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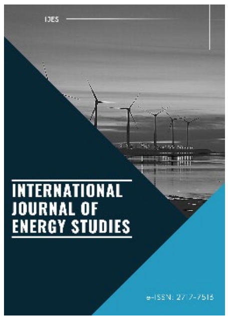

Research Article

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Pressure retarded osmosis in the renewable energy transition: Opportunities, challenges, and cost analysis for coastal river systems in Türkiye

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Highlights

- Pressure Retarded Osmosis offers continuous baseload power with high sustainability potential.
- The Ceyhan River demonstrates significant suitability for PRO based energy generation in Türkiye.
- High costs and membrane limitations remain the main barriers to PRO commercialization.

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ABSTRACT

Pressure Retarded Osmosis (PRO) has emerged as a promising renewable energy technology due to its sustainability, continuous operation capability, and potential to provide baseload power. Unlike intermittent renewable energy sources such as wind and solar, PRO utilizes the salinity gradient between freshwater and seawater to generate electricity without fuel consumption or direct greenhouse gas emissions, making it an environmentally friendly energy option. In recent years, PRO technology has advanced from laborator scale studies to pilot scale projects, with several initiatives worldwide moving toward commercial scale deployment. This progress highlights the growing interest in PRO as a complementary component of future low carbon energy systems. Although no PRO facilities are currently in operation in Türkiye, the country has significant potential for PRO development, particularly along rivers discharging into the Aegean and Mediterranean Seas, where strong salinity gradients exist. In this study, the Ceyhan River was identified as one of the most suitable locations for a PRO power plant. The Levelized Cost of Energy (LCOE) of the proposed facility was estimated at 0.238 USD/kWh. While this value is consistent with existing literature, it remains considerably higher than that of established renewable energy technologies such as hydropower, wind, and solar energy. The main challenges hindering the widespread adoption of PRO include high capital costs, limited membrane lifespan, low membrane permeability, and significant internal energy consumption. Nevertheless, ongoing advancements in membrane technology and system optimization indicate that PRO could become a viable and competitive renewable energy option in the near future, both in Türkiye and globally.

Keywords: Pressure retarded osmosis (PRO), Renewable energy, Hydropower, LCOE

1. INTRODUCTION

The accelerating global demand for clean, reliable, and renewable sources of energy has intensified scientific interest in unconventional resources capable of supplementing or replacing fossil fuel based systems. Among the array of emerging Technologies, salinity gradient energy has attracted renewed scholarly attention for its unique combination of abundance, continuity, and environmental compatibility. Oceans, estuaries, and industrial brine streams collectively contain vast stores of chemical potential energy arising from differences in salt concentration. When freshwater and seawater naturally mix, this potential dissipates, but the underlying physical mechanism can be exploited prior to mixing to generate useful work. Pressure Retarded Osmosis (PRO) represents one of the most promising technologies for converting this otherwise lost potential into electricity. PRO is grounded in a fundamental thermodynamic phenomenon: when a semi permeable membrane separates two aqueous solutions of differing salinity, water molecules spontaneously diffuse from the dilute solution to the concentrated one, driven by the osmotic pressure gradient. A simplified illustration is given in Figure 1 [1].

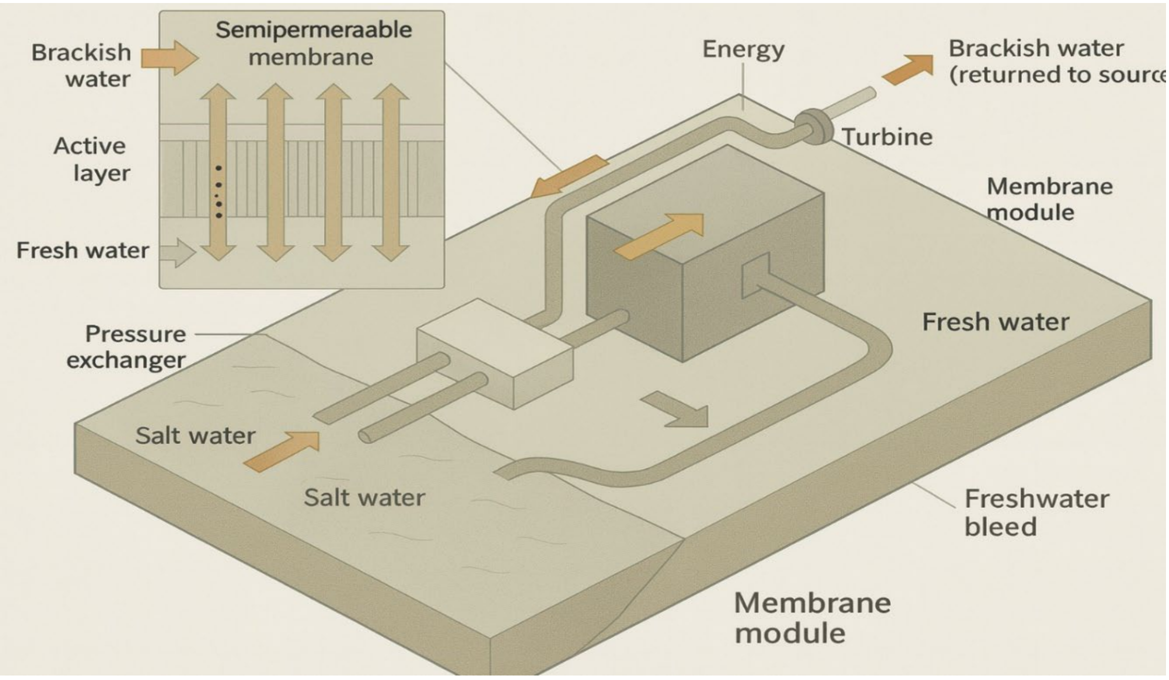

Figure 1. A simplified illustration of the PRO system

In the PRO configuration, this natural flow is permitted, but it occurs into a chamber where a hydraulic pressure lower than the osmotic pressure difference is applied. As water diffuses across the membrane, it increases the hydraulic head on the pressurized side, which in turn can be harvested using a conventional türbine/generator system. The elegance of PRO lies in its ability to transform a ubiquitous and passive environmental process into mechanical energy without the need for thermal input, combustion, or solar irradiation. Although the theoretical foundations of osmotic power date back several decades, only in the last fifteen years has PRO gained momentum as a viable contributor to the future energy portfolio. Advances in membrane science have significantly improved water permeability while reducing internal concentration polarization, a major efficiency bottleneck. At the same time, global patterns of industrialization and population growth have expanded access to high salinity effluent streams and wastewater sources, both of which can serve as feedstocks for PRO systems. These developments have created an environment in which osmotic power is not merely a theoretical curiosity but a technology with practical, commercially relevant potential.

The strategic advantages of PRO stem not only from its renewable character, but also from its operational stability. Unlike solar or wind energy, osmotic energy is not dependent on meteorological variability. Natural estuaries exhibit steady salinity gradients, and industrial brine streams provide predictable, controllable sources of concentrate. The resulting baseload compatible output positions PRO as a complementary technology that can enhance the reliability of hybrid renewable systems. Moreover, because the energy conversion process does not involve combustion or thermal cycles, PRO systems emit negligible greenhouse gases and have low ecological footprints when properly integrated. Nevertheless, the widespread deployment of PRO faces several significant barriers. Membrane performance remains a primary challenge; despite impressive improvements, current membranes still fall short of the ideal balance between high permeability, mechanical robustness, and long term resistance to fouling and scaling. The problem is compounded by concentration polarization, which reduces the effective osmotic driving force and limits overall power density. Additionally, the capital and operational expenditures associated with high pressure pumps, energy recovery turbines, and pretreatment systems remain substantial. Despite these challenges, the scientific and technological prospects of PRO remain compelling. Recent research trajectories point toward a new generation of membranes engineered using advanced nanomaterials, such as graphene oxide, aquaporin embedded structures, and porous carbon architectures. These materials exhibit remarkable water transport properties and have the potential to overcome long-standing limitations in mechanical strength, selectivity, and anti-fouling performance.

The broader implications of successful PRO deployment extend beyond electricity generation. Osmotic power could play a central role in decentralized energy systems, maritime applications, offshore platforms, and remote communities where consistent, low maintenance energy sources are needed. In industrial settings, PRO can serve as an energy recovery technology that enhances the efficiency and sustainability of water treatment and desalination processes. At a systemic level, integrating PRO into national energy and water infrastructures contributes to circular economy principles by transforming waste streams into valuable resources. Such multifunctionality positions PRO as a technology uniquely capable of addressing several global challenges simultaneously: renewable energy generation, sustainable water management, and carbon neutral industrial development.

PRO remained predominantly at the pilot and demonstration stage for many years after the first prototype was built in Norway. The basic technological hurdles limited commercial roll out during the 2010s. Since ~2020, however, renewed private and public R&D investment, novel membrane concepts, and new business models have led to a small but tangible wave of pilot and early commercial projects in Europe and Asia. These initiatives emphasize modular "osmotic power units" (OPUs), coupling with existing salt-producing or desalination operations, and SWRO/PRO hybrid demonstrations. Brief descriptions of globally commissioned facilities are presented below, offering concise insights into their operational characteristics, technological significance, and contributions to the advancement of large scale implementation.

- Statkraft prototype, Tofte/Hurum, Norway (2009–2013): The world's first operational PRO prototype (2-4 kW range). Although technically successful, Statkraft discontinued further investment in 2013 citing economic infeasibility with then available membranes.
- SaltPower - Mariager salt-works (Denmark), (operational March 2023): SaltPower developed a modular osmotic power unit that converts high salinity industrial brine and freshwater into mechanical/electrical energy. The first commercial unit was deployed at a salt production site in Mariager to produce energy while salt is mined. This investment represents one of the earliest commercial (non laboratory) demonstrations of brine based osmotic power and a business model that pairs energy production with existing salt industry processes.
- OsmoRhône / Sweetch Energy pilot -Rhône delta (France), pilot late-(2024 / 2025 activity): Sweetch Energy (and partner teams) have been piloting modular osmotic energy

systems in the Rhône delta. Pilot stage from 2024 onward; important for continental Europe demonstrations and for validating novel membrane architectures for river to sea sites.

- Japan-Fukuoka Osmotic Power Plant (Uminonakamichi Nata Seawater Desalination Center), (commissioned 2025): A municipal / research pilot in Fukuoka Prefecture integrated with a seawater desalination facility; reportedly designed to use high salinity brine from desalination to drive PRO and supply a portion of the desalination plant's energy needs. Began operation in 2025 and reported to produce about 880,000 kWh/year (modest but continuous generation); widely reported as one of the first continuous commercial scale osmotic plants after Denmark's Mariager installation. This demonstrates the SWRO-PRO hybrid concept at a working facility. Pictures from facility is given in below Figure 2 [2].

Figure 2. Images from the Fukuoka PRO facility

Türkiye is hydrologically organized into 25 major river basins, each defined by its catchment area, drainage system, and where the collected surface water ultimately discharges, whether into a sea, gulf, or remains in an inland (closed) basin. These basins can be broadly classified into four categories according to their terminal discharge point or basin type;

- Basins draining into the Black Sea
- Basins draining into the Marmara Sea
- Basins draining into the Aegean or Mediterranean Seas (Western and Southern coasts)
- Closed basins (endorheic) that do not discharge to any sea

This classification is central for hydrological management, water resource planning, environmental assessment, and potential applications that rely on salinity gradient or basin specific water dynamics. Water resources map of Türkiye is given in below Figure 3 [3].

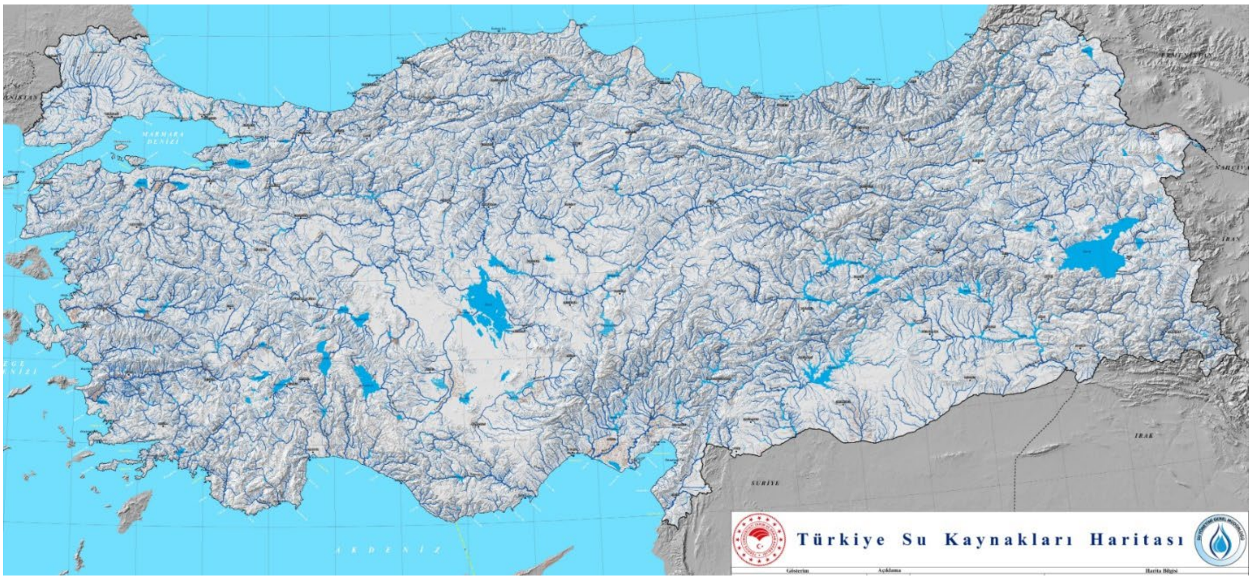

Figure 3. Water resources map of Türkiye

The classification into 25 basins is not only a geographical convenience but forms the backbone of national water management policy in Türkiye. Under the framework of basin scale management, authorities assess water supply potential, surface runoff, basin specific ecological status, and human induced pressures across all sectors. Statistical data indicate that the combined surface water potential of these basins is substantial, though only a fraction is currently exploited. Türkiye's hydrological architecture reflects a rich diversity of climatic zones, topographic conditions, and water resource potentials. From the rain fed Black Sea basins with stable flows to the arid inland closed basins, and from the heavily populated Marmara Basin to the variable coastal basins along the Aegean and Mediterranean, each basin encapsulates distinct environmental and socio economic dynamics. This basin level classification is essential not only for water resource management and environmental planning but also for assessing applications that depend on hydrology, such as irrigation, hydroelectricity, water supply, ecosystem protection, and even novel technologies that exploit water-salinity gradients. Integrative, basin-based management plans are vital to ensure that water use, ecosystem preservation, and socio economic development remain balanced and sustainable across Türkiye's diverse hydrological landscapes.

Türkiye's diverse hydrographic structure, shaped by its varied topography and climatic gradients, offers promising opportunities for the deployment of Pressure Retarded Osmosis (PRO) systems. The convergence of abundant freshwater flows from mountainous inland regions with saline water bodies along extensive coastlines positions several Turkish basins as potential candidates for osmotic energy production. A systematic evaluation of these basins requires consideration of hydrological capacity, water chemistry, environmental sensitivities, and infrastructural feasibility. The Marmara Basin, with its dense river network feeding into the semi enclosed and moderately saline Marmara Sea, represents a theoretically favorable zone for PRO integration. The relatively stable hydrological regime and proximity to major industrial centers could facilitate efficient energy transmission. The Black Sea Basin, receiving substantial discharge from high rainfall catchments such as the Sakarya and Kızılırmak Rivers, provides one of the strongest freshwater inflows in Türkiye. The lower salinity of the Black Sea compared to global oceans typically reduces the attainable osmotic pressure differential; nonetheless, the significant flow volumes may compensate for this limitation, enabling competitive energy yields. Advancements in membrane materials designed for low salinity environments further improve the basin’s suitability. Additionally, the relatively preserved ecological conditions along parts of the Black Sea coast support environmentally responsible implementation. In contrast, the Aegean Basin benefits from both high gradient rivers and the high salinity of the Aegean Sea, offering an optimal osmotic differential for PRO systems. The basin’s fragmented river systems, although shorter in length, deliver substantial seasonal flow, particularly during winter and spring. This region’s combination of saline richness and accessible freshwater outlets makes it one of the most compelling candidates for pilot scale PRO facilities. Nonetheless, seasonal variability and drought related flow reduction must be incorporated into energy yield projections. The Mediterranean Basin, characterized by steep river catchments descending rapidly toward the coast, presents favorable hydrodynamic conditions for the creation of controlled mixing environments necessary for PRO operations. The Mediterranean Sea’s high salinity enhances osmotic potential, yet the basin’s pronounced temporal flow fluctuations present operational challenges. Strategic reservoir management and hybridization with other renewable sources could mitigate these issues, enhancing system stability. Türkiye’s basins exhibit a spectrum of suitability for PRO energy generation, shaped by their freshwater discharge patterns, salinity contrasts, and regional environmental constraints. While the Aegean and Mediterranean basins stand out for their high osmotic potential, the Black Sea and Marmara basins offer opportunities for technologically adaptable solutions.

As a rapidly emerging topic within the scientific community, PRO technology has gained substantial scholarly attention. Numerous studies in the literature now explore the conversion of osmotic energy into electricity, reflecting both the growing relevance of salinity gradient power and the expanding research efforts dedicated to advancing its theoretical foundations and practical applications. Matsuyama et al. investigated the feasibility of PRO for electricity generation using seawater and freshwater. A commercially available hollow fiber membrane module was evaluated, yielding a measured power density of 3.1 W/m², below the 6.5 W/m² required for commercial viability. Under a draw solution pressure of 1.5 MPa and a feed solution pressure of 0.1 MPa, the net power output reaches 2.8 W/m². Power generation costs are estimated at $0.20/kWh for a plant processing 1 million m³/day. Achieving commercial feasibility necessitates improving membrane performance, specifically water and salt permeability coefficients (A = 2.05 $\times 10^{-6}$ m/s/MPa; B = 5.5 $\times 10^{-9}$ m/s), as predicted by the solution diffusion model [4]. Maisonneuve et al. evaluated commercial PRO membranes, achieving gross power densities up to 7.1 W/m². Non ideal effects like concentration polarization reduce net power, but optimized operating conditions improve it to 4.5 W/m². Experimental results aligned with a mathematical model, highlighting the importance of membrane performance and operating parameters for efficient PRO energy conversion [5]. Einarsson and Wu examined thermal associated PRO processes, showing that elevated temperatures enhance energy production. Hybrid systems, including PRO membrane distillation and PRO thermosiphons, and utilization of geothermal heat or waste gas as draw solutions improve efficiency. Process optimization and techno economic assessments are emphasized to advance commercially viable, high performance PRO energy systems [6]. Touati and Rahaman assessed the economic feasibility of PRO configurations. SWRO/PRO and OLPRO are generally uneconomical due to low driving forces, whereas CLPRO and OLPRO with hypersaline sources may be viable under specific conditions. Achieving competitiveness requires technological improvements, optimized draw solute regeneration, and sufficient membrane power density for commercially feasible PRO power generation [7]. Touati and Tadeo reviewed the historical development and technological progress of PRO for converting salinity gradients into electricity. It examined cost viability, environmental impacts, and recent advancements, highlighting stages of technological evolution. Strategies to enhance efficiency and mitigate negative effects were also discussed, emphasizing PRO’s potential as a sustainable renewable energy source [8]. Kim et al. examined PRO harnesses salinity gradients between freshwater and seawater to generate renewable energy through semi permeable membranes. They stated that despite historical economic limitations, recent advances in membrane technology, process design, and hybrid systems have revived PRO’s feasibility. Pilot projects worldwide demonstrate its potential, while ongoing research focuses on modeling, fouling control, and commercialization strategies [9].

Al-Musawi et al. evaluated PRO for sustainable energy generation using RO-brine as draw solution and demineralization effluent as feed solution. Experimental measurements of osmotic pressure and transport properties of commercial seawater membranes show power densities up to 2.83 W/m². Results highlight the effects of applied pressure, flow rate, concentration, and dilution on system performance without requiring DS or FS pretreatment [10]. Touati and Mulligan modelled thermo osmotic energy conversion (TOEC) for harvesting low grade heat. Expressions for power density and specific energy were developed, revealing maximum extractable energy of 2.2 kWh/m³ under ideal conditions, but ≤0.09 kWh/m³ realistically. Techno economic analysis indicates a high LCOE of $0.66/kWh, highlighting current limitations and pathways for improved feasibility [11]. Aktij et al. explored co-polyamide (Co-PA) membranes for PRO applications. Incorporating 1.5 wt% piperazine enhanced water flux by 41.5% and power density to 10.22 W/m², while reducing reverse salt flux by 36.7%. Characterization confirmed chemical modification and increased crosslinking. Life cycle assessment demonstrated reduced energy demand, highlighting Co-PA membranes' sustainable potential for energy and water treatment [12]. Li developed novel PRO configurations, including atmospheric batch (ABPRO) and semi-closed (SCPRO) modes, to enhance energy production efficiency. Integrating PRO with reverse osmosis in a desalination osmotic energy storage (DOES) system enables coordinated water-energy management, achieving practical energy efficiencies up to ~75%, high specific energy production, and improved water energy resilience for sustainable, low-carbon applications [13]. Chen et al. proposed a standalone DC microgrid integrating PV/T, PRO, and SOFC systems for continuous, 24 hours power generation. A meta-heuristic MPPT controller using TTAO is introduced and compared with RSA and other algorithms. The energy management strategy, evaluated with real meteorological data, demonstrates superior efficiency, stability, and renewable energy utilization [14]. Touati et al. compared PRO, RED, and NPG for salinity gradient energy. PRO achieves the highest net energy output, capturing 37 % of theoretical energy using brine and wastewater, while RED and NPG capture <10 %. Techno economic analysis shows PRO reaches competitive LCOE (~0.26 $/kWh), whereas RED and NPG remain costly (>0.6 $/kWh) [15]. Yu et al. explored biopolymer based reverse electrodialysis (RED) for powering bionic devices, integrating biocompatible ion selective membranes with osmotic energy conversion. RED harnesses salinity gradients to generate electricity via ion flux, mimicking biological ionic signaling without harmful byproducts. Biopolymers such as chitosan, alginate, cellulose, and silk offer high ion conductivity, tunable channel structures, biodegradability, and biocompatibility, enhancing energy conversion efficiency and tissue integration. The paper examined RED mechanisms, bioinspired designs, and ionic current generation for implantable and wearable devices. By bridging biopolymers, RED, and biomedical applications, it highlights sustainable, autonomous power solutions aligned with next-generation soft and multifunctional bioelectronics [16].

Pakdaman et al. examined PRO sytems. They stated that PRO represents a promising salinity gradient energy technology, yet its large scale application is limited by feed impurities, membrane fouling, and suboptimal system design. Integrating membrane based pretreatments, advanced membrane modifications, and hybrid multi stage configurations significantly enhances water quality, power density, and overall energy efficiency, advancing PRO toward commercial viability [17]. Suárez-Alfonso et al. assessed a full scale PRO system by analyzing the influence of draw solution concentration, pressure, and flow rate on net power generation. Using a 10 inch hollow fiber membrane, optimal conditions achieved 2.56 W m^{-2}, demonstrating the energetic feasibility of single stage PRO systems [18]. Guan et al. evaluated $CaCO_3$ polymorph induced scaling in a DAC/PRO hybrid system. Results show that calcite-rich layers exhibit higher porosity and lower resistance, while ACC dominated scaling causes severe water flux decline and reverse salt flux. Dynamic polymorph transformations critically influence PRO membrane performance [19]. Menon synthesized the fundamentals, membrane technologies, and practical applications of pressure retarded osmosis as a salinity gradient energy technology. It critically examines hybrid PRO systems, key operational challenges, and recent technological advances, highlighting future research pathways required to enable large scale commercialization and integration into sustainable energy and water management frameworks [20]. Ruiz-Navas et al. proposed a modified solution diffusion model for PRO that incorporates rotational kinetic energy to mitigate internal concentration polarization. An analytical formulation and simulations demonstrated that controlled rotation can significantly offset ICP losses, enhancing power density and indicating promising design parameters for efficient, scalable PRO systems [21]. Tan et al. compared water flux models with and without solute permeability (B) in FO and PRO processes. While both models perform well for FO, neglecting B leads to major overestimation of water flux and misprediction of internal concentration polarization in PRO, underscoring the necessity of including reverse solute flux for accurate modeling [22].

Marx and Gasser developed a detailed mathematical model of RO and PRO membrane units for a seawater RO/PRO hybrid system, incorporating internal and external concentration polarization and energy recovery devices. Simulation and optimization results demonstrate the hybrid system's potential to reduce specific energy consumption through effective utilization of RO brine in PRO [23]. Chong and Liang presented a semi empirical model incorporating pressure dependent structural parameters to more accurately predict flux in FO, PAO, PRO, and OARO processes. The model outperformed existing approaches, eliminates the need for separate FO testing, and demonstrates that constant porosity assumptions can significantly misrepresent flux, particularly under low transmembrane pressure conditions [24].

Isla-Cabaraban et al. offered salinity gradient energy (SGE-blue Energy), a sustainable renewable energy source by exploiting the osmotic pressure difference between freshwater and seawater. This study evaluated the energetic and economic feasibility of a full scale pressure retarded osmosis (PRO) power plant in the Philippines, a country characterized by abundant river sea interfaces ideal for osmotic energy extraction. A conceptual 1 MW PRO system was designed, incorporating pre treatment units, semi permeable membranes, pressure exchangers, and a hydraulic turbine generator. Process simulations, including detailed mass and energy balances, were performed to assess system performance, while economic analysis considers net present value (NPV), internal rate of return (IRR), discounted payback period (DPP), and levelized cost of energy (LCOE). Findings demonstrated that the PRO system can achieve substantial net energy generation, with positive economic indicators. At a 10 % discount rate, the plant yielded a positive NPV, a DPP of approximately seven years, and an IRR of 12.16 %, while the LCOE was estimated at $0.17 per kWh using cellulose triacetate membranes with approximately 90 % efficiency. Sensitivity analysis highlighted that membrane properties, including water permeability, selectivity, and long term durability, significantly affect both energy output and economic feasibility. Optimal system operation can ensure stable power generation while minimizing operational and environmental costs. In addition to energy production, PRO presented environmental benefits, producing net zero greenhouse gas emissions and complementing intermittent renewable sources such as solar and wind. The findings suggested that PRO is particularly suitable for archipelagic and coastal regions, contributing to energy security, water energy integration, and sustainable development. This study confirms that with advancements in membrane technology and optimized system design, PRO has the potential to become a scalable and cost effective blue energy solution, supporting both regional energy transition goals and global efforts toward decarbonized, sustainable power generation [25]. Kim et al. presented a novel hybrid desalination configuration that integrated seawater reverse osmosis (SWRO), solar driven desalination (SD), and pressure retarded osmosis (PRO) to enhance both energy efficiency and freshwater recovery. They stated that conventional SWRO/PRO systems were constrained by limited water recovery and insufficient energy generation. To overcome these limitations, the proposed system strategically incorporated an intermediate SD process that exploits solar energy to recover additional freshwater from SWRO brine without external energy input. In the proposed configuration, pressurized seawater was the first treated via SWRO to produce freshwater, while the resulting brine was directed to the SD unit. There, a floating solar evaporator facilitated rapid evaporation, increasing freshwater yield and further concentrating the brine. The remaining highly saline solution was subsequently utilized as the draw solution in the PRO process to generate renewable energy. They stated that system modeling and experimental validation led to a 14.54% increase in freshwater recovery, a 38.86% reduction in specific energy consumption, and a 16.67% decrease in the levelized cost of water compared to a conventional SWRO/PRO system. Life cycle assessment results indicated notable improvements in environmental sustainability. Overall, the findings confirmed that the SWRO/SD/PRO hybrid system represents a technically feasible and economically attractive solution for sustainable and Energy efficient desalination [26].

Chapuis and Bocquet stated that osmotic energy represents a largely untapped source of renewable and non-intermittent power. However, the performance of established recovery technologies, such as pressure-retarded osmosis (PRO) and reverse electrodialysis (RED), remains insufficient for sustainable industrial deployment, while nanopore-based approaches, despite their promise, face significant scalability challenges. In this study, an alternative large scale osmotic energy harvesting strategy was proposed based on a capacitive energy recovery mechanism, termed capacitive reversed electrodialysis. The proposed approach employed low cost, porous capacitive electrodes fabricated from activated carbon and operates by periodically alternating high salinity and low salinity solutions on either side of a commercial cation exchange membrane. Controlled switching between the two salinity streams prevented full capacitive charging of the electrodes, resulting in enhanced power extraction. Experimental results revealed that the harvested power density exhibits a non monotonic dependence on the switching frequency. Theoretical modeling demonstrated that this behavior arises from the intrinsic dynamic response of the membrane, which must be matched to the switching frequency to maximize energy recovery. Under a 100 fold salinity gradient, the system achieved a peak power density of 5.3 W m^{-2} over a square centimeter scale membrane, exceeding both previously reported large scale osmotic energy systems and the widely accepted economic break even threshold of 5 W m^{-2}. These findings confirmed the feasibility of high power density osmotic energy harvesting at the membrane scale and provide a systematic framework for material selection and process optimization toward sustainable energy generation [27].

Devandran stated that seaports play a vital role in global trade by serving as strategic hubs for cargo transportation and facilitating cross border market connectivity. Despite their economic significance, port operations generate a substantial environmental footprint, largely due to heavy reliance on non renewable energy sources, which results in considerable carbon emissions. Addressing this challenge is essential for aligning port development with global sustainability objectives. Devandran stated that by exploiting the natural salinity gradient between seawater and freshwater, seaports can integrate salinity gradient energy systems, such as salinity gradient osmosis (SGO), to produce clean, renewable electricity. The adoption of such blue energy technologies directly supports several United Nations Sustainable Development Goals (SDGs), particularly Goal 7 (Affordable and Clean Energy), Goal 13 (Climate Action), and Goal 14 (Life Below Water). Implementing salinity gradient energy systems within port infrastructure can significantly reduce dependence on conventional energy sources, lower CO_2 emissions, and enhance the overall sustainability performance of port operations. Furthermore, harnessing locally available saltwater and freshwater resources to generate electricity improves energy security and operational resilience while promoting a transition toward a more sustainable economic model. In this context, blue energy systems represent a promising pathway for seaports to achieve long term environmental stewardship and strengthen their commitment to sustainable development [28].

Ali et al. proposed a demand adaptive superstructure based Reverse Osmosis/Pressure Retarded Osmosis (S/RO/PRO) system to enhance the efficiency and economic viability of integrated water and energy recovery under fluctuating demand conditions. Conventional RO/PRO systems often suffered from suboptimal membrane allocation when water and energy demands vary, leading to increased specific energy consumption (SEC) and reduced operational efficiency. To overcome these limitations, the proposed framework employs a flexible, multi stage superstructure that dynamically adjusts RO and PRO membrane staging in response to real-time demand and wastewater characteristics, supported by demand-side management (DSM) strategies tailored for community scale applications. System simulations across multiple demand scenarios demonstrated that the S/RO/PRO configuration consistently outperforms conventional RO/PRO systems. Under high demand profiles, the proposed system achieved up to a 10.5% reduction in SEC and an overall SEC decrease of 10-25% across scenarios. The optimized PRO operation sustained stable power densities of 2-5 W m^{-2}, significantly exceeding the 0-1 W m^{-2} observed in conventional configurations. In addition, the levelized cost of water is reduced by approximately 25%, while energy costs decline by up to 51%. Sensitivity and economic analyses further revealed enhanced financial robustness, with net present value increasing by as much as 55% under high demand conditions. The DSM integrated S/RO/PRO system demonstrated strong potential for scalable, cost effective, and sustainable water/energy nexus applications, supporting circular economy principles and long term resource resilience [29].

Ng et al. developed a module scale modeling framework to evaluate the performance of spiral wound membranes (SWMs) in hybrid reverse osmosis/pressure retarded osmosis (RO/PRO) desalination systems, with a focus on accurately assessing specific energy consumption (SEC) and power density (PD). Modeling PRO SWMs is inherently challenging due to complex flow patterns, non uniform pressure and concentration distributions, and non linear water flux behavior. To address these challenges, a validated SWM scale model was established and shown to agree well with reported module scale water flux data. An improved SEC metric is proposed that more realistically accounts for RO operating conditions, overcoming the limitations of conventional minimum SEC definitions that underestimate actual energy demand in RO/PRO systems. A detailed breakdown of energy losses revealed that inefficiencies in energy recovery devices and pumps are the dominant contributors to reduced PRO performance, followed by concentration polarization and frictional losses in the feed and draw channels. Using the validated model, the effects of key SWM design parameters on SEC and PD are systematically quantified. Results indicated that a fourfold increase in PRO membrane area reduces desalination SEC by up to 2.2% by enhancing energy recovery, albeit at the expense of a modest (~1%) reduction in PD. The study further elucidated the trade off between maximizing PD and minimizing SEC, providing quantitative guidance for optimizing PRO/SWM design. This work offered critical insights into RO/PRO system optimization and provides a robust modeling tool to support the development of more energy efficient and economically viable desalination Technologies [30].

Marx and Gasser presented a detailed modeling and optimization framework for a hybrid seawater reverse osmosis/pressure retarded osmosis (SWRO/PRO) system aimed at reducing the specific energy consumption (SEC) of desalination. While reverse osmosis remains the dominant desalination technology, its energy demand was substantial and the highly concentrated brine was typically discharged without energy recovery. By integrating PRO to exploit the osmotic energy of RO brine, the hybrid system offersed the potential for further energy savings. A high resolution mathematical model was developed to describe flow, pressure, and concentration profiles along the membrane length for both RO and PRO units. The model accounted for internal and external concentration polarization effects and was coupled with a realistic energy recovery device (ERD) model, enabling full system simulation at real module scale. Multi objective optimization was performed to identify Pareto optimal trade offs between freshwater production and SEC for conventional RO, RO with ERD, and RO/PRO hybrid configurations. The findings demonstrated that introducing an ERD alone reduces SEC by 28.1-50.8%, while the RO/PRO hybrid achieved additional SEC reductions ranging from 4.0% to 36.4%, depending on operating conditions and PRO membrane area. Increasing PRO membrane area further enhances energy savings, though at the expense of higher wastewater consumption. The study highlighted that maximum SEC reductions occur at low production rates, which may limit economic feasibility in practice. The proposed model provided a robust and computationally efficient tool for optimizing complex RO/PRO hybrid systems and offers valuable insights for improving their energy performance and practical viability [31].

2. MATERİALS AND METHODS

In PRO, electricity is produced by exploiting the chemical potential difference between a low salinity feed solution (FS) and a high salinity draw solution (DS) across a semipermeable membrane. Water naturally flows from FS to DS due to osmotic pressure, and this flow generates hydraulic pressure, which is then converted into mechanical and finally electrical power through a turbine. The theoretical power density (power per unit membrane area) in PRO is commonly expressed by the equations;

$$\pi = iCRT \tag{1}$$

Where, π is the osmatic pressure (atm), i is the Van't Hoff factor (≈ 2 mol/Lfor NaCl), C is the molar concentration (mol/L), R is the gas constant (8.314 J/mol K), T is the temperature (K).

$$Jw = Aw(\triangle \pi - \triangle P) \tag{2}$$

$$\triangle \pi = \pi saltwater - \pi freshwater \tag{3}$$

Where, Jw is the water flux (m/s), Aw is the water permeability coefficient of the membrane, $\triangle \pi$ is the osmaic pressure difference between salt water and fresh water, $\triangle P$ is the applied hydraulic pressure (Pa).

$$W = Jw \triangle P = Jw = Aw(\triangle \pi - \triangle P) \quad (4)$$

$$\triangle Popt = \frac{\triangle\pi}{2} \quad (5)$$

$$Wmax = \mathrm{Aw}\left(\frac{\triangle\pi}{2}\right)^2 \quad (6)$$

$$Pgross = W\ Amembrane \quad (7)$$

$$Pnet = \eta system\ W\ Amembrane \quad (8)$$

$$Eyear = Pnet\ CF\ 8760 \quad (9)$$

Where, W is the power density (Watt/m^2), $Wmax$ is the maximum power density, Aw is the water permeability coefficient of the membrane, $\triangle \pi$ is the osmaic pressure difference between salt water and fresh water, $\triangle P$ is the applied hydraulic pressure (Pa), $\triangle Popt$ is the optimal pressure, $Pgross$ is the gross power output (Watt), $Amembrane$ is the total area of membrane (m^2), $Pnet$ is the net power output (Watt), $\eta system$ is the efficiency of PRO system (including efficiency of türbine, generator, hydraulic system), $Eyear$ Annual electricity generation amaount of system (kWh/year), CF is the capacity factor of system (consists membrane performance, fouling, maintenance, pumping etc.).

PRO is an osmotic energy conversion technology that generates electricity by harnessing the chemical potential difference between two solutions of differing salinity. In a typical PRO system, a low salinity feed solution (FS), such as river water, and a high salinity draw solution (DS), such as seawater, are separated by a semipermeable membrane. Due to the osmotic pressure gradient, water naturally permeates from the FS to the DS, creating an increase in hydraulic pressure on the draw side. This pressurized flow is subsequently converted into mechanical energy by a turbine and finally transformed into electrical power via a generator. The fundamental driving force of PRO is the osmotic pressure, which can be quantified using the Van't Hoff equation (Equation 1). Osmotic pressure (π) is directly proportional to the molar concentration of the solution, temperature, and the Van't Hoff factor, which accounts for ion dissociation. For saline solutions such as NaCl, the Van't Hoff factor is approximately two, reflecting the dissociation into sodium and chloride ions. This relationship highlights the critical role of salinity gradients and temperature in determining the theoretical energy potential of a PRO system. The net water transport across the membrane is described by the water flux equation (Equation 2), where the water flux (Jw) depends on the membrane water permeability coefficient (Aw) and the effective driving force, defined as the difference between the osmotic pressure gradient ($\Delta\pi$) and the applied hydraulic pressure (ΔP). The osmotic pressure difference itself is calculated as the difference between the osmotic pressures of the saltwater and freshwater streams (Equation 3). While a higher $\Delta\pi$ enhances water flux, the applied hydraulic pressure counteracts this flow and must therefore be carefully optimized. The power density of a PRO system, defined as the power generated per unit membrane area, is expressed in Equation 4 as the product of water flux and applied pressure. This equation reveals a fundamental trade off: increasing ΔP raises the mechanical energy extracted per unit volume of water but simultaneously reduces the water flux. As a result, there exists an optimal operating pressure that maximizes power density. Theoretical analysis shows that maximum power density is achieved when the applied hydraulic pressure equals half of the osmotic pressure difference (Equation 5). Substituting this optimal pressure into the power density equation yields the maximum achievable power density (Equation 6), which is governed primarily by membrane permeability and osmotic pressure gradient. At the system scale, the gross power output (Pgross) is obtained by multiplying the power density by the total membrane area (Equation 7). This relationship underscores the importance of membrane surface area as a key design parameter in PRO power plants. However, not all gross power can be converted into usable electricity due to energy losses associated with hydraulic inefficiencies, turbine performance, and electrical conversion. These losses are collectively represented by the system efficiency (ηsystem), which reduces the gross power to the net power output (Pnet) as expressed in Equation 8. The annual electricity generation of a PRO facility is calculated by incorporating the capacity factor (CF) and the total operating hours in a year (Equation 9). The capacity factor reflects real world operational constraints, including membrane fouling, maintenance downtime, pumping requirements, and variations in feed and draw water conditions. Consequently, annual energy production provides a more realistic measure of system performance than instantaneous power output alone. Together, these mathematical models form an integrated framework for evaluating PRO system performance, linking solution chemistry, membrane properties, hydraulic optimization, and system-scale energy production. A thorough understanding of the interactions among these parameters is essential for accurate feasibility assessments, optimal system design, and the successful deployment of PRO technology as a reliable source of renewable baseload energy.

PRO, a subset of osmotic energy conversion technologies, has emerged as a promising pathway for harvesting salinity gradient power. As global demand for low carbon energy intensifies, PRO has gained attention for its potential to provide reliable, renewable baseload electricity. Yet, successful deployment depends on a rigorous and systematic Project selection framework. Many early PRO initiatives struggled not because the technology lacked merit, but because site characteristics, economic conditions, or operational constraints were misaligned with the technology's requirements. Thus, a robust evaluation methodology is indispensable. The most selective parameters are listed in below for PRO project;

- Resource Quality and Salinity Gradient Availability: The most fundamental parameter in PRO project evaluation is the magnitude and stability of the salinity gradient between the feed (low salinity) and draw (high salinity) streams. Power density is directly proportional to the osmotic pressure difference. Consequently, sites with naturally large and stable gradients, such as river-sea interfaces, desalination brine outfalls, or high salinity industrial effluents, are preferred.
- Membrane Performance Compatibility: Membrane technology remains the technical cornerstone of PRO systems. Thus, project selection must incorporate an evaluation of how well available membranes can withstand the conditions of the target site.
- Site-Specific Infrastructure and Integration Potential: A technically excellent resource may still be impractical if the site lacks essential infrastructure. PRO is most cost effective when integrated with existing water management or industrial systems.
- Energy Efficiency and Net Power Output: A PRO project's viability is ultimately determined by whether it can produce net positive energy at a competitive cost.
- Environmental and Regulatory Considerations: Environmental compatibility is a central criterion for project selection. Although PRO is often framed as environmentally benign, site specific ecological impacts can arise from modified flow regimes, altered salinity levels in discharge zones, or chemical treatment used in pretreatment systems.
- Economic Viability and Financial Modeling: Comprehensive economic assessment is indispensable. PRO projects must compete with other renewable and conventional energy technologies, as well as with alternative uses of water resources.
- Technological Maturity and Scalability: Although PRO has advanced considerably, its deployment remains relatively limited compared to solar, wind, or hydropower. Consequently, a project's success depends on realistic expectations regarding scalability and technological maturity.

Considering Türkiye's diverse hydrological regions and its extensive marine boundaries with the Black Sea, the Aegean Sea, and the Mediterranean, several river basins emerge as promising candidates for PRO electricity generation. The most suitable rivers combine high and stable freshwater discharge, proximity to major saline bodies, and favorable geo infrastructural and environmental conditions. The Sakarya River Basin stands out due to its substantial an advantage for achieving predictable osmotic gradients. The basin's proximity to industrial zones and existing energy infrastructure further enhances integration potential and reduces capital costs. Similarly, the Yeşilırmak and Kızılırmak Rivers, both emptying into the Black Sea, offer large catchment areas, consistent hydrological regimes, and accessible coastal zones suitable for intake and discharge structures. Their relatively low sediment loads, compared to other Anatolian rivers, potentially reduce membrane-fouling risks, improving operational efficiency. In western Türkiye, the Gediz and Büyük Menderes Basins, discharging into the Aegean Sea, present moderate but steady flows coupled with higher salinity levels in the Aegean relative to the Black Sea. These characteristics can yield elevated osmotic pressure differences, although water quality fluctuations driven by agricultural runoff necessitate robust pretreatment strategies. The Ceyhan River, flowing into the Mediterranean, is another strong candidate due to its high discharge, minimal seasonal depletion, and proximity to industrial ports that facilitate grid connection and infrastructure sharing. The Mediterranean's stable, high salinity environment further enhances power density potential.

A comparative pre-feasibility assessment was conducted for the Yeşilırmak (Black Sea) and Ceyhan rivers (Mediterranean Sea), culminating in the estimation of their respective levelized cost of energy (LCOE) values. These LCOE results were subsequently benchmarked against those of other renewable energy technologies. Based on this comparative analysis, a set of insights, recommendations, and evaluative comments was developed regarding the potential deployment and viability of PRO systems. LCOE formula is demostrated in below.

$$\mathrm{LCOE} = \frac{Lifetime\ cost\ (USD)}{Lifetime\ energy\ (kWh)} \tag{10}$$

The lifetime cost is consisting initial capital expenditure (CAPEX), sustain investment expenditure and operational expenditure (OPEX).

LCOE is a widely accepted metric for evaluating the economic viability of energy generation technologies, as it integrates both cost and performance over the entire operational lifetime of a system. In the context of PRO, LCOE provides a comprehensive framework for assessing whether the energy produced through salinity gradient power can be competitive with established renewable technologies. Mathematically, LCOE is defined as the ratio of the total lifetime cost of a project to its total lifetime electricity generation (Equation 10). For PRO systems, lifetime costs comprise three primary components: initial CAPEX, sustained investment expenditure, and OPEX. CAPEX is dominated by membrane modules, pressure vessels, turbines, generators, and civil infrastructure, all of which scale directly with membrane area and system capacity. As shown by the PRO performance model, membrane area is a function of achievable power density, which itself depends on membrane permeability, osmotic pressure gradient, and optimal hydraulic pressure. Consequently, technological improvements that enhance membrane performance can simultaneously reduce required membrane area and lower CAPEX, creating a direct techno economic linkage between the physical and financial models. Operational expenditure includes routine maintenance, membrane replacement due to fouling or degradation, pumping energy, labor, and auxiliary power consumption. These costs are strongly influenced by site specific conditions such as water quality, salinity variability, and fouling propensity. For example, rivers with high sediment loads or seasonal flow variations may increase cleaning frequency and downtime, thereby raising OPEX and reducing the effective capacity factor. Since annual energy production is directly proportional to net power output and capacity factor, any reduction in operational availability has a compounded negative impact on LCOE. A comparative prefeasibility assessment was performed for the Yeşilırmak River discharging into the Black Sea and the Ceyhan River flowing into the Mediterranean Sea. Differences in salinity gradients, flow stability, and temperature regimes between the two sites resulted in distinct power densities and capacity factors, which in turn affected both lifetime energy generation and cost structures. The Ceyhan River, characterized by a higher and more stable salinity gradient, demonstrated a comparatively lower LCOE, indicating stronger economic potential for PRO deployment. The LCOE of PRO systems is governed by a complex interplay between membrane performance, system efficiency, site characteristics, and long-term operational reliability. While current LCOE values remain higher than those of mature renewable technologies, continued advancements in membrane technology, economies of scale, and optimized site selection are expected to significantly improve the economic competitiveness of PRO in future energy markets.

3. RESULTS AND DISCUSSION

PRO is an emerging renewable energy technology that leverages the osmotic pressure difference between freshwater and seawater to generate electricity. Türkiye, endowed with multiple rivers discharging into the Mediterranean and Aegean Seas, presents significant opportunities for harnessing salinity gradient energy. Among the most promising rivers are the Ceyhan, Seyhan, Manavgat, Göksu, and Gediz, each offering a combination of high freshwater discharge, favorable seawater salinity, and accessible infrastructure. A detailed evaluation of their hydrological, sedimentary, and infrastructural characteristics provides a foundation for assessing PRO feasibility. Rivers discharging into the Mediterranean Sea stand out as particularly suitable sites for PRO applications, primarily due to the exceptionally high salinity of the Mediterranean. To illustrate the contrast with other marine environments, the potential energy generation capacities of two representative rivers, the Yeşilırmak, flowing into the Black Sea, and the Ceyhan River, discharging into the Mediterranean, were calculated and comparatively analyzed. Following these estimations, the corresponding LCOE values were evaluated to assess economic performance. The locations of the relevant river basins are presented on the water resources map in the figure below.

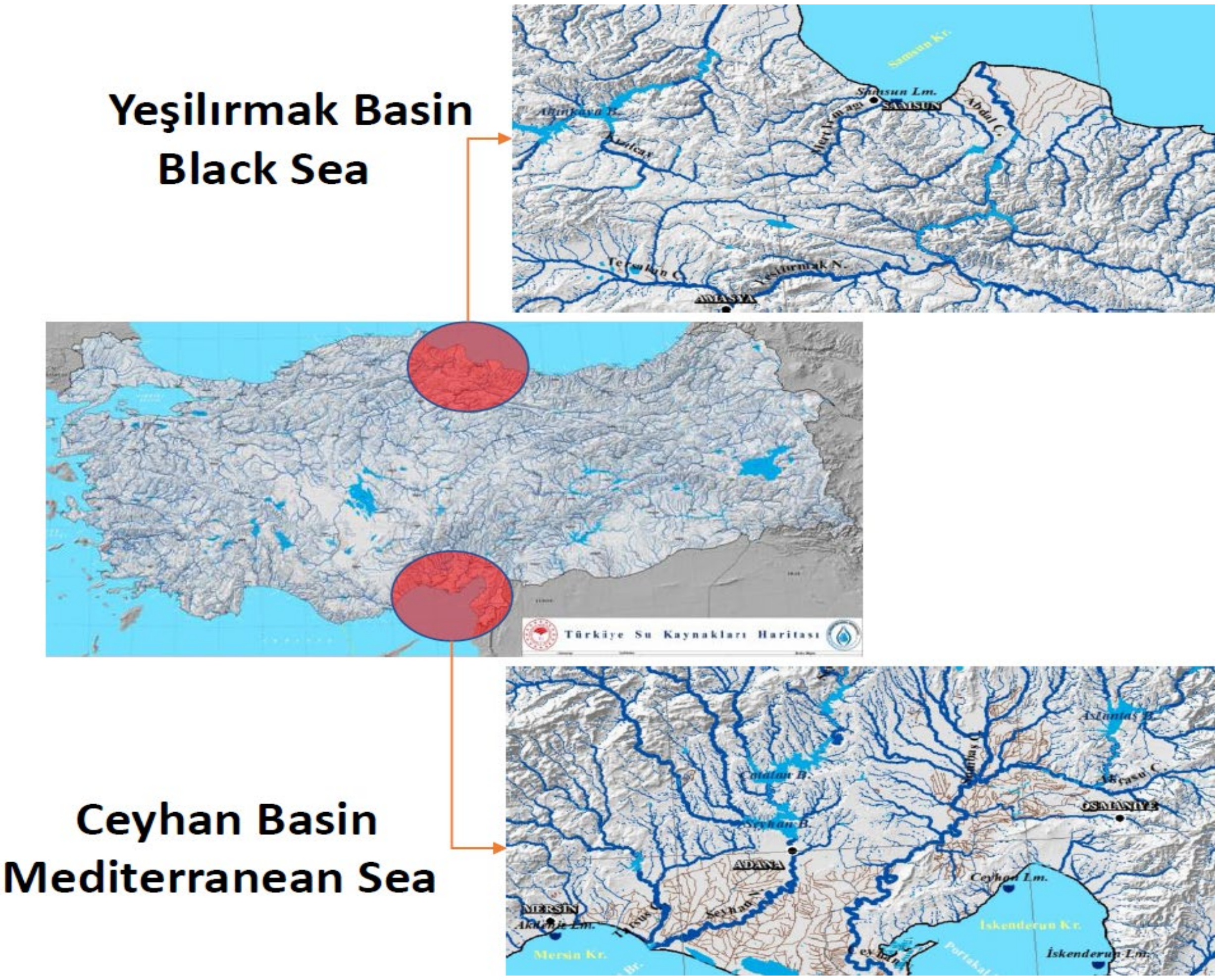

Figure 4. An illustration of Ceyhan and Yeşilırmak basin

The assumptions adopted [32, 33, 34, 35, 36, 37, 38, 39, 40] in the estimation of energy generation potential and the calculation of the LCOE are systematically summarized in the table below, providing a clear methodological framework and ensuring transparency and reproducibility of the analytical approach.

Table 1. Parameters and assumptions of Ceyhan-Yeşilpınar Rivers

Parameter	Assumption of Ceyhan River	Assumption of Yeşilırmak River
Salinity of Sea	38.5 psu for Eastern Mediterranean	17 psu for Balck Sea
Salinity of River	0 psu for Ceyhan River	0 psu for Yeşıırmak River
1 psu	1 g salt/kg ≈ 1 g/L	1 g salt/kg ≈ 1 g/L
NaCl molar mass	58.44 g/mol	58.44 g/mol
Van't Hoff factor for NaCl (i)	2	2
Molar concentration (C)	C=S/NaCl molar mass, S is the salinity	C=S/NaCl molar mass, S is the salinity

Parameter	Assumption of Ceyhan River	Assumption of Yeşilırmak River
Gas constant (R)	8.314 J/mol K	8.314 J/mol K
Temperature (T)	≈25°C (298 K)	≈25°C (298 K)
Water Permeability (Aw)	1.5 L/m^2 ≈ 4.17x 10^{-12} m (Pa s)	1.5 L/m^2 ≈ 4.17x 10^{-12} m (Pa s)
Area of membrane	10,000 m^2	10,000 m^2
Overal system efficiency ($\eta system$)	0.7	0.7
Membrane share of CAPEX	65%	65%
Capacity factor (CF)	35%	35%
Annual OPEX	4% of CAPEX per year	4% of CAPEX per year
Membrane replacement	Every 5 years	Every 5 years
Overall lifetime	25 years	25 years

While this study provides a structured techno economic assessment of PRO deployment potential for selected river/sea interfaces in Türkiye, several limitations should be acknowledged to ensure a balanced interpretation of the results and to guide future research efforts. These limitations primarily arise from model assumptions, data availability, technological maturity, and the inherent simplifications required at the prefeasibility stage. The analysis relies on a set of fixed and idealized parameters, as summarized in Table 1, to ensure comparability between the Ceyhan and Yeşilırmak case studies. Salinity levels, temperature, membrane permeability, system efficiency, capacity factor, and economic parameters were assumed constant over the project lifetime. In practice, these variables exhibit temporal and spatial variability due to seasonal hydrological changes, climate effects, membrane aging, fouling dynamics, and operational interruptions. As a result, real world performance may deviate from the modeled values, particularly in long term operation.

Membrane behavior was represented using a single water permeability coefficient, neglecting concentration polarization, reverse salt flux, and performance degradation over time. While this simplification is consistent with early stage feasibility analyses, membrane related losses are known to significantly influence both power density and operational expenditure in full scale PRO systems. Future studies incorporating dynamic membrane performance models and site-specific fouling characteristics would improve accuracy and reduce uncertainty in energy yield and LCOE estimates.

The economic assessment adopts generalized cost assumptions, including fixed CAPEX shares, membrane replacement intervals, and OPEX ratios derived from the literature. These values may not fully reflect local market conditions, supply chain constraints, labor costs, or regulatory requirements. Moreover, the analysis does not account for potential cost reductions resulting from learning curves, economies of scale, or colocation with existing infrastructure such as desalination plants or wastewater treatment facilities. Consequently, the reported LCOE values should be interpreted as indicative rather than definitive. In addition, the environmental and regulatory dimensions of PRO deployment were addressed at a conceptual level but not quantified in detail. Although PRO is generally considered environmentally benign, site specific impacts related to brine discharge, altered salinity gradients, and intake or outfall design may influence project feasibility and permitting timelines. Comprehensive environmental impact assessments would therefore be essential prior to implementation. Despite these limitations, the study offers valuable insights and a robust methodological framework for early stage PRO project evaluation. By systematically linking salinity gradient availability, membrane performance, system efficiency, and economic metrics, the analysis highlights the dominant parameters governing PRO viability. The pronounced contrast between the Mediterranean and Black Sea case studies underscores the critical importance of resource quality, particularly osmotic pressure gradients, in determining both technical performance and cost effectiveness. Looking forward, future research should focus on integrating high resolution temporal data, advanced membrane transport models, and site-specific environmental constraints into techno-economic assessments. Experimental validation through pilot scale installations, particularly in high salinity regions such as the Eastern Mediterranean, would significantly enhance confidence in model predictions. Furthermore, coupling PRO systems with existing water and energy infrastructure presents a promising pathway for improving economic competitiveness and accelerating technological maturity. While PRO is not yet cost competitive with mature renewable technologies, the findings of this study suggest that under favorable site conditions and with continued technological advancement, PRO holds considerable potential as a niche but reliable contributor to future low carbon energy systems.

The table below presents a concise summary of the installed capacity and electricity generation calculations carried out within the scope of PRO energy production projects for the Yeşilırmak and Ceyhan rivers. These assessments were conducted using river specific hydrological, topographical, and technical data relevant to project development and feasibility analysis. The summarized results provide a comparative evaluation of the projected installed power capacities and expected electricity generation levels for each river. By integrating these calculations, the table serves as a technical reference to support decision making processes in the planning, design, and implementation stages of sustainable PRO energy production projects.

Table 2. PRO calculations of Ceyhan-Yeşilpınar Rivers

Parameter & Calculation	Ceyhan River	Yeşilırmak River
Average discharge	180 m^3/s	120 m^3/s
Osmatic pressure (π)	$3.26x10^6$ Pa= 32.6 bar	1.44 $x10^6$ Pa= 14.4 bar
Water flux at optimum (Jw)	$6.8x10^{-6}$ m/s	$3x10^{-6}$ m/s
The maximum power density ($Wmax$)	11.1 W/m^2	2.17 W/m^2
Area of membrane	10,000 m^2	10,000 m^2
Gross Power Output ($Pgross$)	111 kW	21.7 kW
Overall system efficiency ($\eta system$)	0.7	0.7
Net Power Output ($Pnet$)	78 kW	15 kW
Capacity factor (CF)	0.35	0.35
Annual electricity generation ($Eyear$)	238,000 kWh/year	46,000 kWh/year
Membrane CAPEX	200,000 USD	200,000 USD
Membrane share of CAPEX	65%	65%
PRO CAPEX	307,700 USD	307,700 USD
Annual OPEX	4% of CAPEX per year	4% of CAPEX per year
Membrane replacement	Every 5 years	Every 5 years
Overall lifetime	25 years	25 years
LCOE (USD/kWh)	0.238 USD/kWh	1.23 USD/kWh

A PRO facility proposed on the Ceyhan River emerges as a substantially more attractive investment than an equivalent installation envisaged on the Yeşilırmak River when evaluated in terms of the LCOE. Specifically, the Ceyhan based project demonstrates an LCOE that is approximately five times more favorable. This pronounced disparity primarily stems from the fundamental operating principle of PRO technology, which is highly sensitive to salinity gradients. The Mediterranean Sea, into which the Ceyhan discharges, is characterized by markedly high salinity, whereas the Black Sea, receiving the Yeşilırmak, exhibits comparatively low salinity levels. As a result, the osmotic pressure differential is significantly greater in the former case. Although both rivers are distinguished by substantial flow rates, a standardized and practically feasible scale was adopted to ensure comparability. Accordingly, a representative assessment was conducted assuming a membrane area of 10,000 m² for each scenario. This approach allows the observed differences in techno economic performance to be attributed predominantly to salinity conditions rather than hydrological capacity. For broader context, the accompanying figure also presents LCOE benchmarks for other renewable energy technologies, as reported in recent IRENA publications [26]. These reference values facilitate a comparative assessment, situating PRO based power generation within the wider landscape of contemporary renewable energy options and highlighting its potential competitiveness under favorable environmental conditions.

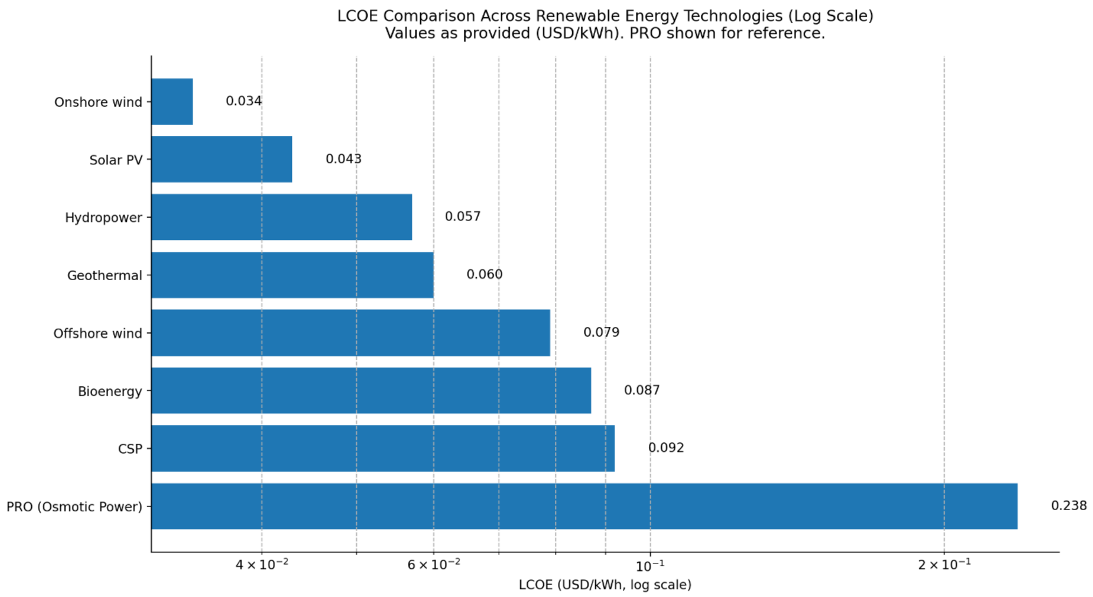

Figure 5. LCOE comparison between PRO and Renewable energies

The LCOE estimated for the facility planned to be constructed on the Ceyhan River is considered to be reasonable when compared with both existing installations and the reference values reported in the literature. Numerous studies on PRO technologies indicate LCOE values ranging between 0.2 and 0.6 USD/kWh, which is consistent with the projected cost level of the proposed facility. These findings suggest that, from a techno economic perspective, the anticipated performance of the plant aligns with the current state of research and development in this field. Despite the notable advantages of PRO based power plants, such as their baseload generation capability, high theoretical energy potential, and continuous operation characteristics, their LCOE remains substantially higher than that of other renewable energy technologies. This cost disadvantage continues to be one of the primary barriers to their widespread deployment. An examination of comparative cost graphs reveals that Concentrated Solar Power (CSP) plants represent the closest alternative in terms of LCOE; however, even in this case, PRO systems exhibit a minimum cost difference of approximately 2.5 times. When benchmarked against onshore wind power plants, the disparity becomes even more pronounced, with PRO facilities demonstrating an LCOE that is at least seven times higher. These comparisons highlight the economic challenges that must be addressed for PRO technologies to become more competitive within the renewable energy market.

To address the determination of the optimum operating point and to improve the transparency of the analytical framework, a parametric evaluation was conducted to explicitly examine the influence of key design and operational variables on PRO system performance and economic outcomes. Rather than selecting a single operating condition a priori, the optimum point reported in the results emerges from the systematic interaction between osmotic pressure difference, applied hydraulic pressure, membrane performance, and resulting power density.

At the core of the optimization lies the applied hydraulic pressure (ΔP), which directly governs both water flux and power density. As described by the governing PRO equations, water flux decreases linearly with increasing ΔP, while power density increases initially due to higher mechanical energy extraction per unit volume of permeating water. However, beyond a certain threshold, the reduction in flux outweighs the gain from increased pressure, causing power density to decline. By parametrically varying ΔP from zero to the full osmotic pressure difference ($\Delta\pi$), a concave power density curve is obtained, with a distinct maximum occurring at $\Delta P = \Delta\pi/2$. This condition, derived analytically and validated numerically, defines the optimal operating pressure used in the present study. The osmotic pressure difference itself is a function of seawater salinity, temperature, and solution chemistry. Parametric comparison between the Ceyhan and Yeşilırmak rivers demonstrates that higher seawater salinity in the Mediterranean directly translates into a larger $\Delta\pi$, thereby shifting the power density curve upward while preserving the same optimal pressure ratio. Consequently, even under identical membrane properties and operating assumptions, sites discharging into high salinity basins inherently achieve higher maximum power densities and net power outputs. Membrane water permeability (Aw) constitutes another critical parameter influencing the optimum outcome. Sensitivity analysis indicates that power density scales linearly with Aw, meaning that improvements in membrane technology simultaneously increase energy output and reduce the membrane area required for a given capacity. This dual effect has direct implications for both capital expenditure and LCOE, highlighting the strong coupling between technological parameters and economic performance. At the system level, the capacity factor (CF) and overall system efficiency (ηsystem) were treated as aggregated parameters capturing operational realities such as fouling, maintenance, pumping losses, and conversion efficiencies. While these parameters do not alter the theoretical optimum pressure, they significantly affect annual electricity generation and therefore the lifetime energy term in the LCOE calculation. Parametric variation of CF demonstrates that reductions in operational availability disproportionately increase LCOE, even when instantaneous power output remains unchanged. Economic parameters such as membrane replacement intervals, OPEX ratios, and project lifetime were varied within ranges reported in the literature to assess their impact on LCOE sensitivity. Results indicate that membrane-related costs dominate total lifetime expenditures, reinforcing the importance of membrane durability and performance stability in achieving economically optimal PRO installations. The optimum point presented in this study is not a fixed assumption but the outcome of a structured parametric evaluation linking physical performance models with economic indicators. This approach ensures that the reported results reflect a realistic and internally consistent optimization of PRO system design and site specific conditions.

4. CONCLUSION

PRO has gained increasing attention in recent years as a novel and promising renewable energy technology, particularly within the context of global efforts to achieve sustainable, low carbon energy systems. One of the most distinctive advantages of PRO lies in its ability to provide continuous and reliable baseload power, a feature that sets it apart from many conventional renewable energy sources such as wind and solar, which are inherently intermittent. In addition, PRO systems utilize natural salinity gradients between freshwater and seawater, enabling energy generation without fuel consumption or direct greenhouse gas emissions. These characteristics have positioned PRO as a trend setting technology in the emerging renewable energy landscape.
At the global level, PRO technology has progressed beyond theoretical modeling and laboratory scale experiments. Several pilot projects have been successfully implemented, and in some regions, these pilot facilities are now evolving into pre-commercial or commercial scale power plants. This transition reflects growing confidence in the technical feasibility and long term sustainability of PRO systems. As research and development activities intensify, PRO is increasingly being recognized as a complementary energy source capable of enhancing grid stability and supporting energy security.

Despite these global advancements, Türkiye has not yet commissioned a PRO based power plant. Nevertheless, the country possesses substantial untapped potential for PRO deployment due to its geographical and hydrological characteristics. In particular, rivers discharging into the Aegean and Mediterranean Seas are considered highly suitable, as these marine environments exhibit relatively high salinity levels that enhance osmotic pressure differentials. Furthermore, beyond major river basins, Türkiye is home to numerous rivers, streams, and smaller waterways that discharge directly into the sea. With adequate infrastructure development, site specific feasibility assessments, and integrated coastal planning, these water bodies could support the establishment of PRO facilities across different regions.

Among the candidate sites evaluated in this study, the Ceyhan River has been identified as one of the most promising locations for PRO implementation. The LCOE calculated for a PRO plant on the Ceyhan River is approximately 0.238 USD/kWh. While this value is in line with LCOE ranges reported in the international literature for PRO systems, it remains significantly higher than the costs associated with established renewable energy technologies such as hydropower, onshore wind, and photovoltaic solar power. This outcome highlights the current economic limitations of PRO and explains why it has not yet achieved widespread commercial adoption.

The main challenges affecting the economic competitiveness of PRO technology are primarily related to technical and operational factors. High initial capital investment costs, largely driven by membrane modules and pressure exchange equipment, represent a major barrier. Additionally, the relatively short operational lifetime of membranes necessitates frequent replacement, increasing both operational expenditures and system downtime. Another critical limitation is the low permeability coefficient of existing membranes, which restricts power density and reduces overall energy efficiency. Moreover, internal energy consumption within PRO systems, significantly diminishes net power output, further affecting economic performance.

Addressing these challenges is essential for the broader commercialization of PRO technology. In this context, recent advancements in membrane science are particularly noteworthy. The development of new generation membranes with higher permeability, improved fouling resistance, and extended economic lifetimes has the potential to substantially reduce both capital and operational costs. Concurrently, system level optimizations aimed at minimizing internal energy losses could further enhance net energy production. Although PRO technology currently exhibits higher energy costs compared to other renewable energy sources, its unique advantages, such as sustainability, baseload capability, and continuous operation, make it a strategically important option for future energy systems. With sustained technological innovation, targeted research investments, and supportive policy frameworks, PRO based power plants are expected to emerge as a viable and competitive renewable energy alternative within the next decade, both in Türkiye and on a global scale.

DECLARATION OF ETHICAL STANDARDS

The author of the paper submitted declares that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

The author contributed to the conceptualization and design of the study, carried out the analytical procedures, and undertook the comparative analysis.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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