Reverse Electrodialysis Technology installation in KwaZulu-Natal coastal region: A modelling study using COMSOL Multiphysics.

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***Abstract*—**Due to high export demand, Sub-Saharan Africa's South Africa is a rapidly developing nation. This has, however, led to a sharp increase in energy demand. Since most industries are experiencing increased production demand, Eskom, the state-owned entity, has been put in more stress. The Energy and Environmental Affairs Ministry has been receiving energy and environmental concerns from citizens. Since the COP21 deal was signed, renewable energy technologies have emerged as alternative energy mix technologies for substantiating Eskom's grid. This has alleviated environmental worries. Emerged renewable technologies include reverse electrodialysis. In South Africa, the technology's advantage of minimizing waste while producing electricity has drawn the interest of research groups in academia and engineers in the industry. KwaZulu-Natal has an untapped resource of blue ocean energy that could be used with this technology. A high salinity gradient can produce high energy due to the high salinity gradient found along the coast. A preliminary assessment of the location where the technology might be installed is the purpose of this paper. Based on the maximum power production, the selection was made. Different streams in coastal KZN, which feed the ocean, have salinity gradients that differ. Tugela, Mgeni, Mvoti, Mfolozi, and Amanzimtoti are among the streams that are considered for technology installation. This paper present results obtained through COMSOL Multiphysics software, based on salinity gradients, for decision-making.

***Keywords*—**Salinity Gradient, Reverse Electrodialysis, Energy, COMSOL Multiphysics.

I. INTRODUCTION

One of the biggest problems the entire globe is dealing with is the generation of sustainable energy. In 2050, it's anticipated that there will be a massive 80% increase in the world's energy demand[1]. Due to global warming concerns caused by the burning of fossil fuels and the increasing demands of energy, environmentally friendly strategies and technologies are being developed to ensure sustainable and alternative energy sources. Utilizing renewable energy sources is one approach to the problem. Salinity gradient energy or blue energy may hold the solution among them. This renewable energy source generates energy from two aqueous natural solutions with different salt concentrations, utilizing an alternative set of anion exchange membranes (AEM), and cation exchange membranes (CEM), through reverse electrodialysis (RED), and this technology is recognized as an attractive membrane-based process[2], [3]. The membranes are packed to be a stack and each stack consists of cell pairs that consist of ion exchange membranes (AEM, and CEM). Salinity gradient energy or blue energy is a renewable energy source that has an estimated global theoretical potential of 1.4-2.6 TW[4], [5], and approximately 1 TW is considered technically retrievable from the theoretical potential[6], [7].

Figure 1 shows the diagram of a reverse electrodialysis stack for salinity gradient energy production, including the electrodes, at which redox reactions occur to change the ionic current into electron current. Pattle in 1954 was the first person to generate power from mixing fresh water and salty water in hydroelectric pile made up of alternate 47 cation exchange membranes and anion exchange membranes, the obtained power density was 0.2 W/m^2 at 39 °C [8], the results demonstrated that the pile was more likely to be economically viable in a warm environment or increased temperature because a higher internal resistance and lower power output were obtained at low temperatures[1].

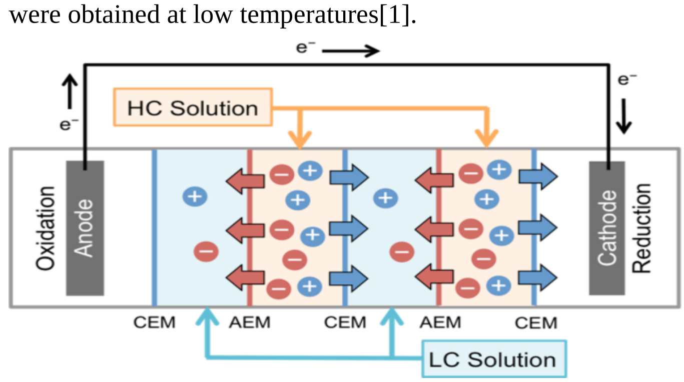

Figure 1: Schematic diagram of the reverse electrodialysis process[9]
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There are two main performance indicators for the generation of electricity using reverse electrodialysis: the power density and the energy efficiency in percentage. The power density index has previously and currently been recognized as a crucial parameter for both large and pilot-scale application of reverse electrodialysis [10], [11]. Current research shows improvements results regarding power density out put through optimized stack design[12],[13].

Salinity gradient or blue energy is considered as a promising renewable energy because of the abundant salty water resources over the world[14], [15]. Several research have been conducted regarding the construction of pilot plant and large-scale plants fer the reverse electrodialysis technology in countries such as Netherlands, Italy [16]. Joao Nunes Guimaraes[17], used five major rivers in Portugal (Douro estuary, Mondego estuary, Tejo estuary, Sado estuary, and Guadiana estuary), to find the potential of salinity gradient energy production, amongst these five revers the Douro estuary was concluded to have high potential then the others.

However, despite the significant advancements made throughout the reverse electrodialysis development during these years, there were still several significant obstacles to be overcome regarding the technical and financial viability of the large-scale implementation of this technology. The cost of this technology is a very important parameter for commercial application. A crucial factor is to lower the cost of manufacturing membranes.

Aim of this work was to investigate the potential, existing in KwaZulu-Natal, of salinity gradient energy and to estimate cost of the reverse electrodialysis pilot plant construction in one of the five major rivers that have high potential of producing this renewable energy theoretical. Also, to optimize and simulate the reverse electrodialysis pilot plant.

II. METHODOLOGY

A. Software

The simulation and optimization in this study was carried out with the COMSOL Multiphysics software. COMSOL Multiphysics was chosen for its ability to enables you to simulate electromagnetics, structural mechanics, acoustics, fluid flow, heat transfer, and chemical phenomena in one environment, following one workflow. The application builder in the COMSOL Multiphysics software makes it possible for simulation specialists to create easy-to-use simulation apps and deploy them within or outside of their organizations with COMSOL server and COMSOL compiler.

B. Process model description

Energy balance

The feed water entering a reverse electrodialysis stack shows or represents a certain amount of exergy or potential energy for a salinity gradient energy[18].

$$U = 2RT\left[C_D Q_D \ln\frac{C_D(Q_C+Q_D)}{C_D Q_D + C_C Q_C} + C_C Q_C \ln\frac{C_C(Q_C+Q_D)}{C_D Q_D + C_C Q_C}\right]$$

Where U is the energy flow rate of the feed or the potential energy, R is the gas constant (8.314 J/mol. K). Temperature (K), Q_D, and Q_C flow rate of river and sea water (m^3/s) and C_D and C_C the salt concentration in the river and sea water (mol/m^3).

After estimating the potential energy of the five major rivers, the second step is to use the information of the river that produced the highest potential energy to design pilot plant by estimating a suitable membrane area through calculations using the design equations listed below which are found in literature.

Unit cell open circuit potential (E_{op}): it is the membrane potential voltage (V) for a cell pair (CEM, AEM) with no losses considered. The modified Nernst equation can be used to describe the electrochemical potential difference across an IEM placed between two different concentration solutions[19].

$$E_{op} = (\alpha_{CEM} + \alpha_{AEM}) \cdot \frac{R\cdot T}{F} \cdot \ln\left(\frac{C_{Sw}\cdot\gamma_{Sw}}{C_{Rw}\cdot\gamma_{Rw}}\right) \quad (2)$$

α is the perm selectivity of IEMs measured at concentration C_{Sw} and C_{Rw} at constant temperature 293 K for specific membrane. For both perm selectivity, assumed to be same for both membranes. F is the Faraday constant. T is room temperature. R is the ideal gas constant.

Area specific membrane resistance (R_{AEM} and R_{CEM}): It is the ohmic resistance (Ωm^2) of the membranes when immersed in the solution. It is expressed as function of concentration[19].

$$R_{CEM} = R_{AEM} = r_1 \cdot (C_{Rw})^{-0.236} \quad (3)$$

R_{CEM} and R_{AEM} are area specific membrane resistances for cation and anion exchange membrane, C_{Rw} is inlet concentration of river water or low concentration solution. r_1 is fitting parameter ($\Omega m^2/M$). It is estimated to be 0.0002 ($\Omega m^2/M$) for present and market scenario and 0.00004 ($\Omega m^2/M$) for future scenario[19].

Unit cell resistance ($R_{u.c}$): The cumulative sum of resistance of membranes and channels in a unit cell (Ωm^2).

$$R_{cell} = R_{CEM} + R_{AEM} + R_{Rw} + R_{Sw} \quad (4)$$

Channel ohmic resistance or compartment resistance (R_{Rw}, R_{Sw}): The resistance (Ωm^2) due to the solution in the channel and spacer geometry. It depends on concentration[20].

$$R_{Rw} = f_{Rw} \cdot \frac{\delta_{Rw}}{\Lambda_{Rw} C_{Rw}} \quad R_{Sw} = f_{Sw} \cdot \frac{\delta_{Sw}}{\Lambda_{Sw} \cdot C_{Sw}} \quad (5)$$

Where δ_{Sw} and δ_{Rw} is the intermembrane distance in (μm), Λ_{Sw} and Λ_{Rw} are the conductivities of the sea water and river water.

Current density at peak power (I_{PP}): The peak power current density occurs at potential half the open circuit potential. As the resistance remains constant the current density (A/m^2) at peak power is calculated using the following equation[19]:

$$I_{PP} = \frac{E_{op}}{2 \cdot R_{cell}} \quad (6)$$

Actual unit cell potential (E_T): The unit cell potential is calculated using the following equation[19]:

$$E_T = E_{op} - R_{cell} \cdot I_{PP} \quad (7)$$

Number of unit cell (N_m), the minimum number of cell pairs to be stacked in series is calculated as follows[21]:

$$N_m = \frac{1.5}{E_T} \quad (8)$$

The overall electromotive force (EMF), (V) is calculated using the following equation[20]:

$$EMF = NE_T \quad (9)$$

The internal stack resistance (R_{stack}, Ω) is defined as[20]:

$$R_{stack} = N \cdot (R_{cell}) + R_{electrode} \quad (10)$$

Where $R_{electrode}$ is the electrode resistance (Ω). The resistance of the electrode system is ascribed to the Nernst voltage of the redox reaction, to overpotential and to ohmic part in the solution. The resistance of the electrodes system can be neglected here considering the operability of reverse electrodialysis on a large scale[10].

The stack gross power (P_{gross}, W) is given as the current times the terminal voltage in the following equation[20],

$$P_{gross} = I \cdot U \quad (11)$$

Where I is the current (A) and U is the terminal voltage (V). The electrical current I can be deduced from the electrical circuit from the EMF, internal stack resistance R_{stack} and external load resistance R_{load}. The terminal voltage is a function of the EMF, the current and the stack's internal resistance[20],

$$I = \frac{EMF}{R_{stack} + R_{load}} \quad (12)$$

$$U = EMF - I \cdot R_{stack} \quad (13)$$

Therefore, the power produced by the stack depends on the value of the EMF and the internal stack resistance. By using Ohm's law and equations 11, 12 and equation 13 becomes[20]:

$$P_{gross} = I^2 \cdot R_{load} = \left(\frac{EMF}{R_{stack} + R_{load}}\right)^2 \cdot R_{load} \quad (14)$$

The maximum power (P_{max}, W) is achieved when the terminal voltage is equal to half of the EMF and if the resistances are equal ($R_{stack} = R_{load}$) and the equation becomes:

$$P_{max} = \frac{EMF^2}{4 \cdot R_{stack}} \quad (15)$$

The gross power is divided by the total active (ion exchange) membrane area installed ($A_{membrane}, m^2$), this is called power density (P_d, W/m^2) and is calculated by the following equation[20].

$$P_d = \frac{P_{gross}}{A_{membrane}} \quad (16)$$

III. RESULTS AND DISCUSSION

This chapter present the result of the annual potential energy assessment of electricity production in the following estuaries: uThukela, Mgeni, uMvoti, uMfolozi, Amanzimtoti. The annual potentials were calculated based on equation (1), assuming that the temperature of sea and river water is 25℃. To calculate the potential energy, the flow rates and salinity concentrations of the five major rivers or estuaries were required and were found in the department of water affairs. The value adopted for the concentration of sea water was 600 mol/m^3.

However, the flow rate found in the Department of water Affairs for the rivers were not constant due to the rain falls which is not constant due to the climate issues, the annual average flow rate was used to perfume calculations. It is important to highlight that the salinity data for the various estuaries under study are scarce.

This fact made the analysis of the potential energy of each of the sites less accurate. For a better comparison of the theoretical potential in each of the estuaries, the ideal would be to have salinity and flow rate data from the different rivers, all in the same time frame or period. However, due to the lack of salinity or salt concentration data and possible lack of flow rates values for a river in a specific period, it was not possible to compare the five estuaries in the same time frame.

TABLE 1: SHOWS POWER PRODUCED BY EACH OF THE FIVE RIVERS ASSUMING TO UTILIZE ALL THE DISCHARGE OF THE RIVER.

RIVER	POWER (MWh)
Thukela	360.6
Mngeni	31.46
Mvoti	55.59
Mfolozi	13.83
Amanzimtoti	9.61

uThukela Estuary

The salinity in this estuary is predominantly controlled by the flow of the river, this means that for high flows the salinity in the estuary is lower. On the other hand, for low flows the salinity along the estuary is higher(reference). The salinity values used at the estuary mouth refer to January 2018 to December 2022. The theoretical potential energy found in the uThukela estuary was $1.137 \times 10^{16}\ J/y$ which makes it the highest producing of blue energy potential energy estuary and the energy density of $2032958.747\ J/m^3$. However practically this high potential energy may not be possible due to rains, which affect flow rates, this means there are some cases where we would not have flow rates at all due to rains and this potential energy may decrease practically. Also, as it is mentioned that reverse electrodialysis uses membranes, so this membranes practical may experience fouling due to solid particles so the pretreatment of this solid particles will be required practically.

uMvoti Estuary

uMvoti estuary, was second highest estuary in theoretical potential production of blue energy or salinity gradient energy. The theoretical potential energy found was $1.753 \times 10^{15}\ J/y$ with energy density of $2036219.23\ J/m^3$. The flow rate and salinity concentration of this estuary was taken under the Department of water affairs, the data is from 2004 till last year 2022 December.

uMngeni, uMfolozi, and Amanzimtoti estuaries

Theoretical potential energy found on uMngeni estuary was $9.992 \times 10^{14}\ J/y$, and for uMfolozi estuary was found to be $4.36 \times 10^{14}\ J/y$. For the Amanzimtoti the theoretical potential energy found was $3.031 \times 10^{14}\ J/y$. However, the theoretical potential may differ as time goes on due to the climate and weather conditions that affect the flow rates of the rivers and also other rivers in KwaZulu natal such as uMngeni and Amanzimtoti they have a salt concentration which fluctuate during different seasons at some times the salinity concentration is equal to zero and this may affect the production of salinity gradient energy and resulting in low electricity production.

IV. Conclusion

Based on the findings it is concluded that salinity gradient may have a chance to meet a notable amount of energy demands in KwaZulu Natal. Also, it is concluded that using the energy produced by reverse electrodialysis to power up pumps for pumping water to the reverse electrodialysis to treat water and produce power could be a suitable idea since, you are cutting up cost by treating water and at the same time producing electricity that can be used to power up pumps for the same plant. For water usage the energy production will not compete with it since water is collected at the discharge point of the river.

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