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A Levelized Cost of Energy (LCOE) Analysis of a Reverse Electrodialysis (RED) Plant in Tuxpan, Mexico

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Abstract

The transition towards low-carbon energy systems requires the adoption of emerging renewable technologies that can diversify energy matrices and reduce greenhouse gas emissions. The present study evaluates the technical and economic feasibility of implementing a Reverse Electrodialysis (RED) plant for Salinity Gradient Energy (SGE) generation on the coast of Tuxpan, Veracruz, Mexico. This area has significant freshwater and seawater resources but high fossil-fuel dependence. A conceptual design was developed considering local hydrological and salinity conditions, membrane performance, and pre-treatment requirements. The analysis applied Levelized Cost of Energy (LCOE) and Net Present Value (NPV) methodologies to six water source combinations. Results indicate that the most favorable scenario, combining effluents from the municipal wastewater treatment plant and the Tuxpan river mouth, achieved the highest potential energy yield. However, high capital (USD 1.54 million) and operational costs resulted in negative NPVs, limiting short-term economic viability. Environmental assessment suggests RED could improve water quality and reduce pollutant discharge, though potential construction and operational impacts require mitigation. Despite current cost barriers, RED integration in coastal regions with similar characteristics offers a promising pathway for clean energy generation and environmental restoration, particularly if coupled with cost-reduction strategies and policy incentives.

Keywords: renewable marine energy; salinity gradient energy; energy production; reverse electrodialysis

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1. Introduction

The use of renewable energy sources has been identified as a key factor in the reduction of carbon emissions and the achievement of the Sustainable Development Goals (SDGs), particularly Goal 7, which aims to ensure universal access to affordable, reliable, sustainable, and modern energy sources [1]. The integration of solar, wind, ocean, biomass, geothermal, and hydroelectric energy sources into the national energy mixes of developing countries has the potential to transform the energy paradigm in these countries, offering profitable, abundant, and reliable energy. However, it should be noted that this transformation will require the complement of battery storage [2,3]. The establishment of sustainable renewable energy production chains tends to stimulate local economies and to reduce long-term costs. Renewable energy can provide a predictable and consistent energy supply with fewer associated risks than fossil fuels, such as volatility in commodity prices [2].

Given the above, the contemporary global context is characterized by a transition in energy production, with a shift from a system reliant on carbon-emitting fossil fuels to one with a lower carbon footprint. Iceland serves as a notable example of this transition, having incorporated renewable energy into its energy mix since the 1980s and now generating 100% of its electricity from hydropower and geothermal energy [4]. In Latin America, Uruguay has emerged as a leader in the generation of electricity from renewable sources, with a matrix comprising 58% biomass, wind, and hydroelectric power [5]. Mexico is advancing in developing a renewable energy industry, but still faces challenges to be overcome. As an example, emissions in Mexico have increased by 63.2% between 1990 and 2017 and are projected to continue increasing until at least 2030. Nevertheless, Mexico is still producing a high volume of greenhouse gases (GHG), the majority of which is carbon dioxide (CO_2) derived from fuel combustion [6]. This stresses the urgent need for the country to switch to clean energy.

The geographical location of Mexico is of particular significance, as it is surrounded by the Pacific Ocean, the Gulf of California, the Gulf of Mexico, and the Caribbean Sea. This strategic positioning renders the country well-suited for the development of marine renewable energy technologies. The latest official report [7] indicates that Mexico, at the end of 2023, had an installed capacity of 89,008 MW, of which 32.04% corresponded to clean renewable energy. Still, there is null contribution of marine energy sources.

Among the available energy sources within the ocean, salinity gradient energy (SGE) is a viable emerging energy conversion technology. SGE is the energy extracted from the mixing of two water sources with different salt concentrations before it turns into free energy [8]. In the context of research and development regarding energy harvesting from salinity gradients, a focus has been placed on two distinct technologies: pressure retarded osmosis (PRO) and reverse electrodialysis (RED). These technologies utilize membranes as separators, thereby facilitating the preferential transportation of specific ions.

Arguably, the largest PRO effort worldwide is located in Seoul, Korea. This is a hybrid system comprising seawater reverse osmosis (SWRO) and pressure retarded osmosis (PRO), which has been in operation for a period exceeding two years. This pilot plant demonstrated that PRO can reduce energy consumption in the SWRO process by approximately 20%, in addition to reducing the dilution of SWRO brine [9]. Similarly, the largest and well-known RED plant is located at the Afsluitdijk in Breezanddjik, The Netherlands, where electricity is produced (~50 kW) and a research facility has also been established (see, for example, [10]). The implementation of technologies such as SGE in Mexico has been identified as a potential solution to mitigating CO_2 emissions [11]. As demonstrated in the research by Gül et al. (2024) [12], PRO has been shown to be more effective in the generation of energy from highly concentrated brines when compared with RED. The latter, on the other hand, has been found to be more favorable in terms of energy generation through the mixing of seawater with river water [12]. Consequently, RED was selected as the most appropriate technology for the case study in the present research.

In order to evaluate the technical and economic viability of SGE, the extant literature has been reviewed, and a consensus has been reached concerning a core set of technical indicators (gross and net power density, VOC, internal resistance, ion-exchange membrane properties, etc.) and techno-economic (LCOE, CAPEX/OPEX) and environmental criteria. As illustrated in Table 1, the available evidence is summarized and provides the basis for comparison in the site-specific Mexican analysis.

Table 1. Technical and economic indicators for the salinity gradient energy system.

Category	Element	Definition/Use	Unit	Reference
Technical indicators	Power density	Power per active membrane area	W·m^{-2}	[13]
	Net power	Usable electrical power of the system	W, kW	[14]
	Open-circuit voltage (VOC)	Upper voltage bound given ionic gradient and membrane selectivity.	V	[13]
	Internal/ohmic resistance	Total resistance (membranes, solutions, spacers)	Ω or Ω·m^2	[13]
	Permselective, conductivity, thickness	Properties of membranes ionic	S·m^{-1}; µm	[13]
	Pumping power	Energy required to circulate streams	W, kW	[13]
Techno-economic/environmental	LCOE	Levelized cost of energy over the project lifetime	USD·MWh^{-1}	[15]
	CAPEX/OPEX	Costs per m^2 and per kW; sensitivity to IEM price/lifetime, cleaning, and electricity costs.	USD	[15]
	Environmental indicators	Impacts of materials and operation	kg CO_2	[16]

Some efforts have been developed to find places in Mexico where SGE may be successfully implemented [17–19]. Among these places, Tuxpan de Rodríguez Cano (from now on Tuxpan), located on the Gulf of Mexico coast, seems to be a viable location. Tuxpan's energy requirements are met by the Adolfo López Mateos thermoelectric power station, which is among the most environmentally detrimental in the nation. The facility is projected to operate six power stations utilizing fuel oil and conventional technology, with an effective capacity of 1750 MW [20]. At present, the pollution emanating from the thermoelectric plant disseminates over a radius of 100 km [21]. The unsustainable energy provision to Tuxpan and its surroundings poses a threat to a minimum of 37 protected species. Furthermore, four types of mangroves and other endemic species are also endangered.

In this context, the purpose of this article is to evaluate the levelized cost of energy (LCOE) and to explore the potential impact of the conceptual design of a saline gradient power plant located on the coast of Tuxpan, Veracruz, Mexico. We investigate how a conceptual design of a saline gradient power plant employing RED technology could contribute to the reduction of carbon emissions and the diversification of the energy matrix. The analysis has identified economic challenges, including high initial and supply costs, but it also highlights the potential of RED implementation to mitigate long-term economic and environmental impacts, making this technology a viable option for energy sustainability.

Specifically, the contributions of the present research can be summarized as follows:

- This study presents the inaugural conceptual analysis of a reverse electrodialysis (RED) plant in Tuxpan, Veracruz (Gulf of Mexico). The region's current electricity generation is predominantly reliant on thermoelectric systems that utilize fossil fuels.
- This research underscores the untapped potential of salinity gradient energy (SGE) in Mexico's renewable energy portfolio, thereby aligning with national commitments to Sustainable Development Goal 7 and decarbonization strategies.
- The establishment of this foundation will serve as a foundational element for the future development of marine renewable energy. The findings provide essential design and cost parameters for scaling up RED technology in Mexican coastal regions, thus advancing marine energy research and policy in Latin America.

2. Materials and Methods

2.1. Study Site

The region of Tuxpan, Veracruz, is distinguished by its access to coastal water resources and its proximity to energy infrastructures, rendering it a suitable location for the implementation of emerging technologies such as SGE. This analysis will concentrate on the exploration of its viability in this particular region. Tuxpan is an urbanized area that has been impacted by the presence of large industries, resulting in high energy demand. Consequently, the utilization of SGE could offer an innovative and sustainable solution to address these energy requirements. The study area is delineated by the coast of Tuxpan, extending from the confluence of the Pantepec River with the sea to the crossing of the river with the Tampamachoco Lagoon (Figure 1).

Figure 1. Tuxpan–Tampamachoco lagoon system.

Tuxpan is an agricultural area where the predominant coastal activity is fishing, carried out by small communities. The physicochemical composition of the wastewater at the exit of the conurbation of Tuxpan is characterized by a high content of suspended solids, sand, and grease because the treatment plants in the city do not fully treat the municipal wastewater.

The Alamo–Tuxpan aquifer is vulnerable to hydrocarbon contamination due to the presence of Petroleos Mexicanos infrastructure, compounded by the risk associated with the extensive exploitation of groundwater, leading to drawdown cones that reverse the direction of underground flow towards the sea outlet and result in marine intrusion [22].

The electricity provision data for the municipality of Tuxpan from 2010 to 2017 is shown in Figure 2 [23]. The growing trend in electricity availability evidences a growing demand. As a consequence, during 2018, the residential tariffs increased significantly.

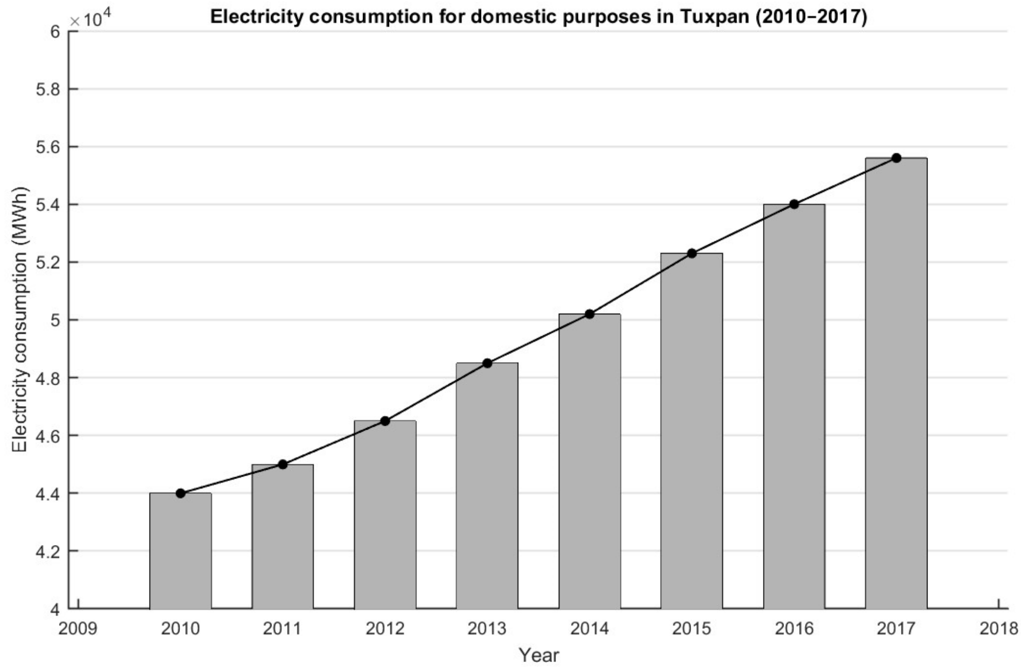

Figure 2. The following report details energy consumption in Tuxpan, Veracruz, Mexico, from 2010 to 2017.

2.2. Economic Assessment

A study of the levelized cost of energy (LCOE, USD*MWh-1) will be conducted for the conceptual design of the power generation plant to ascertain its economic viability and potential contribution to the energy matrix. A simple model for the calculation of the Net Present Value (*NPV*, USD) for a RED plant is used [24]. In this model, the total net power (*TNP*, kW); the load factor (*LF*, %) which is the percentage of hours per year that the RED plant works; the electricity price (*ep*, USD/kWh); the carbon price (*cp*, USD/TCO2e); the emission factor (*ef*, kg CO2e/kWh); and the capital recovery factor (*CRF*) are the independent variables as shown in Equation (1).

$$NPV = \frac{TNP \times LF \times 8760(ep + cp \times ef) - TAC}{CRF} \quad (1)$$

The total annual cost (*TAC*, USD/year) is employed to denote the expenses associated with the operation and maintenance of the project's assets during 12 months. The capital costs (*CAPEX*, USD/year) encompass the RED module, pumps, and civil and infrastructure costs. In turn, the annual operating costs (*OPEX*, USD/year) include the electricity costs of the pumps, membrane replacement, and operational and maintenance costs [25].

$$TAC = CRF \times CAPEX + OPEX \quad (2)$$

CRF is shown in Equation (3), where *r* is the interest rate and *LT* is the expected plant lifetime in years.

$$CRF = \mathrm{r}/1 - (1 + r)^{(-LT)} \quad (3)$$

The total net power, *TNP*, is the sum of the net power (*NPr*) produced by the RED unit ($r \in RU$) as shown in Equation (4):

$$TNP = \sum\nolimits_{r \in U} NPr \quad (4)$$

The efficiency of the energy capture phase in each case study is assessed via the total net specific energy (*TNSE*), which is the ratio of TNP to the low concentration flow rate of the RED plant, Q_{LC}; Equation (5).

$$TNSE = TNP/Q_{LC} \tag{5}$$

The Levelized Cost of Energy (*LCOE*) calculation enables the determination of the average cost of energy production over the plant's useful life. Consequently, it facilitates the assessment of the economic competitiveness of an emerging technology, such as RED, about other energy sources. The *LCOE* is, thus, computed using Equation (6).

$$LCOE = CRF \times CAPEX + OPEX/8760 \times TNP \ \times \ LF \tag{6}$$

For *ep*, an average value taken from the Mexican Electricity Company was used; this is the standard medium voltage high demand rate (GDMTO). A comprehensive overview of the parameters considered in the calculation of *LCOE* is provided in Table 2.

Table 2. Parameters used for the LCOE assessment [25].

Parameter	Symbol	Value	Unit	Reference
Electricity price	*ep*	0.12	USD/kWh	[26]
Carbon price	*cp*	34.05	USD/ton	[27]
Emission factor	*ef*	0.438	$kgCO_{2eq}/kWh$	[28]
Interest rate	*r*	10	%	[29]
Load factor	*LF*	90	%	[24]

We understand the concern. In the revised version and given the early stage of development of the technology and Mexico's risk profile, we have adopted a real, post-tax discount rate of 10%. This aligns with the International Energy Agency/Nuclear Energy Agency (IEA/NEA, 2020) [30], which reports levelized cost of electricity (LCOE) at 3%, 7%, and 10%, using 10% to represent higher-risk cases. Therefore, the choice is consistent with international practice for technologies and contracts involving greater uncertainty [30].

2.3. RED System

To ascertain the quantity of energy that can be produced by the RED plant, it is necessary to consider the parameters listed in Table 3. These parameters form the foundation for the conceptual design of a RED plant.

Table 3. Parameters used in the RED plant design.

Parameter	Symbol	Value	Unit
Temperature	T	293.15	K
Concentration of Alamo–Tuxpan River	C_{AT}	0.0205	M
Concentration of Treatment Plant	C_{Tp}	0.0171	M
Concentration of Tampamachoco Lagoon	C_{TL}	0.3420	M
Concentration of Tuxpan mouth	C_{TM}	0.5990	M

3. Results

3.1. RED Plant Description

The conceptual design of the RED plant consists of a coupled system comprising four main sections: pre-treatment, energy generation, grid integration treatment, and complementary areas (see Figure 3).

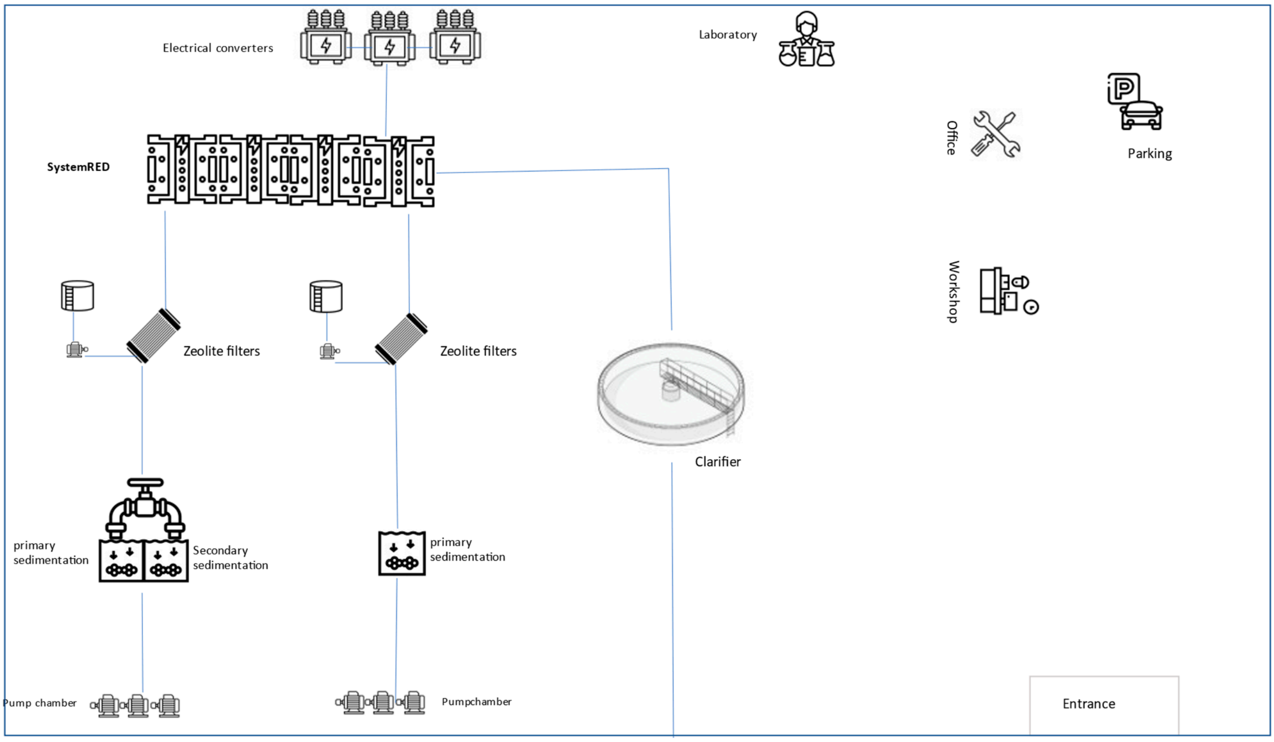

Figure 3. Tuxpan–Tampamachoco lagunar system.

3.1.1. Pre-Treatment

The process begins with the removal of solid waste, sand, and grease at the facility's entrance. The facility incorporates primary sedimentation tanks, which exhibit an average efficiency of 40% in terms of organic matter removal. In instances such as Tuxpan, the implementation of a secondary sedimentation tank is necessary to achieve an efficiency of 80%. This section also comprises two pumping stations that facilitate the inflow of materials and regulate the flow to the sedimentation tanks. Before the effluent enters the plant's core, it undergoes filtration through zeolite filters [31]. These filters are notable for their ability to retain loads of sediment and organic matter, thereby preventing the embedding of particles and the subsequent damage to the system.

3.1.2. Energy Generation

The plant's core comprises a set of electrochemical cells in which a redox reaction takes place and a potential difference is produced, leading to the generation of electricity in the central part of the plant. The membranes proposed to be adapted to the design of the plant are the Fujifilm AEM Type 10 and Fujifilm AEM Type 10. These membranes have a perm-selectivity range of 95–99% and low electrical resistance [32–34]. As illustrated in Table 4, the parameters necessary for the evaluation of the *LCOE* are outlined in detail.

Table 4. Parameters used to compute the electricity generation of the RED plant.

Parameter	Symbol	Value	Unit
IEM price	cm	114.75	USD/m^2
IEM lifetime	LT_m	5.0	years
Cell pairs	N_{cp}	550	Non-dimensional
Width	b	0.015	m
Length	L	0.015	m

The RED system can be considered a volt-open circuit (VOC) represented as the sum of the potential differences in the N membranes. The voltage, then, is a function of the ratio between the activity coefficients (γ, γ') of the saline and diluted flow, c and d, respectively (Equation (7)) [35].

$$VOC = 2N\alpha\ (R\ T/F)\ ln\ (\gamma_c - \gamma'_c/\gamma_d - \gamma'_d) \tag{7}$$

In Equation (7), the permeability of the membrane is denoted by α, the universal gas constant is R, the absolute temperature is T, and the Faraday's constant is F. In turn, γ is the activity coefficient and γ' the concentration of the corresponding solution on the surface of the membrane.

RED reactors are serially connected, so that the internal resistance of the membrane stack, R_i, is the sum of the resistances of the anion (R_{AEM}) and cation exchange (R_{CEM}) membranes. These resistances are located in the compartments of each membrane, where the thickness of the compartment (distance between membranes) is h, k is the conductivity of the solution, R_{DBL} is the resistance due to the diffusion limit, and R_{el} is the resistance of the electrodes (Equation (8)).

$$R_i = N\ (R_{CEM} + R_{AEM} + h_c/k_c + h_d/k_d + R_{DBL}) + R_{el} \times v \tag{8}$$

The total power between the electrodes, $PNet$, is the ratio of the squared VOC to the internal resistance (Ri). This expression quantifies the effective power that can be extracted between electrodes under steady-state conditions (Equation (9)).

$$P_{Net} = VOC^2/4R_l \tag{9}$$

In Equation (9), VOC and Ri were evaluated for each sampling station in Tuxpan, using the measured temperature and salinity data to represent the specific hydrological and saline conditions of the study area. The resulting PNet values were then utilized as the primary physical input for the subsequent economic assessment of the RED system.

Gibbs free energy of mixing is the energy available to convert the mixture of low and high-concentration solutions into power, where Cc/d is the equilibrium mixing concentration (10).

$$\Delta G = 2RT\ [V_d\ C_d\ ln(C_d/(Cc/d)) + V_c\ C_c\ ln(C_d/(Cc/d))] \tag{10}$$

The final step in the calculation is the energy efficiency of the RED system, which is defined as the ratio of P_{Net} to ΔG (Equation (11)).

$$\eta = P_{Net}/\Delta G \tag{11}$$

As illustrated in Table 5, there are four effluent feeders: the Alamo–Tuxpan River, the Tuxpan Treatment Plant, the Tampamachoco Lagoon, and the Tuxpan Mouth. The flows presented correspond to those available for use.

Table 5. Water availability from the sources near Tuxpan.

Source	Flow Rate (m^3/Day) Winter	Flow Rate (m^3/Day) Summer	Salinity (M)
Alamo–Tuxpan River	966,776	1,596,922	0.025
Treatment plant	12,168	12,168	0.0171
Tampamachoco Lagoon	95,904	158,544	0.3420
Tuxpan mouth	1,062,766	1,755,466	0.5990

3.1.3. Complementary Areas

The design incorporates a dedicated section where the control panels are situated, along with a laboratory that facilitates continuous monitoring of the water quality throughout the process, enabling observation of the internal dynamics within the batteries, electrodes, and membranes. Additionally, a maintenance room has been included to address any equipment-related issues and ensure the optimal functioning of the plant.

3.1.4. Waste and Effluent Management

The suspended solids, grease, and sand should be discarded in the first part of the process, which is the sedimentation tanks. These will be left to dry completely and will be divided into two: the plastics will be collected and sent to a recycling plant, and the remaining sludge will be used as compost in agricultural fields. The same thing will happen in the filtering process as with the sedimentation tanks.

The effluents will be subject to continuous monitoring throughout the process. The composition of the effluent leaving the RED tanks may vary due to fluctuations in concentration. In such instances, it is imperative to undertake pH measurements prior to, during, and following the clarification process. This ensures adherence to regulatory guidelines and facilitates the reintegration of the effluent into the network [36].

The physical–chemical composition of wastewater leaving the Tuxpan conurbation has been found to contain elevated levels of suspended solids, sand, and grease, indicative of inadequate treatment in the city's treatment plants. The implementation of an SGE plant would ensure that effluents do not reach river mouths contaminated, thereby preventing adverse effects on local flora and fauna. The proposed conceptual design (Figure 3) aims to enhance water quality and generate energy for the coastal area of Tuxpan, Veracruz. Upon exiting the RED system, the plant's effluents would be integrated into the network, contingent on their prior passage through a clarifier that ensures compliance with the stipulated standards (see Table 6). These standards delineate the permissible limits of pollutants in the water.

Table 6. Mexican standards on effluent management.

Legal Instrument	Objective
NOM-001-SEMARNAT-2021 [37]	Stipulates the permissible limits of pollutants in wastewater discharges into receiving bodies of water owned by the nation.
NOM-001-ECOL-1996 [38]	Establishes the maximum permissible limits of pollutants in wastewater discharges into national waters and property.
NOM-002-ECOL-1996 [39]	Determines the maximum permissible limits of pollutants in wastewater discharges into urban or municipal sewer systems.
NOM-003-ECOL-1997 [40]	Establishes the maximum permissible limits of pollutants for treated water that is reused in public services.

Specifically, the maximum density permitted for NaCl effluents is 1206 kg/m^3, a threshold that, given the high salt concentration, is known to be particularly deleterious to living organisms [28].

The salt gradient generation plant would have the capacity to supply the city's temporary services and the supply of some homes on an annual basis. According to previous studies, a lifespan of 30 years is recommended.

Table 7 summarizes the design water flow rates to be used to feed the RED power plant. Only flow rates below the effluent availability will be considered. Table 8 presents the results of the economic evaluation of implementing the RED power plant, including capital expenditure (CAPEX), operating expenditure (OPEX), total net energy (TNE), total annual cost (TAC), the capital recovery factor (CRF), the net present value (NPV), and the levelised cost of energy (LCOE). These calculations were performed in accordance with [25], considering the present values of the technical, energy, and economic parameters of the system, and are based on the previously detailed procedures [41].

Table 7. Values of the hydraulic variables used for each modelled scenario.

No	Case Name	Season	Flow Rate m^3/h	Salinity M
1	Treatment Plant and Alamo–Tuxpan River	Winter	12,168 15,000	0.0171 0.0205
2	Treatment Plant and Alamo–Tuxpan River	Summer	12,168 25,000	0.0171 0.0205
3	Treatment Plant and Tampamachoco Lagoon	Winter	12,168 15,000	0.0171 0.3420
4	Treatment Plant and Tampamachoco Lagoon	Summer	12,168 25,000	0.0171 0.3420
5	Treatment Plant and Tuxpan mouth	Winter	12,168 15,000	0.0171 0.5990
6	Treatment Plant and Tuxpan mouth	Summer	12,168 25,000	0.0171 0.5990

Table 8. Results of the economic assessment.

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Units
Life time	30	30	30	30	30	30	Years
CAPEX	1,519,546.32	1,519,546.32	1,519,546.32	1,519,546.32	1,519,546.32	1,519,546.32	USD/year
OPEX	33,302.42	33,298.88	54,216.71	50,835.33	57,748.99	57,822.79	USD/year
TAC	194,495.75	194,491.21	215,409.04	209,959.10	216,873.05	216,946.84	USD/year
CRF	0.10608	0.10608	0.10608	0.10608	0.10608	0.10608	Non-dimensional
LCOE	260.23	274.10	1.23	1.21	0.94	0.94	USD/kWh
NPV	−1,727,570.36	−173,890.81	22,774,447.81	22,617,997.25	30,718,387.87	30,804,845.24	kUSD

The net present value (NPV) is negative in the first two cases because the potential difference is negligible. However, the cost of the membranes is usually high, which represents a considerable additional expense. Maintenance and operation of membrane technology requires the expertise of highly specialized personnel and the execution of intricate procedures. However, cases 3 to 6 present a positive NPV because the energy generated is greater and the LCOE decreases considerably.

A system has been proposed that facilitates the integration of small cells into existing systems, thereby reducing installation costs and initial investment.

A sensitivity analysis was conducted, assuming an interest rate of 7.5%, to ascertain the technology's resilience in a moderately uncertain regulatory or financial environment, as shown in Table 9.

As demonstrated in Table 10, the LCOE is high due to the high CAPEX costs, which include installation costs estimated at USD 1,500,000, plus membrane and installation costs, OPEX, which includes operation and maintenance, as well as electricity costs. The optimal scenario was case 6, which is the combination of the Treatment Plant and Tuxpan mouth; it has the best conditions in terms of salinity difference and flows. It is evident from the data presented in Table 10 that the LCOE is high due to the high CAPEX costs, which include installation costs estimated at USD 1,500,000, membrane and installation costs, and OPEX costs, which include operation and maintenance as well as electricity costs. The optimal scenario was Case 6, which is the combination of the Treatment Plant and Tuxpan Mouth; it has the best conditions in terms of salinity difference and flows. With the energy generated in the RED Generation Plant, it would be possible to cover half of the demand for street lighting in Tuxpan.

Table 9. Results of the economic sensitivity analysis under different discount rates.

Parameter	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Units
Life time	30	30	30	30	30	30	Years
CAPEX	1,500,048.87	1,500,048.87	1,500,048.87	1,500,048.87	11,500,048.87	1,500,048.87	USD/year
OPEX	30,098.08	30,278.03	51,011.37	50,835.40	57,755.03	57,823.15	USD/year
TAC	157,109.07	1,571,289.02	178,022.36	177,846.39	184,766.02	184,834.14	USD/year
CRF	0.0846	0.0846	0.0846	0.0846	0.0846	0.0846	Non-dimensional
LCOE	210.21	210.21	1.02	1.02	0.80	0.80	USD/kWh
NPV	−1,722,812.81	−1,458,686.02	28,974,219.60	28,715,925.26	30,718,387.87	38,972,710.15	kUSD

Table 10. Projection of electricity price (ep) under inflationary scenarios in Mexico.

Annual Inflation (%)	2.5	3.5	4.5	Units
5 years	0.136	0.143	0.150	USD/kWh
10 years	0.154	0.169	0.186	USD/kWh
30 years	0.252	0.337	0.449	USD/kWh

The projection of the electricity price (EP) was conducted for three distinct time horizons (5, 10, and 30 years) under various inflationary scenarios. The objective of this projection is to evaluate the potential increase in the operational cost of the RED system due to long-term variations in the national energy market.

The future price of electricity was estimated using a compound growth model, which was expressed in Equation (12):

$$P_t = P_0\ (1 + g)^t \quad (12)$$

P_t is the future price, P_0 the current Price, t the number of years considered, and g the annual inflation rate. In the present study, three rates were taken into consideration: 2.5%, 3.5%, and 4.5%. These rates are representative of low, medium, and high inflation scenarios, as established by the official inflation target and long-term projections of the Bank of Mexico [42,43]. The results of applying this formulation to the electricity price projection are summarized in Table 10, which presents the expected evolution of ep under different inflationary scenarios and time horizons.

As illustrated in Table 11, a sensitivity analysis was conducted to assess the impact of varying inflation rates (2.0%, 2.5%, 3.5%, and 4.5%) and time horizons (5, 10, and 30 years) on financial outcomes. The findings indicate that both the electricity price (ep) and the levelized cost of energy (LCOE) exhibit a proportional increase in conjunction with inflation.

Utilizing the receptor–stressor–effect–impact–cumulative impact framework [44,45], we assess the potential repercussions on the Tuxpan estuary (a project situated within a region that has previously been impacted). Key receptors include the mangrove fringe and wetlands, estuarine fish and planktonic early-life stages, benthic communities, and water quality. It is anticipated that during the construction phase, stressors such as noise, land modification, and sediment-laden runoff will result in short-term avoidance behavior, temporary habitat reduction, and benthic disruption. These effects are expected to be largely confined to the work footprint. The reversibility of these impacts is contingent upon the implementation of restoration measures. During operation, stressors include low-level operational noise, physical infrastructure, intake hydraulics, and effluent discharge. The repercussions of these actions (for example, the risk of impingement and entrainment, in addition to alterations in the properties of nearby water bodies and traces of treatment chemicals) may result in localized alterations to the habitat and a decline in primary productivity in the vicinity of the outfall. Conversely, reef-like colonization may occur on submerged structures. The process of decommissioning would entail the removal of colonized structures and could generate transient noise and sediment disturbance. It is vital to consider the site's current condition when assessing the overall cumulative impact of the proposed mitigation measures. The implementation of mitigation measures, as outlined in Table 12 (e.g., low-velocity intake, diffuser, adequate outfall depth, and chemical neutralization), is expected to result in an impact that is low to moderate and confined to the intake–outfall near field. This impact is predicted to be temporally constrained to construction windows and seasonal low-dilution periods.

Table 11. The present study investigates the economic sensitivity of the RED system under varying inflation rates and time horizons.

	Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**	**Units**
			5 years 2.5%				
Electricity price (ep)	0.136	0.136	0.136	0.136	0.136	0.136	USD/kWh
LCOE	266.68	253.19	1.26	1.23	0.95	0.95	USD/kWh
			5 years 3.5%				
Electricity price (ep)	0.143	0.143	0.143	0.143	0.143	0.143	USD/kWh
LCOE	266.69	253.20	1.29	1.23	0.96	0.96	USD/kWh
			5 years 4.5%				
Electricity price (ep)	0.150	0.150	0.150	0.150	0.150	0.150	USD/kWh
LCOE	266.69	253.20	1.29	01.24	0.97	0.97	USD/kWh
			10 years 2.5%				
Electricity price (ep)	0.154	0.154	0.154	0.154	0.154	0.154	USD/kWh
LCOE	266.70	253.21	1.30	1.24	0.97	0.97	USD/kWh
			10 years 3.5%				
Electricity price (ep)	0.169	0.169	0.169	0.169	0.169	0.169	USD/kWh
LCOE	266.71	253.22	1.39	1.26	0.98	0.98	USD/kWh
			10 years 4.5%				
Electricity price (ep)	0.186	0.186	0.186	0.186	0.186	0.186	USD/kWh
LCOE	266.74	253.24	1.33	1.28	1.0	1.0	USD/kWh
			30 years 2.5%				
Electricity price (ep)	0.252	0.252	0.252	0.252	0.252	0.252	USD/kWh
LCOE	266.80	253.30	1.39	1.34	1.07	1.07	USD/kWh
			30 years 3.5%				
Electricity price (ep)	0.337	0.337	0.337	0.337	0.337	0.337	USD/kWh
LCOE	266.88	253.39	1.48	1.43	1.15	1.15	USD/kWh
			30 years 4.5%				
Electricity price (ep)	0.449	0.449	0.449	0.449	0.449	0.449	USD/kWh
LCOE	267	253.50	1.59	1.54	1.26	1.26	USD/kWh

Table 12. Summary of potential stressors, effects, and environmental impacts of an SGE facility through construction, operation, and decommissioning stages if it is implemented at impacted sites.

	Main Environmental Considerations	Mitigation and Management Strategies
Site preparation and construction	Temporary increases in turbidity and sediment disturbance may occur during site preparation and pipeline installation. The presence of construction vessels and heavy machinery has been shown to generate underwater noise and vibrations that could affect benthic and pelagic organisms. Furthermore, extracting sediments or eradicating coastal vegetation could lead to the loss of localized habitats.	Construction activities should be scheduled to avoid impacting reproductive or migratory seasons, so they must be carried out during periods of minimal biological sensitivity. Implementing turbidity curtains and sediment traps is an effective way of mitigating sediment plumes. The use of certified low-noise machinery is strongly recommended, as is continuous environmental monitoring throughout the construction phase.
Operation	It has been established that pumps and hydraulic systems have the potential to generate continuous low-frequency noise during operation. Discharging concentrated brine has the potential to alter local salinity gradients and water column stratification. Furthermore, the intake of water may result in the entrainment or impingement of small marine organisms. Biofouling, whereby organic matter accumulates on surfaces and is subsequently colonized by microbes, is a potential concern.	To minimize the capture of organisms, water intakes should be fitted with fine meshes and have low flow velocities. Brine discharges must be diluted and dispersed before release to prevent salinity build-up in localized areas. The use of chemical biocides should be replaced with eco-friendly coatings or ultraviolet (UV) systems. A long-term monitoring program must track physical, chemical, and biological indicators.
Decommissioning	During the process of decommissioning, there is the possibility of sediment resuspension and a short-term increase in turbidity, as structures are removed. The dismantling process generates underwater noise, which may result in the loss of artificial habitats formed around equipment.	For ecological sustainability and conservation purposes, decommissioning processes must be carried out using a methodical, phased approach that is carefully designed to minimize adverse ecological impact. Prior to and following the removal process, a thorough analysis of the sediment quality must be undertaken. Where it is ecologically beneficial, remaining structures can be converted into artificial reefs to facilitate the recovery of local habitats.

4. Conclusions

From a policy standpoint, our site-specific findings are consistent with recent reviews of Mexico's MRE framework. These reviews identify applicable regulations and public policy gaps, such as a lack of clarity around licensing and barriers/incentives to investment, and highlight niche opportunities for salinity-gradient technologies. Addressing these gaps through pilot-friendly permitting and targeted investment signals would mitigate the cost and risk factors identified here and could accelerate the deployment of renewable energy devices (RED) in contexts like Tuxpan [46].

Notwithstanding the contributions outlined above, it is imperative to acknowledge the limitations of the present analysis. Firstly, it is important to note that the results obtained are based on scenario-based projections as opposed to long-term operational data. Secondly, seasonal hydrological variability and extreme events have the potential to alter net power and auxiliary loads. Consequently, the LCOE/NPV is susceptible to factors such as fouling, in addition to the assumed 10% after-tax real discount rate. In addition, the trajectories of electricity and carbon prices are stylized and subject to policy and market changes. The scope excludes environmental input/discharge engineering and clean-up chemicals, and the process of scaling up carries integration and availability risks.

It is evident that the regulatory and legal uncertainties in Mexico have the potential to influence the temporal aspects and financial requirements of the project. These limitations underscore the necessity for a long-term, site-specific pilot study, as well as the need for the technoeconomic assessment to be updated periodically as empirical data becomes available. The findings indicate that, while RED technology demonstrates considerable potential in terms of clean energy generation and carbon emission reduction, its economic viability is limited by significant capital and operational expenditures. The integration of water sources exhibiting varying salinity gradients significantly influenced system performance, with the blend of the wastewater treatment plant and the Tuxpan River mouth emerging as the optimal configuration for power generation.

The environmental analysis suggests that the implementation of a RED plant in the area would contribute to the improvement of water quality by reducing the pollutant load before it is discharged into natural water bodies. Nonetheless, potential ecological impacts associated with the construction, operation, and decommissioning of the plant were identified, emphasizing the necessity of implementing suitable mitigation measures. In conclusion, it is evident that the optimization of the plant's design, the reduction in material costs, and the implementation of financial incentives have the potential to enhance the competitiveness of this technology in the future. The integration of RED with other renewable energy sources, as well as its application in regions with similar characteristics, are identified as areas of opportunity for future research.

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