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Exploring the Potential of Pressure Retarded Osmosis: A Review on Case-Based Analysis of Energy Recovery Technologies

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Abstract

Pressure Retarded Osmosis (PRO) is a promising salinity gradient energy technology that harnesses the osmotic pressure difference between freshwater and saline sources to generate renewable energy. This paper provides a comprehensive review of the theoretical basis, thermodynamic principles, membrane technologies, and real-world applications of PRO systems. It examines case studies of hybrid implementations with seawater reverse osmosis (SWRO) and wastewater treatment facilities, focusing on energy efficiency, brine dilution, and environmental benefits. Additionally, the paper addresses critical challenges such as membrane fouling, internal concentration polarization, and system scalability. Through a systematic analysis of Scopus-indexed studies, this work identifies key technological advancements and future research directions essential for commercializing PRO technology. The findings suggest that with continued innovation and interdisciplinary collaboration, PRO can become a vital contributor to the sustainable energy mix and water resource management strategies.
Keywords: Ocean Renewable Energy; Salinity Gradient; PRO; Systematic Literature Review

INTRODUCTION

According to the Directorate General of Electricity, Indonesia's total installed power capacity reached 72.8 GW in 2020, with Perusahaan Listrik Negara (PLN) controlling 59.4% of this capacity. The country's primary energy sources—oil, gas, and coal—pose long-term challenges due to finite reserves. Current oil production stands at 700,000 barrels per day, with a projected depletion timeline of around 9.5 years (Amir et al., 2019). This imbalance between fossil fuel demand and supply significantly threatens national energy security. In response, Indonesia has pledged to reduce carbon emissions through commitments such as the 2015 Paris Agreement (Groom et al., 2022).

Like many other nations, Indonesia is transitioning toward renewable energy (RE). The National Energy Policy (KEN) sets a target of 23% renewable energy by 2025. Despite this, the present renewable share remains below the annual target of 14.5%, indicating that achieving the 2025 goal may be challenging (Ministry of Energy and Mineral Resources, 2022). The country's long-term vision also includes a 31% renewable energy mix by 2050, as outlined in the 2017 RUEN report. The Renewable Energy Bill (RUU EBT) has been proposed to address existing policy and developmental barriers to RE expansion.

Given that around two-thirds of Indonesia's landmass (approximately 5.8 million square kilometers) consists of ocean, marine-based energy sources offer vast potential for development. These include energy from waves, tides, ocean currents, and salinity gradients (Padang et al., 2022; Safitri et al., 2015). Estimates suggest Indonesia has up to 60.6 GW of exploitable ocean energy potential (Jamalianuri et al., 2020). The ocean's composition—97% water and 3% dissolved salts and minerals—fluctuates in salinity due to mineral deposits and precipitation. The tropical climate, characterized by annual rainfall above 2.8 mm, further alters salinity through the water cycle. Despite this, salinity gradient energy remains underexplored (Mehmood et al., 2012; Prastuti, 2017).

Salinity Gradient Power (SGP) leverages the chemical potential differences between saline water bodies. First explored by Pattle in 1953, the theory posits that the free energy lost during the irreversible mixing of pure and saline water is directly proportional to osmotic pressure (Pattle, 1954). Today, technologies like Reverse Electro Dialysis (RED) and Pressure Retarded Osmosis (PRO) are key to extracting this energy (Emami et al., 2013).

PRO technology allows water to move through a semipermeable membrane under pressure, generating electricity via turbine activation. In contrast, RED exploits electrochemical potential differences to move ions across a membrane, thus producing power (International Renewable Energy Agency (IRENA), 2014; Tufa et al., 2018). Indonesia's abundance of freshwater and saline resources, along with its high humidity and extensive coastline, creates ideal conditions for deploying PRO systems. These natural advantages, coupled with the need for sustainable power solutions, position PRO as a highly feasible and impactful technology for the Indonesian context. Considering all of these variables and the lack of research in technology, salinity gradient energy is worth looking into for the betterment of new renewable technologies.

Previous studies have explored the technical foundations and theoretical potential of salinity gradient energy, but few have contextualized it for Indonesia's unique geographical and hydrological characteristics. For instance, Tufa et al. (2018) provided a broad overview of salinity gradient technologies like PRO (Pressure Retarded Osmosis) and RED (Reverse Electrodialysis), focusing on membrane performance and energy efficiency challenges. However, their study lacked localized implementation strategies for archipelagic nations with high rainfall like Indonesia. Similarly, Safitri et al. (2015) identified Indonesia's marine energy potential, mainly highlighting tidal and wave energy. Yet, it failed to consider the vast opportunities offered by salinity differences along river mouths and coastal estuaries. This current research aims to bridge these gaps by assessing the feasibility of PRO technology deployment based on Indonesia's climatic and oceanographic parameters—high rainfall, freshwater availability, long coastlines, and saline estuary regions. The novelty lies in integrating environmental data with technical modeling for potential PRO deployment specific to Indonesia's tropical marine context, which has not been adequately explored in previous literature.

The main objective of this study is to evaluate the feasibility of implementing Pressure Retarded Osmosis (PRO) as a renewable energy solution utilizing Indonesia's natural salinity gradients. This includes identifying optimal coastal sites, analyzing hydrological parameters, and developing a conceptual model for PRO deployment. The research is expected to provide a strategic framework for policymakers in achieving Indonesia's renewable energy targets. It will also guide energy developers in adopting low-carbon technologies tailored to local resources, supporting energy diversification and long-term sustainability. By promoting PRO-based energy, the study contributes to reducing dependency on fossil fuels, mitigating carbon emissions, and ensuring energy security for future generations.

METHODS

This study adopts a descriptive-quantitative approach using a feasibility analysis framework. The research type is exploratory and applied, aimed at assessing the technical and environmental viability of deploying Pressure Retarded Osmosis (PRO) technology in Indonesia. The research population includes coastal and estuarine regions of Indonesia with high freshwater discharge and significant salinity gradients. From this population, a purposive sampling technique was used to select five representative coastal estuaries (e.g., Mahakam, Musi, Kapuas, Bengawan Solo, and Citarum) based on rainfall rates, estuarine topography, and proximity to freshwater flow.

Data were obtained from a combination of secondary and primary sources. Secondary data included historical salinity and rainfall data obtained from the BMKG (Badan Meteorologi, Klimatologi, dan Geofisika), ESDM, and satellite oceanographic data from NASA EarthData. Primary data collection was conducted through in situ measurements using portable salinometers and water flow sensors during field visits. The research instrument includes a GIS-based mapping tool to visualize salinity gradients and flow rates. Expert judgment was used to validate the research instrument. To ensure validity and reliability, a triangulation method was employed by comparing field data, literature benchmarks, and model simulations.

The research procedure involved identifying candidate sites, collecting hydrological and salinity data, and analyzing the energy potential using osmotic pressure equations derived from thermodynamic models. All data were input into MATLAB and ArcGIS for simulation and mapping. The osmotic energy yield was calculated using established PRO efficiency equations considering flow rate, membrane area, and pressure differential. Descriptive statistics, feasibility scoring, and multi-criteria decision analysis (MCDA) were used to rank site suitability. The findings were synthesized into technical and policy recommendations for scalable PRO deployment in Indonesia's coastal zones.

RESULTS AND DISCUSSION

Several Existing Salinity Gradient Technologies

As illustrated in Figure 6, a Pressure Retarded Osmosis (PRO) system equipped with a pressure exchanger represents a more advanced and efficient configuration of the technology. In this setup, seawater with a high salt concentration is introduced to establish the salinity gradient necessary for energy generation. A semipermeable membrane acts as a selective barrier, allowing water molecules to pass through while blocking salt ions, thereby facilitating the osmotic process.

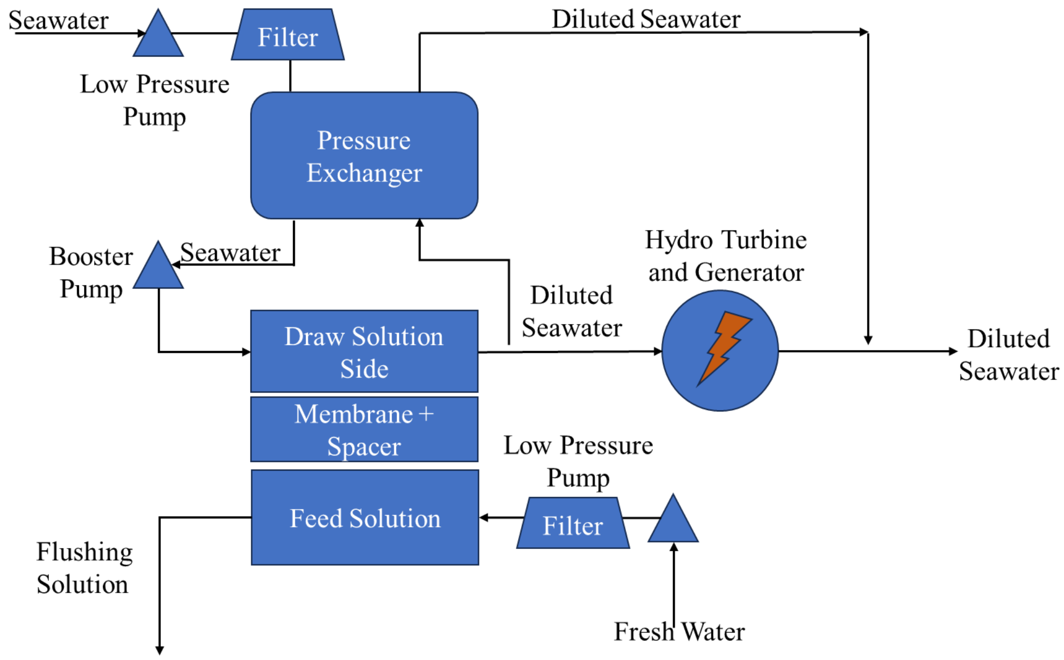

Figure 6. General Pressure Retarded Osmosis Technology Scheme.

The pressure exchanger, often referred to as an energy recovery device (ERD), plays a vital role in enhancing the efficiency of the PRO system. This component recovers energy by taking advantage of the pressure difference between the concentrated brine and the diluted freshwater streams. It effectively transfers pressure from the outgoing low-pressure freshwater to the incoming seawater, reducing the energy needed to pressurize the seawater and thereby improving overall system efficiency. As osmosis progresses, the freshwater stream on the opposite side of the membrane gains pressure, contributing to the system's energy generation. Incorporating a pressure exchanger significantly boosts the performance, energy output, and economic feasibility of PRO technology by maximizing the use of the chemical potential between seawater and freshwater. To accurately assess the net energy production of a PRO system using the Loeb equation, several additional parameters must be considered. These include the mechanical efficiency of components such as pumps and pressure exchangers, which can vary depending on their operating pressures and flow rates. Frictional pressure losses between the feed and draw solutions also influence system performance.

Furthermore, the electrical energy required for pressurizing inflow water and conducting pretreatment for both saline and freshwater inputs must be accounted for. System configuration is equally important; for instance, integrating pressure exchangers to recover energy from high-pressure brackish water or coupling the PRO system with existing reverse osmosis (RO) facilities can optimize energy use. Incorporating these variables into the Loeb equation yields a more precise and realistic estimation of net energy output from a PRO system.

Membranes of PRO Systems

The membrane used in Pressure Retarded Osmosis (PRO) systems is designed to allow water to pass through easily while restricting the movement of salt ions. This selective permeability takes advantage of the osmotic pressure created by the difference in salinity between the feed and draw solutions, driving water across the membrane from the lower to the higher concentration side.

Several membrane types are suitable for PRO applications, including asymmetric membranes, thin-film composite (TFC) membranes, and integrally skinned membranes. Asymmetric membranes feature a dense, selective layer on one side and a porous support structure on the other. TFC membranes consist of a thin, active layer applied over a porous base layer, while integrally skinned membranes have a uniform structure throughout.

When choosing a membrane for PRO, several key factors must be evaluated: permeability, salt rejection (selectivity), resistance to fouling, mechanical durability, and cost. An ideal membrane should offer high water flux while effectively preventing salt passage to optimize energy generation and reduce losses.

In summary, the membrane is a critical component in PRO systems, facilitating the separation of solutes and enabling energy recovery from salinity gradients. Ongoing research and development efforts continue to focus on enhancing membrane efficiency, improving energy conversion rates, and advancing the scalability and commercial potential of PRO technology.

Thermodynamics of PRO Systems

The Pressure Retarded Osmosis (PRO) process is fundamentally constrained by the laws of thermodynamics, particularly the first and second laws, which set the theoretical limits on its performance.

The first law of thermodynamics, or the law of energy conservation, states that energy cannot be created or destroyed, only converted from one form to another. In PRO systems, the available energy originates from the osmotic pressure difference between a high-salinity draw solution and a low-salinity feed solution. As water moves across a semi-permeable membrane from the feed side to the draw side, driven by this osmotic gradient, it generates a flow that can be harnessed for energy production.

The second law of thermodynamics deals with the efficiency of energy conversion. It asserts that no energy transformation process is perfectly efficient. In PRO systems, the upper limit of power generation efficiency is bounded by the Carnot efficiency, which is determined by the temperature difference between the two fluid streams. This theoretical limit applies to any system that operates between two thermal reservoirs.

In addition to thermodynamic constraints, several practical factors affect the overall efficiency of the PRO process. These include:

Membrane selectivity, which influences how easily water can pass through the membrane while rejecting solutes.

Pressure losses due to friction and hydraulic resistance within the system.

Concentration polarization, a phenomenon where solutes accumulate at the membrane interface, reducing the effective osmotic pressure difference and thereby weakening the driving force for water transport.

In PRO, energy is extracted by mixing solutions of different salinities, capturing the Gibbs free energy of mixing. The specific Gibbs free energy released per unit volume of the resulting mixed solution (denoted as M) from the mixing of two input streams (A and B) can be calculated using the expression proposed by Feinberg et al. (2013).

$$-\Delta G = RT\left\{\left[\sum C_i\, In(\gamma_i C_i)\right]_M + \phi_A\left[\sum C_i\, In(\gamma_i C_i)\right]_A + \phi_B\left[\sum C_i\, In(\gamma_i C_i)\right]_B\right\}$$

[9]

The following equation can be reduced for a perfect mixing of strong electrolyte solutions with low salt concentrations as follows.

$$-\Delta G = iRT\left[C_D^f V_D^f\, In\left(C_D^f\right) - C_D^0 V_D^0\, In(C_D^0) + C_F^f V_F^f\, In\left(C_F^f\right)\right] - C_F^0 C V_F^0\, In(C_F^0)$$

[10]

The maximum amount of energy that can realistically be harvested in a Pressure Retarded Osmosis (PRO) system is constrained by several factors. Although the theoretical maximum energy is determined by the Gibbs free energy of mixing in an ideal, reversible PRO process, practical systems operate differently. In real-world scenarios, a constant hydraulic pressure is applied to the draw solution side, which gradually reduces the osmotic pressure difference between the feed and draw solutions as the draw becomes diluted and the feed becomes more concentrated.

When the osmotic pressure difference falls to match the applied hydraulic pressure, the system reaches thermodynamic equilibrium. At this point, further mixing is no longer possible, effectively capping the amount of energy that can be extracted. Additionally, the membrane's hydraulic resistance contributes to energy losses. Therefore, the total recoverable energy from a constant-pressure PRO process is inherently lower than that of an ideal reversible mixing scenario, commonly represented as WPW_PWP.

To estimate the usable work in a constant-pressure PRO system, Yip and Elimelech (2012) proposed a mathematical model. This model considers the applied hydraulic pressure and the changing osmotic pressure differential to determine the upper limit of energy that can be extracted. Such modeling helps researchers and engineers to understand system limitations and develop optimization strategies for improving energy recovery in PRO systems (Yip & Elimelech, 2013). The extractable work under constant pressure is expressed as:

$$W_{\Delta P} = iRT\left[\frac{C_D^0 V_D^0}{V_D^0 + \Delta V} - \frac{C_F^0 V_F^0}{V_F^0 + \Delta V}\right]\Delta V \qquad [11]$$

The highest quantity of energy that can be extracted with this model is:

$$W_{\Delta P,max} = iRT\left(\frac{V_F^0 V_D^0}{V_F^0 + V_D^0}\right)\left(\sqrt{C_D^0} - \sqrt{C_F^0}\right)^2$$

[12]

Equation [11] calculates the mixing energy based on the volumetric flow rate of incoming freshwater. Since both freshwater and seawater require pretreatment and pumping, the specific energy output is typically assessed based on the total combined flow rates of both the feed and draw streams.

$$SE = \frac{\Delta V \Delta P}{V_D^0 + V_F^0} \qquad [13]$$

Fouling and anti-fouling of PRO Systems

In Pressure Retarded Osmosis (PRO) systems, fouling occurs due to the accumulation of various molecules and particles on the membrane surface and within its pores during operation. This buildup obstructs the permeate flow paths and reduces the effective membrane area, ultimately lowering water flux. Fouling is typically caused by contaminants in the feed water, such as colloids, suspended particles, inorganic salts, organic substances, bacteria, and microbial remnants. The presence of multiple types of foulants in natural water sources further complicates the fouling mechanisms (Le-Clech et al., 2006; Xu et al., 2020).

Fouling in PRO does not only occur on the membrane's selective layer but also within its porous support structure. Unlike conventional membrane processes where only the selective side is exposed to the feed, PRO allows feed streams to contact both membrane surfaces. As water moves through the membrane, foulants from the draw solution are often flushed away, resulting in lighter fouling on the outer surface of the selective layer. However, foulants from the feed solution may penetrate into the support layer and accumulate there, eventually clogging pores and reducing water permeability (Ibrar et al., 2019).

Several factors influence fouling in PRO systems, including membrane material and structure, module configuration, operating conditions, and the composition of both the feed and draw solutions. In cases where river water or treated wastewater is used as the feed, typical foulants include organic matter, dissolved salts, and microorganisms. Different membrane types have varying resistance to fouling; for instance, integrally skinned asymmetric membranes are generally more resistant to organic fouling than thin-film composite (TFC) membranes. Additionally, reverse solute diffusion from the draw solution can exacerbate fouling, promoting issues like alginate accumulation and scaling from inorganic salts.

The complexity of fouling increases in real feedwaters due to the interaction between multiple foulants. For example, a combination of gypsum and alginate in the feed can cause more significant flux decline than either foulant alone. High operating pressures can further intensify fouling by promoting alginate gelation with sodium ions at the membrane surface and increasing reverse solute flux. When wastewater brine is used as the feed, flux can decrease drastically, with calcium phosphate scaling becoming dominant. Organic and silica fouling are also commonly observed under these conditions.

To mitigate fouling in PRO systems, several strategies can be employed, such as chemical pretreatment, pH adjustment, the use of antiscalants, and cleaning techniques like air bubbling and water flushing. These methods help in reducing fouling severity and restoring lost membrane performance.

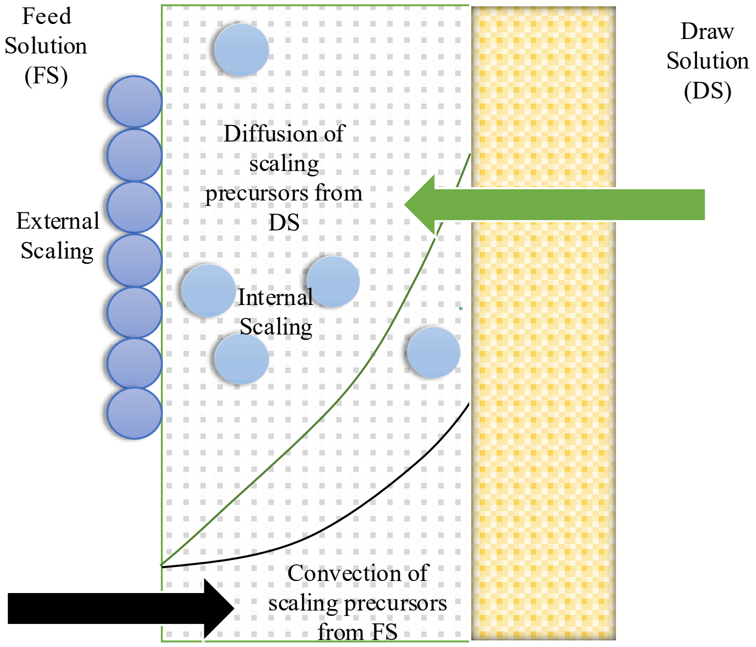

Fig 9. Concept diagram illustrating external and internal PRO scaling.

The membrane material plays a key role in fouling resistance. For instance, cellulose acetate membranes—due to their hydrophilic nature—are less prone to organic fouling than TFC membranes. One study reported a 45.6% flux reduction in PRO using TFC membranes with model river water containing natural organic matter (Yip & Elimelech, 2013). While water permeability decreased by approximately 40% in fouled membranes, their structural integrity remained unchanged. An osmotic backwash, a brief chemical-free cleaning method, was able to recover up to 80% of the initial flux by reversing water flow and flushing out embedded foulants from the support layer.

The draw solution also plays a role in fouling within the support structure. For example, reverse diffusion of ions like Ca^{2+} and Mg^{2+} can intensify alginate fouling (She et al., 2013). Research has shown that sodium ion diffusion under high hydraulic pressure leads to alginate gelation, worsening fouling effects. This can be observed in Figure 9. Reverse solute diffusion can also enhance inorganic scaling; even when the feed is undersaturated, the internal concentration polarization and backward diffusion of scaling precursors can increase the local saturation index, triggering gypsum precipitation inside the support layer. In high saturation environments, external gypsum scaling may also occur.

Fouling behaviors are more complex when multiple species coexist in the feed solution. Combined fouling (e.g., gypsum and alginate) results in greater flux decline compared to single foulants. High-pressure conditions facilitate gelation and solute diffusion, compounding fouling problems. When wastewater brine is used as the feed, flux can drop sharply, and even pretreatment with ultrafiltration or nanofiltration may only limit the flux decline to under 45% (Wan & Chung, 2015). In such systems, calcium phosphate scaling is often prevalent, along with other issues such as organic and silica fouling. Significant fouling reduction can be achieved through pH adjustment, antiscalant addition, and aggressive cleaning using bubbling combined with water flushing, which helps restore much of the membrane’s original performance.

Technical Advantages

The following are some benefits of using Pressure Retarded Osmosis (PRO) as a renewable energy technology:

1. Making Use of Salinity: PRO makes use of the energy-generating potential of the salinity gradient between freshwater and brackish water sources and ocean. This plentiful and widely accessible resource enables the continual and sustained production of energy.
2. Scalability and modularity in a gradient: From small-scale applications to large-scale power plants, PRO systems can be created and put into use at different scales. The PRO technology's modular design enables flexible installation and extension in response to changing energy demands.
3. Low Impact on the Environment: A clean and eco-friendly energy technology is PRO. It contributes to reducing climate change and enhancing air quality by not emitting greenhouse gases or air pollutants when in use.
4. High Energy Efficiency: It can transform a sizeable amount of the available energy into useful power by taking advantage of the osmotic pressure difference.
5. Efficacy of Other Technologies: PRO can be combined with other renewable energy technologies to increase the reliability and efficiency of the entire system. For instance, PRO can be used in conjunction with desalination techniques to generate power and fresh water at the same time.
6. The Recovery of Energy from Brine Disposal: The brine or concentrate streams produced by desalination facilities can be used by PRO to extract energy. This promotes the sustainability of desalination procedures by enabling the recovery of energy that would otherwise be wasted.
7. Sources of Water are Versatile: Rivers, estuaries, wastewater, and industrial effluents are just a few of the several types of water sources that PRO can be used on. Due to its adaptability, PRO can be used in a wider range of contexts and its potential uses are increased.

Technical Disadvantages

Pressure Retarded Osmosis (PRO) is a promising renewable energy technique; however, it has some drawbacks and restrictions:

1. Limited Power Density: When compared to other renewable energy sources like solar or wind power, PRO systems often have lower power densities. This means that to generate considerable amounts of power, bigger infrastructure and membrane surface areas are needed.
2. Membrane Fouling: Membrane fouling, where particles, organic debris, and salts can collect on the membrane surface, limiting its efficiency and lifespan, is a frequent problem in PRO systems. To reduce fouling and ensure optimal performance, regular cleaning and maintenance are required.
3. Salt Concentration Polarization: In PRO systems, salt concentration polarization can occur. In this condition, a buildup of salt close to the membrane surface lessens the osmotic driving force and affects the overall efficiency of power

generation. Concentration polarization reduction techniques are still being investigated and developed.

4. Environmental Effects of Draw Solution Discharge: Following the power production procedure, the draw solution—typically a highly concentrated saltwater solution—used in PRO must be discarded. The receiving water bodies may have environmental effects from the discharge of the concentrated solution, especially if it is not properly handled or treated.
5. Cost and Technological Maturity: Commercialization and development of PRO technology are still in their early phases. Because of this, PRO systems may be more expensive than traditional energy producing techniques. To make PRO more competitive commercially, additional technological developments and scale-based cost savings are required.
6. Limited Suitable Water Sources: PRO needs access to both a high salinity draw solution and a freshwater source. In some regions, it can be difficult to locate adequate water sources with the required salinity gradient, which restricts the widespread usage of PRO.

Regulatory and Environmental Challenges: There may be regulatory barriers and environmental considerations when implementing PRO systems. To ensure the sustainable and responsible use of PRO technology, concerns including water rights, potential effects on aquatic environments, and integration with existing infrastructure must be properly considered.

Recent advancements in Pressure Retarded Osmosis (PRO) have led to several pilot-scale and hybrid system applications that showcase the technology's promise in sustainable energy generation and water treatment. A notable example is the development of a 240 m^3/day SWRO–PRO hybrid plant in South Korea, which combines Seawater Reverse Osmosis (SWRO) with PRO to reduce energy consumption and environmental impact. Over a two-year operational period, this system demonstrated a 20% energy reduction in the SWRO process and a 63% dilution of the high-salinity brine (Achilli & Childress, 2010; Kim & Elimelech, 2013; Yip & Elimelech, 2013). Such integration not only supports energy recovery but also contributes to environmental protection by lowering brine discharge salinity. Additionally, PRO has been explored in wastewater treatment by pairing with reclamation processes, offering dual benefits of energy recovery and enhanced water purification (Kim & Elimelech, 2013). However, operational challenges such as membrane fouling, particularly in the porous support layer, necessitate advanced pretreatment strategies to maintain system performance and extend membrane life.

High-pressure PRO applications have gained attention for their potential to significantly boost power output when using seawater and hypersaline solutions (Achilli & Childress, 2010; Chou et al., 2012; Yip & Elimelech, 2013). Theoretical studies suggest that specific energy production can be increased up to tenfold compared to conventional systems, provided key design criteria, such as maintaining a membrane structural parameter below 100 µm, are met. However, these benefits are tempered by increased internal concentration polarization at elevated pressures, which can reduce flux and limit practical power densities. Despite promising results, PRO's commercial viability remains constrained by technical limitations, such as membrane durability, scaling, and the discrepancy between lab-scale and pilot-scale performances. Continued research and innovation in membrane development, operational strategies, and hybrid system design are essential to addressing these challenges and fully realizing PRO's potential in real-world applications.

Implementing PRO technology offers environmental benefits, such as reduced brine discharge salinity and lower greenhouse gas emissions. Economically, PRO can decrease operational costs by recovering energy from salinity gradients. However, commercialization faces challenges, including discrepancies between lab-scale and pilot-scale power densities, membrane durability, and system scalability. Addressing these challenges through technological advancements and optimized system designs is crucial for the broader adoption of PRO technology. For instance, techno-economic analyses of PRO plants utilizing hypersaline sources, such as the Dead Sea–Red Sea conveyor, have demonstrated the potential for significant energy generation with competitive levelized costs of electricity, highlighting the feasibility of integrating PRO into large-scale water conveyance projects.

The future of PRO technology lies in continued interdisciplinary research and development efforts aimed at overcoming existing limitations and enhancing system performance. Areas of focus include the development of advanced membrane materials with improved selectivity and antifouling properties, optimization of system configurations to minimize concentration polarization effects, and integration with renewable energy sources to further reduce environmental impacts. Additionally, comprehensive techno-economic assessments are essential to evaluate the viability of PRO systems in various contexts, guiding investment decisions and policy development. Collaborative initiatives between academia, industry, and government agencies will play a pivotal role in advancing PRO technology from pilot-scale demonstrations to widespread commercial applications.

CONCLUSION

The study of Pressure Retarded Osmosis (PRO) as a salinity gradient energy technology reveals its strong potential as a sustainable solution to future energy and water challenges. With a theoretical foundation rooted in osmotic pressure and thermodynamic limits, PRO offers a unique opportunity to convert the chemical potential between freshwater and saline sources into usable energy. Pilot-scale applications, such as the SWRO–PRO hybrid systems in South Korea, and feasibility studies involving hypersaline sources, demonstrate tangible progress toward commercial viability. However, challenges such as membrane fouling, concentration polarization, and membrane structural limitations must be addressed to enhance system efficiency and scalability. Technological innovations in membrane materials, system configuration, and hybrid integrations with desalination or wastewater treatment plants are proving essential to overcoming these hurdles. Environmental and economic evaluations also underscore PRO's role in reducing carbon emissions, lowering brine discharge salinity, and enhancing the cost-effectiveness of water-energy nexus systems.

In conclusion, while PRO is still transitioning from experimental and pilot stages to full-scale deployment, the synergy between engineering innovation, environmental need, and policy support positions this technology as a critical component in the global renewable energy landscape. Continued interdisciplinary research and investment are crucial to unlocking its full potential.

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