Salinity gradient energy in Colombia: an efficiency analysis

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I. INTRODUCTION

The most representative situation for obtaining energy from salinity gradient (SGE), is one that which involves seawater as concentrated solution and freshwater from rivers as diluted solution. Feasibility of an energy harnessing project relies on individual evaluations foreach point of freshwater discharge. In fact, the spatial and temporal behavior of the salinity gradient and the availability of freshwater play a key role in the gross energy potential [1]. Additionally, the status of the technology for the conversion of the salinity gradient also must be considered when an implementation of any SGE project is evaluated.

Therefore, a feasibility analysis for the implementation of a SGE project requires a methodology that quantitatively supports the decision-making regarding the profitability of the energy generation in terms of the energy consumed and/or the net energy produced in the conversion process at the plant while maintaining the salinity gradient as stable as possible.

Here, an efficiency analysis for several river mouth systems located on the Caribbean and Pacific coasts from Colombia is presented. Our analysis includes the facility locations used for the energy conversion as well as the points for intake and discharge streams. We also provide the performance of the PRO and RED technologies, and the estimation of the net energy.

Accordingly, the feasibility of using plants to convert energy from the salinity gradient in Colombia is evaluated by estimating the technical potential, which includes the selection of suitable locations for the intake and discharge of the streams, the projected capacity of the main technologies for the conversion of the salinity gradient, as well as the estimation of energy consumption during the process, which determines the efficiency of the conversion for each river mouth system.

II. METHODS

The properties of the seawater, specifically salinity and temperature at different depth levels, are considered using the information from the Global Ocean Physics Reanalysis GLORYS12V1 [2], including daily average values from 1993 onwards. The salinity and temperature from several river mouths from Colombian coasts were obtained from the report of Red de Vigilancia para la Conservación y Protección de las Aguas Marinas y Costeras de Colombia – REDCAM and Instituto de Investigaciones Marinas y Costeras "José Benito Vives De Andréis – INVEMAR [3], values measured at the river mouth and/or near to this reference. The volumetric flow at the river mouth from several rivers in Colombia was reported by Restrepo and Kjerfve [4], including values from 1963 until 1995.

The net energy generated in a SGE plant was estimated from the effective potential, which includes the inefficiencies and energy losses in the conversion according to the technology used for the conversion. This effective potential depends on the theoretical potential, which is estimated as a function of the technology. The theoretical potential for Pressure Retarded Osmosis (PRO) and Reverse Electrodialysis (RED) (the main technologies for the conversion of the salinity gradient) is computed from (1) and (2), respectively [5]:

$$\Delta\pi = \frac{2\mathrm{R}}{\mathrm{PM}_{\mathrm{NaCl}}}\left((\mathrm{T}\cdot\mathrm{S})|_{\mathrm{concentrated}}\text{-}(\mathrm{T}\cdot\mathrm{S})|_{\mathrm{diluted}}\right) \tag{1}$$

$$\Delta\phi = (\Delta G_{\mathrm{diluted}} + \Delta G_{\mathrm{concentrated}}) - \Delta G_{\mathrm{Mix}} \tag{2}$$

where,

$$\Delta G_i = CRT\left(x_{\mathrm{NaCl}} \ln(x_{\mathrm{NaCl}}) + x_{\mathrm{H_2O}} \ln\left(x_{\mathrm{H_2O}}\right)\right) \tag{3}$$

The effective osmotic potential includes the fact that the support of the semipermeable membrane increases the NaCl concentration, decreasing the osmotic gradient. Therefore, a support resistance (k) and the volumetric flux of pure water (J_w) are used as described in (5) [5].

$$\Delta\pi_{eff} = \pi_{\mathrm{concentrated}} - \pi_{\mathrm{diluted}} e^{kJ_w} \tag{4}$$

The volumetric flux can be evaluated from the effective net driving force and the permeability coefficient of the membrane (A_w) (view (6)).

$$J_w = A_w\left(\Delta\pi_{eff} - \Delta p\right) \tag{5}$$

The permeation coefficient for hollow fiber membranes, the most used in PRO applications, can be estimated using (7),

$$A_w = i\left(\Delta\pi_{eff} \cdot 1 \times 10^{-5}\right)^j \qquad (6)$$

where, i and j represent experimental parameters. For instance, for a Permasep semipermeable membrane the values of i and j are 2×10–13 and –5×10–8, respectively.

The effective potential of using the RED technology includes the inefficiencies and energy losses in the conversion of chemical potential into electricity. Indeed, a loss of electromotive force in reverse electrodialysis is expected due to the flow of counterions through the membrane. Therefore, the potential must be corrected using the membrane permselectivity coefficient (α), as shown in (8). For instance, permselectivity coefficients of 91% and 92.5% have been reported for Neosepta anionic and cationic membranes, respectively [6].

$$\Delta\phi_{eff} = \alpha\Delta\phi \qquad (8)$$

On the other hand, to include the conversion efficiency through the complete process, a RED cell that can operate at high efficiency is considered. In particular, using dilute and concentrated waters flowing in opposite directions at a volumetric ratio of one, fixing an adequate spacer distance, and by means of multiple segmented electrodes. Thus, the conversion efficiency for RED cells can range from 90 to 95% [6–7]. Therefore, an efficiency of 90% is used in the present study. On the other hand, Yip et al. [8] evaluated the performance of a PRO plant at different conditions, and they reported a conversion efficiency of 80% (not including pretreatment of waters) when the volumetric flow of concentrated water is two times the volumetric flow of the diluted water and for treated waters, whose value is used in the present study.

The energy consumption in a SGE plant includes the water pre-treatment of the intake streams and the water transport from the intake points (freshwater and seawater) until the plant and from the plant until the discharge point (brackish stream). For the pre-treatment, properties such as the quality of output water, the plant size for water pre-treatment, the environmental impact of the process, and the energy consumption are improved when microfiltration is implemented [9–10]. In this study, a microfiltration system reported to treat freshwater and seawater from the north coast of Colombia is used for the analysis, wherein an energy consumption of 0.22 MJ/m^3 was established [11].

The fluid transport can consume high amounts of energy, depending on the design of the pipe network. The conversion of the salinity gradient into electricity is performed on stacks for PRO and RED technologies. The number of stacks depends on the installed capacity at each point. It is particularly important because each river mouth system has its own potential. Besides, the layout of the stacks impacts the energy consumed transporting the streams of the process. The design reported by Keilpt was considered for the PRO technology [12], as shown in Fig 1.

In the case of RED technology, the design proposed by RedStack (the main company developing the RED technology and who is currently scaling-up a prototype) is used, where the multi-cell arrays with a similar configuration to the PRO module with manifolds connecting the cells are located on a commercial container leading to units of 200 kW [12]. In these units, there is expected to be a hydrodynamic loss of around 25% of the electrical power [13].

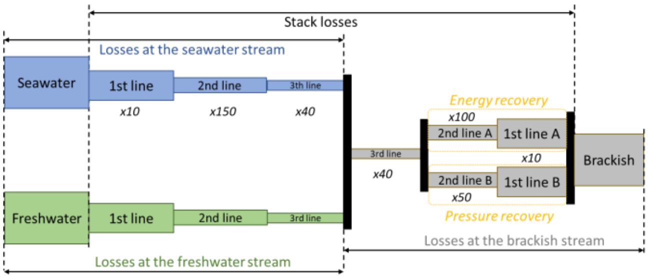

Fig. 1. Design of PRO stack for the conversion of the salinity gradient. The design includes the configuration of the network.

Thus, the energy required to transport the water streams is estimated according to the fluid properties (seawater, freshwater, and brackish) and the pipe characteristics (size and material) for each line, according to the equation of friction losses for pipelines, including the friction factor of Darcy-Weisbach (see (9) and (10).

$$\Delta P_{\mathrm{L}} = f\,\frac{L}{D}\,\frac{\rho V^2}{2} \qquad (9)$$

$$W_{\mathrm{Bomba}} = Q\Delta P_{\mathrm{L}} \qquad (10)$$

A realistic energy consumption in fluid transport can be estimated according to the performance of a water pump with an efficiency factor of 0.95.

The installed capacity for each point is determined according to the annual average volumetric flow of the river at the river mouth and a realistic capacity of the plant (i.e., maintaining the upper limit of the capacity as that observed in theoretical designs, for instance, 200 MW), selecting values that do not exceed the limit for the environmental flow (although this value is specific for each site, it is assumed that only 10% of the annual average volumetric flow can be used for an energy project [14]).

In addition, a power plant downtime outfall of around 0.6% of the installed capacity is expected for a SGE plant [14], which was also implemented in the present work.

Finally, to obtain a stable and high salinity gradient during the operation of the plant, the location of the seawater and freshwater intakes, the discharge of the brackish, and the possible location of the plant must be selected. This selection involves a minimization of the distance and the height between these points and a maximization of the salinity gradient among seawater and freshwater, avoiding the circulation of brackish into the river mouth system.

III. RESULTS

The selected river mouth systems for the analysis, their annual average volumetric flow at the river mouth, the distances between the plant and the intake and discharge points, and the height difference between the water intake and discharge points and the plant surfaces are shown in Table I. Greater distances and heights for Pacific sites

TABLE I
MAIN PROPERTIES OF RIVER MOUTH SYSTEMS AND FACILITIES

River Mouth System	River Discharge (m^3/s)	Distance to seawater intake (km)	Distance to freshwater intake (km)	Distance to brackish water discharge (km)	Plan altitud (m.a.s
Magdalena	7233	2.0	0.1	1.0	4
Canal Dique	299	1.5	1.5	0.3	2
Ranchería	12.4	6.3	0.1	2.5	4
Mira	743	1.9	3.4	1.1	12
Chagüi	134	27.8	0.3	0.5	15
Dagua	126	36.9	0.5	1	9

TABLE II
EFFECTIVE POTENTIAL AND NOMINAL POWER FOR SELECTED RIVER MOUTH SYSTEMS

River Mouth System	$\Delta\pi_{eff}$ (MW/m^3)	$\Delta\phi_{eff}$ (MW/m^3)	Freshwater flow (m^3/s)	Nominal power (MW)
Magdalena	2.444	1.788	150	200
Canal Dique	2.254	1.524	20	36
Ranchería	2.257	1.565	1.0	1.0
Mira	2.538	1.815	21.0	36
Chagüi	2.446	1.892	13.0	19
Dagua	1.600	1.189	12.0	19

(Mira, Chagüi, and Dagua) than those for river mouth systems from the Caribbean can be appreciated in Table I.

The difference in salt concentrations and the freshwater availability are the main factors influencing the power potential. Fig, 2 displays the historical average of the salinity for the seawater at both surface and 20 m depth and for the freshwater salinity and flow at different river mouths in Colombia.

The seawater salinity at the surface is around 28 g/l at the Pacific coast and ranges from 30 to 35 g/l at the Caribbean coast. At 20 m depth, the seawater salinity displays values larger than 35 g/l in all cases. The freshwater salinity depicts higher values for river mouths in the Pacific than those on the Caribbean coast.

The effective potential (for PRO and RED technologies), the flow selected for each river mouth system, and the nominal power of a plant are presented in Table II.

The highest potentials are for the river mouth systems at Mira, Chagüi, and Magdalena, at the selected intake and discharge points. This is due to the high salinity gradient and water temperature at these sites. Additionally, the potentials for PRO are larger than that those for RED, probably due to the necessity of more restrictive membranes in the case of the RED technology (i.e., semipermeable and ion exchange membranes for PRO and RED, respectively).

The flow of freshwater (i.e., the limit flow of the process) is only near to the 10% of the annual average volumetric flow for the Chagüi, Dagua, and Ranchería river mouth systems, whereas the volumetric flows for energy conversion for Mira and Canal del Dique were limited to the capacity of the reported plants (<40 MB). The flow selected for Magdalena is lower than 2% of the annual average volumetric flow, whose value was limited by the maximum capacity reported (200 MB) for the design of a SGE plant.

The Fig. 3 shows the potentials of PRO and RED technology, the energy consumption for water pre-treatment, and transport, the energy used in the salinity gradient conversion, and the power plant downtime outfall expected for a SGE plant.

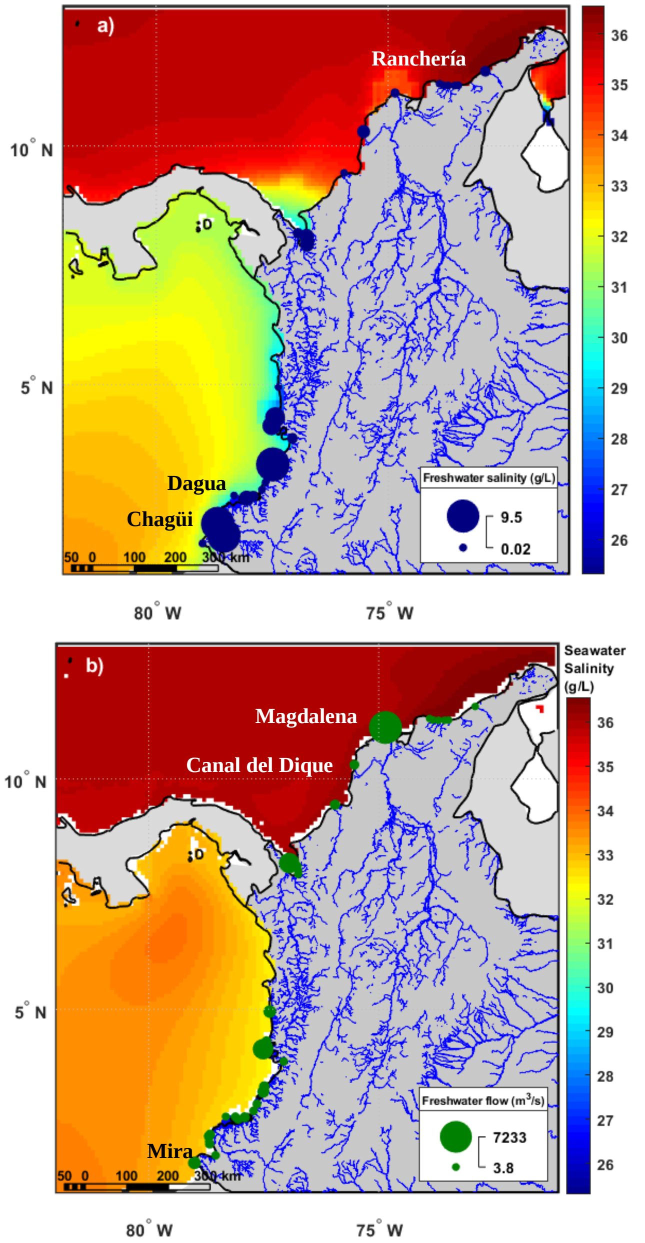

Fig. 2. Salinity for the main river mouths (bubbles) and seawater (color map) from Colombia. The seawater salinity is presented at the surface (above) and at 20 m depth (below). At 20 m the salinity is higher with low spatial (and temporal) variation. Additionally, the freshwater salinity in the Caribbean is lower than that in the Pacific, whereas the Pacific region has a higher number of river discharge systems.

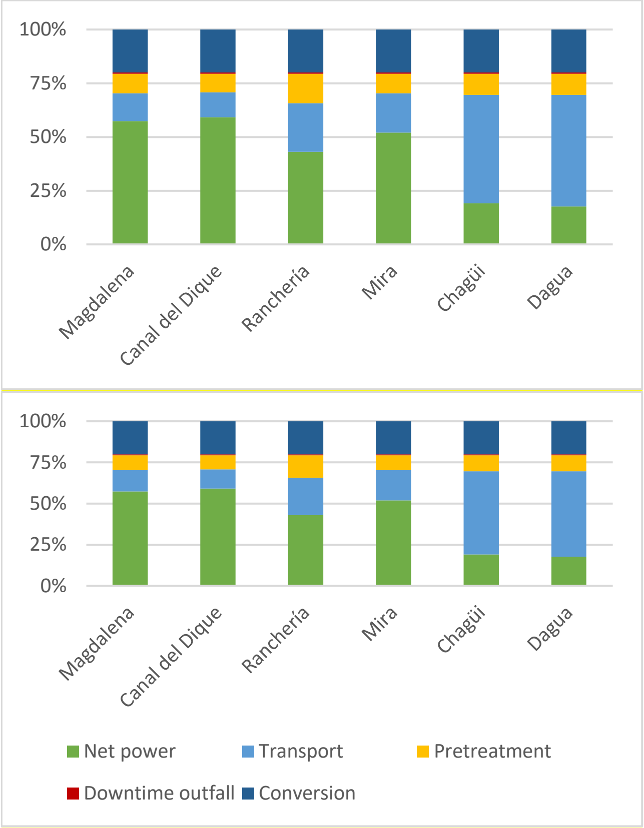

Fig. 3. Net energy for some river mouth systems in Colombia was estimated with PRO (above) and RED (below) technologies. The differences in energy consumption among these technologies are compensated in the conversion of the salinity gradient, leading to similar net powers for both PRO and RED technologies.

Chagüi and Dagua river mouth systems possess water quality and recirculation processes, as well as site properties that involve high energy consumption in the salinity gradient conversion. Indeed, the potential energy generated is barely enough for the operation of a RED plant, and the percentage of net energy from a PRO plant is low (<20%), indicating unfavorable conditions for a SGE implementation.

Magdalena and Canal del Dique are river mouth systems with high potential for a SGE implementation because the net power from PRO and RED technologies was estimated to be around 58% and 61% of the installed capacity, respectively. Mira River exhibits around 50% of recovered energy, suggesting a potential of application despite the long pipe networks needed to transport the water streams from and to the conversion plant. In the case of Rancheria River, the net power accounts for 40% of the initial power, which can be considered a promising value, but the capacity at the site is low (up to around 1 MW of installed capacity).

IV. DISCUSSION & CONCLUSION

The greater distances and plant altitudes for river mouth systems from the Pacific coast compared to those for Caribbean sites are shown in Table I can be attributed to the high recirculation of waters in the Pacific due to the high tidal stream and the low river discharge. Even so, it can explain the longer distances for Ranchería river mouth than those for Magdalena and Canal del Dique. In fact, the larger values of salinity for river mouths in the Pacific than those on the Caribbean coast can be attributed to the considerable effect of the tidal stream and the local geography at each point. Most of the rivers discharge their water into systems such as bays or coves along the Pacific coast. Thus, the depth of the rivers at their mouths is usually low. Additionally, a mean tidal range larger than 1 m for the Pacific Sea has been reported on the Colombian coast [15] (i.e., the southern Colombian Pacific is a meso-tidal zone with a semidiurnal tidal regime of 2.47 m ± 0.61 m [16]), suggesting the possibility that the tidal forcing overlaps the buoyancy forcing, increasing the occurrence of weakly stratified structures. Meanwhile, a microtidal range ranging from 0.2 to 0.4 m of tidal amplitude has been reported for the Caribbean Sea at the Colombian coast [17], which is most appropriate to observe stratified structures at the river mouths. In any case, the local geography and the behavior of the river play a key role in the water circulation at the river mouth system.

Consequently, the water circulation at the river mouth system impacts the gap distance between the intake points of freshwater and seawater and the discharge point of brackish water, influencing the energy used to transport these streams. Therefore, adequate selection of the intake and discharge points must be performed based on the stability of the salinity gradient while also minimizing the distance between these points and the conversion plant.

Although the results shown here are consistent with those reported in previous studies [18], the methodology proposed in the present work includes the quantification of the net power, the selection of the site for the plant, and the analysis of the technology for the conversion, approaching the efficiency of the entire process, which can be very useful in supporting the decision-making involved in the implementation of SGE projects.

The observed results lead to the conclusion that the methodology presented in this work has a high potential for the evaluation of the technical feasibility of an SGE project, based on salinity gradient behavior, the properties of the site, and the performance of the technology. In particular, the efficiency of the main components of PRO and RED technologies based on the site constraints and the potential that the salinity gradient entails for net power allow a quantitative evaluation of the technical feasibility of a SGE project. In this regard, river mouth systems such as the Magdalena River, Canal del Dique, and Mira River show a high potential for a SGE implementation, including the stability of the salinity gradient, the environmental flow of the river, and the performance of the technology for the energy conversion, including pressure-reduced osmosis and reverse electrodialysis.

The effect of the technology on the net power was minor because the decrease in energy consumption for fluid transport obtained with the RED technology is compensated with an increase in the conversion with ion exchange membranes. This can be attributed to the larger stack losses in RED technology as a consequence of the larger resistance to flow derived from the use of ion exchange membranes rather than that resistance with semipermeable membranes in PRO technology.

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