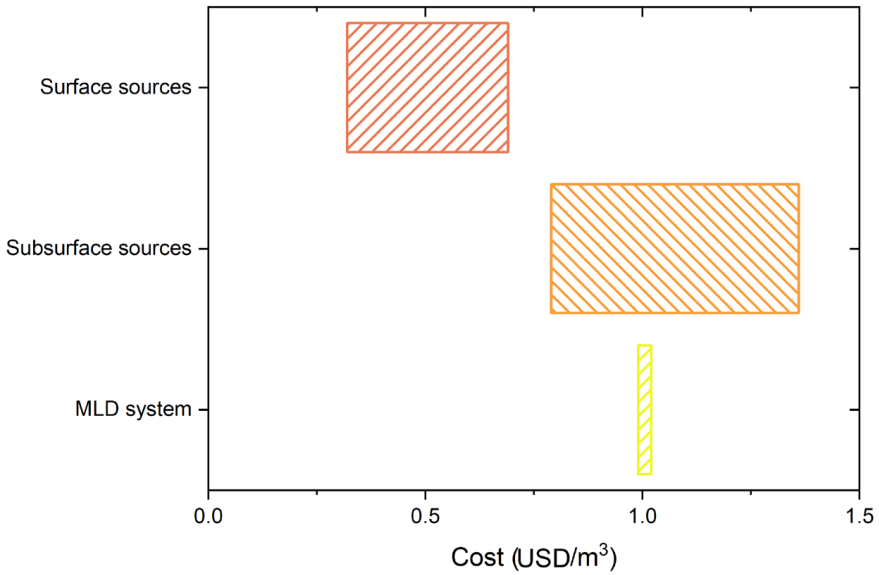


Figure 6. Cost comparison between the MLD system and conventional drinking water sources.

Several alternatives for brine disposal are available, including evaporation ponds, discharge into sewage systems or surface water bodies, deep-well injection, and other methods. Nevertheless, these approaches encounter substantial challenges and environmental impacts, making them unsuitable for sustainable, long-term use. A comparison of the costs of MLD systems with those of brine disposal methods, excluding potential income from the sale of recovered water or solid salt, is essential. As illustrated in Figure 7, the financial outlay for MLD systems exceeds that of lower-cost disposal options, such as discharge into surface water or sewer systems. However, the expenses of MLD systems are comparable to those of land application and deep-well injection, which is expected due to the greater complexity of these disposal methods relative to surface water or sewer discharge. Importantly, MLD systems are considerably more economical than evaporation ponds, with costs at least 3.3 times lower. To further elucidate the economic aspects, Figure 8 presents a profit and loss analysis of brine disposal methods and MLD systems. As shown in Figure 8, traditional disposal methods only incur costs, as they do not produce marketable water. In contrast, MLD systems generate revenue, with the highest profitability observed in the island of Cyprus.

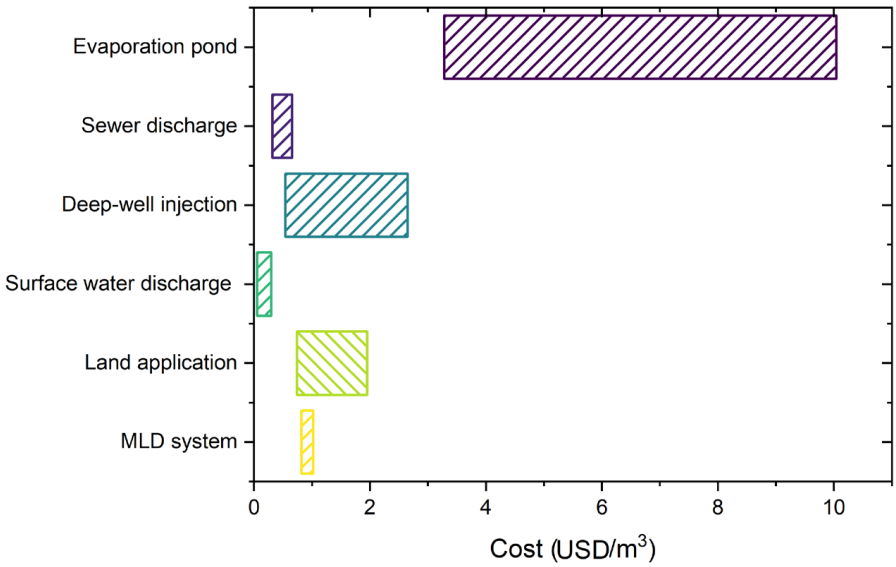


Figure 7. Cost comparison of the MLD system versus disposal methods, excluding profit considerations.

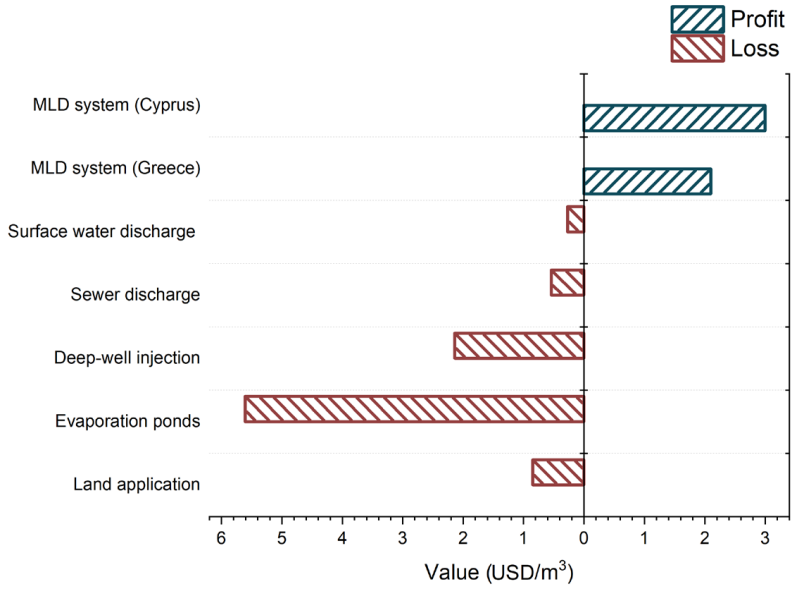


Figure 8. Value assessment of the MLD system compared to disposal methods, including profit considerations.

3.4. Present Developments and Future Outlook

While MLD systems aim to maximize water production and reduce waste generation, their deployment may result in unintended environmental consequences. These systems often prioritize the management of liquid waste during the treatment process, leading to the creation of concentrated multi-component streams that require disposal in evaporation ponds. However, such disposal methods pose risks of leakage and generate odors that can harm ecosystems. To mitigate these risks, impermeable liners and monitoring systems are essential to prevent environmental contamination. In recent years, the concept of brine mining has emerged as a complementary approach to water recovery, focusing on extracting valuable resources from waste streams. Although discharge remains a necessity in MLD systems, industries can utilize high-purity concentrated streams internally, thereby reducing raw material costs. By designing MLD systems to recover reusable raw materials, industries can adopt a circular economy approach.

Although MLD systems, which rely on membrane-based technologies, consume significantly less energy than ZLD systems that combine thermal and membrane processes, their energy requirements still contribute to substantial greenhouse gas (GHG) emissions and air pollutants. To address this issue, the integration of renewable energy sources (RESs), such as solar, wind, and geothermal energy, or the utilization of industrial waste heat, is recommended. For instance, solar-powered RO systems emit only 0.2 kg of CO_2 per cubic meter of water, which is nine times lower than the emissions from conventional fossil-fuel-powered RO systems (1.8 kg of CO_2 per cubic meter). Consequently, combining MLD systems with RESs is seen as a viable strategy to reduce GHG emissions [65,68,69].

To further enhance the efficiency of MLD systems, advancements in the technologies employed are necessary. Energy consumption in the MLD systems can be minimized through strategic integration of energy recovery devices (ERDs) in the HPRO stage, optimizing operating pressures, and utilizing waste heat for the MD unit. Additionally, coupling RESs, such as solar thermal for MD, can further reduce reliance on grid electricity [59]. In particular, adding an ERD directly lowers the HPRO unit's estimated net specific energy consumption, and integrating solar thermal energy for the MD process lowers electricity-related operating costs, both of which significantly improve the assessment's overall economic viability and sustainability. Recent developments in membrane technology, such as omniphobic, Janus, and superhydrophobic membranes, have demonstrated significant potential to improve MD performance [47,51,70–74]. Additionally, innovations in membranes and modules are anticipated to increase the upper limit operating pressure in HPRO systems in the near future.

Concentrated brine streams from the MLD system can be valorized through salt extraction (e.g., NaCl for road de-icing) or mineral recovery (e.g., magnesium hydroxide). Emerging strategies include integrating ED or FO to extract valuable ions (e.g., lithium, cesium), aligning with circular economy principles [75–79]. The proposed MLD system is adaptable for industrial effluents, provided that pretreatment removes non-ionic contaminants (e.g., heavy metals, oils) [80–85]. Future work will explore scaling the system for textile and pharmaceutical wastewater treatment. This methodology for techno-economic assessment is inherently flexible. The system could be extended to incorporate different pretreatment options to handle specific contaminants found in complex industrial effluents [86]. For example, this could involve integrating advanced oxidation processes (AOPs) for the degradation of non-ionic, refractory organic compounds or nanofiltration (NF) for the targeted removal of divalent ions and certain micropollutants prior to the MLD system. In overall, the specific energy consumption (23.2 kWh/m^3) and operational cost (USD 0.99/m^3) of the proposed HPRO-MD MLD system align with values reported for comparable MLD/ZLD configurations in the literature (e.g., 15–30 kWh/m^3 and USD 0.80–USD 1.50/m^3) [53,66]. However, these metrics are highly sensitive to site-specific parameters, such as plant capacity, feed salinity, energy tariffs, and regulatory requirements, underscoring the need for context-driven assessments.

4. Conclusions

This study conducted a TEA of a MLD membrane-based system integrating HPRO and MD for desalination brine treatment. The results demonstrate that the hybrid HPRO-MD system achieves a high water recovery rate of 78.65%, with 39.65 m^3/day recovered from MD and 39 m^3/day from HPRO.

The total energy consumption of the system is 23.2 kWh/m^3, with MD accounting for 89% of the energy demand and HPRO contributing only 11%. The cost analysis reveals an operational cost of USD 0.99/m^3, with MD representing 60% of total expenses and HPRO representing 40%. Economic feasibility varies by region, with the system generating

a net revenue of USD 228/day in Cyprus and USD 157/day in Greece. Compared to conventional brine disposal, MLD is 3.3 times cheaper than evaporation ponds and offers cost parity with land application and deep-well injection.

While the system offers a sustainable solution for brine management, challenges remain regarding energy consumption and concentrated waste disposal. Future research should explore the integration of RESs to reduce GHG emissions, advancements in membrane materials (e.g., omniphobic, Janus, and superhydrophobic membranes), and opportunities for resource recovery via brine mining. The system exhibits great potential for adaptation to other challenging water streams in terms of future applications. Its use in industrial effluents that contain organic dyes or heavy metals, for example, might be investigated. This would probably require the integration of particular pretreatment processes, like advanced oxidation or ion exchange, before the HPRO unit. The impact of this MLD approach could be increased if future modeling and experimental research confirm the techno-economic viability of these enlarged applications. Overall, the HPRO-MD MLD system provides an energy-efficient, cost-effective, and environmentally sustainable approach to brine treatment, supporting circular economy principles and water resource sustainability.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/separations12090224/s1, Table S1: The formulas utilized in the techno-economic assessment (TEA) carried out in this study; Figure S1: A visual representation (including flows) showing the configuration of the MLD system, particularly the HPRO-MD process.

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