

## Article

# Economic and Reliability Assessment of Hybrid PRO-RO Desalination Systems Using Brine for Salinity Gradient Energy Production

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**Abstract:** The energy requirements for desalination have made it an expensive process, however, it is still a viable and cost-effective means of water purification amidst freshwater scarcity. The management and disposal of brine is an external and extra desalination cost due to the effect of brine on the environment. The integration of Pressure Retarded Osmosis (PRO) with the Reverse Osmosis (RO) technique as modelled in this paper enhances brine management. The brine is fed back into the PRO unit to create a salinity gradient for water transfer via membrane and generate salinity gradient energy. The hybrid desalination model is designed to be powered by grid-tied offshore wind power. The use of wind power, a clean, renewable energy source devoid of carbon emission, as the main power source to drive the RO unit reduces the cost and effect of carbon emissions from the grid. The proposed model is assessed using Levelized cost of energy (LCOE), Annualized cost of the system (ACS), and cost of water (COW) as economic matrices. In contrast, loss of energy probability is used as a reliability matrix. Obtained results show a LCOE of 1.11 \$/kW, ACW of \$110,456, COW of 0.13 \$/m<sup>3</sup>, loss of energy probability of 0.341, a low total carbon emissions of 193,323 kgCO<sub>2-e</sub>, and zero brine production. Results show that the proposed model is economically viable, technically reliable, environmentally friendly, and generally sustainable.

**Keywords:** renewable energy; salinity gradient energy; wind energy; pressure retarded osmosis; reverse osmosis



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## 1. Introduction

### 1.1. Background and Motivation of Study

Freshwater is a basic human need, and access to it is a fundamental right recognized in the 2010 United Nations General Assembly (UNGA) [1]. Yet, its scarcity in many parts of the world is still a significant challenge. This challenge is aggravated by the continuous increase in population, increase in industrial demand, and agricultural purposes. On the other hand, the effect of climate change and other factors decreases supply sources of freshwater. The global demand for water is growing by 1% every year and can get to 120–130% of the immediate consumption by 2050 [1]. Desalination has become a suitable option for freshwater production, considering the abundance of seawater. Though desalination is considered expensive because of its energy requirement and environmental impact, it continues to gain popularity as several desalination methods have been initiated. Several attempts have been made to reduce its energy requirement and environmental impact, thus minimizing cost. The reverse osmosis (RO) desalination method has been identified as a less energy-intensive desalination method, as it typically requires 3–6 kWh to produce 1 m<sup>3</sup> of freshwater, hence, it has gained 65% of global desalination installations [2]. Despite its

lower energy requirement and popularity, reverse osmosis desalination (ROD) is still considered expensive. The environmental impacts of the commonly used energy sources and brine production are major challenges. To minimize or completely eradicate gas emissions from desalination power sources, renewable energy sources have been favored, either with the integration of conventional grid energy sources [3–5] or as stand-alone energy sources for desalination [6–8]. One of the main challenges of powering RO systems by renewable energy is the intermittent operation effect in the long-term on the performance of these systems [5,9]. Therefore, to further minimize the GHG emissions, the optimization of RO systems is key, as well as studying RO systems powered by renewable energy for example, studying SWRO systems under variable operating conditions and studying the operation windows and optimal operating points [10–12].

On the other hand, the hybridization of desalination methods has been suggested for brine management [13,14]. Therefore, to achieve sustainable desalination, most efforts aim to improve energy efficiency and address environmental concerns by using clean, renewable energy and efficient management of concentrated brine.

Thus far, solar and wind power are mostly used for desalination and integrated with thermal or fossil fuel generators to compensate for their intermittency. To further reduce the use of thermal or fossil fuel energy for desalination, energy storage systems have been explored alongside solar and wind energy. Energy storage systems have been explored alongside solar and wind energy to augment their inconsistency. Additionally, geothermal energy has been considered for desalination in locations where it is feasible. The full range and prospects of utilizing ocean energy for desalination purposes have not been extensively examined [15]. Few attempts have been made to investigate the use of wave and tidal energy, with most of these investigations at experimental stages. Ocean energy is predictable and has the highest energy density; therefore, it is more reliable than other forms of renewable energy [15]. Other advantages of ocean energy use for desalination include natural collocation of production and use, thereby eliminating the need and cost of energy transmission, and closeness to human settlements, as most human populations are settled along coasts [15]. In addition, there are different categories of ocean energy: thermal, mechanical, and chemical (salinity gradient). These varieties give room for dynamic applications. This article, therefore, presents a further examination of the application of one form of ocean energy (salinity gradient), with its unique characteristic, alongside wind energy to the hybrid of pressure-retarded osmosis (PRO) and RO.

Desalination processes are either thermal or membrane-based. The thermal processes, including humidification–dehumidification, multi-stage flash distillation, vapor compressor distillation and multi-effect distillation, are based on change state. In comparison, membrane desalination methods use membranes with unique chemical and physical properties, and examples of membrane desalination methods include: electrodialysis, forward osmosis, electrodialysis reversal, membrane distillation, nano-filtration, PRO and RO [9]. Thermal processes require both thermal and electrical energy; thus, they are highly energy-intensive, with specific energy consumption (SEC) ranging from 5.5 to about 27 kWh/m<sup>3</sup>. The membrane processes usually required only electrical energy or pressure differences for desalination, with SEC ranging between 2 to 6 kWh/m<sup>3</sup>. Despite the lower energy requirement of membrane processes, all desalination techniques have their peculiar limitations and share a common challenge of brine management.

Despite being the most reliable membrane method of seawater desalination, RO is faced with membrane fouling and some soluble rejection efficacy. Improvement on RO systems has led to extensive research on membrane development using nanomaterials [16–18]. In addition, several studies have suggested the hybrid of RO and other desalination methods to improve performance. The authors of [13,14,19] designed a model that combined RO, ED, and crystallization methods to achieve salt production and minimize brine production from seawater desalination. The cost and energy requirements of the systems were examined and prove to be economically viable and fit for brine management, but the capital and operational costs of ED and crystallization were not considered in the economic analysis.

Hybridization of RO with either forward osmosis (FO), reverse electrodialysis (RED), or PRO is considered very promising, since the three (FO, RED, and PRO) are major technologies that utilize ocean salinity gradient energy. The authors of [20–22] present the hybrid of FO-RO technologies and evaluate the system's performance and economic viability. It was suggested that the FO-RO hybrid could approach a SEC threshold of 1.3–1.5 kWh/m<sup>3</sup> for seawater desalination using a FO membrane of about 10 L/m<sup>3</sup> [20]. This hybrid process reduces energy demand and freshwater cost and reduces the environmental impact of brine.

### 1.2. Environmental Impacts and Treatment of Brine

The environmental effects and treatment of brine is a major concern of producing freshwater via desalination processes. Other than freshwater, brine is another product of desalination, but it has very high salinity and contains chemicals such as FeCl<sub>3</sub>, H<sub>2</sub>SO<sub>4</sub>, and many others [23]. The management of brine to avert negative impacts on the environment is considered an extra cost of desalination [24]. Currently, most desalination plants dispose of the brine product back into waterbodies nearest to the site of installation. This practice has a very hazardous impact on marine life [25,26]. Other forms of brine disposal are either on the land surface or dug pits. These methods are also not considered viable options, because the high temperature of the brine is capable of destroying arable land that could be used for other purposes. The methods are also cost-intensive. Several researchers agree on the danger and severity of the environmental impact of indiscriminate disposal of brine and further proposed different methods of treatment to mitigate the menace [27–29]. Roberts et al. [27] performed a critical review of the impacts of brine discharges on marine environment and suggested a control–impact testing and monitoring system to ascertain the severity of impact before and after the process of desalination. Noam Lior [28] suggested a holistic approach that considered social, economic, and environmental impacts for a paradigm sustainability model when performing assessment of desalination processes. Feed water pretreatment and post-treatment of brine using hybrid methods of desalination has been suggested as a sustainable means of brine management [20–22]. This approach has the additional advantage of energy generation and efficient utilization.

This paper presents the hybrid of PRO and RO for adequate brine management from seawater desalination, adopting a similar approach to the integration of FO-RO in [20–22]. While the focus of [20,21] is on the thermodynamic process optimization of the hybrid systems, [22] extends this to economic evaluation of the system using the life cycle cost index. This present study uses LCOE, ACS, and COW as economic indices while considering reducing carbon emissions and its associated cost. This study further assesses the reliability of the PRO-RO hybrid system using the LOLP index, considering optimal energy scheduling.

## 2. Materials and Methods

### 2.1. System Architecture

The proposed system configuration is such that the ocean water (feed water) is passed through the PRO process before the RO desalination process. At the PRO stage, the ocean water is also used as a low salinity solution to create a salinity gradient with the concentrated draw solution (brine), which is the byproduct of desalination. The salinity gradient is the pressure difference between the low concentrated feed water and the high concentrated brine solution that allows the transmission of feed water via the PRO membrane. The low salinity feed water from the PRO is then fed into the RO section, requiring low pressure for desalination. The low pressure needed for the RO unit is provided by wind energy and backed up by grid power. Figure 1 depicts a schematic diagram of the integrated PRO-RO desalination process powered by ocean salinity gradient and grid-tie offshore wind.

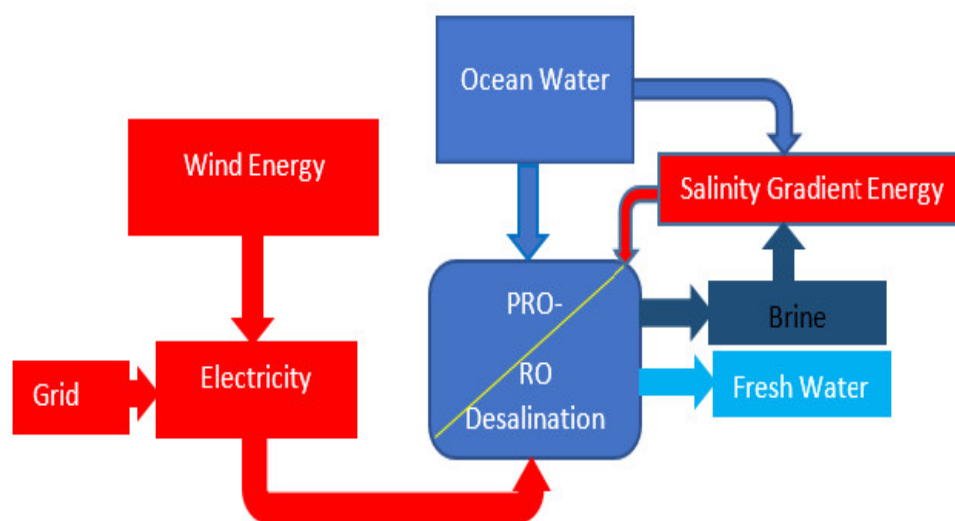


**Figure 1.** Integrated PRO-RO desalination process powered by grid-tied offshore wind and ocean salinity gradient.

## 2.2. Salinity Gradient Energy

Salinity gradient energy, like other forms of ocean energy, is very predictable and has high energy density; therefore, it is more reliable than other forms of renewable energy [30]. It has the potential to improve energy sustainability if given adequate attention. This form of energy is yet to be harnessed for large-scale application, owing to limited technology. Few attempts have been made to investigate the use of ocean energy, with most of these investigations at experimental stages [30]. This energy, called blue energy, is sourced from the salinity concentration difference between two solutions. It can be used directly for desalination with technologies like FO, RED, and PRO or be captured and converted to electrical energy. The entropy change resulting from the irreversible mixing of two solutions of different salinity concentrations can be utilized to convert part of the thermal energy of the fluids into electrical energy [30]. While Jia et al. [30] reviewed different technologies used to capture salinity gradient energy, Tufa et al. [31] detail the thermodynamic characteristics of the process. According to Tufa et al. [31], the chemical potential  $\mu_i$  of a solution, if known, determines the amount of free energy of mixing.

$$G = \sum \mu_i n_i \quad (1)$$

where  $n$  is the number of moles of each component, which can be expressed in terms of molar concentration  $c$  and total volume  $V$  as:

$$n_i = c_i V \quad (2)$$

The Gibbs free energy of mixing ( $\Delta G_{mix}$ ) of two salt solutions at different concentrations is given by the difference between the Gibbs free energy of the mixed solution ( $G_t$ ) and the Gibbs free energy of the initial solutions:

$$\Delta G_{mix} = G_t - (G_c + G_d) \quad (3)$$

where subscripts  $c$  and  $d$  refer to concentrated and dilute solutions, respectively. Combining (1)–(5),  $\Delta G_{mix}$  can be calculated as:

$$\Delta G_{mix} = \sum_i (c_{i,t} V_t R T \ln \gamma_{i,t} x_{i,t}) - (c_{i,c} R T \ln \gamma_{i,c} x_{i,c}) + (c_{i,d} R T \ln \gamma_{i,d} x_{i,d}) \quad (4)$$

In theory, the maximum extractable energy during the irreversible mixing of a low-concentration stream with high-concentration (draw) solutions is substantial, ranging from

0.75 kWh/m<sup>3</sup> to 14.1 kWh/m<sup>3</sup> depending on the low-concentration stream [30,31]. In this study, the salinity gradient energy is required only to run the PRO section, since there is no widely available commercial technology to harness it for a large desalination system.

### 2.3. PRO Power and Cost Model

The PRO process allows the transfer of water from a low concentration to a higher concentration via a membrane due to osmotic pressure difference between the two solutions. It requires a back pressure on the high concentration side that retards the permeate flow and can generate power when the solution is depressurized via a turbine, making it a very promising technology for salinity gradient energy generation [32,33]. The power demanded by PRO is mainly for the pressure pump, which a salinity gradient can effectively provide at no cost.

In PRO, the driving force across the membranes can be expressed as the osmotic pressure difference ( $\Delta\pi$ ) and the hydrostatic pressure difference ( $\Delta P$ ). The resulting pressure-retarded osmotic water flux  $J_w$  can be calculated from the membrane water permeability  $A$  and the driving force [31]:

$$J_w = A(\Delta\pi - \Delta P) \quad (5)$$

In the same form as hydroelectric power, the power density  $P_d$  produced in a PRO process is the product of the augmented flow rate and pressure drop through a hydro-turbine:

$$P_d = J_w \Delta P = A(\Delta\pi - \Delta P) \Delta P \quad (6)$$

The differentiation of (3) will give the maximum power as (7).

$$P_{d,max} = \frac{A}{f} \Delta\pi^2 \quad (7)$$

This is achieved when the applied force is half of the osmotic pressure ( $\Delta P = \Delta\pi/2$ ). The net salinity gradient power output ( $SG_p$ ) from the PRO plant would be “generated power” minus “consumed power”, expressed in (8) [34,35].

$$SG_p = SG_{pg} - SG_{pc} \quad (8)$$

The capital cost of a PRO system is difficult to estimate, since there is yet no commercial PRO plant in operation. Therefore, there is an unavailability of detailed data in the literature as to the capital cost of PRO systems, except for experimental cases and test systems [36,37]. Therefore, we benchmark capital expenditure for the RO system, similar to the approach of [35–37].

### 2.4. Wind Power and Cost Model

The wind energy is used mainly to power the RO unit of the desalination system. The proposed system design indicates that the wind station is closely located to the ocean and the RO unit; thus, the cost of power transmission and energy losses are considered negligible. The hourly power output of the wind generator ( $W_p(t)$ ) is given as [38]:

$$W_p(t) = \frac{1}{2} \times \eta'_w \times \rho_{air} \times C_p \times AWT \times V(t)^3 \quad (9)$$

where  $\eta'_w$  is the efficiency of the wind generator,  $\rho_{air}$  is the air density,  $C_p$  is the power coefficient,  $AWT$  is the swept area of the wind turbine, and  $V(t)$  is the hourly wind speed, given as [39] and depicted in Figure 2:

$$V(t) = V_R \times \left[ \frac{h}{h_R} \right]^\alpha \quad (10)$$

where  $V(t)$  is the hourly speed at projected height ( $h$ ),  $V_R$  is the hourly speed at reference height ( $h_R$ ), and  $\alpha$  is the power-law exponent, equivalent to  $1/7$ .

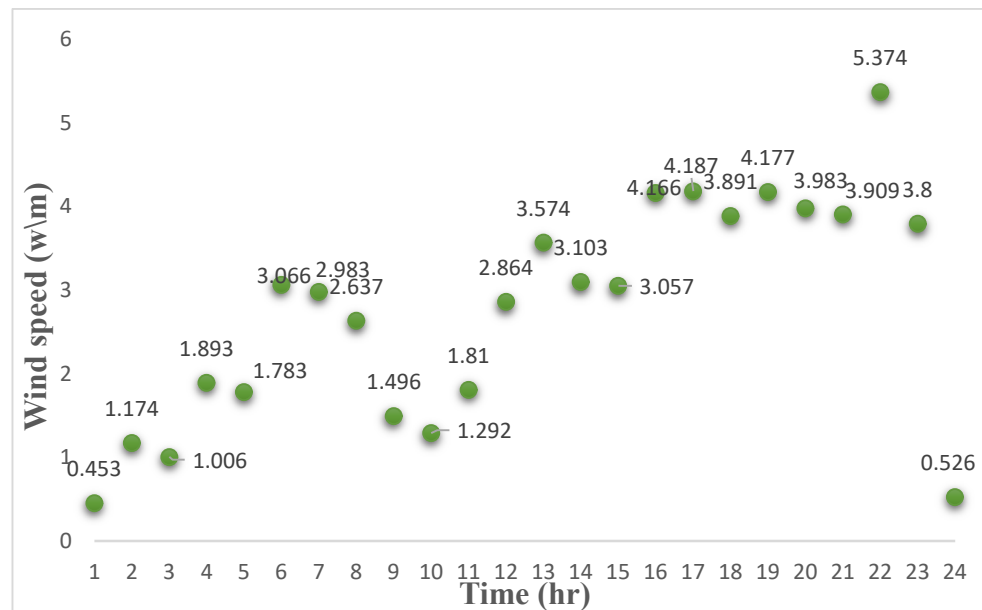


**Figure 2.** Hourly wind speed of a coastal area of Cape Town, South Africa.

The economics of using wind power for desalination is analyzed based on the initial capital cost ( $IC_{WT}$ ) and total maintenance cost ( $TMC_{WT}$ ), depending on the area of the wind turbine, as follows:

$$IC_{WT} = AWT \times C_{WT} \quad (11)$$

$$AMC_{WT} = AWT \times MC_{WT} \times r \quad (12)$$

### 2.5. Grid Power, Cost, and Carbon Emission Factor

For reliability of power supply, the grid power is used as a backup to complement the intermittency of the wind power supply in order to satisfy the load demand of the RO unit at every hour of the day. The grid power supply per hour ( $GP_i(t)$ ) is an optimized variable ranging between zero and the maximum power demand by the RO unit. Additionally, the excess power output from the wind source is transferred to the grid at a cost equivalent to buying power from the utility. This tradeoff offsets certain energy costs. The grid power cost is a factor of the energy price and the difference between power bought and power sold back to the grid. Thus,

$$CGP = \sum (GP_i(t) \times P(t) - GP_e(t) \times P(t)) \quad (13)$$

$$\forall t = 1, 2, 3, \dots, 8760$$

where, CGP is the total annual cost of transferable grid power, and  $GP_i(t)$  is hourly power imported from the grid. In contrast,  $GP_e(t)$  is the hourly exported power to the grid and  $P(t)$  is the hourly unit price of transferable grid power in South Africa, as represented in Figure 3 [40].

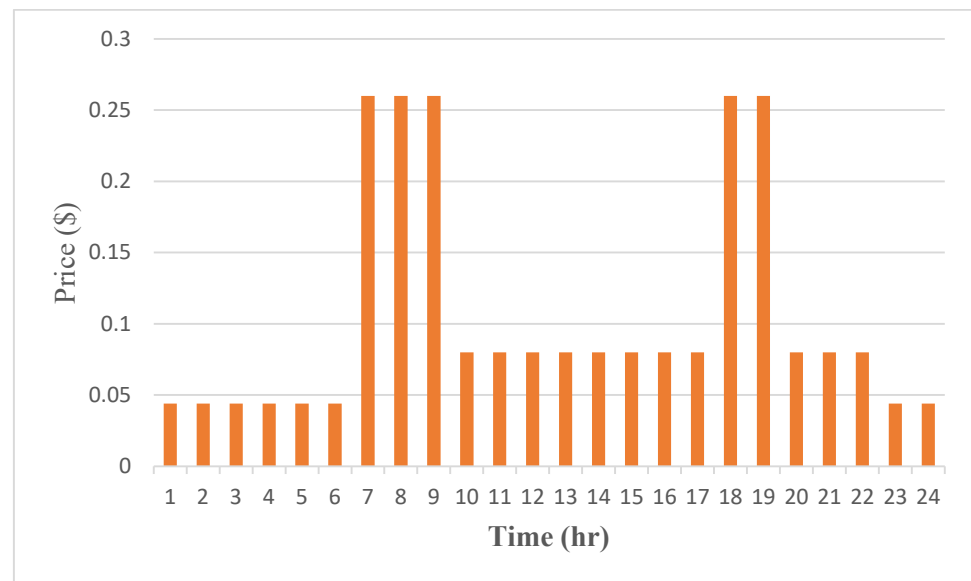


**Figure 3.** Hourly price of grid power from the South Africa utility company.

The emission of greenhouse gases, especially carbons, by the conventional energy sources of the power grid has been of great environmental concern, and yet most desalination plants depend on such energy sources for production of freshwater. In order to discourage overdependence on fossil energy sources by industries, there are standard measures put in place by governments of different countries to regularize such energy use. One such measure is a carbon tax. For effective implementation of carbon tax law, there is usually a standard benchmark, which is the specific emission factor. Therefore, the carbon tax and emission factor are used to determine the carbon emission cost, which also depends on the country where the plant is located. Additionally, the carbon emission cost is a function of energy consumption [24,41,42], as shown in (14).

$$CE \left( \frac{\$}{\text{m}^3} \right) = \text{Energy supply} \left( \frac{\text{kWh}}{\text{m}^3} \right) \times \text{Emission factor} \left( \frac{\text{kgCO}_2\text{-e}}{\text{kWh}} \right) \times \text{Carbon tax} \left( \frac{\$}{\text{kgCO}_2\text{-e}} \right) \quad (14)$$

This study adopted the calculated emission factor for South Africa by reference [13,40,43]. The lowest value of \$0.41 is utilized in this study such that the effect of carbon emissions cost is considered proportional to carbon tax rate.

## 2.6. RO Desalination Power Demand and Cost Model

The hourly power demand ( $P_{WD}(t)$ ) of the RO desalination unit depends on the specific energy consumption (SEC) to produce  $1 \text{ m}^3$  of freshwater and the actual volume of water ( $Q_{WRO}(t)$ ) produced per hour [44,45]. The SEC of a conventional RO system ranges between 3 and 6 kWh/ $\text{m}^3$ , but a hybrid with PRO reduces this energy requirement to 1.2 kWh/ $\text{m}^3$  [41].

$$P_{WD}(t) = Q_{WRO}(t) \times \text{SEC} \quad (15)$$

The daily water production capacity is given as:

$$DQW = \sum_{t=1}^{24} Q_{WRO}(t) \quad (16)$$

The water tank capacity ( $W_{TK}$ ), expressed in  $\text{m}^3$ , is assumed to be twice the daily water production capacity in order to make enough space for extra water produced.

$$W_{TK} = DQW \times 2 \quad (17)$$

The RO desalination cost model includes the initial capital cost ( $IC_{RO}$ ), annual maintenance and operational cost ( $AMC_{RO}$ ), annual membrane replacement cost ( $AC_{MR}$ ), annual treatment chemical cost ( $AC_{CH}$ ), and water tank cost ( $CW_{TK}$ ) [4,8].

$$IC_{RO} = C_{RO} \times DQW \quad (18)$$

$$ICW_{TK} = CW_{TK} \times W_{TK} \quad (19)$$

## 2.7. Economic and Reliability Assessment

### Cost Optimization Problem Formulation

Optimization, in simple terms, is the minimization or maximization of a function of a system, such as cost or technical and operational functions. In this study, the ACS, LCOE, and COW cost matrices are used for the economic evaluation of the PRO-RO desalination. The ACS is the summation of the total system component cost with the capital recovery factor (CRF), a function of total initial system cost (TISC) [46–48]. The COW and the LCOE are other cost matrices for evaluating the cost of energy expended and the cost of producing 1 cm<sup>3</sup> water, respectively.

$$TISC = IC_{WT} + IC_{PRO} + IC_{RO} + ICW_{TK} \quad (20)$$

$$TMC = AMC_{WT} + AMC_{PRO} + AMC_{RO} \quad (21)$$

$$ACS = TISC \times CRF + TMC + AC_{MR} \times CRF + AC_{CH} \quad (22)$$

where:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad n = 1 \dots 19 \quad (23)$$

TMC is total maintenance and operation cost, and  $AC_{MR}$  and  $AC_{CH}$  are annual cost of membrane and treatment chemicals, respectively, while  $n$  is the number of years in the lifetime of the system, of which interest rate  $i$  is considered.

$$COW = \frac{ACS}{\sum DQW(t)} \quad (24)$$

$$LCOE = \frac{ACS}{\sum W_p(t) + SG_p(t)} \quad (25)$$

$$\forall t = 1, 2, 3 \dots 8760$$

The multi-objective optimization problem is to minimize ACS while the quantity of freshwater produce is maximized, as expressed by (28). This linear programming problem is subject to constraints (29) to (33), with weighting factors ( $W_1$  and  $W_2$ ) which were allocated to rank the objective components on a preferential order of significance. The ACS is ranked higher than quantity of water produced, because this study considered that meeting water demand at lower cost is paramount than producing excess. The optimization problem is then solved with the aid of the COMPLEX solver of the advanced interactive multidimensional modeling system, commonly referred to as AIMMS.

### Objective Function

$$Min[w_1 \times ACS + w_2 \times \sum DQW(t)] \quad (26)$$

S.t.

$$W_p(t) + G_{pi}(t) = P_{WD}(t) + G_{pe}(t) \quad (27)$$

This constraint ensures power balance between supply and demand at time  $t$ . Similarly, (28) ensures that daily water produced equals or is in excess of water demand, while (29) maintains a boundary limit of water produced per hour.

$$DQW(t) \geq WD(t) \quad (28)$$

$$QW^{min} \leq QW_{RO}(t) \leq QW^{max} \quad (29)$$

The power required by RO is kept within a limit expressed by (30), while constraint (31) limits the wind turbine area.

$$P_{WD}^{min} \leq P_{WD}(t) \leq P_{WD}^{max} \quad (30)$$

$$\forall t = 1, 2, 3 \dots 8760$$

$$AWT \geq 0 \quad (31)$$

### 2.8. Reliability Assessment

The reliability assessment of this integrated system is aimed at evaluating the energy security of the system. This is to guarantee energy efficiency, considering the stochastic nature of wind energy. In this study, this reliability assessment focuses on the interruption caused by the intermittency of wind energy. The salinity gradient energy complements the loss of energy supply from the wind energy source. Therefore, the loss of load probability (LOLP) index is utilized for this assessment. Utilities often employ the LOLP to measure the total number of days in a year that generator capacity could not meet daily peak load. It is expressed as (32) [49].

$$LOLP = \sum_{j=1}^j p_j \ell_j \quad (32)$$

where  $j$  is the capacity outage state,  $p_j$  is the state probability of the capacity outage state  $j$ , and  $\ell_j$  is the outage duration of the capacity outage state  $j$ .

Figure 4 represents the flow chart of the optimization model.

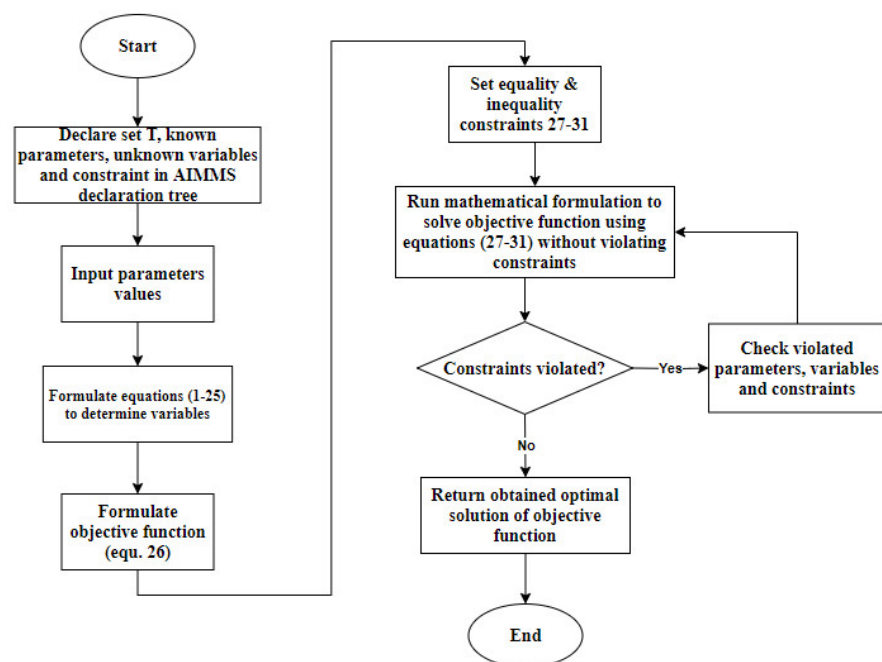


Figure 4. Flow chart of the optimization model.

### 3. Results and Discussion

The metrological data, energy price, carbon emission cost, and emission factor used in this study are those obtainable in South Africa, similarly presented in [5,13,40]. Figure 5 represents the assumed hourly quantity of water demand, while Table 1 contains essential input parameters for optimal cost analysis.

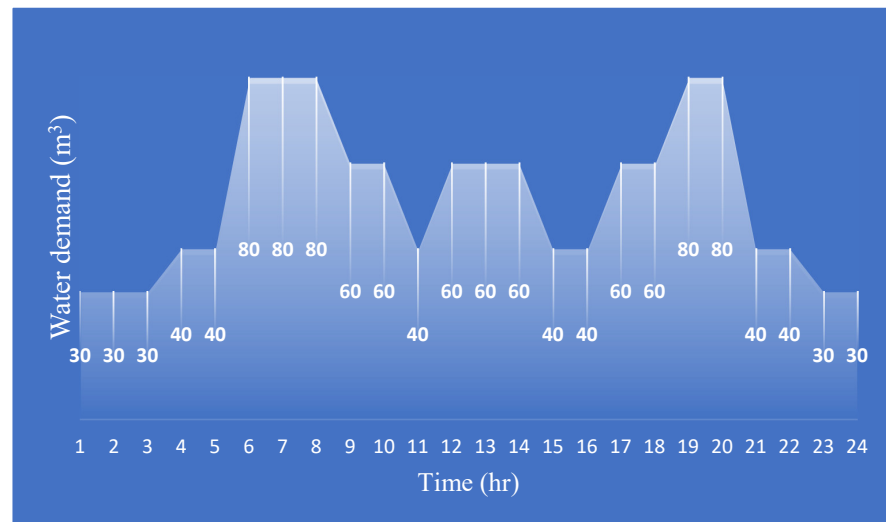


Figure 5. Hourly water demand.

Table 1. Input parameters [4,8,13].

| Parameters      | Value    | Parameters             | Value                      | Parameters     | Value                                 |
|-----------------|----------|------------------------|----------------------------|----------------|---------------------------------------|
| Project time    | 20 years | $C_p$                  | 0.59                       | $B$            | $0.85 \text{ Lm}^{-2} \text{ h}^{-1}$ |
| Interest rate   | 5%       | $C_{WT}$               | \$1804                     | $\Delta\pi$    | 25.35 bar                             |
| Discount rate   | 3%       | $C_{RO}$               | 532 \$/m <sup>3</sup> /day | $A$            | $4.0 \text{ Lm}^{-2} \text{ h}^{-1}$  |
| Emission factor | 1.07     | Plant maintenance cost | 0.2 \$/m <sup>3</sup>      | WT rated power | 1 kW                                  |
| Emission tax    | 0.41 \$  | Chemical cost          | 0.6 \$/m <sup>3</sup>      | $C_{MR}$       | 0.6 \$/m <sup>3</sup>                 |
| $\eta_w$        | 85%      | $CW_{TK}$              | 255 \$/m <sup>3</sup>      | $\rho_{air}$   | 1.23 kg m <sup>3</sup>                |

This proposed model shows the hourly power output from the wind and grid sources as depicted in Figure 6 and the optimal hourly quantity of water produced represented in Figure 7. Furthermore, the summary of optimized parameters is contained in Table 2.

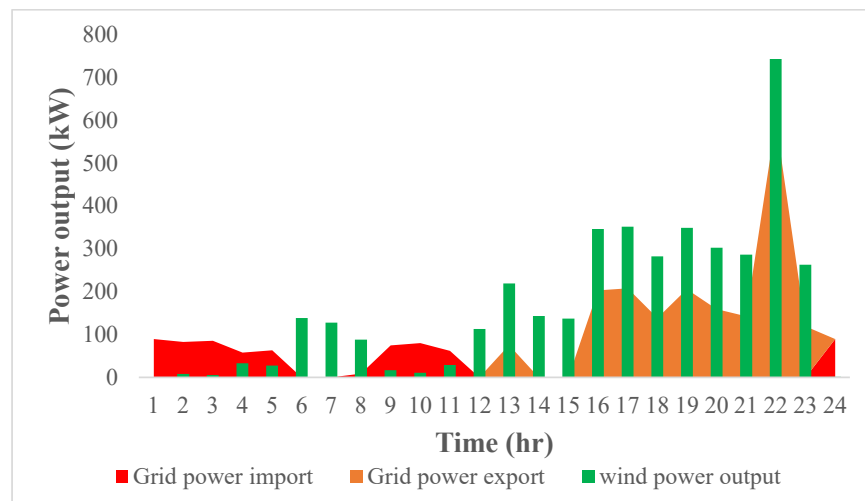


Figure 6. Hourly energy dispensed from the grid and wind power generators.

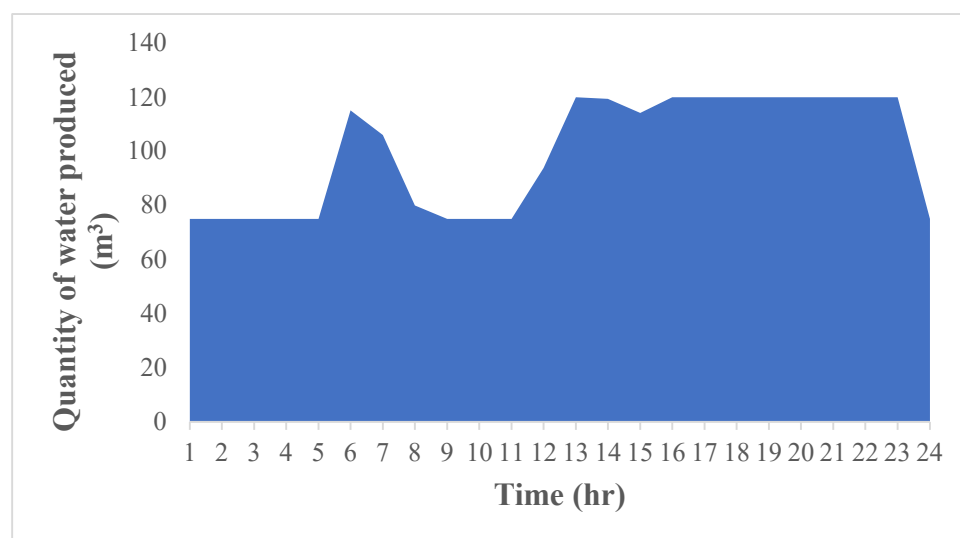


Figure 7. Hourly freshwater produced from the integrated PRO-RO system.

Table 2. Summary of optimized parameters.

| ACS (\$) | LCOE (\$/kW) | COW (\$/m <sup>3</sup> ) | Emission (kgCO <sub>2-e</sub> ) | Emission Cost (\$) | Daily Water Produced (m <sup>3</sup> ) | AWT (m <sup>2</sup> ) | J <sub>W</sub> (m <sup>3</sup> m <sup>-2</sup> h <sup>-1</sup> ) |
|----------|--------------|--------------------------|---------------------------------|--------------------|----------------------------------------|-----------------------|------------------------------------------------------------------|
| 110,456  | 1.11         | 0.13                     | 269,405                         | 110,456            | 2384                                   | 15,543                | 17.031                                                           |

Figure 6 clearly shows that wind energy is preferred over grid power. When there is available wind power, the wind generator powers the RO desalination system. For hours where there is a shortage of wind energy due to wind speed variation, the grid power serves as a backup power to the RO desalination unit. The excess power output from the wind source is exported back to the grid at a cost equivalent to purchasing from the grid. As previously stated in Section 2.2, the salinity gradient energy is mainly used to run only the pressure pump of the PRO unit in order to enable water transfer through the membrane into the RO unit. This first stage can be considered a pretreatment process, while helping to reduce the RO unit's energy requirement, and reduces the fouling effects on the RO membrane, thus increasing permissibility. The impact of these is the large quantity of water produced at every hour of the day, not just to meet demand but also to have excess, especially at hours with high wind energy output, as shown in Figure 7.

The summary results of the optimized parameters shown in Table 2 present the ACS of the integrated system to be \$110,456, the LCOE 1.11 \$/kW, and the COW 0.13 \$/m<sup>3</sup>. These costs are relatively lower than some cases of standalone RO units and some similar hybrid cases in the literature that did not consider carbon emission cost and the component cost of PRO, assumed to be the same as that of RO in this study. For instance, [5,40] reported 1.33 \$/m<sup>3</sup> and 1.77 \$/m<sup>3</sup> for COW, respectively, for a standalone RO unit. It can be noted that these economic values are subject to change with variation in the actual cost of the PRO component, if known. In addition, the cost of this proposed model, if viewed extensively to cover brine management cost and the reduction in carbon emissions and its cost, is far more economical, as there is no need for the extra external cost of brine disposal or management. The carbon emission of 269,405 kgCO<sub>2-e</sub> is advantageously lower than a similar system with diesel generators or desalination systems predominantly powered by the grid's conventional energy source. The LOLP is as low as 0.341, because the higher wind energy output is enough to power the RO desalination unit. This is especially so, because the energy requirement of the unit is reduced because of the reduced pressure required to get feed water through the RO membrane after passing through the PRO unit.

#### 4. Conclusions

This study presents an optimal techno-economic and reliability evaluation model of a PRO-RO hybrid desalination system powered by a grid-tied wind energy source and salinity gradient energy. The design is of two stages. Stage one is the PRO unit powered by salinity gradient energy produced due to the mixture of ocean feed water (low concentration) and RO brine solution (high concentration). Stage two is the RO unit powered by grid-tied wind energy, where a secondary ocean feed water desalination is carried out. The brine produced from stage two is channeled back to stage one to create a salinity gradient for water transfer via PRO membrane and generation of energy. The proposed model optimally sized the grid-tied wind energy sources in order to minimize carbon emission and its cost and the whole system in order to minimize the ACS, LCOE, and COW. The results from the techno-economic evaluation of the proposed design model show ACS of \$110,456, LCOE of 1.11 kW/m<sup>3</sup>, and COW of 0.13 \$/m<sup>3</sup>. These cost values are relatively lower than those of the standalone RO desalination systems available in the literature. For instance, [5,40] reported 1.33 \$/m<sup>3</sup> and 1.77 \$/m<sup>3</sup> for COW, respectively, for a standalone RO unit. The extended advantages of zero brine disposal and management cost and the low carbon emission and emission cost make the hybrid PRO-RO model more environmentally friendly. The PRO-RO desalination system can also be considered economical, considering that the extra cost of brine disposal or treatment will no longer be a factor. The reliability index of low LOLP of 0.341 suggests the reliability of the proposed system. This is because of high power output from the wind energy source and the low energy required by the RO unit after the PRO unit partially desalinates the feed water.

In conclusion, the hybrid PRO-RO desalination system powered by wind energy is a promising approach to solving freshwater scarcity and the associated environmental issues of brine disposal. Furthermore, it solves the challenge of large carbon emissions when a conventional fossil fuel generator is used for RO desalination. In the future, with the advancements in PRO technology, salinity gradient energy can be harnessed to meet the energy requirements of RO desalination. This will substantively reduce the energy costs of desalination systems. By extension, it will reduce the cost of freshwater production.

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#### Abbreviations

|      |                                 |
|------|---------------------------------|
| FO   | Forward osmosis                 |
| PRO  | Pressure-retarded osmosis       |
| RO   | Reverse osmosis                 |
| ROD  | Reverse osmosis desalination    |
| UNGA | United Nations General Assembly |
| Set  |                                 |
| t    | time (hr)                       |

**Parameters**

|                  |                                                                     |
|------------------|---------------------------------------------------------------------|
| $v$              | Partial molar volume ( $\text{m}^3 \text{mol}^{-1}$ )               |
| $V$              | Total volume of concentration ( $\text{mol m}^3$ )                  |
| $c$              | Molar concentration ( $\text{mol m}^3$ )                            |
| $x$              | Mole fraction ( $\text{mol}^{-1}$ )                                 |
| $z$              | Valence of ion (equiv/mol)                                          |
| $F$              | Faraday constant (c/equiv)                                          |
| $R$              | Gas constant ( $\text{J mol}^{-1} \text{K}^{-1}$ )                  |
| $T$              | Absolute temperature (K)                                            |
| $G$              | Gibbs free energy (J)                                               |
| $n$              | Number of moles                                                     |
| $\mu_i$          | Chemical potential ( $\text{J mol}^{-1}$ )                          |
| $\mu_i^0$        | Chemical potential under standard condition ( $\text{J mol}^{-1}$ ) |
| $\Delta\rho$     | Pressure gradient (Pa)                                              |
| $\Delta\varphi$  | Electrical potential difference (V)                                 |
| $\gamma$         | Activity coefficient                                                |
| $\Delta G_{mix}$ | Gibbs free energy of the mixed solution (J)                         |
| $G_t$            | Mixed solution                                                      |
| $G_c$            | Concentrated solution                                               |
| $G_d$            | Dilute solution                                                     |
| $J_w$            | Osmotic water flux ( $\text{m}^3 \text{m}^{-2} \text{h}^{-1}$ )     |
| $\Delta\pi$      | Osmotic pressure difference (Pa)                                    |
| $\Delta P$       | Hydrostatic pressure difference (Pa)                                |
| $A$              | Membrane water permeability ( $\text{ms}^{-1} \text{Pa}^{-1}$ )     |
| $P_d$            | Power density ( $\text{Wm}^{-2}$ )                                  |
| $P_{d,max}$      | Maximum power density ( $\text{Wm}^{-2}$ )                          |
| $SG_{pg}$        | Salinity gradient power generated (kW)                              |
| $SG_{pc}$        | Salinity gradient power consumed (kW)                               |
| $\eta'_w$        | Efficiency of wind generator                                        |
| $\rho_{air}$     | Air density                                                         |
| $C_p$            | Power coefficient                                                   |
| $V(t)^3$         | Hourly wind speed (W/m)                                             |
| $h$              | Projected wind turbine height (m)                                   |
| $V_R$            | Reference wind speed (W/m)                                          |
| $h_R$            | Reference wind turbine height (m)                                   |
| $\alpha$         | Power law exponent                                                  |
| $IC_{WT}$        | Initial capital cost of wind turbine (\$)                           |
| $C_{WT}$         | Cost of wind turbine (\$)                                           |
| $TMC_{WT}$       | Maintenance cost of wind generator (\$)                             |
| $AMC_{WT}$       | Annual maintenance cost of the wind generator (\$)                  |
| $MC_{WT}$        | Cost of maintenance of a wind turbine (\$)                          |
| $r$              | Discount rate                                                       |
| $CRF$            | Capital recovery factor                                             |
| $SEC$            | Specific energy consumption ( $\text{kWh/m}^3$ )                    |
| $WD(t)$          | Hourly water demand ( $\text{m}^3$ )                                |
| $IC_{RO}$        | Initial capital cost of RO ( $\$/\text{m}^3/\text{day}$ )           |
| $C_{RO}$         | RO cost ( $\$/\text{m}^3$ )                                         |
| $AC_{CH}$        | Annual cost of RO treatment chemicals (\$)                          |
| $AC_{MR}$        | Annual cost of RO membrane replacement (\$)                         |
| $AMC_{RO}$       | RO annual maintenance cost (\$)                                     |
| $C_{PRO}$        | PRO cost ( $\$/\text{m}^3$ )                                        |

|                              |                                               |
|------------------------------|-----------------------------------------------|
| $IC_{PRO}$                   | Initial capital cost of PRO ( $\$/m^3/day$ )  |
| $AMC_{PRO}$                  | PRO annual maintenance cost (\$)              |
| $W_{TK}$                     | Water tank capacity ( $m^3$ )                 |
| $CW_{TK}$                    | Water tank cost ( $\$/m^3$ )                  |
| $C_{WT}$                     | Wind turbine cost (\$)                        |
| $ICW_{TK}$                   | Initial capital cost of the water tank (\$)   |
| TICC                         | Total initial capital cost of system (\$)     |
| TMC                          | Total maintenance and operational cost (\$)   |
| $QW^{min}, QW^{max}$         | Minimum and maximum water produce ( $m^3$ )   |
| $P_{WD}^{min}, P_{WD}^{max}$ | Minimum and maximum power demand (kW)         |
| $W_1, W_2$                   | Weighting factor                              |
| $j$                          | Capacity outage state                         |
| $p_j$                        | State probability of $j$                      |
| $\ell_j$                     | Outage duration of $j$                        |
| <b>Variables</b>             |                                               |
| $P_{WD}(t)$                  | Hourly power demand by RO unit (kW)           |
| $QW_{RO}(t)$                 | Hourly volume of water produced ( $m^3$ )     |
| DWQ                          | Daily water production capacity ( $m^3$ )     |
| AWT                          | Swept area of wind turbine (m)                |
| $W_p(t)$                     | Hourly power wind generator power output (kW) |
| $SG_p(t)$                    | Hourly net salinity gradient power out (kW)   |
| $G_{pi}(t)$                  | Grid power imported (kW)                      |
| $G_{pe}(t)$                  | Grid power exported (kW)                      |
| COW                          | Cost of water ( $\$/m^3$ )                    |
| ACS                          | Annualized cost of system (\$)                |
| LCOE                         | Levelized cost of energy (\$)                 |
| LOLP                         | Loss of load probability                      |

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