Feasibility Study of a Hybrid Reverse Electrodialysis System for Wastewater Treatment and Energy Production from Reverse Osmosis System Effluent

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ABSTRACT

RO concentrate is often discharged into natural aquatic environments, increasing salinity and threatening marine ecosystems. Recently, new processes have been developed to treat and recover brine from the RO process, with reverse electrodialysis (RED) emerging as a promising solution. RED is an electrical membrane process that separates mineral ions using direct electric current, offering a method to treat high-salinity concentrate from the RO process with moderate energy consumption. In this study, the effluent from the Konarak desalination plant was evaluated for use as feed for the RED system. Results showed that the suspended solids in the effluent were approximately 10,000 mg/L, the TDS was around 50,000 mg/L, and the water hardness was about 5 mg/L. The findings indicate that the effluent from the desalination unit is suitable for use in hybrid systems such as RED-RO. The integration of the RED process in desalination plants can lead to a more environmentally friendly approach and achieve greater energy efficiency.

***Keywords**: Reverse electrodialysis(RED), Reverse Osmosis (R.O.), Hybrid systems,Renewable energy, Wastewater Treatment*

1. INTRODUCTION

Water scarcity is an increasing global challenge that necessitates innovative approaches in water management. With the growing population and expansion of industrial activities, the demand for clean water intensifies. Simultaneously, the environmental impacts of wastewater discharge and the salinization of natural aquatic ecosystems are significant threats that require attention. In this context, desalination technologies play a crucial role in meeting water demands while minimizing environmental harm[1].

1.1 Reverse Osmosis (RO) and Its Limitations

Reverse Osmosis (RO) is widely used as a desalination method due to its ability to produce high-quality fresh water at relatively low costs. However, RO systems generate a concentrated brine stream, which is a high-salinity byproduct. Discharging this brine into natural waters can disrupt marine ecosystems and pose a threat to human health. Addressing this challenge requires innovative solutions that effectively treat and recycle RO concentrate[2].

1.2 RED System

Reverse Electrodialysis (RED) is an evolving membrane-based process that focuses on the salinity gradient energy between seawater and river water. This system utilizes the chemical potential difference resulting from varying salt concentrations to generate energy. The chemical potential difference between these two water sources causes cations and anions to move in opposite directions, which can be converted into electrical current at the electrodes through redox reactions[3]

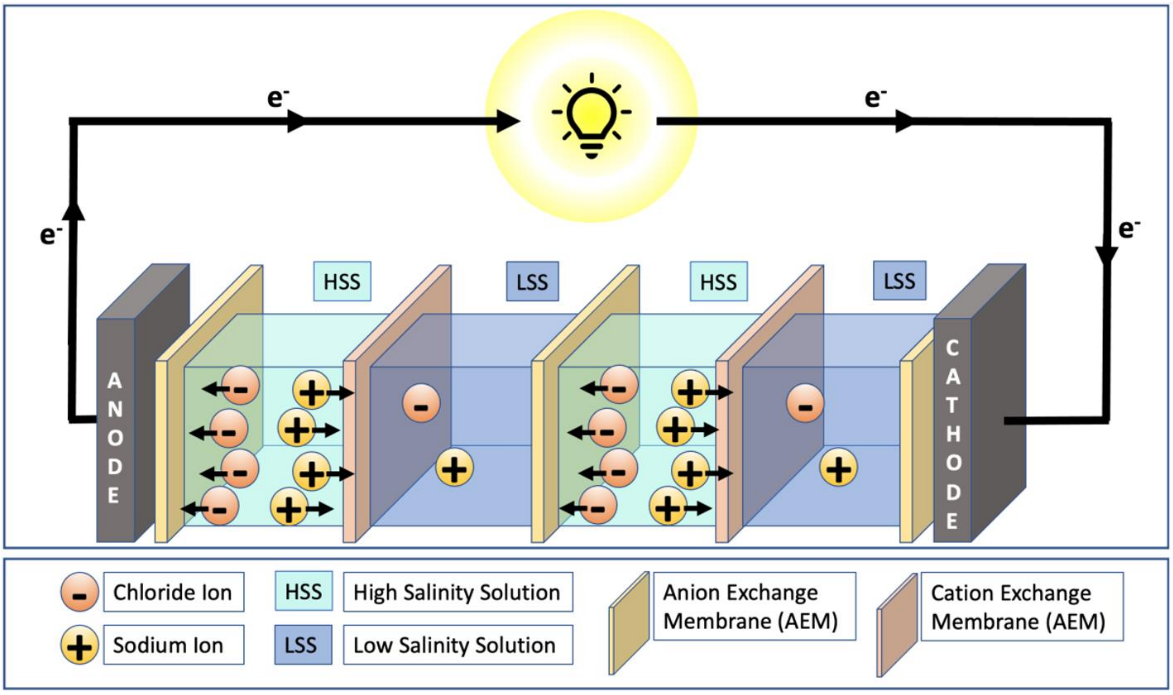

Figure 1 Principles of Energy Production in Reverse Electrodialysis System[4].

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1.2.1 Membrane Cells and Energy Potential

Similar to fuel cells, RED cells are placed side by side. At a real scale, a membrane cell with a capacity of 250 kilowatts can be housed in a shipping container. For instance, in the Netherlands, where over 3,300 cubic meters of fresh water flows into the sea every second on average, halving the pressure difference using a membrane creates a water column of approximately 135 meters. In membrane filtration, the term 'water column' is used to describe the pressure difference across a membrane. This means the pressure difference across the membrane is equivalent to the pressure exerted by a vertical column of water 135 meters high. The pressure of a water column is calculated based on the density of water and the height of the column. For example, a 1-meter water column exerts a pressure of approximately 0.098 bar on the membrane. Therefore, a 135-meter water column exerts a pressure of about 13.2 bars. By using membranes to halve the pressure difference, the RED system can operate at a pressure equivalent to a 135-meter water column, which is relatively low compared to many other membrane filtration applications. This system helps optimize the efficiency and performance of the membrane system[5].

The energy potential from a 135-meter water column is obtained as follows:

$E = m \cdot g \cdot \Delta h$

In this formula:

E = energy in joules (J)

m = mass flow rate

g = acceleration due to gravity

Δh = change in height

Substituting the values into the energy equation:

E = 4.5 × 10^9 J.s

This equates to an output power of approximately 4.5 gigawatts.

1.3 Integration of RED with Seawater Desalination Units (SWDU-RED)

Reverse Electrodialysis (RED) is commonly known as a method for energy production using saline and freshwater. However, it can also be employed in scenarios where saline and highly saline water, such as brine leftover from desalination units, are available [6].

Integrating a seawater desalination unit (SWDU) with the RED method has the potential to produce renewable electricity that can be directly utilized in the desalination process. In the SWDU-RED integration approach, seawater is first desalinated through the SWDU. Then, the highly concentrated brine, a waste product of the desalination process, is used as the high-concentration solution in RED to generate electricity. The low-concentration solution typically consists of a solution with ion concentration lower than brine, such as seawater, brackish water, treated wastewater, or a combination thereof. The products of this process include fresh water, electricity, and diluted effluent [7], [8].

Overall, the SWDU-RED process is influenced by various contextual factors, such as the type of seawater desalination unit employed. In reality, there are several SWDU-RED processes, depending on the type of SWDU and the availability of low-concentration solutions [8].

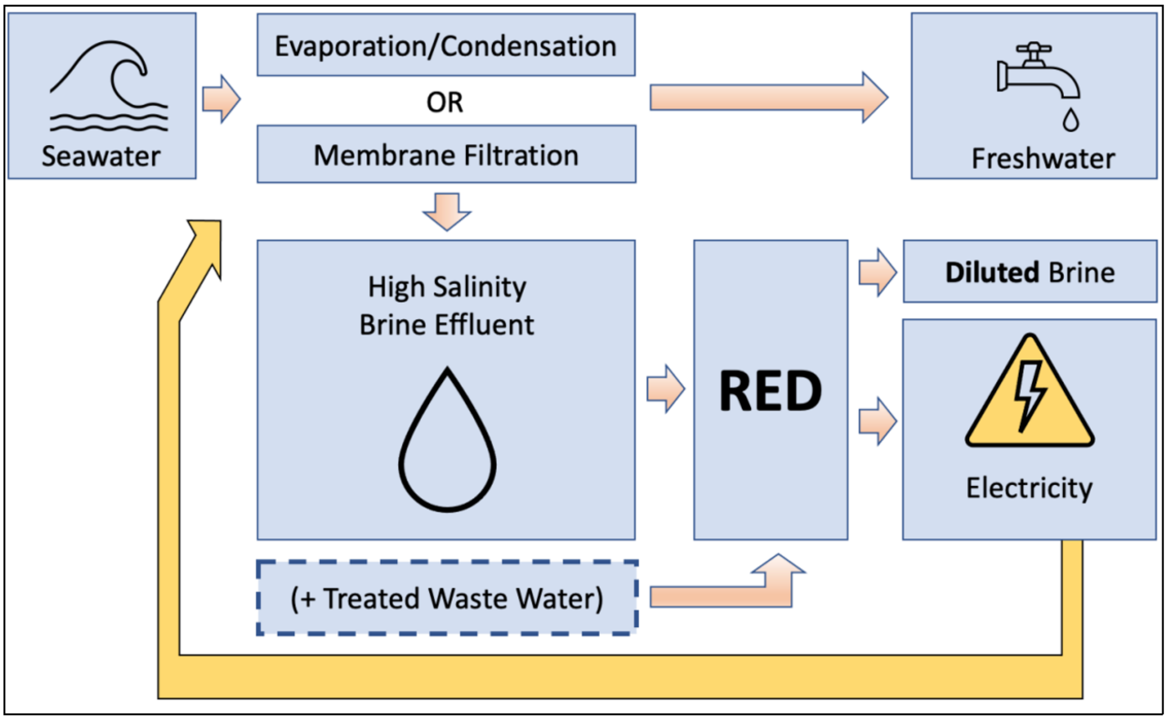

Figure 2 Schematic of the Seawater Desalination Process and Integration of the Output with the RED System [9].

2. Material and Methods

Sample Collection and Identification

Samples were collected to measure key parameters such as pH, temperature, salinity, total dissolved solids (TDS), total suspended solids (TSS), and electrical conductivity (EC). The results serve as primary data for comparison. Brine was collected from the reverse osmosis (RO) system effluent at the Konarak desalination station. The collection process followed scientific protocols to ensure sample accuracy. The main steps included:

Sampling Site: Konarak was chosen for its accessibility and relevance to the study, providing continuous RO effluent for the hybrid RO and RED system under investigation.

Sample Collection: Two liters of brine were collected directly from the RO system discharge using clean plastic containers to prevent contamination.

Sample Preservation: Samples were sealed and stored at 4°C to maintain chemical composition and transported to the lab under controlled conditions.

Initial Analysis: Preliminary analysis was conducted on-site to determine initial physical and chemical characteristics such as pH, salinity, and temperature.

2.1Temperature and pH Measurement

Temperature and pH of the collected brine samples were measured immediately after collection to ensure accuracy. A calibrated thermometer was used for temperature readings, recorded in degrees Celsius. pH was determined using pH test paper, with color changes compared to a standard chart for documentation[10].

2.2Salinity Measurement

Salinity of the brine samples was measured using a handheld refractometer. A drop of each sample was placed on the prism, and readings were taken under light to ensure consistent and accurate measurements. Salinity values were recorded immediately after measurement[11].

2.3Total Dissolved Solids (TDS) Measurement

TDS of the RO effluent was determined by gravimetric method using:

Oven (Parsian Teb)

Digital Scale (Acculab)

Filtered samples were placed in pre-weighed evaporation dishes and dried in an oven at 180°C until constant weight was achieved, indicating complete evaporation. The TDS concentration was calculated by subtracting the initial dish weight from the final weight and expressed in mg/L[12].

2.4Total Suspended Solids (TSS) Measurement

TSS of the RO effluent was determined using UV-Visible spectrophotometry (Hach). Samples were filtered to remove larger particles, and the absorbance was measured at a specific wavelength. A calibration curve with known concentrations was used to calculate TSS, expressed in mg/L[13].

2.5Electrical Conductivity (EC) Measurement

EC of the RO effluent was measured using a multiparameter photometer (POmeter) following the standard method St.M.2510. The device was calibrated with a standard potassium chloride solution, and EC readings were taken using a probe[14].

3. Results

3.1 Key Findings of RED Experiments for RO Concentrate Treatment

Temperature and pH Measurement

The temperature and pH of brine samples from the Konarak RO unit were measured and recorded as follows:

Temperature: Both samples had a temperature of approximately 25°C.

pH: Both samples had a pH level of approximately 6.

The stability of temperature and pH in both samples indicates stable brine conditions, making them suitable for reverse electrodialysis (RED) feasibility studies.

Salinity Measurement

Salinity of the brine samples was determined using a refractometer and recorded as Brix percentages at 20°C:

Sample 1: Salinity measured at Brix 20%, with a value of 4.9.

Sample 2: Salinity also measured at Brix 20%, with a value of 4.9.

The uniform chemical composition of the brine samples indicates their suitability as feed for the RED system.

Total Dissolved Solids (TDS) Measurement

TDS of the RO effluent was determined as follows:

Calculation: TDS concentration was calculated by measuring the weight of the residue remaining after the evaporation of water from the RO effluent sample.

Result: TDS concentration was approximately 43,744 mg/L, indicating a high level of dissolved solids, which is typical for RO effluent.

Total Suspended Solids (TSS) Measurement

TSS of the RO effluent was determined using spectrophotometry:

Calculation: TSS concentration was calculated by measuring the sample's absorbance and comparing it to a pre-determined calibration curve.

Result: TSS concentration was approximately 2 mg/L, indicating low levels of suspended solids in the sample.

Electrical Conductivity (EC)

EC of the RO effluent was measured using a calibrated multiparameter photometer (POmeter) following standard method 2510 B (St.M.2510 B):

Result: EC was approximately 5,700 µS/cm, indicating relatively high concentrations of dissolved salts and ions. This level of conductivity suggests significant mineral contamination, consistent with the expected characteristics of RO effluent.

4. Analysis and Discussion

Temperature and pH Stability Temperature and pH measurements of brine samples from the Konarak RO unit showed significant stability, with both samples having a temperature of approximately 25°C and a pH level of around 6. This stability is crucial for the feasibility of the reverse electrodialysis (RED) process as consistent temperature and pH prevent variations that could impact the system's efficiency and effectiveness[15].

Uniformity of Salinity Levels Salinity measurements using a refractometer showed a consistent salinity level of 4.9 Brix for both samples. This uniformity in chemical composition is vital for the RED system as it ensures consistent osmotic pressure across the membrane, which is essential for maximizing energy production and treatment efficiency[16].

High Total Dissolved Solids (TDS) The TDS concentration in the RO effluent was approximately 43,744 mg/L, indicating a high level of dissolved solids, which is typical for RO effluents. High TDS levels necessitate efficient post-treatment processes like RED to manage the environmental impacts of RO brine disposal. Additionally, the high TDS concentration indicates a significant potential for resource recovery, as the brine can be a source of valuable minerals and salts[17].

Low Total Suspended Solids (TSS) TSS concentration was around 2 mg/L, indicating low levels of suspended solids in the RO effluent. Low TSS levels are advantageous for the RED system as they minimize the risk of membrane fouling and deposition, which could negatively impact the system's efficiency and operational lifespan. This low TSS level also indicates efficient pre-treatment and filtration processes in the Konarak RO unit[18].

Electrical Conductivity (EC) EC of the RO effluent was measured at approximately 5,700 µS/cm, indicating high concentrations of dissolved salts and ions. This high EC level corresponds with the high TDS concentration and indicates significant mineral content in the effluent. Elevated EC levels can pose challenges for brine disposal due to potential toxicity but also present opportunities for energy production through processes like RED that can utilize the ionic content of the brine to generate electricity [19].

Implications for RED Feasibility The stability of temperature, pH, and salinity levels, along with high TDS and low TSS concentrations, indicate the suitability of the Konarak RO unit effluent for treatment using the RED system. The stable brine conditions ensure predictable and efficient operations, while the high ionic content provides the potential for energy generation. Low TSS levels also enhance the implementation of the hybrid system by reducing the likelihood of membrane fouling and extending the operational lifespan of the RED system. Overall, the findings suggest that the implementation of the RED system for treating RO brine is likely to be successful, offering benefits of resource recovery, environmental sustainability, and energy production [20].

4.1 Proposed Reverse Electrodialysis (RED) System Design

4.1.1 System Configuration

The proposed RED system for the Konarak desalination station seeks to transform the high-salinity brine. Previously deposited into the Persian Gulf, into a valuable resource for electricity generation. By utilizing the RO brine as the concentrated solution and seawater or treated brackish water as the low-concentration solution, the system capitalizes on the natural ionic gradient between these fluids. The design consists of ion-selective membranes arranged in alternating compartments, engineered in a way to maximize ionic movement and enhance electricity production. This configuration optimizes ion transport while minimizing energy losses, thereby improving overall system efficiency.

The proposed RED unit features several key technical specifications designed to optimize performance. It employs an alternating arrangement of cation and anion exchange membranes to facilitate selective ion transport, effectively channeling ions and enhancing electricity generation. With an effective membrane area of approximately 10–15 m^2, the system provides a substantial surface for energy production. The operating temperature is maintained at 25 °C, aligning with the brine's natural temperature to eliminate additional thermal requirements and improve energy efficiency. By leveraging the high total dissolved solids (TDS) of 43,744 mg/L present in the RO brine, the system creates a significant ionic concentration differential that drives the reverse electrodialysis process. The expected power output is estimated between 0.5 and 1.0 W per square meter of membrane area, contributing meaningfully to the facility's energy needs.

4.1.2 Performance and Integration

Integrating the RED system directly with the existing Konarak desalination infrastructure allows for seamless operation and resource utilization. By converting the high-salinity brine into electrical energy, the system addresses two pressing issues: effective brine management and the generation of renewable energy. The low total suspended solids (2 mg/L) in the brine reduce the risk of membrane fouling, enhancing the RED system's operational lifespan and reliability. This integration not only optimizes the use of existing resources but also streamlines the overall process, making it more sustainable and cost-effective.

4.1.3. Environmental and Economic Benefits

The implementation of the RED system offers numerous advantages, including transforming RO brine into a source of clean energy, thereby contributing to the facility's power supply. It minimizes the challenges associated with brine disposal, reducing the ecological footprint of the desalination process. Additionally, the system converts waste into a valuable asset, promoting sustainable resource management practices. The electricity generated can partially power the desalination process, which helps reduce operational costs and dependence on external energy

5. Conclusion

In conclusion, the integration of Reverse Electrodialysis (RED) with seawater desalination units (SWDU-RED) presents a promising solution to address the dual challenges of water scarcity and environmental sustainability. By utilizing the high-salinity brine generated from Reverse Osmosis (RO) desalination, the RED system not only mitigates the environmental impact of brine discharge but also harnesses salinity gradient energy to produce renewable electricity. Experimental results demonstrate the feasibility of this approach, with stable temperature, pH, and salinity levels in RO brine samples, alongside high total dissolved solids (TDS) and electrical conductivity (EC) that are conducive to energy generation. The low total suspended solids (TSS) further enhance system efficiency by minimizing membrane fouling.

The proposed RED system presents an innovative solution that enhances both environmental sustainability and economic efficiency at the Konarak desalination station. By turning a waste byproduct into a resource for renewable energy, the facility can achieve greater self-sufficiency and contribute positively to sustainable development initiatives. This approach represents a meaningful step toward a more sustainable and resilient future in water management.

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