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Energetic and Economic Viability of Full-Scale Pressure Retarded Osmosis for Blue Power Generation in the Philippines

Maria Theresa Isla-Cabaraban[1,3,a*], Ivan Vergel Iligan[1,b], Romelie Albia[1,c], Czarine Maderal[1,d], Jenny Navarro[1,e] and Gunnar Marc Shane Cabaraban[2,f]

[1]Department of Chemical Engineering, Xavier University – Ateneo de Cagayan, Cagayan de Oro City, Philippines

[2]Department of Electrical Engineering, Xavier University – Ateneo de Cagayan, Cagayan de Oro City, Philippines

[3]Department of Science and Technology (DOST), Philippine Council for Industry, Energy and Emerging Technology Research and Development (PCIEERD), Gen. Santos Avenue, Bicutan, Taguig City

[a*]matheresa.cabaraban@pcieerd.dost.gov.ph, [b]vergeliligan@gmail.com, [c]romalbia@gmail.com, [d]czarine.maderal@gmail.com, [e]20150007935@my.xu.edu.ph, [f]gcabaraban@xu.edu.ph

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Abstract. Salinity gradient power (SGP), also known as blue energy, represents a promising renewable energy (RE) source that can diversify global RE portfolios and address energy security challenges. The Philippines, with its extensive network of estuaries where river outflows meet the sea, offers a strategic opportunity for deploying SGP technologies like the pressure retarded osmosis (PRO). PRO utilizes the osmotic energy produced when freshwater diffuses through a semi-permeable membrane into seawater, generating pressurized flow that can drive turbines for electricity generation. This paper explores the energetic and economic feasibility of stand-alone PRO-based power generation in the Philippines, highlighting its potential to support the country's transition to RE. The work employed a process simulation that integrates unit operation models with mass and energy streams. Key economic indicators were evaluated, including net present value (NPV) for total project feasibility, internal rate of return (IRR) for the annualized return rate, and discounted payback period (DPP) for the time needed to recover investments. The levelized cost of PRO energy (LCOE), reflecting the lifetime cost per kWh produced, was compared against benchmarks from other RE sources. Results indicate the viability of PRO, demonstrating a positive NPV at a 10% discount rate, with a 7-year DPP and an IRR of 12.16%. The study found that the LCOE value of \$0.17 per kWh, using cellulose triacetate membranes with approximately 90% efficiency, is cost-competitive with other RE sources. However, advancements in membrane properties, particularly durability and water permeability, are essential to improving both cost-effectiveness and scalability of PRO power plants. This investigation emphasizes the potential of blue energy as a RE source uniquely suited to archipelagic countries like the Philippines. By prioritizing innovation in membrane technology, PRO can transition from an emerging technology to a cornerstone of sustainable energy strategies, aligning with global carbonization efforts.

Introduction

The Department of Energy's Philippine Energy Plan for 2023-2050 projects that the Philippines' annual peak power demand will increase from 12,113 MW in 2022 to 48,014 MW by 2050 [1]. To meet this rising demand, the Philippine government aims to boost its total installed power capacity from 453.8 TWh in 2020 to 111.5 TWh in 2050. The new capacities for power generation under this scheme will result in a composition that will consist of 14.05% coal, 34.98% natural gas, and 50.73% renewable energy (RE) by 2050.

Coal-fired power plants dominated the mix at 59.57% in 2022. This dependence on coal for energy is correlated with harmful emissions that have resulted in a global climate crisis [2]. The fight against climate change and its disastrous impacts made necessary shifting toward clean energy sources. A transition to an energy infrastructure that is based on renewable technologies should have considerable positive effects on the economy at the national and international levels.

The International Renewable Energy Agency (IRENA) underscores the need to achieve a 90% RE share in the world's electricity production by 2030 to realize the goals of the Paris Agreement [3]. This approach is crucial in reducing emissions and keeping the global average temperature rise to 1.5°C by the end of this century. The RE sector in the Philippines includes hydropower, geothermal, solar, biomass, and wind resources [1]. However, significant issues remain: solar and wind are often constrained by their inherent intermittence, which depends on solar radiation and wind speed. Therefore, the development of effective energy storage solutions is crucial, although most of the current systems suffer from the issues of high costs [4] as well as the possible contributions towards overall greenhouse gas (GHG) emissions [5].

Here, salinity gradient energy (SGE), also called blue energy, has the potential to be an alternative green energy source. Blue power can substantially impact the global energy balance in the future. Research suggests that the total volume of all rivers pouring into the sea has the potential to generate blue energy between 1.4 and 2.6 TW that can sufficiently meet the power requirements of over 80% of the global population [6]. For the Philippines, this technology presents and opportunity to enhance energy security, reduce reliance on imported fossil fuels (accounting to 63% of the energy mix in 2022 [1]), and deliver reliable power to coastal communities.

In addition to its technical potential, the potential of blue energy, particularly through the implementation of SGE, offers considerable environmental benefits. Unlike coal-fired plants, SGE systems generate net-zero carbon emissions, significantly mitigating the contributions to climate change. Furthermore, SGE operates continuously, unaffected by weather variability, making it a reliable complement to the intermittent nature of solar and wind sources. Notably, research conducted by Mashrafi et al [7]demonstrates that PRO results in the lowest net GHG emissions among RE technologies, as it does not require an energy storage system or the extensive use of rare earth elements, a requirement often associated with other RE technologies such as solar PV and wind. This distinctive advantage highlights the promising role of SGE in the transition towards sustainable energy solutions.

SGE is derived from the osmotic pressure difference from varying ionic concentrations typically between freshwater and seawater. Two main SGE technology types, reverse electrodialysis (RED) and pressure-retarded osmosis (PRO), utilize semi-permeable membranes to harness the osmotic potential and generate electricity through a hydraulic turbine [8–13]. RED generates electricity from the controlled mixing of two water bodies with different salinities. The typical RED configuration involves the arrangement of cation and anion exchange membranes assembled in stacks between a pair of electrodes to form high- and low-salinity compartments [14]. The salinity difference between the saltwater and freshwater passing through these membranes results in the transport of positively and negatively charged ions, creating a net charge transport that can be efficiently converted into electrical energy through redox reactions [9].

Similarly, PRO technologies generate energy from the difference in salt concentration between saltwater and freshwater. In PRO, a semi-permeable membrane separates the draw (saltwater) and feed (freshwater) solutions, allowing the osmotically driven permeation of the feed to the draw chamber. The pressure surge on the seawater side drives the hydraulic turbine to generate electricity [9]. PRO is being explored as a promising technology to enable blue power [7,15], and is the subject of investigation in this work.

Several studies have focused on assessing the economics of PRO technology using different approaches and measurement standards. In a study by Mashrafi et al [12], a life cycle cost analysis (LCCA) was used to evaluate the economic feasibility of the PRO system. This system sourced brine from a seawater desalination plant and assessed two scenarios for transferring treated wastewater from nearby plants as feed solutions. The LCCA findings revealed a relatively high levelized cost of energy (LCOE) for the PRO system, ranging from \$ 0.62/kWh to \$ 0.69/kWh. This cost is not competitive compared to mainstream RE sources like wind ($ 0.23/kWh) and solar ($ 0.13/kWh). The study identified transmission and pretreatment costs as significant contributors to the high LCOE.

Al-Musawi et al. [16] used the LCOE to assess the economic viability of PRO technology across different hyper-saline (defined as having >30 g/L NaCl) draw solution concentrations and varying flow rates. The results showed that, like other RE sources, the LCOE for PRO ranged from $0.0563/kWh to $0.0721/kWh, implying that osmotic energy has the potential to be harnessed. The lower limit of the LCOE was achieved when the draw solution concentration was 44.1 g/L.

The work of Khasawneh et al [17] integrated three PRO power plants using different combinations of feed and draw solutions. While all plants were found to be technically viable for power generation, only the PRO plant running at a high osmotic pressure difference was deemed economically feasible with an LCOE of $ 0.056/kWh. This configuration maximizes power density and minimizes the required membrane area. As per their conclusions, the project’s financial viability depended heavily on the prices of membranes and energy recovery devices. Though the study was carried out on high salinity differences, it provided important insights into how optimizing system components and membrane performance improves the economic feasibility of PRO systems. These findings may also hold for moderate salinity gradients.

These findings were reinforced by Matsuyama et al [18], who examined the performance of a commercial hollow fiber PRO membrane module using seawater as the draw solution and treated sewage as the feed solution. They reported an estimated cost of power generation of $ 0.20/kWh when operating with 1×10^6 m^3 of seawater per day. Improving membrane water permeability and salt permeability could achieve this level of operation.

The study of Obode et al [19] evaluated the performance of both single- and multi-stage PRO systems, using LCOE as the primary economic indicator. Findings indicate that while high salinity water for draw solution is promising for electricity generation, its economic viability is heavily contingent on membrane properties and system configuration. At the current membrane properties, the LCOE for PRO stands at $ 0.352/kWh, rendering it non-competitive compared to other RE sources. However, assuming ideal membrane properties, the LCOE dropped to $ 0.0704/kWh, demonstrating significant cost-reduction potential by improving membrane technology.

Given the Philippines' extensive coastlines, numerous estuaries, and river networks, SGE has a large potential as a RE source. To the authors’ knowledge, there has been no assessment of the potential of this blue energy source in the country. This paper presents the first exploration of the potential of SGE as a source of blue power for the Philippines and its contribution to the country’s energy mix. It evaluates the energetic and economic viability of implementing a full-scale 1 MW PRO power plant, considering in the analysis Cagayan de Oro River as a freshwater source and Macajalar Bay as a saltwater source (Fig. 1).

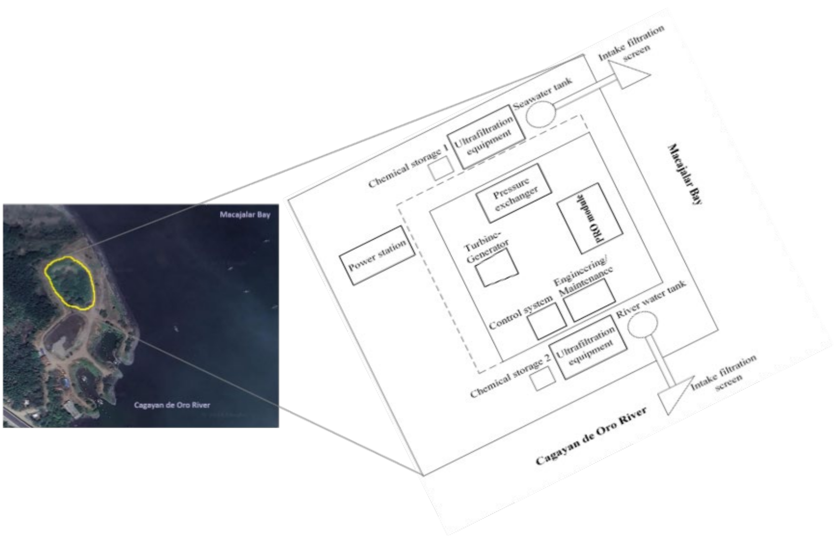


Fig. 1. Location and conceptual layout of the PRO power plant in Cagayan de Oro City, Philippines.

Materials and Methods

This section presents details of the PRO power plant conceptual model, the procedure used to determine energy requirements, and the assumptions applied to carry out the assessment of economic feasibility. A flow diagram illustrating the methodology is presented in Fig. 2.

The proposed PRO power plant consisted of a pretreatment system, the PRO system, pumps and circulation system, and the hydraulic pressure converter system. The diagram showing the various processes of the PRO power plant which is the subject of the present study is given in Fig. 3.

The PRO facility commences its operation by sourcing seawater and river water, which undergo filtration treatments before entering the PRO system. To maintain equipment integrity and prolong membrane life, it is crucial for streams to contain minimal solids. Ultrafiltration efficiently removes particles and suspended solids from the feed water (river water) and draw solution (seawater) entering the PRO system, thus preventing membrane fouling caused by these contaminants [20–22]. This results in more stable and efficient operation, ultimately reducing maintenance costs.

A booster pump is utilized to propel seawater toward the membrane. To minimize the pumping energy needed by the booster pump, the incoming seawater stream first passes through the pressure exchanger [19,23], where it is pressurized by the brackish solution discharged from the PRO module [18]. Water flows across the semi-permeable membrane in the PRO module due to the osmotic pressure difference, transforming the chemical potential from the salinity differences into hydraulic pressure. This pressure is harnessed to drive a turbine, which is connected to an electric generator that generates electricity from the turbine's mechanical energy. Through osmosis, 90% of river water permeates the membrane [24], increasing the seawater flow and creating a pressurized brackish solution. This solution is then split into two streams: 2/3 of the flow is used to drive the pressure exchanger, while the remaining 1/3 powers the Francis-type turbine to generate electricity [14]. The non-permeating portion of the intake feed water stream, known as the freshwater bleed, is recycled back into the process for reuse.

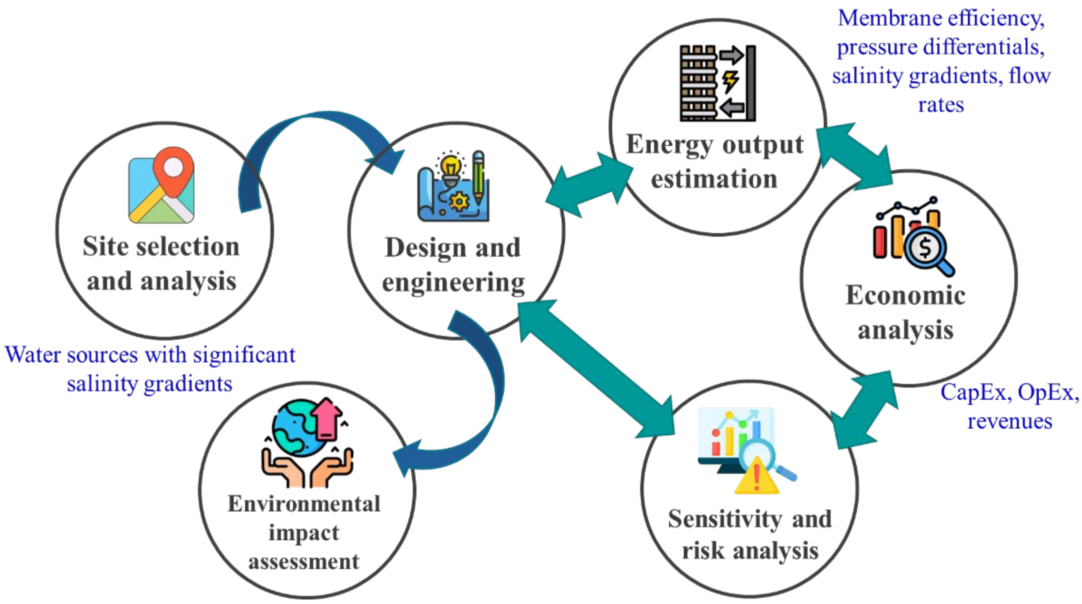


Fig. 2. Methodological framework for evaluating the salinity gradient energy.

The PRO System.

At the heart of the PRO is the osmotic-driven flow of water through the semi-permeable membrane from a low concentration feed water into a pressurized high-concentration draw solution. Throughout this process, water permeating through the membrane progressively dilutes the draw solution while concentrating the feed water. This process continues until an equilibrium in chemical potential is attained across the membrane.

The types of membranes used in PRO are essential for optimizing energy generation efficiency. For optimal performance, membranes should exhibit high water permeability, superior salt rejection to sustain the osmotic driving force, minimized structural parameters to reduce internal concentration polarization—which is a significant contributor to fouling—and sufficient mechanical strength to withstand the hydraulic pressures encountered during operation [25]. Over the past decade, multiple studies have highlighted significant advancements in the properties of novel PRO membranes [26], accompanied by performance validation. These investigations cover a range of membrane types, including hollow fiber membranes [27,28], innovative thin-film composite membranes designed to achieve high-power density [29,30], and high-strength hollow fibers enhanced with carbon quantum dots incorporated into the membrane matrix [31]. Additionally, zwitterionic modification of membrane surfaces has demonstrated remarkable hydrophilicity, which effectively reduces the adsorption of foulants [32]. The incorporation of nanomaterials into membranes has also led to enhanced resistance to membrane fouling and improved hydrophilicity, resulting in higher permeability [26,33].

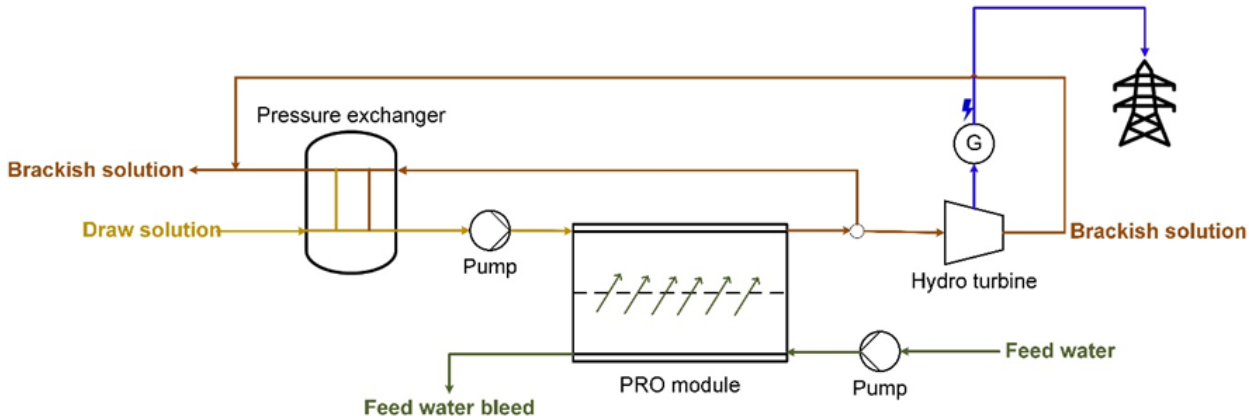


Fig. 3. Process flow diagram for the PRO power generation system in Cagayan de Oro City, Philippines.

The proposed PRO power plant described in this study will be located at the delta where the Cagayan de Oro River flows into Macajalar Bay. This location strategically utilizes the salinity gradient between the bay's saline waters and the river's outflow to maximize the osmotic pressure for PRO power generation. The salinity of the feed water and draw solution was expressed in terms of the total dissolved solids (TDS), with NaCl being the most abundant dissolved salt.

The van't Hoff equation serves as a critical tool in the analysis and optimization of PRO systems. This equation is based on the assumption of ideal solution behavior, which indicates that solute interactions are negligible. In the case of NaCl as the solute, this assumption holds true for mass fraction concentrations in both the feed water (0.00013) and the draw solution (0.02949) below 0.09 [34]. The osmotic pressure difference between the feed water (f) and draw solution (d) was determined via the van't Hoff equation is valid [17,24,35].

$$\Delta\Pi_{osm} = \frac{iR}{M_{NaCl}}\left(T_d S_{NaCl,d} - T_f S_{NaCl,f}\right), \quad (1)$$

where i is the ionic concentration per dissociated solute molecule (for NaCl i = 2), R is the universal gas constant, T is the temperature in K, M_{NaCl} is the molar mass of the solute, and S is the salinity in g/L. $\Delta\Pi_{osm}$ serves as the theoretical upper limit for the driving force facilitating the transport of water [36].

In the modeling of PRO systems, the $\Delta\Pi_{osm}$ is mitigated by the externally applied hydraulic pressure (ΔP). This interaction establishes a net driving force ($\Delta\Pi_{osm} - \Delta P$) that dictates the water flux across the membrane. The complete theoretical osmotic pressure difference cannot be achieved. To maximize the power density of the semi-permeable membrane, it is optimal to utilize half of the osmotic pressure difference [24,37].

$$\Delta P_h = \frac{1}{2}\Delta\Pi_{osm} \quad (2)$$

Water flux through the membrane, J_w [in m^3/m^2-s], was calculated using the following [17,18,38]:

$$J_w = A\,(\Delta\Pi_{osm} - \Delta P_h) \tag{3}$$

where A is the water permeability coefficient of the membrane. The volumetric discharge rate of the brackish water (Q_{br}) was calculated based on the assumed intake draw solution to feed water ratio (Q_d/Q_f) of 1.5 [24,39].

$$Q_{br} = J_w A_m + Q_d = 2.4Q_f \tag{4}$$

since $J_w A_m = 0.9\ Q_f$. A_m is the total membrane area, which was determined based on power plant capacity of 1 MW and power density of the cellulose triacetate membrane [24,40].

Pumps and Circulation System.

The mechanical energy balance described in Eq. 5 assumes steady-state operation and adiabatic conditions for the pump. It also assumes negligible changes in the fluid's potential energy and turbulent flow.

$$\frac{1}{2}\left(v_{out}^2 - v_{in}^2\right) + \frac{1}{\rho}\left(P_{out} - P_{in}\right) + \sum F + W_{s,p} = 0 \tag{5}$$

The total energy loss due to friction accounts for losses in turbulent flow through equivalent lengths of pipes with relative roughness (F_f), and through bends and fittings (F_b).

$$F_f = 4f\,\frac{\Delta L}{D}\frac{v^2}{2} \tag{6}$$

where f is the friction factor, ΔL is the length of pipe, v is the fluid velocity, and D is the pipe diameter.

$$F_b = k\frac{v^2}{2} \tag{7}$$

where k is a fitting-specific coefficient.
The effective pump work, which factors in an overall pump efficiency (η) of 70-75% was calculated as:

$$W_{actual,p} = \frac{W_s}{\eta_p}. \tag{8}$$

Hydraulic Pressure Conversion System.

The pressure exchanger is a crucial energy-recovery device in the PRO system, functioning similarly to a fluid piston. It enhances efficiency by transferring energy from the pressurized draw solution to the incoming feed water through continuously rotating ducts, all while preventing mixing. This recycling of hydraulic energy minimizes the external energy required to pressurize the feed solution, thus improving the net power output of the PRO system.

Recent studies highlight the importance of pressure exchangers in hybrid PRO configurations, particularly when integrated with reverse osmosis (RO) or desalination plants. In these setups, energy from saline brine can be harnessed to reduce operational costs [28,41]. For instance, Kim et al. [28] revealed that the incorporation of isobaric pressure exchangers in PRO-RO systems can lead to energy savings of approximately 42%, significantly boosting economic feasibility. Nevertheless, optimizing the pressure exchanger efficiency relies heavily on accurate flow rate matching and the minimization of irreversible losses [28,42,43], especially in systems with fluctuating salinity gradients.

Initially, the pressure exchanger is supplied with low-pressure draw water and a portion of brackish water from the PRO module. Subsequently, it transfers the high-pressure energy from the brackish water to the low-pressure energy of the draw water. Upon exiting the pressure exchanger, the high-pressure draw water is directed toward the membrane module.

The pressure of the draw water at the exit was determined by applying the overall mechanical energy balance as detailed in Equation 5, accounting for negligible changes in kinetic energy and energy losses arising from friction.

$$W_{s,j} = \frac{\dot{m}_j}{\rho_j}\left(P_{out,j} - P_{in,j}\right) \quad (9)$$

where j is a stream identifier, $\dot{m}_j$ is the mass flow rate of the stream, ρ_j is the stream density, and $P_{in,j}$ and $P_{out,j}$ are the pressures of the streams entering and exiting the pressure exchanger. The stream densities used in the calculations were 1,022.65 kg/m^3 and 1,012.94 kg/m^3 for draw water and brackish water, respectively. Considering a 98% efficiency for the pressure exchanger [44], the exiting draw water pressure was computed from Eq. 10.

$$\frac{\dot{m}_d}{\rho_d}\left(P_{out,d} - P_{in,d}\right) + \eta_{PX}\, W_{s,b} = 0 \quad (10)$$

where η_{PX} is the pressure exchanger efficiency.

Analogous to calculating effective pump work, effective hydraulic turbine work was determined using Eq. 11.

$$W_{actual,t} = \eta_t\, W_{s,t} \quad (11)$$

where η_t was assumed to be 90% [26].

Economic Analysis.

Determining economic viability requires undertaking a detailed examination of the project's expected cost structure and revenues to evaluate its economic sustainability over time. This analysis involved quantifying capital expenditures (CapEx), operating expenses (OpEx), and revenue forecasts as well as performing sensitivity analysis on these elements to assess possible risks and uncertainties. The aim is to ensure that the investment provides an adequate return relative to the financial commitments across the lifespan of the investment. Key financial indicators, including net present value (NPV), internal rate of return (IRR), discounted payback period (DPP), and levelized cost of energy (LCOE), offer a comprehensive assessment of the project's profitability and competitiveness in the energy market.

Preliminary cost estimation techniques were employed to approximate the initial costs of the proposed PRO power plant. CapEx estimates were derived from a combination of vendor quotations and established costing models [45,46], yielding a baseline calculation for essential components such as pre-treatment systems, piping, membrane modules, pressure exchangers, and turbines.

The power law was employed to extrapolate the costs of equipment with a known capacity based on the costs associated with a comparable piece of equipment of different capacities, as illustrated by Eq. 12 [46].

$$\frac{\text{Cost of equipment A}}{\text{Cost of equipment B}} = \left(\frac{\text{Capacity of equipment A}}{\text{Capacity of equipment B}}\right)^{0.6} \quad (12)$$

Similarly, historical costs that may have fluctuated due to shifts in economic conditions were adjusted using appropriate cost indices, as shown in Equation 13.

$$\frac{\text{Present cost}}{\text{Original cost}} = \left(\frac{\text{Index value at present}}{\text{Index value at time original cost was obtained}}\right) \quad (13)$$

C_M, which stands for the membrane module's overall cost, was calculated by multiplying the module's unit cost [47] with the number of modules required to produce the planned power output.

OpEx was determined by combining expenses for membrane replacement, labor, maintenance, and repair. In this work, it was assumed that the membranes would last (L_M) 5 years [19,48,49], and the power plant using PRO would have a lifespan (N) of 15 years [16,19]. The annual operating cost for membrane replacement ($C_{op,mr}$) was estimated as [17,19].

$$C_{op,mr} = \frac{C_M}{N}\left(\frac{N}{L_M} - 1\right). \quad (14)$$

Annual costs of equipment maintenance and repairs was set at 2% of the fixed capital investment [17].

The DPP accounts for the time value of money, thus providing a more precise assessment of investment viability than the conventional payback period. NPV was calculated by discounting the expected future cash flows to their present value at a discount rate (r) of 10%, as shown in Eq. 15.

$$NPV = \sum \frac{C_t}{(1+r)^t} - C_0 \quad (15)$$

where C_t is the net cash flow during period t. The IRR was estimated by finding the r that makes the net NPV of all cash flows from the investment equal to zero. It represents the project's expected annual return, useful for assessing whether the investment meets the required r of 10%. The LCOE represents the minimum cost of energy required to achieve break even over the operation lifespan of the PRO system [50]. This metric was calculated from Eq. 16.

$$LCOE = \frac{NPV}{W_{actual,t}} \quad (16)$$

where the total energy production of the system ($W_{actual,t}$) is 1 MW. System up-time was set at 7,896 hours.

A sensitivity analysis was conducted to determine how fluctuations in key parameters affect the system's performance and economic feasibility. This analysis ensures the factors that have the greatest impact on the results are determined.

Results and Discussion

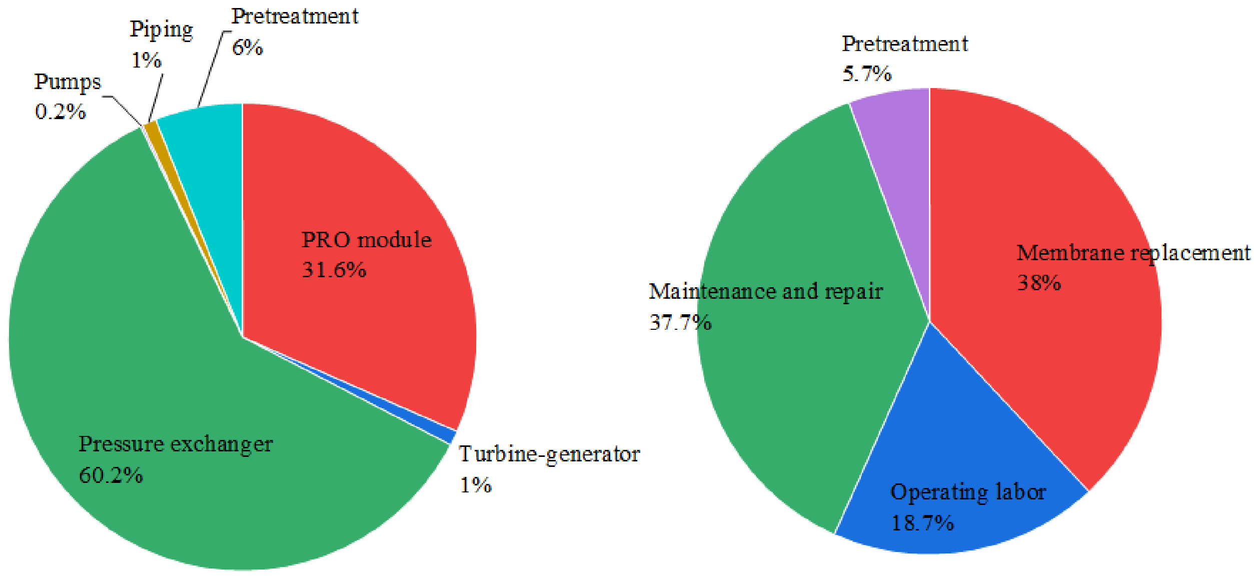
Table 1 presents the computed power output from the PRO system utilizing feedwater sourced from the Cagayan de Oro River and draw solution derived from Macajalar Bay. The plant achieved an annual net energy generation of 7.322 GWh. Based on this output, the facility's energy efficiency was determined to be 93%. The substantial net output points to the PRO system's viability as a RE source, demonstrating its capacity to generate considerable electricity with comparatively minimal operational energy input.

Table 1. Flow rates and net energy generation of PRO power plant in Cagayan de Oro City, Philippines.

$\Delta\Pi_{osm}$	bar	25.96
ΔP_h	bar	12.98
Q_f	10^6 m^3/d	0.07193
Q_d	10^6 m^3/d	0.1079
Q_{br}	10^6 m^3/d	0.1726
$W_{actual,t}$	GWh/y	7.896
$W_{actual,p}$	GWh/y	0.5740
Net energy	GWh/y	7.322

The analysis of the potential energy generation from the full-scale PRO system reveals promising results for blue energy production, indicating a strong potential for efficiency in harnessing osmotic energy. Nevertheless, the financial outlook is equally crucial to determining its overall feasibility. Fig. 4(a) presents the contribution of the various components to the CapEx of a PRO power plant. A substantial portion of the budget is directed toward the pressure exchanger (60%) and the PRO module (32%) [17], critical components that affect the overall efficiency of the osmotic energy conversion process.

Fig. 4(b) shows how the operational cost components are distributed in a PRO power plant. Membrane replacement, as well as maintenance and repair, dominate the OpEx, each accounting for 38% of the total cost. This highlights the critical role that membrane performance and durability play [17,19], as well as the need for routine maintenance, in driving OpEx. The high cost of membrane replacement indicates that the membrane deteriorates over time from exposure to draw solutions or contaminated feed water. Maintenance and repair expenses refer to routine servicing that the system carries out to ensure that it works in a reliable manner. A focus on future optimization initiatives must be placed on improving the durability of membranes and developing better maintenance methods to address the low efficiency and high operational costs resulting from the wear and tear of such elements.



(a) (b)

Fig. 4. Breakdown of (a) capital and (b) operating costs for a PRO power plant.

A projected NPV of $265,452 shows that the power plant using PRO technology will create significant value over its lifetime, more than covering the present-day equivalent of the initial investment. This suggests that the investment is financially viable and warrants further pursuit.

The IRR of 12.16% exceeds the typical discount rate of 10%, implying that the project could deliver returns higher than comparable investments with similar risk profiles. Investors will have an interesting project in this case, since it has the potential for a fair return rate.

The 7.03-year DPP is justified, owing to the large capital outlay and the long operational lifetime of the project. However, competition from other RE initiatives that offer better payback periods must be considered as well. For instance, solar photovoltaic (PV) systems exhibit DPPs ranging from 1 to 5 years [51–53], which provides a more rapid return on investment and may render the 7-year DPP less appealing to potential investors. Despite the 7-year DPP, a higher IRR than the cost of capital, coupled with a positive NPV, indicates that the investment remains viable.

The energy industry in the Philippines relies heavily on coal and oil imports [1], especially in the production of thermal power. This makes the economy vulnerable to the changes in the global pricing of fossil fuels that tend to be affected by political conflicts, supply chain interruptions, and demand changes. These weaknesses have a detrimental impact on electric power pricing, something that could be complicated even further by fluctuating exchange rates. The PRO power plant is clearly well-positioned in this energy market with an LCOE of $0.17/kWh. This dependence on imports poses a critical risk to the stability and predictability of the country's energy market. In the current energy market context, an LCOE of $0.17/kWh positions the PRO power plant as highly competitive. The rising cost of conventional energy sources, driven by fluctuating fuel prices, has made alternative energy sources that are cheaper or comparable in cost to conventional options more desirable to investors.

Sensitivity Analysis.

A sensitivity analysis was carried out to gain a clearer understanding of how changes in key assumptions might affect the overall profitability of the plant. The project's ability to withstand market changes was assessed by looking into these potential fluctuations, and the main risk factors that can affect its financial results were determined.

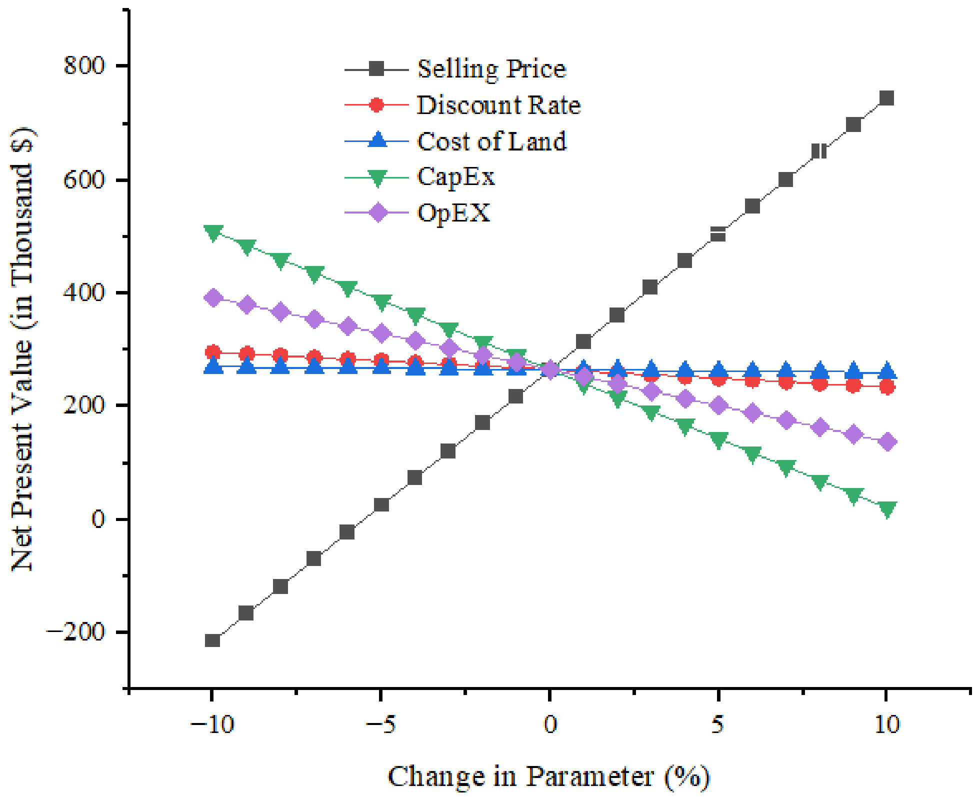


Fig. 5. Influence of parameter variations on the net present value of the PRO power plant.

Fig. 5 shows the sensitivity of the NPV for the PRO power plant project to variations in key cost parameters, namely CapEx, OpEx, selling price, land cost, and discount rate. Each parameter was altered by ±10%, and the effects on NPV are presented.

The electricity selling price serves as the primary factor influencing the NPV of the project. It exhibits the strongest direct correlation with NPV; for example, a ±10% change in the selling price can result in substantial fluctuations in NPV, as demonstrated in Table 2. However, this relationship comes with significant risks. The revenue generated from the sales of electricity exposes the project's financial performance to market price volatility. Such volatility is driven by various factors, including competition and shifts in energy demand, representing a considerable challenge. Additionally, when electricity prices decline to around $0.267 per kWh, especially in conjunction with high discount rates exceeding 10%, it often results in a negative NPV, as further emphasized in Table 2.

Securing strategic electricity pricing through long-term contracts or favorable market conditions may improve the project's profitability. Implementing sound revenue optimization strategies, for example, standardizing power purchase agreements (PPAs) or establishing carbon-pricing mechanisms is crucial because of the significant impact of electricity selling price on the NPV. Other determinants such as variation in energy demand, changes in legislation or competition from other RE sources have an impact on the economic performance of the PRO power plant as well. Thus, it will be imperative to manage price risks and to guarantee stable proceeds from electricity sales to enhance the viability and profitability of the project in the long term.

CapEx represents a crucial initial investment necessary for the success of a project. It has been noted that there exists a moderate negative correlation with CapEx and the NPV. An increase in CapEx necessitates greater or more sustained cash flow, along with a larger initial capital outlay. Conversely, a decrease in the CapEx lowers the breakeven point, enabling the project to quickly generate positive returns. However, there are significant risks associated with this expenditure. Given that NPV is sensitive to CapEx, mismanagement during the early stages of the project implementation can erode profit margins and delay the project's DPP, thereby reducing its appeal to investors. Implementing an efficient project design coupled with the optimum procurement strategies and adequate risk management is imperative in achieving project profitability.

While OpEx may not have the same pronounced effect on the power plant's NPV, the continuous operating costs incurred over the lifespan of the power plant, such as membrane replacement, labor, maintenance, and repair, are critical considerations in long-term financial planning. OpEx is particularly relevant given the demands of technology. The power plant based on PRO technology relies on the continuous functionality of the membranes to efficiently convert osmotic pressure into useful energy. However, issues such as fouling and scaling reduce overall energy output [22,54–56] and simultaneously increase operational costs, affecting profitability. To mitigate the adverse effects of fouling, equipment needs to be routinely serviced, and membranes replaced regularly. These recurrent and periodic maintenance activities contribute to OpEx [7,57,58]. Furthermore, unplanned maintenance can result in downtime, complicating operational efficiency and overall performance. The sensitivity of NPV to OpEx highlights the need to optimize operational efficiency and reduce downtime throughout the plant's lifespan. Several strategies can be employed such as optimizing advanced membrane technologies and implementing predictive maintenance to be able to reduce costs and improve the performance metrics.

When considering land costs, it is important to recognize that while they may appear marginal, they possess significant strategic value. Compared to other financial variables like CapEx, OpEx, and the pricing of electricity sales, land acquisition costs have a relatively minor impact on the project's overall profitability. Land use for PRO power plants tends to be significantly lower than conventional RE installations, such as solar PV or wind energy systems [7], which require extensive land areas to accommodate large arrays of solar panels or turbine farms [59–62]. While the effect of land costs on the project's NPV is marginal, it is nevertheless a critical consideration in the site selection for the PRO facility. The volatility in land prices in coastal areas is influenced by factors such as proximity to water for productive uses and stringent regulatory environment. The project's overall viability could be affected where land prices are high or where regulations increase land purchase costs. The PRO system's use of the osmotic pressure gradient between river water and seawater for energy production makes it suitable for integration into existing coastal or industrial infrastructure. Extensive land acquisition is thus circumvented, which reduces the vulnerability to land pricing fluctuations on the project's overall economic viability. Consequently, even though land acquisition is not a primary driver of NPV fluctuations, strategic site selection and cost-efficient land procurement approaches are important for enhancing project financial performance.

In contrast to CapEx and OpEx, which experience a pronounced decrease in NPV as their values increase, the effect of changes in the discount rate on NPV is relatively minimal within the -10% to +10% range. However, this impact becomes critical at higher rates. For example, at a 10% discount rate, the cost of electricity at \$0.267 per kWh results in a negative NPV of -\$21.57 million. Moreover, when discount rates exceed 12%, it becomes necessary to raise electricity prices to maintain the project's viability.

Several key risks are associated with this scenario. A primary concern is the potential for escalating financing costs, which can arise from macroeconomic changes such as inflation and interest rate increases. Additionally, the long lifespans of these projects can intensify the effects of discounting on future cash flows, highlighting the importance of careful consideration of these factors in financial planning. The findings suggest that the performance of a power plant utilizing PRO technology is not highly sensitive to short-term variations in market interest rates, provided those changes remain within a reasonable range. Nonetheless, it is important to recognize that, although the discount rate may appear to have limited impact within the narrow range tested, its influence on NPV becomes more significant when considering larger deviations, as evidenced in Table 2.

At a selling price of \$0.27/kWh, the NPV remains positive at lower discount rates, but experiences a swift decline as the discount rate increases. This implies that for projects seeking returns below this price level, variations in the discount rate have strong, if not compelling, implications on the NPV of the project. Such sensitivity indicates that even with high discount rates, the project's financial prospects are still at risk. It suggests that lower electricity prices do not allow the project's cash flows to cover the more expensive cost of capital. Consequently, the financial viability of the project is critically tied to sustaining lower discount rates.

Table 2. Sensitivity of NPV [million $] to discount rate and electricity selling price for a PRO power plant in Cagayan de Oro City, Philippines.

	Electricity selling price [$ per kWh]		
Discount rate (r)	$0.267	$0.270	$0.284
6%	86.15	139.09	385.94
8%	32.29	84.10	325.69
10%	(21.57)	29.11	265.45
12%	(75.44)	(25.88)	205.21
14%	(129.30)	(80.87)	144.97

An increase in the discount rate, driven by macroeconomic shifts or rising financing costs, results in a proportional decrease in NPV at all levels of electricity prices. This aligns with established financial theory, which posits that a higher discount rate – which represents the opportunity cost of capital – diminishes the present value of projected future cash flow, particularly for long-term projects like PRO power plants, where cash inflows are realized over an extended period. For all the electricity selling prices analyzed, the project's NPV stays positive even at 6% and 8% discount rates indicating that the project is financially viable. Given the long operational lifespan of PRO power plants and the fact that their primary revenue streams come from steady, long-term energy production, securing low financing costs and minimizing risk premiums are crucial for maintaining project viability.

However, as the discount rate increases to 12% and 14%, NPVs become negative at lower electricity prices. The project's viability, therefore, relies on sufficiently high electricity pricing that offsets the adverse effects caused by an increase in the discount rate. The project would then need financial optimization or modifications in operational parameters to ensure profitability.

To address the 7-year payback period and enhance the financial viability of the PRO power plant project in Cagayan de Oro City, several strategic recommendations are proposed. First, securing long-term power purchase agreements (PPAs) with local off-takers, such as the Cagayan Electric Power and Light Co. (CEPALCO), industrial consumers, or wastewater treatment facilities is essential. Such agreements will help stabilize revenue streams, thereby mitigating the project's exposure to fluctuations in the spot market. By negotiating government-backed PPAs at or above $0.27 per kWh, project developers can establish predictable cash flow, which, in turn, will improve the project's NPV and lower the overall cost of capital.

Second, the project's economic outlook may be substantially improved through the utilization of incentives offered under the Philippines' Renewable Energy Act of 2008 (Republic Act No. 9513). Eligible PRO plants may qualify for feed-in tariffs (FITs), which guarantee above-market rates for clean electricity. Additional incentives include the provision of corporate income tax holidays and value-added tax exemptions on imported membranes and RE equipment. Moreover, the duty-free importation of advanced membrane modules can significantly reduce CapEx. Furthermore, funding opportunities provided by the Philippines' Department of Science and Technology (DOST) and the Department of Energy (DOE) could play a crucial role in offsetting research and development costs during the demonstration phase. Such financial support not only diminishes associated financial risks but also facilitates the acceleration of technology maturation processes.

Advocacy for PRO-specific subsidies under RA 9513 should prioritize facilities that utilize non-freshwater feed streams, such as municipal brine effluent and industrial wastewater, to align with national water-energy nexus objectives. To further enhance returns and promote long-term sustainability, project developers should be encouraged to invest in infrastructure that effectively reduces non-revenue water (NRW), including advanced leak detection and recovery systems. These initiatives will not only improve operational efficiency but also bolster the case for sustained policy support and private investment in PRO, recognizing it as a strategic complement to the Philippines' RE portfolio.

A third avenue for enhancing financial viability lies in the exploration of carbon finance mechanisms, such as the Clean Development Mechanism (CDM) under the United Nations Framework Convention on Climate Change (UNFCCC) or emerging domestic carbon-trading platforms. These mechanisms may provide an additional revenue stream by monetizing reductions in GHG emissions.

Operations can also be optimized, and costs reduced through targeted strategic initiatives addressing CapEx and OpEx. On the CapEx side, it is advisable for the City Government and project partners to negotiate bulk purchasing or leasing arrangements with membrane suppliers, particularly those engaged in the Mindanao desalination sector, thereby securing more favorable pricing terms. The implementation of a modular PRO plant design would facilitate phased execution aligned with municipal demand projections, allowing for the amortization of CapEx across multiple budget cycles. Additionally, situating the PRO facility in proximity to the Macajalar Bay desalination and wastewater treatment complexes could effectively lower land acquisition costs while enabling the utilization of intake, discharge, and utility infrastructure.

In terms of OpEx, investing in advanced, fouling-resistant membranes may prolong service life and reduce the frequency of replacements. The integration of Internet of Things (IoT)-enabled sensors within the membrane modules will allow for real-time monitoring of pressure differentials and salt passage rates, thus facilitating the development of predictive maintenance schedules intended to minimize unplanned downtime. Finally, establishing a training partnership with local technical schools and the Cagayan de Oro City Water District (COWD) would promote a specialized workforce, thereby reducing reliance on external contractors and enhancing in-house operational efficiency.

Potential Environmental Impacts of the PRO Project

Positive Impacts.

The project presents a promising pathway toward cleaner energy production by offering a low-carbon alternative to traditional fossil fuel-based power generation. It aligns with the Philippines' RE goals, aiming to diversify the energy mix, address the country's growing electricity demand, and reduce dependence on imported fossil fuels. By integrating a clean, locally sourced energy solution into the grid, the plant supports national objectives of reducing GHG emissions and promoting sustainable economic development. Utilizing the natural osmotic pressure difference between seawater drawn from Macajalar Bay and freshwater from the Cagayan de Oro River, PRO has the potential to significantly decrease GHG emissions, making it a compelling component in global efforts to combat climate change. While the current scale of PRO deployment is modest compared to solar and wind energy, its low operational carbon footprint positions it as a valuable contributor in a diversified RE portfolio.

In contrast to traditional thermal power plants, which release considerable amounts of air pollutants like sulfur dioxide, nitrogen oxides, and particulate matter [63,64], the PRO technology generates minimal emissions during operation. The lack of combustion processes alleviates concerns associated with smog formation, acid rain, and respiratory health risks for nearby communities. Consequently, PRO provides a cleaner and safer operational profile that is in line with increasingly stringent environmental regulations and the growing public demand for sustainable energy solutions.

Another advantage of the PRO technology is in its capacity to integrate seamlessly with existing water treatment infrastructure. When used in conjunction with desalination or wastewater treatment plants, PRO systems can effectively utilize process byproducts that often present management challenges, such as brine or brackish water. This synergy not only enhances resource efficiency but also lowers the operational costs associated with water treatment facilities. Additionally, employing PRO to recover energy from waste streams addresses two vital sustainability goals: improving energy efficiency while simultaneously minimizing the environmental impacts associated with waste disposal.

Negative Impacts.

Filtration processes for seawater and river water play a vital role in preventing membrane fouling in PRO systems. However, these processes inevitably generate waste streams, including removed suspended solids, which can smother benthic habitats, diminish light penetration, and adversely affect fish and invertebrate populations [65,66].

The mixing of water with the draw solution results in a brackish effluent that, if not managed properly, could severely impact estuarine ecosystems. Elevated salinity levels may disrupt the delicate equilibrium between freshwater and saltwater systems, posing a threat to aquatic biodiversity, particularly in sensitive regions such as the Cagayan de Oro River estuary. Species that are specifically adapted to particular salinity ranges might experience stress, suffer population declines, or even face local extinction [67,68]. Additionally, long-term alterations in ecosystems could lead to reduced fishery productivity, adversely affecting the livelihoods of communities that rely on estuarine resources.

The proposed plant's demand for freshwater resources may further strain an already stressed water system in Cagayan de Oro City, where non-revenue water levels have exceeded 50% due to leakage and illegal connections [69]. Increased competition for limited water supplies could exacerbate tensions between the facility and local communities, especially during periods of drought or low river flow.

Strategies to Mitigate Negative Impacts.

The potential ecological risks to estuarine ecosystems linked to the discharge of removed solids during the filtration processes of the proposed PRO plant necessitate stringent compliance with regulatory frameworks designed to minimize ecological harm and safeguard downstream users. This includes adherence to the Water Quality Guidelines and General Effluent Standards of 2016 [70]. Consequently, it is imperative that robust environmental regulations govern not only the permissible limits on discharges but also the practice for treating and disposing of residual solids.

The establishment of wetland buffers between discharge points and estuaries presents a natural and effective strategy for mitigating the environmental impacts associated with PRO technology. These vegetated buffers provide an element of passive remediation that requires minimal energy input compared to engineered systems, thereby aligning with the low-carbon principles characteristic of RE projects. Wetlands, which are often populated by resilient plant species such as mangroves and seagrasses, can significantly reduce the risk of salinity imbalances in sensitive estuarine ecosystems by sequestering excess salts and nutrients from discharged brine or wastewater.

Furthermore, the development of partnerships with local industries represents a strategic approach to the sustainable management of brine or brackish water. By repurposing these high-salinity streams for industrial applications, it is possible to substantially reduce the volume of environmentally detrimental discharges. For instance, coastal salt production facilities could effectively utilize concentrated brine, as exemplified in the Mega-ton Water System [71], converting what would otherwise be a waste byproduct into a valuable resource. Similarly, aquaculture facilities that focus on salt-tolerant species can incorporate brackish water into their operations, thereby enhancing resource efficiency. Collaborative efforts of this nature not only advance the goals of environmental sustainability but also yield reciprocal economic advantages, thereby promoting circular economy principles within the local community.

To alleviate river water demand, particularly in regions already experiencing water stress, such as Cagayan de Oro, a strategic approach would involve utilizing treated wastewater as a source of feed water. By capitalizing on wastewater streams from the various industries, particularly those located along the Macajalar Bay area, the PRO system can circumvent the additional extraction of freshwater resources. This approach not only reduces the ecological risks typically associated with diverting or altering estuarine salinity regimes, such as biodiversity loss, vegetation die-off, disruptions to nutrient cycling [72–74]but also brings economic advantages.

Comparative Analysis between PRO Technology and Traditional Renewables

Cost.

The LCOE of $0.17 per kWh points to the economic competitiveness of the PRO technology compared to other RE alternatives [16,75]. It is noteworthy that this potential niche of the PRO may be augmented through advancements in membrane technology [7,16], as well as the incorporation of the PRO into hybrid systems to reduce the overall costs associated with the process [76,77].

The LCOE for solar PV systems and offshore wind technologies have seen a significant decline over the last few years. This reduction can be attributed to technological advancements and economies of scale, which have improved efficiency and lowered costs overall. However, in some regions, the LCOE for solar PV and other renewables continues to be at or above $0.17 per kWh [78–80]. Such heterogeneity can be attributed significantly to locational issues such as the availability of renewables, economic and financial conditions and policy instruments. For instance, in regions with less optimal solar resources, higher land costs, or weaker grid infrastructure, solar PV can be priced closer to or even above the $0.17 per kWh threshold [81]. Offshore wind usually has a higher LCOE because of the substantial capital and operational costs involved in installing and maintaining turbines in marine settings. However, the LCOE for offshore wind can exhibit considerable variability, especially in regions where maritime logistical challenges, grid integration complexities, and permitting procedures entail increased costs [82,83].

Table 3. Levelized cost of energy (LCOE) comparison of renewable energy technologies, emphasizing the competitiveness of pressure-retarded osmosis (PRO), solar photovoltaic (PV), and offshore wind systems.

Technology	LCOE range ($ per kWh)	Key cost factors	Notes
PRO (blue energy)	0.17*	Membrane efficiency, hybrid system integration, R&D advancements	Competitive with renewables; costs may decrease further with membrane tech improvements [7,16,76,77].
Solar PV	0.026 – 0.422	Resource availability [84], land costs, grid infrastructure [85], regional policy incentives	Declining costs globally, but regionally variable (e.g. higher in areas with weak solar resources) [78–81].
Offshore wind	0.016 – 0.285	Marine installation/ maintenance, grid integration, logistics [86]	High capital/operational costs; location-dependent challenges inflate LCOE in some regions [82,83].

* this study

Scalability.

While the PRO technology presents an innovative approach to RE generation, it faces notable challenges. The semipermeable membrane is a crucial component in ensuring efficient energy production, and achieving commercial viability necessitates membranes that can sustain power densities above 6.5 W/m^2. The Statkraft project, a real-world pilot PRO plant, demonstrated that this threshold is indeed achievable; it successfully reached power densities of approximately 13.5 W/m^2 when integrated into the Mega-ton project, which primarily focused on seawater desalination [71,77]. Moreover, PRO is geographically limited to areas with salinity gradients, such as estuaries and desalination brine outfalls, which significantly restricts its broader applicability. While PRO currently serves as a small-scale solution, its modular design allows localized deployment near costal industries (e.g. desalination facilities) or wastewater treatment plants [76].

In contrast, solar and wind energy technologies have established themselves on a global scale, with solar power boasting an installed capacity of around 1,420 GW and wind energy at around 1,017 GW worldwide [87]. Their modular designs enable deployment across a wide variety of environments, i.e. from residential rooftops to expansive offshore farms, highlighting their versatility and scalability.

Environmental Impact.

PRO systems operate with minimal carbon emissions, thereby positioning them as a comparatively clean energy source. Nevertheless, ecological concerns remain, particularly regarding potential disruption to salinity regimes in estuarine ecosystems and competition for water resources. Importantly, the environmental footprint of PRO can be significantly mitigated through integration with desalination facilities or wastewater treatment processes, where high-salinity brine streams can be effectively repurposed, reducing the standalone environmental effects.

While solar and wind energy play crucial roles in global decarbonization efforts, they are not without their own environmental challenges. The production of solar panels necessitates extensive mining of silica-containing materials and metals such as cadmium, aluminium, copper, nickel, gallium, selenium, and tellurium, leading to substantial carbon footprints [88]. Furthermore, photovoltaic panels can become hazardous e-waste at their end-of-life phase, posing environmental and health risks [89]. Wind turbines also contribute to the mortality of birds and bats [90,91] and face recyclability challenges, especially concerning composite turbine blades [92]. Additionally, the installation of both solar and wind energy systems requires substantial land take, which amplifies their environmental footprint due to land-use competition and habitat disruption [93,94].

Conclusions and Recommendations

This study gives an assessment of the technical and economic feasibility of a full-scale PRO facility for SGP generation in the Philippines, utilizing the Cagayan de Oro River as the feedwater source and Macajalar Bay as the draw solution. The findings reveal that the PRO system achieves a remarkable energy efficiency of 93%, resulting in an annual net energy output of 7.322 GWh. Moreover, the estimated LCOE of $0.17/kWh ranks PRO technology at a competitive level with other RE sources, but only under certain circumstances.

The financial assessment indicates a positive NPV of $265,452, an IRR of 12.16%, and a DPP of 7.03 years. These metrics suggest that the PRO power plant is a sound investment. However, the extended DPP may deter investors from supporting the project, especially when it is compared with PV systems and other RE options with faster returns. Nevertheless, the sensitivity analysis highlights the resilience of the PRO system, with NPV being particularly sensitive to factors like electricity selling prices, CapEx, and OpEx. The LCOE and profitability of the proposed PRO power plant can be improved by enhancements in membrane technology and operational efficiencies.

The viability of this project is contingent upon strategic interventions that address its projected seven-year payback period alongside inherent ecological risks. Financial assessments highlight the necessity for stabilizing revenue streams through long-term PPAs with stakeholders such as the CEPALCO or industrial consumers. Such agreements can effectively mitigate exposure to market volatility and enhance the project's NPV. Additionally, the implementation of government incentives outlined in the RA 9513, including feed-in tariffs, tax exemptions, and grants, serves to augment the economic feasibility of the project by alleviating CapEx and operational risks.

From an environmental perspective, PRO technology emerges as a promising low-carbon alternative to fossil fuel reliance, thereby aligning with national decarbonization objectives. However, the ecological consequences, particularly those associated with potential disturbances to estuarine ecosystems due to salinity imbalances and competition for water resources, necessitate the establishment of proactive mitigation strategies. Measures such as repurposing treated wastewater, developing wetland buffers, and forging industrial partnerships for brine reutilization represent best practices reflective of circular economy principles. These strategies not only decrease freshwater demand but also convert waste streams into valuable resources, ultimately enhancing both environmental integrity and economic viability.

A comparative analysis with solar and wind energy technologies reveals the distinctive advantages of PRO. Despite the inherent limitations posed by geographic dependencies on salinity gradients, PRO's LCOE at $0.17 per kWh and its minimal land-use requirements afford it a unique position as a complementary energy solution within coastal or industrial contexts. In contrast to solar and wind energy, which contend with challenges related to material-intensive manufacturing processes and habitat disruption, the integration of PRO technology with existing water infrastructure mitigates standalone environmental impacts. Moreover, advancements in membrane technology, as demonstrated by initiatives such as Statkraft's pilot plant, suggest substantial potential for improved power densities and expanded applicability across diverse environments.

Based on the findings of this study, the following recommendations are proposed:

1. *Membrane technology enhancement*. The economic viability of the proposed PRO power plant can be significantly improved by enhancing membrane performance, especially relating to water permeability [18] and fouling resistance. The use of more durable and efficient membrane technologies has the potential to reduce OpEx associated with membrane replacement and maintenance.
2. *Optimization of operational efficiency*. Looking into the large contribution of the OpEx, particularly with respect to membrane maintenance and system efficiency, it is surmised that the use of more advanced predictive maintenance and automation of the systems would significantly reduce the occurrence of downtime and lower OpEx. In addition, applying novel techniques to optimize energy conversion processes as well as minimizing energy losses can further improve the system's performance.
3. *Market strategies for electricity pricing*. The sensitivity analysis underscored the substantial impact of electricity selling prices on the project's financial viability. To mitigate revenue risks and achieve financial viability, it is necessary to either secure long-term PPAs or target markets with a more stable electricity price. This strategic improvement would internally increase the return on investment and would equally help with reducing market risk exposure.
4. *Government and policy support*. It is evident that the PRO technology has an immense potential to aid the growth of the RE sector in the Philippines, hence the need for policies from the government to reinforce and broaden the incentives for RE initiatives, one of which is blue energy sources of energy such as PRO. Adding PRO technology in the mix of the RE resources deployed in the country will not only help to diversify energy sources in the country and lower its dependence on external fossil fuels, but also contribute to the improvement of energy self-sufficiency and environmental sustainability.
5. *Expansion of site assessments*. Though the present research is limited to Cagayan de Oro City, it is recommended that other prospective sites in the Philippines, especially those with notable salinity gradient regions, be explored in-depth. This could further enhance the comprehension of SGP generation in the entire country and assist in locating areas that would be most advantageous for the use of PRO technology.

Future Outlook

The proposed PRO power plant in Cagayan de Oro City presents a blueprint for scaling decentralized energy solutions for coastal communities. However, expanding its capacity beyond 1 MW entails addressing various technical, economic, and environmental challenges. The development and testing of next-generation membranes with customized surface chemistries and hierarchical pore structures will be critical for maintaining high water flux and salt rejection under elevated hydraulic pressures. To scale capacities to 1–5 MW, membrane areas will need to reach approximately 10,000–50,000 m^2. Thus, pilot-testing modular membrane skids in both serial and parallel configurations will be crucial for validating performance under real-world fouling conditions and pressure cycles. Current pilot projects, such as the Statkraft prototype and the Megaton Water Initiative, have demonstrated power densities exceeding 10 W/m², suggesting significant potential for scalability provided that membrane costs are reduced and modular designs are optimized.

Hybrid systems integrating PRO with solar, wind, or desalination infrastructure could significantly boost energy output and grid stability, especially in coastal regions that exhibit salinity gradients. For instance, integrating PRO with desalination plants could mitigate brine disposal issues while simultaneously producing clean water and energy, particularly relevant to water-stressed areas like the Middle East and North Africa. In summary, while PRO is unlikely to rival solar and wind as dominant RE technologies, it offers significant promise as a complementary solution in specific niche applications, particularly in coastal areas with significant salinity gradients or at industrial sites looking to repurpose waste brine streams.

Comprehensive life-cycle and cost-benefit assessments at scales exceeding 1 MW are needed to quantify the long-term environmental and economic viability of PRO in tropical regions. The global relevance will be further enhanced by evaluating hybrid configurations, such as PRO-solar and PRO-wind co-location, to optimize RE yield per unit of land or water resource.

Globally, PRO's niche is found in regions where freshwater converges with seawater, such as river deltas, industrial coastal zones, and areas near hypersaline lakes. Countries with extensive coastlines, including Indonesia, Brazil, and India, can utilize PRO to diversify their RE portfolios while addressing localized challenges related to the energy-water nexus. However, achieving scalability necessitates tackling site-specific ecological risks, such as salinity disruption, through adaptive strategies like dynamic brine dilution and AI-driven discharge management. Insights gained from the integration of treated wastewater as feedwater underscore the importance of adopting circular economy approaches, which can be effectively replicated in regions such as California or Israel, where water reuse is a priority.

Economically, achieving economies of scale will depend on reducing CapEx through standardized membrane manufacturing and leveraging green financing mechanisms. The proposed project in Cagayan de Oro City, with its LCOE of $0.17 per kWh, aligns with costs observed in early-stage solar and wind projects, suggesting PRO could follow a similar cost-reduction trajectory with sustained R&D. International collaboration, such as joint ventures under ASEAN's RE frameworks or European alliance for osmotic energy, could accelerate innovation and policy alignment.

Ultimately, the future of PRO depends on effectively transitioning from pilot-scale achievements to commercial viability. By integrating osmotic energy into hybrid systems, advocating supportive policies, and emphasizing ecological protections, PRO has the potential to become a cornerstone of sustainable energy strategies in coastal regions worldwide. Rather than competing with established renewable sources, PRO can complement them. The proposed Cagayan de Oro project highlights that PRO's global relevance is not in replacing solar or wind, but in filling critical gaps in the renewable landscape, particularly at the intersection of water and energy sustainability.

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