Applied Energy 351 (2023) 121876

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Unlocking synergies between seawater desalination and saline gradient energy: Assessing the environmental and economic benefits for dual water and energy production

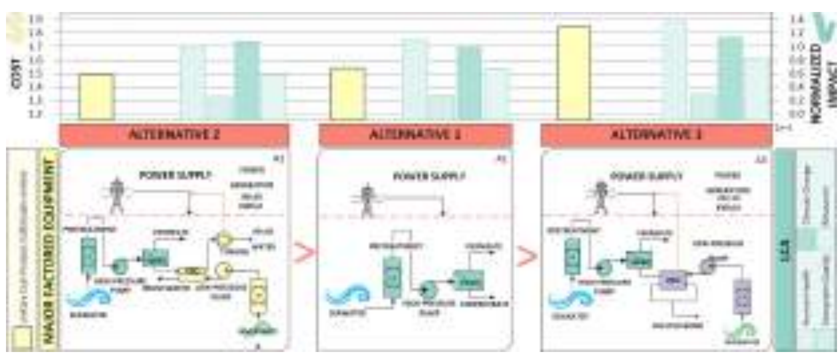
Luis Mendoza-Zapata, Aymer Maturana-Córdoba, Ricardo Mejía-Marchena, Anggie Cala *, Joseph Soto-Verjel, Salvador Villamizar

Instituto de Estudios Hidráulicos y Ambientales (IDEHA), Departamento de Ingeniería Civil y Ambiental, Universidad del Norte, km 5 antigua vía a Puerto Colombia, Barranquilla, Colombia

HIGHLIGHTS

- The SGE-SWRO synergy would maximize water and energy production.
- Holistic approach to analyze the environmental and economic impacts of the SGE-SWRO alternatives.
- SWRO-PRO is more cost-effective, energy-efficient, and environmentally friendly than SWRO.
- Despite lower benefits, SWRO-RED maintains huge future potential.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Life cycle assessment
Economic analysis
Reverse osmosis (RO)
Pressure retarded osmosis (PRO)
Reversal electrodialysis (RED)

ABSTRACT

The global scarcity of fresh water has increased the desalination systems' importance. Although these systems face certain limitations, significant efforts are being made using renewable energy sources like Saline Gradient Energy (SGE). This led to the emergence of two technologies: Pressure Retarded Osmosis (PRO) and Reversal Electrodialysis (RED). Hence, this innovative study aims to contrast the potential environmental and economic benefits by performance of PRO and RED integration into desalinating seawater by Reverse Osmosis (SWRO). We comprehensively assessed their life cycle using SimaPro® software and conducted a stochastic economic evaluation to achieve this. For the calculation basis, the systems were dimensioned using Wave® software and theoretical-analytical methods based on technical literature. Our findings revealed SWRO-PRO is cheaper (1.49 USD/m^3), less energy-intensive (4.602 kWh/m^3), and more environmentally friendly than SWRO (emission

Abbreviations: CAPEX, Capital Expenditures; LCA, Life Cycle Assessment; LCIA, Life Cycle Impact Assessment; MEFE, Major Equipment or Factored Estimation; NPD, Net Power Density; NTU, Nephelometric Turbidity Units; OPEX, Operational Expenditures; PRO, Pressure Retarded Osmosis; R&D, Research and Development; RED, Reverse Electrodialysis; RO, Reverse Osmosis; SDI, Silt Density Index; SEC, Specific Energy Consumption; SGE, Saline Gradient Energy; SWRO, Sea Water Reverse Osmosis; TDS, Total Dissolved Solids; TOC, Total Organic Carbon; TSS, Total Suspended Solids; UCP, Unitary Cost Product; UF, Ultrafiltration; UN, United Nations.

* Corresponding author.
E-mail address: canggie@uninorte.edu.co (A. Cala).

https://doi.org/10.1016/j.apenergy.2023.121876
Received 30 May 2023; Received in revised form 5 August 2023; Accepted 1 September 2023
Available online 11 September 2023
0306-2619/

reductions in the following categories: 10.31% human health, 11.79% ecosystem quality, and 11.44% natural resources depletion). SWRO was the second-best option with moderate costs (1.53 USD/m^3), energy requirement (5.569 kWh/m^3), and environmental impacts, while SWRO-RED was the least favorable, with higher costs (1.83 USD/m^3), energy consumption (5.573 kWh/m^3), and environmental impacts (increases of 22.20%, 21.02%, 15.2%, 22.2% of mentioned categories, respectively). PRO integration represented an enhancement, and despite lower benefits, RED maintains a substantial future potential. Thus, this study is a unique holistic approach that integrates environmental and economic considerations and endeavors to revolutionize our understanding of synergistic water-energy systems. Therefore, this pioneering research could pave the way to address global water scarcity and clean energy challenges.

1. Introduction

According to UN predictions, by the year 2050, 5.7 billion people may be affected by the physical and economic scarcity of drinking water due to increasing water stress [1], adding to the about 2.2 billion people currently without access to it [2]. Some of the contributing factors include population growth, urbanization, climate change, and depletion of limited freshwater sources [3]. Physical water scarcity refers to decreased available water, often caused by human influence, policies, institutions, and capital constraints. Instead, economic water scarcity alludes to the lack of mechanisms to access water resources and, hence, the inability to obtain clean water. Physical water scarcity occurs in the USA, the MENA region, southern India, Central Asia, and western Australia. In contrast, economic shortage is experienced in Central and Latin America, including the Caribbean region, southern and central Africa, northern India, parts of China, and other Asian countries [4]. Regarding availability, it is essential to recognize that available surface water resources will not increase at the continental level and problems in their quality, distribution, and availability will be profound. Aquifers will be depleted, and saline intrusion will significantly affect coastal areas [5]. Similar issue with groundwater, where over 30% of the world's largest systems are at risk [6]. Therefore, desalination has become an increasingly important solution to address the scarcity of water resources affecting many regions [7].

Seawater accounts for 97% of the total natural water resources [8]. Therefore, society has large amounts of this usable resource through desalination to produce drinking water. Reverse Osmosis (RO) is one of the most demanded technologies for seawater desalination. According to E. J. Okampo and N. Nwulu, this technique is currently the most widely used, accounting for 65% of the methods used to desalinate seawater [9]. However, despite the arduous efforts of the last decades, technical solutions are required for its significant limitations; above all, its high energy consumption (see Table S4) caused by pumping to overcome the osmotic pressure of seawater, the handling of the brine that arises from the process, and the membrane fouling [10]. In general, desalination systems are powered by fossil fuel combustion. This implies some environmental problems and to overcome them, considerable efforts have been made, one of which is the application of renewable energies. This approach has been gaining ground and extensively studied in recent years ([11–15]).

Keeping the focus on the ocean, the ability to provide potable water through desalination is not the only resource that can be harnessed from seawater; there is a type of renewable energy known as Saline Gradient Energy (SGE) with worldwide capacities of between 1.4 and 2.6 TW [15]. SGE results from mixing two solutions with different salt concentrations through membranes. Then, free energy, known as Gibbs-free energy, can be converted into electricity ([11,12,16]). Technology advancement has led to the emergence of two promising methods for SGE: Pressure Retarded Osmosis (PRO) ([17,18]) and Reverse Electrodialysis (RED) ([19,20]). These technologies have been the subject of extensive research and identified as the most favorable for SGE (see Table S2 – S3). Among different renewable energy sources, PRO and RED stand out for their distinctive features, such as low costs, minimal greenhouse gas emissions, and notable energy efficiency conversion rates in comparison with others as shown in Fig. 1.

The water-energy nexus concept provides insight into the interconnection between water and energy resources to optimize synergy and manage trade-offs between the two. Despite this, the exchanges between the two have yet to be thoroughly studied and quantified. SWRO-SGE integration has the potential to become a sustainable alternative to water resource management and power generation (see Table S1). It is estimated that this integration could provide environmental and economic benefits compared to the SWRO process fed from a conventional energy source ([15,22]).

The hybrid SWRO-PRO systems offer various benefits, such as the ability to reduce costs by using less energy for desalination and the potential to produce up to 50% more water than conventional systems. Additionally, these systems are highly efficient and selective when harvesting osmotic energy ([23,24]). On the other hand, SWRO-RED hybrid systems also provide several advantages, including reduced hydraulic pressure, reduced flux decline because of membrane fouling, and increased flux when combining two technologies [25]. Despite the potential benefits of hybrid SWRO-SGE systems, there still needs to be more evidence to support the environmental and economic advantages. Furthermore, the absence of comparative data on SGE technologies limits the ability to decide which would be the best to combine with SWRO [26]. Through our comprehensive study, we endeavor to satisfy this knowledge gap providing robust evidence to support the potential environmental and economic benefits of hybrid SWRO-SGE systems in real scenarios.

To determine which technology is more viable in the context of the Colombian Caribbean, we aim to contrast the potential environmental and economic performance of PRO and RED integration into SWRO by conducting a life cycle analysis (LCA), and a major equipment or factored estimation (MEFE). These analyses of coupled SWRO-SGE processes unveil an innovative and transformative attempt the synergistic water-energy systems. Besides, these serve as relevant guidelines to identify process improvements by reducing energy, chemicals, and water consumption, as well as detecting areas for further optimization, which can ultimately enhance the SWRO processes. This unique holistic and detailed study of the potential economic and environmental benefits of SGE coupled reverse osmosis systems presents an innovative approach to address the global challenges of water and energy scarcity.

2. Methods

Below is a graphical representation of the methodology employed in this study. Fig. 2 illustrates the step-by-step approach to analyzing the environmental and economic aspects of SWRO desalination and its integration with PRO and RED as SGE technologies.

2.1. Study case

For sizing purposes, the estimates and water quality parameters provided during the analysis of the alternatives, the location of the plants corresponds to the area of the Magdalena River estuary in the Atlantic Ocean in Barranquilla - Colombia, known as "Bocas de Ceniza", indicated in Fig. 3. This area is strategic for using SGE due to its large discharge flow between 4210 m^3 and 10077 m^3 [27] and the proximity to the river mouth [28]. In addition, it represents 97% of the total SGE potential in Colombia, with an average long-term specific potential of 15157 MW under very stable conditions [29].

2.2. Water characterization

To ensure accuracy and reproducibility of the study, we performed the sampling and water characterization from the Magdalena River and the Caribbean Sea (see Table S5) based on the Standard Methods for the Examination of Water and Wastewater [30]. The sampling sites correspond to those mentioned in section 2.1 (surface and seawater). Samples were collected in composite form, and various parameters were analyzed, such as turbidity, total suspended solids (TSS), total dissolved solids (TDS), total organic carbon (TOC), chlorides (Cl^-,) and others. The data obtained served as input parameters in the sizing of the operating units.

2.3. Formulation and design of alternatives

A comprehensive review of unit operations for coupling with SWRO was conducted on scientific literature to identify those proven and suitable, as well as adequate pretreatments for the main treatment units focusing on operational and efficiency aspects.

Consequently, we chose PRO and RED as coupled technologies, Ultrafiltration (UF) as pretreatment, and SWRO as a baseline. For the dimensioning phase, we considered a population of 30000 citizens over a life cycle of 20 years as the design basis, with 140 Liter per inhabitant per day as the maximum net demand, and a population increment rate of 1.1% (see Table S6). Table 1 exhibits the treatment and source type for the design method for each unit operation, including the water intake (see Table S7**)** and outfall structures (see Table S13 – S16**)**.

2.4. Economic assessment

For the economic analysis, we adopted the MEFE method proposed by R. Turton to estimate the Capital Expenditures (CapEx) (see Table S70) and Operational Expenditures (OpEx) (see Table S80). Nevertheless, we also considered other specific methods referenced in the literature and commercial values for special cases not covered in the mentioned procedure, prioritizing the Colombian market. All values obtained from the previous considerations were used as basic modular costs. Annual cash flow was also estimated (see Table S85). For the calculations, we assumed that the system's lifetime is 20 years as other studies [37].

2.5. Life cycle assessment (LCA)

The worldwide standard series ISO 14040 and 14044 determined the LCA methodological framework adopted in this study. It comprised four iterative phases: (i) Goal and scope definition; (ii) Inventory analysis; (iii) Impact assessment; and (iv) interpretation. ([38]).

2.5.1. Goal and scope definition

This LCA aims to identify and quantify the potential environmental benefits of SWRO-PRO and SWRO-RED over only SWRO. This is a relevant and distinctive study that has not yet been covered in the current state-of-the-art. The functional unit corresponds to 1 m^3 of water treated by the alternative, which reflects the primary function of the specific product system. The product system boundaries for each case are presented in Fig. 4. In them is important to appreciate the processes, such as Seawater catchment, River water catchment in the coupling cases, and chemical inputs. Also, transport is associated with the subprocess. Additionally, the components out of the system as post-treatment and distribution and the avoided impacts due to the contribution of part of the energy requirement in the couplings, by PRO and RED, respectively. The convention of the proposed alternatives corresponds to: SWRO (A1), SWRO-PRO (A2), and SWRO-RED (A3).

LCA is an extensive analytical method, so there were some constraints on the information got from software databases and other sources. On this basis, the following exclusions were made in this cradle-to-grave study:

1. Utilities for post-treatment processes.
2. The social or political implications.
3. Distribution networks for produced water.
4. Materials contributing with an insignificant input.

2.5.2. Inventory analysis

In this comprehensive inventory, every aspect has been meticulously

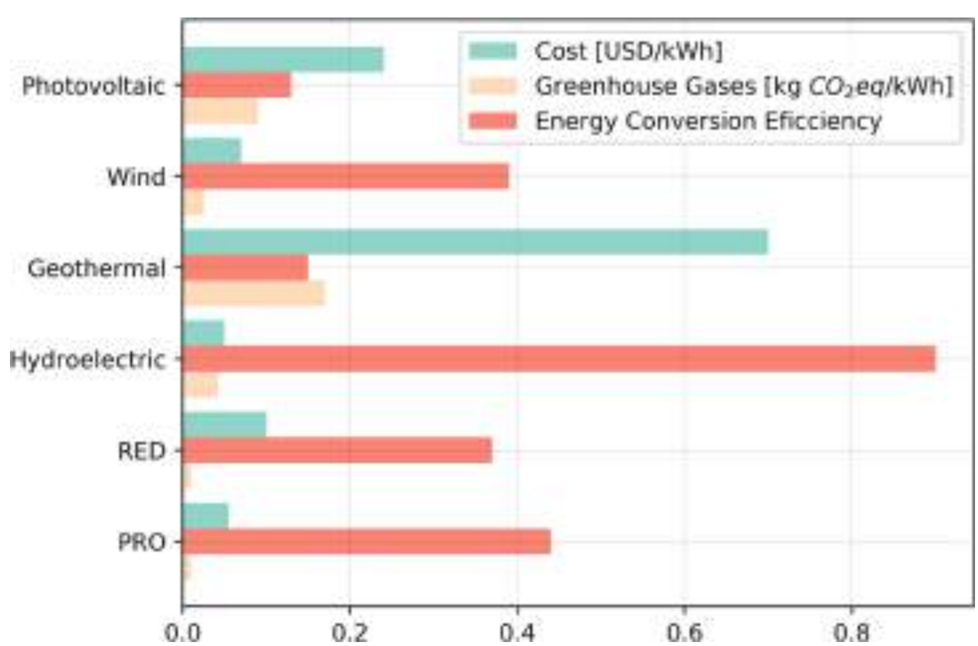


Fig. 1. Comparison between renewable energy sources. Source: Based on [21].

examined, including all relevant materials and processes. The distances from the source of production and commercialization of the materials to the proposed location have been carefully determined, and the modes of transport employed have been thoroughly researched and evaluated. Accordingly, we considered the following system modeling per cycle stage:

1. Construction: It includes the materials and processes for building the unit operations, civil works, the area for construction, and transportation to the plant site. Just main materials per equipment are considered by collecting weight information from commercial units. For civil works, we scaled the information from real plants and peer-reviewed papers.
2. Operation: It consists of the chemicals and energy consumption of the process. This varies from case to case. Thus, we estimated them according to the information provided by the manufacturing process and simulations. Most of these are of high quality and certain. No major assumptions were made.
3. Dismantling: This includes the dismantling of the plant and the transport to the landfill.

2.5.3. Impact assessment

An impact assessment was performed in SimaPro®. Being IMPACT 2002 + The LCA method used for it. This set in from the combination of methodologies such as Ecoindicator 99, CML, IPCC. Thus, this proposes a practical implementation of a joint approach linking many LCI results through 15 categories of medium state and 4 of final damage in the chain of cause-effect, as reported elsewhere [39].

2.5.4. Interpretation

It was performed a contribution and sensitivity analysis for the three cases. For sensitivity analysis, the energy requirement was chosen as the variable of interest.

3. Results and discussion

The results and the discussion are given below, following the sequence of technical formulation, economic analysis, and environmental analysis.

3.1. Technical formulation

Regarding the technical formulation of the three alternatives: SWRO (A1), SWRO-PRO (A2), and SWRO-RED (A3), the estimated permeate flow rate was 6535 m^3/d. This corresponded to the minimum design flow. The results associated with each treatment stage are presented below:

3.1.1. Pretreatment

The pretreatment for seawater and surface was equal, but independent. Both included a screening operation and a UF process. For seawater pretreatment (see Table S8), the most representative parameters input in Wave® simulation, previously analyzed in the laboratory, were Turbidity (90 NTU), TSS (79 mg/L), SDI15 (5), and TDS (35506.45 mg/L). These values were consequent with the interval considered in another study of the Atlantic Ocean (33,000–37,000 mg/L TDS) [40]. In the pretreatment, the Turbidity decreased to ≤0.1 NTU, TSS to non-detectable, SDI_{15} decreased to ≤2.5 and TDS remained constant. This indicates that UF is suitable for seawater pretreatment to prevent fouling problems in the SWRO membranes in the desalination step. The specific energy consumption (SEC) for this stage was 0.07 kWh/m^3 with a recovery of 85.67%.

On the other hand, for surface water pretreatment (see Table S9), the most representative parameters input in Wave® simulation, previously analyzed in the laboratory, were Turbidity (90 NTU), TSS (151 mg/L), TOC (6 mg/L) and TDS (134 mg/L). In the pretreatment, the Turbidity decreased to ≤0.1 NTU, TSS to non-detectable, TOC decreased to 5.4, and TDS remained constant. The SEC for this stage was 0.09 kWh/m^3 with a recovery of 78.07%. Performing this process was important to accomplish high river water quality before the mixture of seawater and river water in the PRO and RED processes, avoiding fouling and damage to the membranes. River water pretreatment SEC is higher than Seawater pretreatment SEC because of high turbidity.

3.1.2. Desalination

The SWRO simulation was conducted using the permeate output from seawater UF. Given this, we set the SWRO with a configuration of one step in two stages (see Table S10). The recovery rate of the reverse osmosis process was 62.5%, common for this type of water treatment by this membrane technology. For TDS, it passed from 35,506 mg/L to 488.6 mg/L. In Table 2, we summarize the flows and some parameters for the seawater pretreatment and SWRO process, both simulated in Wave®. Another essential parameter is the SEC of the system, which corresponds to 5.57 kWh/m^3. Being 5.46 kWh/m^3 (98%) due to the SWRO operation and 0.07 kWh/m^3 (2%) due to the seawater pretreatment. This value contrasts with the range specified in other studies ([41,42]) (2–4 kWh/m^3). On the other hand, other reference states that SWRO plants typically operate at 10 kWh/m^3 without energy recovery,

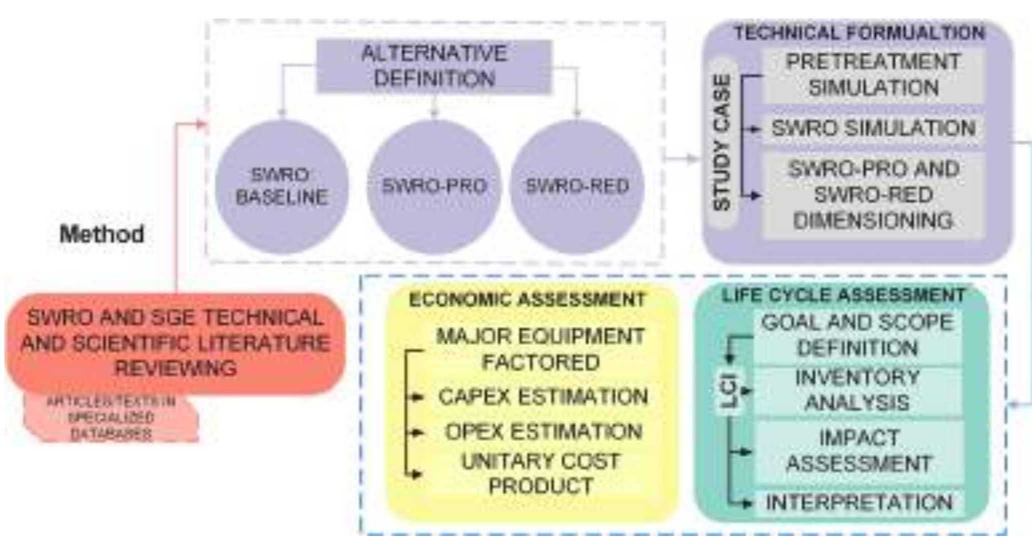


Fig. 2. Graphical summary of the methodology.

Fig. 3. Geographic location. Coordinate system: UTM Zone P18. Source: Generated with 2023 Microsoft corporation Earthstar Geographics SIO.

Table 1
Source of alternative dimensioning.

Item	Treatment type	Source type	References
UF	Pretreatment	Software-based method: Wave®	[31,32]
SWRO	Desalination	Software-based method: Wave®	[33,34]
PRO	Energy generation	Theoretical method: Experimental models	[35,37]
RED	Energy generation	Theoretical method: Experimental models	[36]
Intake and Outfall structures	Collection and Discharge	Analytical methods: Bibliographic information	[37,40]

2–5 kWh/m^3 with energy recovery and > 15 kWh/m^3 for smaller plants [2]. From these references, it could establish that the SEC of SWRO, for the study case, is acceptable. These values are reasonable considering that the most energy demand is in the desalination process to exert sufficient pressure on membranes. Indeed, it is essential to consider each specific study case, context, size, and performance of the systems.

3.1.3. SGE

Up to this point, we have presented the results for SWRO, including pretreatment of seawater and surface water. Once those have brine from SWRO (High concentration solution) and effluent of surface water pretreatment (Low concentration solution) was possible to use them to simulate PRO (see Table S11 – S12) and RED (see Table S13). processes.

The main information and results related to the estimation of PRO are given in Table 3. One of the most important parameters is the System Net Power Density (NPD). In other words, the ability of the system to produce energy and consequently contribute to supply energy requirements in the coupling SWRO-PRO. The result was above the reference that indicates that PRO has an NPD of around 2.4 W/m^2 [19]. This suggested that PRO could provide energy to the coupling SWRO-PRO. As mentioned before, the pretreatment (sea water and surface water) and the SWRO process both consume around 5.569 kWh/m^3 regardless of the necessary energy to pump the water by the intake system. On the other hand, the estimated net Specific energy production of PRO was 0.0902 kWh/m^3.

For the SWRO-RED coupling where the net Specific energy production of RED was 0.0478 kWh/m^3. Table 4 presents the main data estimated for the RED arrangement. Therefore, in both cases, the major benefits that can be obtained in the SWRO-SGE coupling are conditioned to the quantity of produced water, and the possibility of reuse of byproducts, or enhancements in the configurations. PRO and RED arrangements offer substantial energy contributions, yet they do not reach a significant differential level. Despite this, it is important to emphasize that, in both alternatives (A2 and A3), exists a contribution to the energy requirement of the whole system based on the energy production from the coupling.

Even though the minimum flow design was set the same for all alternatives, A2 was projected to provide more utilities based on more water produced due to recycling possibilities based on the configuration; we considered it as a benefit compared with the A1 and A3. This was because of the quality of the effluents from PRO compared to RED. It is important to mention that this produced water would have an eventual post-treatment.

3.1.4. Process flow diagram by alternative

The main results are shown through Process Flow Diagrams (see Fig. 5). From these, is possible to appreciate the mass balance and the fluxes in each alternative (Table 5). A1, A2, and A3 share the same UF seawater pretreatment idea, and A2, and A3 have the same river water pretreatment idea. Additionally, the SWRO process for A1, A2, and A3 has the same characteristics. A2 and A3 reflect the possibility of reuse of the concentrated (flux 7) from the SWRO process, together with river pretreated water (flux 15) to produce new resources (treated water and energy). As shown in Fig. 5, this requires a greater number of treatment units, which leads to greater complexity in coupled alternatives (A2 and A3) and in more intensive use of reagents. As well, this implies two intakes systems versus one in A1. Technically, this suggests a bigger operative effort in A2 and A3 and would also involve major challenges at the design and assembly stages in contrast to A1. Instead, the technical results indicated that the best alternative was A2.

The PRO process lets to obtain more water produced and is capable of contributing energy for the coupling during the life operation in opposition to A1 and A3 (A2: 4.602 kWh/m^3, A1: 5.569 kWh/m^3, and A3: 5.573 kWh/m^3). The additional water produced is represented in flux 20. This water for reuse means more produced water during the life cycle. This advocates the idea that the coupling SWRO-SGE presents better technical performance than SWRO alone and, specifically, the possibility to obtain more benefits in A2 in contrast to A1. Furthermore, the idea of reusing by-products between process units leads to a reduction in wastewater flows which eventually are discharged (compare fluxes 25 and 23 for A2 and A3, respectively).

3.2. Economic analysis

In economic terms, the results suggest that A2 outperformed A1 and A3. As is exhibited in Table 6, the Unitary Cost Product (UCP) of A2 was 1.498 USD/m^3 versus 1.538 USD/m^3 and 1.829 USD/m^3 from A1 and A3, respectively. It denotes a reduction of 2.60% versus A1 in the UCP during the 20 years of operation adopted for the estimation. It is possible to explain this by the possibility of A2 for recovering water from the PRO process that indeed becomes produced water. A3 registered an increment of 18.92% versus A1 in the UCP.

This is explained accordingly to the principles of the MEFE method, by the requirement of a greater number of equipment, without obtaining enough water and energy to compensate the higher initial capital investment in contrast to A1. According to the MEFE method, a more significant number of pieces of equipment means higher capital investment. Nonetheless, if A3 could produce enough water and energy to offset its investment capital during the operational phase, it could compete economically with A1.

A noteworthy topic to address is the relationship between the CapEx (see Table S71 – S79) and OpEx (see Table S81 – S84), comparing the alternatives. Despite A1 presenting a higher UCP in front of the other alternatives, its CapEx is less than A2 and A3, which implies that the benefits of coupling SWRO-PRO are clustered in the operational stage. This is attributable to the number of equipment, pumps, and others, which are higher in A2 and A3 in contrast to A1. This behavior is also evident in Fig. 6 (see Table S86), where A2 annual cash flow reflects the lowest costs during most operation periods. The exceptions are period 0, where CapEx is higher, and periods 7, and 14, where, as in the 10 period, the membrane replacements are necessary. A3 is also negatively influenced by the necessary replacement of more membranes than in A1 in the same periods.

Focusing on the operational stage, A3 relative to A1 presents increments in all the components. The most meaningful is the increment in Wastewater disposal costs, 88.09%. The configuration of A3 does not allow to recycle the byproducts fluxes. Bigger residual fluxes than in A1, lead to greater efforts and costs for the final disposal of wastewater. Additionally, the increase in energy costs per cubic meter is only 0.07%. Quite low in relation to the other areas of the OpEx. This reflects the importance of the energy provided by the coupling to the process for reducing costs. A2 relative to A1, utility costs were reduced by 17.37%,

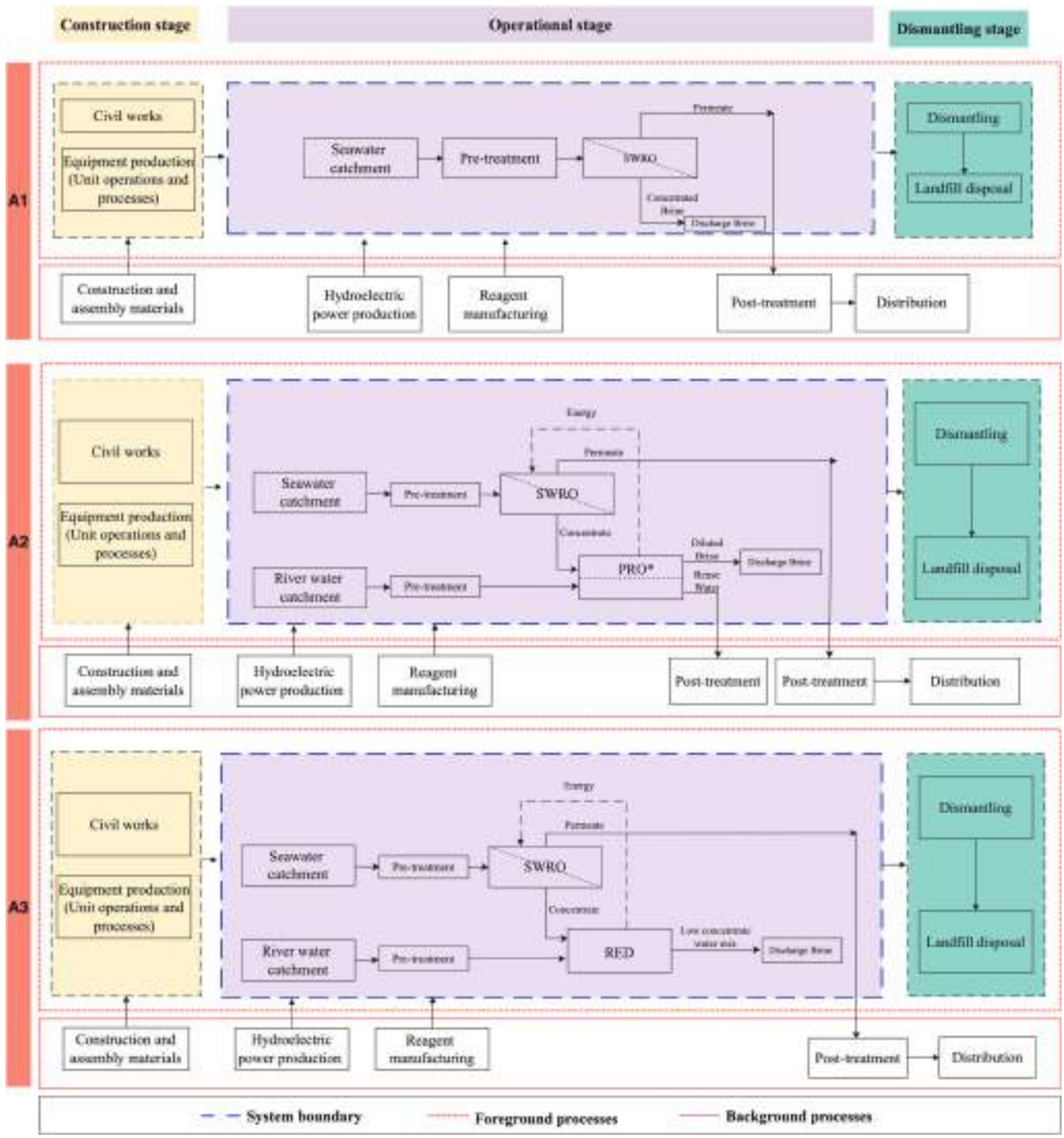


Fig. 4. Boundaries diagram. A1) SWRO; A2) SWRO-PRO; A3) SWRO-PRO.
*Turbine and pressure exchanger considered.

wastewater disposal costs by 0.12%, and research and development costs by 5.26% (see Fig. 7).

The first is especially relevant in evidencing the economic benefits of the couplings against SWRO because utility costs represent 59.00% of the OpEx for A1, 52.00% for A2, and 51.60% for A3 (see Fig. 8).Likewise, Fig. 8 shows the significant impact of Raw material, Wastewater disposal, Labor operating costs, and Research and development costs in the summary of the OpEx for each alternative. These should be key elements in designing strategies that achieve greater economic efficiency. However, the various technical possibilities of couplings with SGE and imminent developments set a profit in front of SWRO in pursuit of this goal.

3.3. Environmental analysis

The environmental results are based on the system boundaries (see Fig. 4) and Life cycle inventory (see Table S17 – S68), related to the objective of the study and the scope.

Table 2
Summary of SWRO Wave® simulation (including pretreatment).

	Parameter (unit)	Pre-filter	Ultrafiltration	Reverse Osmosis
		(Pretreatment)		(Treatment)
Feed	Flow (m^3/d)	12265.5	12204.2	10456
	TDS (mg/L)	35506.5	35506.5	35506
	pH	8.2	8.2	8.2
	Pressure (Bar)	1.4	1.4	81.5
	Temperature (°C)	25	25	25
Product	Flow (m^3/d)	12204.2	10455.9	6534.9
	TDS (mg/L)	35506.5	35506.5	488.5
	pH	8.2	8.2	7.2
	Rate conversion (%)	99.5	85.67	62.5
	SEC (kWh/m^3)		0.07	5.46
System	SEC (kWh/m^3)	5.57		
	Feed flow (m^3/d)	12265.6		
	Product flow (m^3/d)	6534.9		
	Rate conversion (%)	53.3		

Table 3
Main information of PRO estimation.

Principal parameters	Amount	Unit
The total area of membranes	12267.21	m^2
Maximum obtainable power	61.29	kW
Power generated by the system	49.03	kW
The net power generated by the system	29.42	kW
Membrane flux	2.47×10^{-6}	m^3/m^2s
System Net Power Density	3.99	W/m^2
Treated water flow (From Magdalena River)	1293.96	m^3/d
Net Specific energy production	0.0902	kWh/m^3

Table 4
Main information of RED estimation.

Principal parameters	Amount	Unit
The total area of membranes	7653.89	m^2
Power generated by the system	16.26	kW
The net power generated by the system	13.01	kW
Membrane flux	6.00×10^{-6}	m^3/m^2s
System Net Power Density	2.15	W/m^2
Net Specific energy production	0.0478	kWh/m^3

Regarding the Life Cycle Impact Assessment (LCIA), according to the IMPACT 2002+ method, the life cycle of A2, presents fewer emissions in 11 out of 15 medium-state impact categories (see Table S69) than the life cycle of A1 and A3, so it can be said that it presents higher environmental performance. In addition, is evidence of the benefits of coupling SWRO-SGE versus SWRO alone. The mentioned categories were human ecotoxicity potential (carcinogenic and non-carcinogenic), respiratory inorganics, ozone depletion potential, photochemical oxidation (organic respiratory), aquatic ecotoxicity potential, terrestrial ecotoxicity potential, terrestrial eutrophication potential, aquatic acidification potential, non-renewable energy, and extraction of minerals. Furthermore, in all the alternatives, the major impacts are caused by the categories: Respiratory inorganics, Global warming, and Mineral extraction categories.

These results are reflected subsequently in the final damage categories (see Fig. 9) where A2 produces fewer negative environmental effects on human health, ecosystem quality, and the exploitation of resources than A1. Thus, A2 seems to be more advantageous in environmental terms than the other two configurations. It is notable that the categories in which the greatest environmental damage occurs during the life cycle are human health and climate change.

Quantitatively, occurred a 10.31% reduction of emissions that affect human health, a 11.79% emissions reduction that influences climate change, and a 11.44% emissions reduction that affects the natural resources comparing A2 with A1. The last, reaffirm the potential benefits of SWRO-SGE coupling in contrast to SWRO alone. In counterpart, the emissions of A3, related to A1, resulted higher. Human health at 22.20%, ecosystem quality at 21.02%, climate change at 15.02%, and resources at 22.02%. This means that this alternative failed to maximize profits to achieve environmental offsets under the presumed design considerations. This is due to a significant use of raw materials and more generating pollutants related to the functional unit production, in contrast to A1. However, it does not mean that there can be no offsets by improving or changing the configuration of the alternative to increase efficiencies in water and energy production during the life cycle. Nor that the RED as a SGE technology is not feasible.

The contribution analysis reflects the components of every stage: construction, operation, and disassembling. This analysis allows identifying which are the largest contributors to negative environmental impacts. Results show the operational stage as the main cause of environmental impacts on the three alternatives, the most notable being the impacts caused by using electricity. This result is in agreement with those gotten by Mohamed Alha [43] who applied a LCA to a desalination process and concluded energy consumption during operation stage related with the pumps was the primary contributor. However, is important to denote that this stage is mainly responsible for the reduction of environmental impacts in A2 instead of A1 in the categories of human health, ecosystem quality, and resources. The results indicate higher environmental damage by reagents in alternatives with couplings than in A1 due to the use of more unit processes. Specifically, Citric acid, HCl, NaCl, and NaOH, used for PH adjustment and Backwash requirements in the river water pretreatment, are not present in A1. This implies a greater reagents requirement. These results are comparable with the results achieved by Mohsen Nasrollahi [44] who applied an environmental assessment of desalination processes with different indicators, finding that reagents involved in the treatment generate the highest effects on climate change, human health, and resource depletion. Membranes and civil works also represent significant environmental damage in all alternatives and have special impacts on human health and climate change. In Fig. 9 is presented an item called "other units" which included the materials and processes required to build pumps, pressure vessels and tanks These were considered but could have been more representative, unlike all previously remarked components for the contribution analysis. To improve couplings, in environmental terms, these must be the specific points of interest. For example, the findings show that civil works in A2 and A3 are slightly more harmful than in A1.

This is a result of more processing units and a larger area of occupation. Using compact systems and sustainable materials can be critical in maximizing the environmental advantages of SWRO-SGE over SWRO. Another area of concern is the use of reagents. The use of more environmentally friendly reagents or their reduction to the necessary

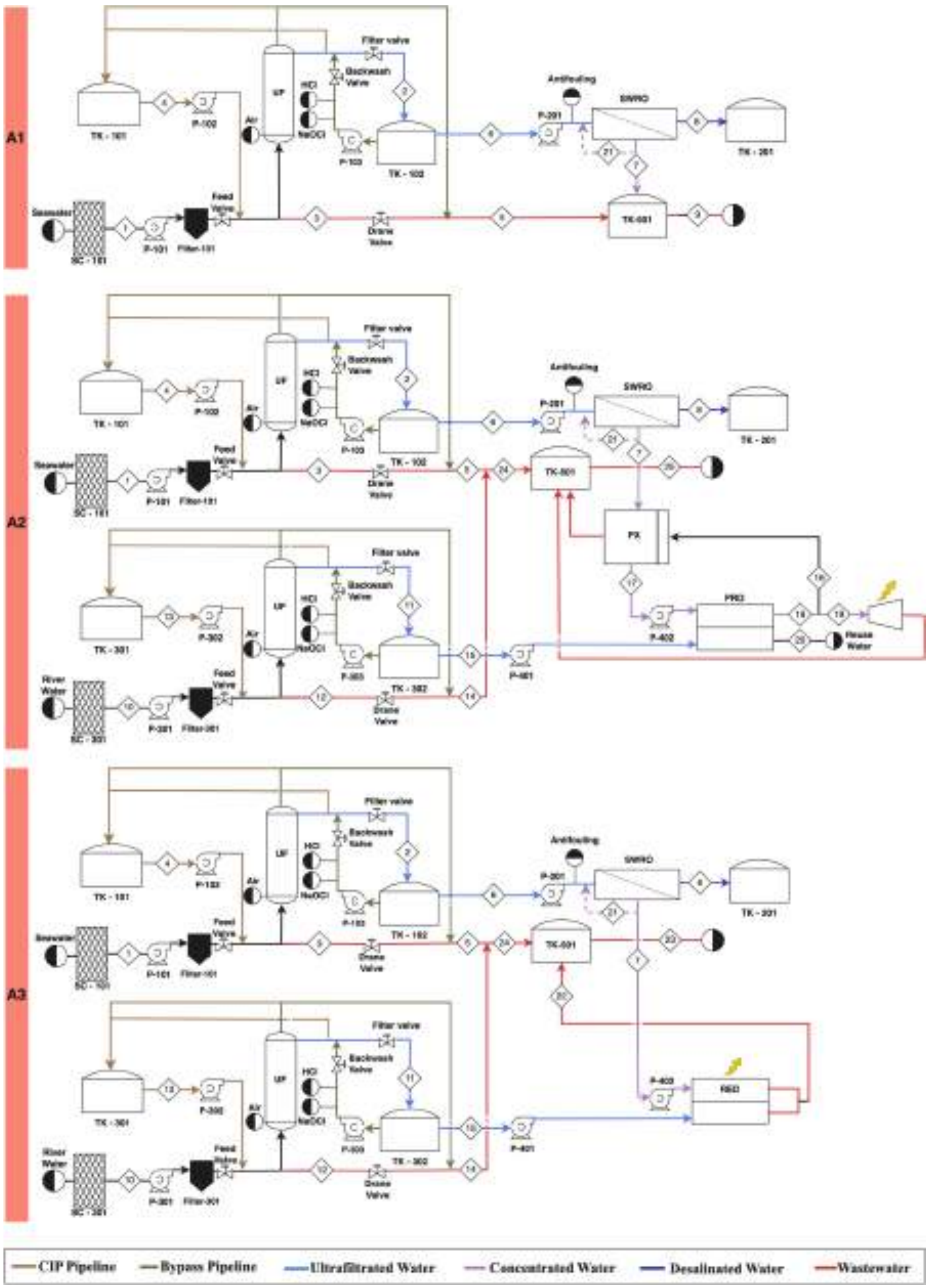


Fig. 5. Process flow diagrams.

Table 5
Nomenclature and fluxes for alternatives.

NOMENCLATURE

Process	Stage	ID	Description	Present in: A1	A2	A3
SWRO	Pretreatment for seawater	CR-101	Fine screening	✓	✓	✓
		P-101	Feed pump	✓	✓	✓
		P-102	Pump for cleaning in place	✓	✓	✓
		P-103	Backwash pump	✓	✓	✓
		TK-101	Cleaning in place tank	✓	✓	✓
		TK-102	Filter storage tank	✓	✓	✓
		FLTR-101	Pre-filter of UF unit	✓	✓	✓
		UF	UF Module	✓	✓	✓
	Treatment for seawater	P-201	Feed pump SWRO	✓	✓	✓
		SWRO	SWRO Unit	✓	✓	✓
		TK-201	Desalinated water storage tank	✓	✓	✓
		TK-202	Wastewater storage tank	✓	–	–
River water	Pretreatment	CR-301	Fine screening	–	✓	✓
		P-301	Feed pump	–	✓	✓
		P-302	CIP pump	–	✓	✓
		P-303	Filter storage tank	–	✓	✓
		TK-301	CIP Tank	–	✓	✓
		TK-302	Filter storage tank	–	✓	✓
		FLTR-301	Pre-filter of UF unit	–	✓	✓
		UF	UF Module	–	✓	✓
PRO/RED	PRO/RED components	P-401	River pre-treated water feed pump	–	✓	✓
		P-402	concentrate feed pump	–	✓	✓
		C-401	energy recovery turbine	–	✓	–
		RED	RED module	–	–	✓
		PRO	PRO module	–	✓	–
		PX	Pressure exchanger	–	✓	–
Wastewater storage		TK-501	Wastewater storage tank	–	✓	✓

FLUXES

ID	Q (m^3/d)	Description	Present in: A1	A2	A3
1	12265.50	Feed water	✓	✓	✓
2	11815.20	Seawater filtered water	✓	✓	✓
3	61.30	Seawater pre-filter residue	✓	✓	✓
4	2592.00	CIP Pump flow (Seawater)	✓	✓	✓
5	1809.60	Seawater ultrafiltration residue	✓	✓	✓
6	10455.90	Feed for RO	✓	✓	✓
7	3921.10	Concentrated water	✓	✓	✓
8	6534.90	Desalinated water	✓	✓	✓
9	5730.70	Wastewater	✓	–	–
10	5047.60	Feed water (river water)	–	✓	✓
11	4801.90	Gross filtering UF (river water)	–	✓	✓
12	25.20	Prefilter residue (river water)	–	✓	✓
13	3384.00	CIP Pump flow (river water)	–	✓	✓
14	1126.60	UF residue (river water)	–	✓	✓
15	3921.20	Feed water PRO/RED (river water)	–	✓	✓
16	1307.1	Less concentrated brine after PRO	–	✓	–
17	3921.10	Feed for PRO (Concentrated on SWRO)	–	✓	–
18	6535.40	Less concentrated brine with recirculate flux	–	✓	–
19	2614.10	Turbine feed	–	✓	–
20	1307.10	Reuse water	–	✓	–
21	2104.00	Recirculated brine	✓	✓	✓
22	7842.40	Less concentrated brine after RED	–	–	✓
23	10778.70	Wastewater	–	–	✓
24	2936.20	Wastewater	–	✓	✓
25	6857.40	Wastewater	–	✓	–

Table 6
Main parameters of the economic analysis.

	A1	A2	A3
CapEx [a] (USD/m^3)	0.025	0.174	0.208
OpEx [b] (USD/m^3)	1.398	1.325	1.621
UCP [c] (USD/m^3)	1.538	1.498	1.829

[a] : Capital Expenditure.
[b] : Operational Expenditure.
[c] : Unitary cost product.

minimum should be prioritized.

For the sensitivity analysis, the energy requirement was used as a parameter of interest. A high energy requirement could be the major contributor to global warming potential, linked to the category of final damage Climate change [14]. Sensitivity analysis was based on the normalized results of the life cycles comparison of each alternative. There, the influence of reducing and increasing the energy requirement for each system by 30%, 60%, and 90%, on the environmental impacts was analyzed. Table 7 shows that the normalized results in A1 change more when the energy requirement varies, respect to the other two alternatives, which would make it more significant to achieve a reduction of the energy requirement in SWRO, in contrast with SWRO-EGS couplings to diminish environmental impacts. However, the rates of change between the three alternatives are not far apart (see Table 7). This would not represent, strictly speaking, an advantage of SWRO-EGS over SWRO alone, but in both processes, a reduction in the energy requirement would lead to reductions in environmental damage in the categories of final damage. For example, if the energy requirement were reduced by 60% for A1, the environmental impacts would be reduced by 37% for human health, 39% for ecosystem quality, 35% for climate change, and 39% for the exploitation of resources. Doing the same for A2 would reduce environmental impacts by 33% for human health, 34% for ecosystem quality, 27% for climate change, and 34% for resource

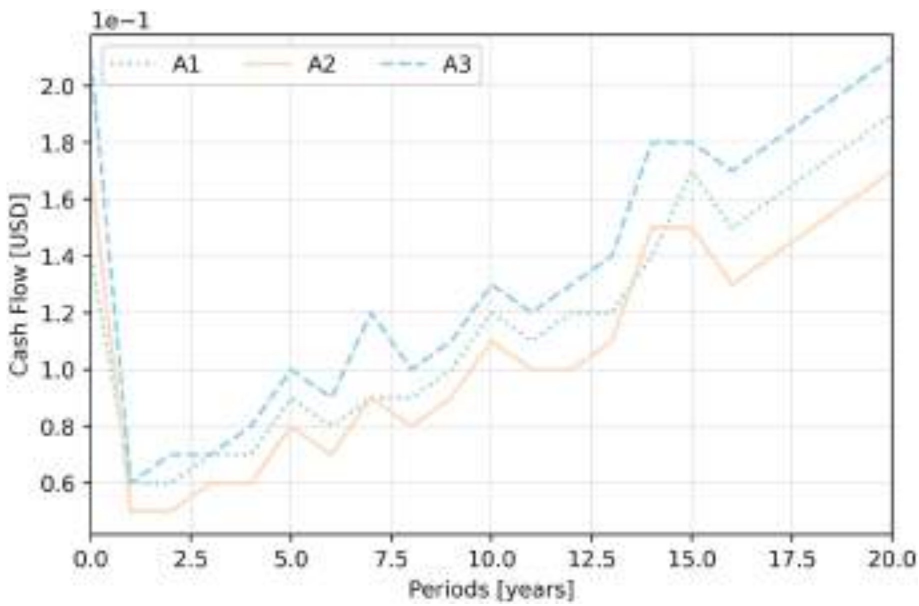


Fig. 6. Summary of annual cash flow.

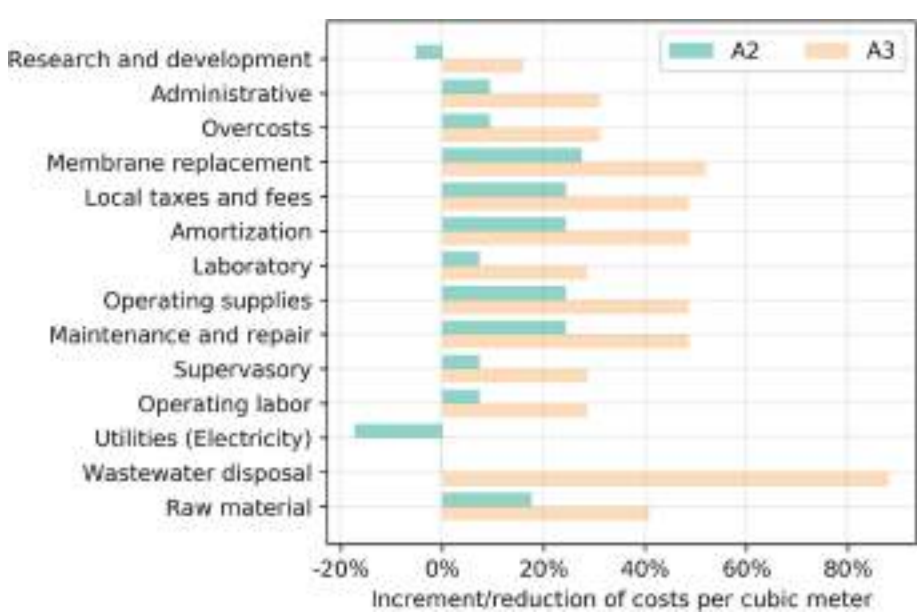


Fig. 7. Percentage increase or decrease in operating costs versus A1.

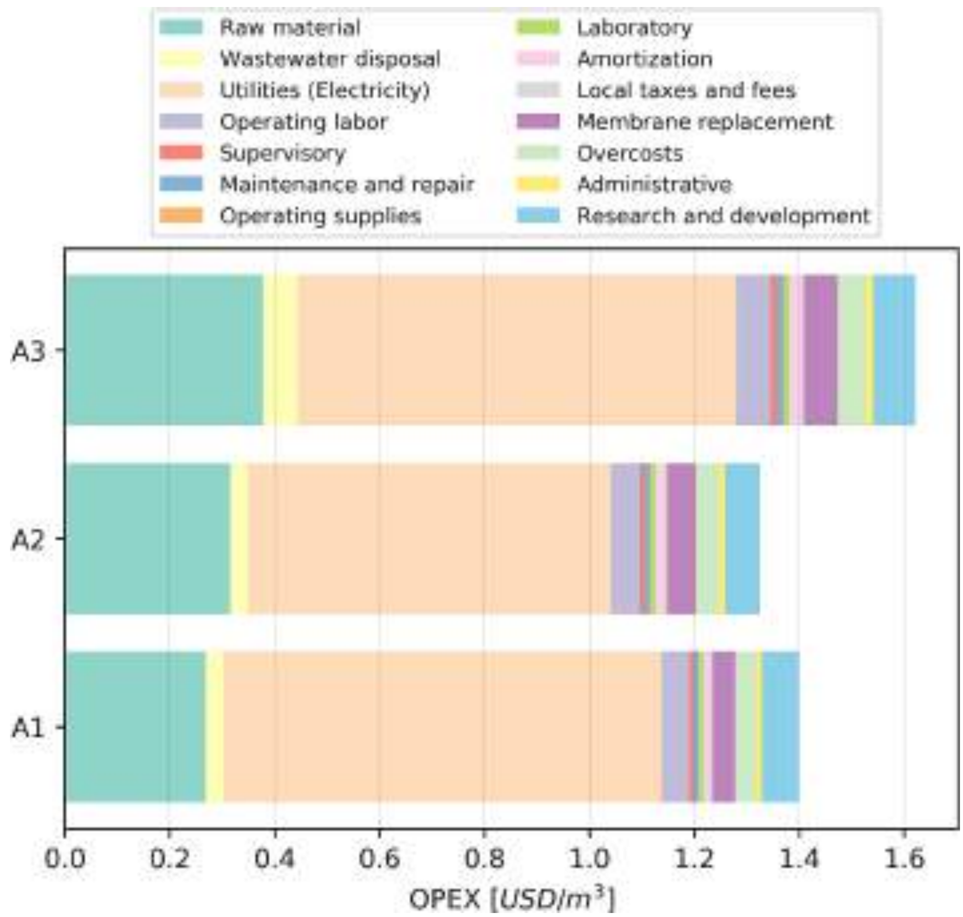


Fig. 8. Summary of operational expenditure.

exploitation. Likewise, for A3 the environmental impacts would be reduced by 30% for human health, by 32% for the quality of the ecosystem, by 30% for climate change, and by 32% for the exploitation of resources.

4. Conclusions

From the technical formulation and environmental analysis presented in this study, several important conclusions about the feasibility and sustainability of boarded desalination alternatives can be drawn.

The SWRO process was suitable for seawater desalination, with a high recovery rate of 62.5% and a Specific Energy Consumption (SEC) of 5.57 kWh/m^3, which is within an acceptable range compared to other studies. Seawater pretreatment by UF effectively reduced turbidity to ≤0.1 NTU, TSS to non-detectable, and SDI15 to ≤2.5, indicating its suitability to avoid fouling problems in SWRO membranes. Surface water pretreatment also effectively reduced turbidity and TSS to non-detectable levels, which is necessary for achieving high-quality river water before mixing with seawater in the PRO and RED processes. Additionally, it was observed that the PRO and RED processes contributed to the energy needs of the entire system since they could produce energy and, therefore, partially satisfy the energy needs of the SWRO-PRO coupling. However, the most significant benefits that can be obtained in the SWRO-PRO (A2) and SWRO-RED (A3) couplings are conditional on the amount of water produced and the possibility of reuse of by-products or improvements in the proposed configurations.

In comparative terms, the most significant benefits were found in A2, suggesting PRO as a prominent salinity gradient energy technology suitable for coupling seawater reverse osmosis. A3 was the least favorable under the assumptions considered, but RED-SWRO maintains substantial future potential despite lower benefits. The results allow us to discuss the arguments that support the idea that the SWRO coupling techniques improvement of SWRO with SGE in the context of water and energy cogeneration could also improve the environmental and economic performance of SWRO-SGE alternatives in comparison with SWRO. The main advantages of A2 over A1 are: The cost per m3 of treated water was reduced by 2.6% (1.49 USD/m3 rather than 1.53 USD/m3), the specific energy consumption was reduced by 4.00% (4.6 kWh/m3 rather than 5.56 kWh/m3). In the operational stage, utility costs were reduced by 17.37% (this item represents >50% of total OpEx), wastewater disposal costs by 0.12%, and research and development costs by 5.26. Likewise, findings of lower emissions and impacts during its life cycle as illustrated in the following impact reduction categories: 10.31% in Human health, 11.79% in Ecosystem quality, and 11.44% in Resource exploitation. These benefits obey mostly the capability of A2 to produce a larger quantity of the functional unit in contrast to A1, as well as the potential of A2 to provide part of the energy requirement of its system. As opposed to that, the cost (1.83 USD/m3), energy consumption (5.56 kWh/m3), and emissions of A3 resulted higher than A1. The emissions increased by category: Human health at 22.20%, ecosystem quality at 21.02%, climate change at 15.02%, and resources at 22.02%. This means that this alternative could have to maximize profits to achieve environmental offsets. However, it does not mean there can be no offsets by improving or changing the configuration of the alternative.

This study is innovative in exploring the emergence of two relevant technologies: PRO and RED. Its groundbreaking character lies in the quest to contrast and evaluate the potential environmental and economic advantages of integrating PRO and RED with seawater desalination by reverse osmosis (SWRO) in a natural water scenario. This novel

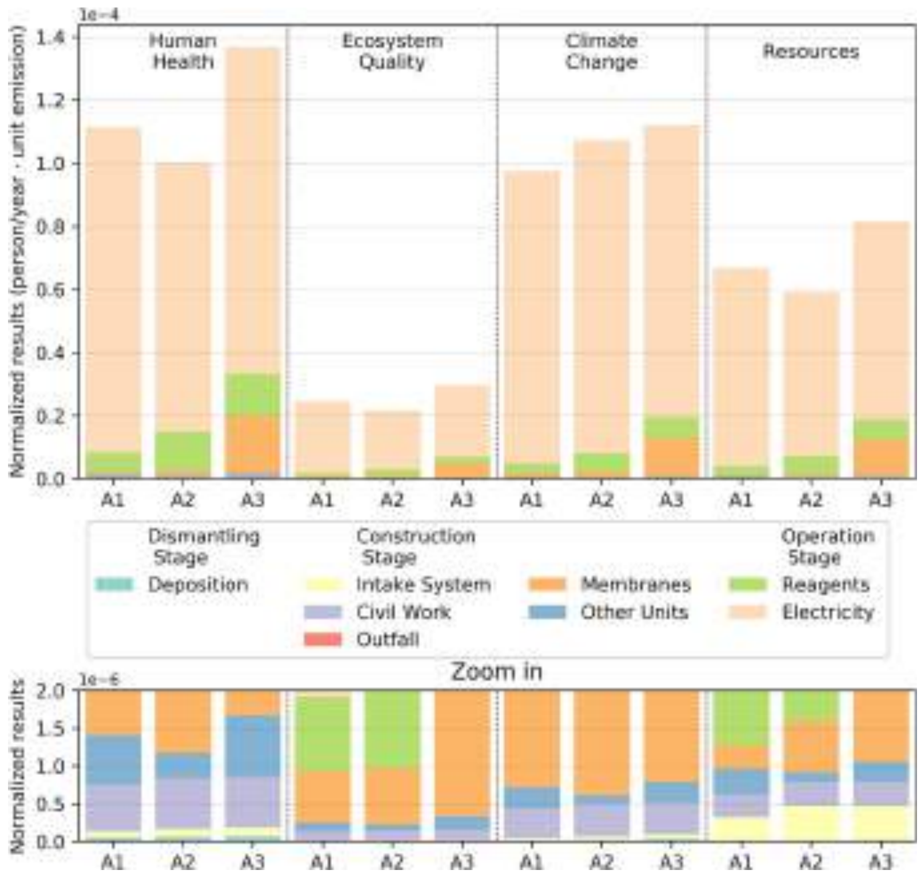


Fig. 9. Normalized results. Final damage categories.

Table 7
Rates of change of normalized results based on the normalized base value of the LCIA comparison of alternative 1: SWRO, alternative 2: SWRO-PRO, and alternative 3: SWRO-RED.

Final damage category	Life cycle SWRO						
	Increment in energy requirement			Normalized Base Value	Increment in energy requirement		
	90%	60%	30%		30%	60%	90%
Human health	−56%	−37%	−19%	100%	19%	37%	56%
Ecosystem quality	−59%	−39%	−20%	100%	20%	39%	59%
Climate change	−52%	−35%	−17%	100%	17%	35%	52%
Resources	−59%	−39%	−20%	100%	20%	39%	59%

Final damage category	Life cycle SWRO-PRO						
	Increment in energy requirement			Normalized Base Value	Increment in energy requirement		
	90%	60%	30%		30%	60%	90%
Human health	−49%	−33%	−16%	100%	16%	33%	49%
Ecosystem quality	−52%	−34%	−17%	100%	17%	34%	52%
Climate change	−40%	−27%	−13%	100%	13%	27%	40%
Resources	−52%	−34%	−17%	100%	17%	34%	52%

Final damage category	Life cycle SWRO-RED						
	Increment in energy requirement			Normalized Base Value	Increment in energy requirement		
	90%	60%	30%		30%	60%	90%
Human health	−45%	−30%	−15%	100%	15%	30%	45%
Ecosystem quality	−47%	−32%	−16%	100%	16%	32%	47%
Climate change	−45%	−30%	−15%	100%	15%	30%	45%
Resources	−48%	−32%	−16%	100%	16%	32%	48%

approach addresses pressing global challenges and opens promising avenues for sustainable cogeneration of water and energy.

The conclusions of this study offer valuable insights, considering that the economic and environmental analysis results are based on the specific characteristics of the case studied (physicochemical properties of the water, site-specific potential, costs of local services and materials). It is essential to approach the generalization of these results to other scenarios with caution due to these contextual considerations. Nevertheless, these results can be considered a valuable reference for analogous scenarios, as they provide a solid basis for other researchers to conduct analyses tailored to their specific context.

In addition, this study opens the opportunity to compare coupling alternatives in implementing sustainable processes. The results provide a starting point for future research and encourage new researchers to make further developments in water and power cogeneration based on SWRO-SGE couplings by considering technical and environmental factors in the design and selection of technologies. These potential benefits represent new ways to help communities suffering from the scarcity of these resources and promote the study and establishment of these couplings in areas such as "Bocas de Ceniza". Further work should focus on energy efficiency, using compact systems and sustainable materials.

Funding

This work was funded by 'Ministerio de Ciencias, tecnología e innovación de Colombia (MINCIENCIAS)', in the framework of the projects: 'Estudio y prueba piloto de un sistema de desalinización de agua de mar acoplado a una unidad de generación de Energía de Gradiente Salino', in the programe: "Desalinización de agua de mar acoplada a Energía de Gradiente Salino como estrategia para aumentar la eficiencia energética y la disponibilidad de agua potable en zonas de alto estrés hídrico en el Caribe Colombiano'. developed under the contingent reclamation financing agreement No. 80740-538-2020.

Ethics approval

Not applicable.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and material

Not applicable.

Code availability

Not applicable.

Authors' contribution

All authors contributed to the study conception and design. Luis Mendoza, Aymer Maturana and Ricardo Mejía had the idea for the article; the literature search was performed by Luis Mendoza, Anggie Cala, and Salvador Villamizar; The first draft of the manuscript was written by Luis Mendoza, Ricardo Mejía, Anggie Cala, Joseph Soto, and Salvador Villamizar. All authors critically revised and approved the final manuscript.

Notes on contributors

Mendoza-Zapata, Luis; https://orcid.org/0000-0002-4543-4131

Mendoza-Zapata, Luis is a Civil Engineer, MSc in Environmental Engineering. His main areas of research have been life cycle assessment, water treatment, sustainability, and environmental management, focused on construction and demolition waste recovery. Currently, he works as senior manager on a road infrastructure project and as consultant in environmental and civil engineering issues.

Maturana-Córdoba, Aymer; https://orcid.org/0000-0003-3518-0606

Maturana-Córdoba, Aymer is a Chemical Engineer, MSc in Environmental Engineering and Ph.D. in thermal engineering and fluids. His main research areas are Industrial processes, biomass and fossil fuels to energy conversion, water and wastewater treatment by membranes, subsea water treatment, renewable energy, and environmental management. He is currently a researcher and Associate Professor at Universidad del Norte.

Mejía-Marchena, Ricardo; https://orcid.org/0000-0001-9529-4029

Ricardo Mejía-Marchena is a Chemical Engineer, MSc in Environmental Engineering and Ph.D. candidate in Civil Engineering. He works on sustainable development, specializing in industrial wastewater treatment, waste recovery, water quality monitoring, and cross-flow membrane treatment. He is currently a Ph.D. student at Universidad del Norte.

Cala, Anggie; https://orcid.org/0000-0002-6470-4168

Anggie Cala is a chemical engineer. She has worked in bioprocesses. Her current work focuses on membrane separation processes, including water purification and energy generation. She is about to graduate with a master's degree in civil engineering with an emphasis in environmental engineering from the Universidad del Norte.

Soto-Verjel, Joseph; https://orcid.org/0000-0003-3162-9330

Soto-Verjel is an environmental engineer and Ph.D. candidate in Civil Engineering. His main research interests include environmental sustainability and complex wastewater treatment through biological and advanced oxidation processes focusing on photochemical alternatives. He is currently a PhD student at Universidad del Norte.

Villamizar, Salvador; https://orcid.org/0000-0002-6485-2494

Salvador Villamizar is an environmental engineer and Ph.D. candidate in Civil Engineering. His main research interests include environmental sustainability and complex wastewater treatment through biological and advanced oxidation processes focusing on photochemical alternatives. He is currently a PhD student at Universidad del Norte.

CRediT authorship contribution statement

Luis Mendoza-Zapata: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Aymer Maturana-Córdoba:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Conceptualization. **Ricardo Mejía-Marchena:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Conceptualization. **Anggie Cala:** Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation. **Joseph Soto-Verjel:** Writing – review & editing, Writing – original draft, Visualization. **Salvador Villamizar:** Writing – review & editing, Writing – original draft, Investigation.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

The authors reports financial support was provided by Ministerio de ciencias, tecnologia e innovacion de Colombia.

Data availability

No data was used for the research described in the article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2023.121876.

References

[1] WWAP/UN-Water. The United Nations world water development report 2018: Nature-Based Solutions for Water. 2018.

[2] Ahmed FE, Hashaikeh R, Hilal N. Hybrid technologies: the future of energy efficient desalination – a review. Desalination 2020;495. https://doi.org/10.1016/j.desal.2020.114659.

[3] Okampo EJ, Nwulu N. Optimisation of renewable energy powered reverse osmosis desalination systems: a state-of-the-art review. Renew Sustain Energy Rev 2021;140. https://doi.org/10.1016/j.rser.2021.110712.

[4] Tristán C, Fallanza M, Ibáñez R, Ortiz I. Recovery of salinity gradient energy in desalination plants by reverse electrodialysis. Desalination 2020;496. https://doi.org/10.1016/j.desal.2020.114699.

[5] Ziolkowska JR, Reyes R. Impact of socio-economic growth on desalination in the US. J Environ Manage 2016;167. https://doi.org/10.1016/j.jenvman.2015.11.013.

[6] Prisciandaro M, Capocelli M, Piemonte V, Barba D. Process analysis applied to water reuse for a 'closed water cycle' approach. Chem Eng J 2016;304. https://doi.org/10.1016/j.cej.2016.06.134.

[7] UPME. Informe Mensual de Variables de Generación y del Mercado Eléctrico Colombiano - Diciembre de 2016. In: Subdirección de Energía Eléctrica - Grupo Generación, no. 69; 2016.

[8] Jia Z, Wang B, Song S, Fan Y. Blue energy: current technologies for sustainable power generation from water salinity gradient. Renew Sustain Energy Rev 2014;31. https://doi.org/10.1016/j.rser.2013.11.049.

[9] Sales BB, Saakes M, Post JW, Buisman CJN, Biesheuvel PM, Hamelers HVM. Direct power production from a water salinity difference in a membrane-modified supercapacitor flow cell. Environ Sci Technol 2010;44(14). https://doi.org/10.1021/es100852a.

[10] Veerman J, Saakes M, Metz SJ, Harmsen GJ. Reverse electrodialysis: performance of a stack with 50 cells on the mixing of sea and river water. J Membr Sci 2009;327(1–2). https://doi.org/10.1016/j.memsci.2008.11.015.

[11] Lee K, Jepson W. Environmental impact of desalination: a systematic review of life cycle Assessment. Desalination 2021;509. https://doi.org/10.1016/j.desal.2021.115066.

[12] Kim J, Park K, Yang DR, Hong S. A comprehensive review of energy consumption of seawater reverse osmosis desalination plants. Appl Energy 2019;254. https://doi.org/10.1016/j.apenergy.2019.113652.

[13] Chung HW, Swaminathan J, Banchik LD, Lienhard JH. Economic framework for net power density and levelized cost of electricity in pressure-retarded osmosis. Desalination 2018;448. https://doi.org/10.1016/j.desal.2018.09.007.

[14] Elsaid K, Kamil M, Sayed ET, Abdelkareem MA, Wilberforce T, Olabi A. Environmental impact of desalination technologies: a review. Sci Total Environ 2020;748. https://doi.org/10.1016/j.scitotenv.2020.141528.

[15] Restrepo JC, et al. Freshwater discharge into the Caribbean Sea from the rivers of northwestern South America (Colombia): magnitude, variability and recent changes. J Hydrol (Amst) 2014;509. https://doi.org/10.1016/j.jhydrol.2013.11.045.

[16] Vallejo-Castaño S, Sánchez-Sáenz CI. Design and optimization of a reverse electrodialysis stack for energy generation through salinity gradients. Dyn Med 2017;84(202). https://doi.org/10.15446/dyna.v84n202.59321.

[17] Bello AS, Zouari N, Da'ana DA, Hahladakis JN, Al-Ghouti MA. An overview of brine management: emerging desalination technologies, life cycle assessment, and metal recovery methodologies. J Environ Manage 2021;288. https://doi.org/10.1016/j.jenvman.2021.112358.

[18] Wojtarowski A, et al. Renewable energy production in a Mexican biosphere reserve: assessing the potential using a multidisciplinary approach. Sci Total Environ 2021. https://doi.org/10.1016/j.scitotenv.2021.145823.

[19] Heck N, Lykkebo Petersen K, Potts DC, Haddad B, Paytan A. Predictors of coastal stakeholders' knowledge about seawater desalination impacts on marine ecosystems. Sci Total Environ 2018;639. https://doi.org/10.1016/j.scitotenv.2018.05.163.

[20] Lee S, Choi J, Park YG, Shon H, Ahn CH, Kim SH. Hybrid desalination processes for beneficial use of reverse osmosis brine: current status and future prospects. Desalination. 2019. https://doi.org/10.1016/j.desal.2018.02.002.

[21] Zoungrana A, Çakmakci M. From non-renewable energy to renewable by harvesting salinity gradient power by reverse electrodialysis: a review. Int J Energy Res 2021;45(3). https://doi.org/10.1002/er.6062.

[22] Alharbi T, Alfaifi H, Almadani SA, El-Sorogy A. Spatial distribution and metal contamination in the coastal sediments of Al-Khafji area, Arabian Gulf, Saudi Arabia. Environ Monit Assess 2017;189(12). https://doi.org/10.1007/s10661-017-6352-1.

[23] Uddin S. Environmental impacts of desalination activities in the Arabian Gulf. Int J Environ Sci Develop 2014. https://doi.org/10.7763/ijesd.2014.v5.461.

[24] Mohamed AMO, Maraqa M, Al Handhaly J. Impact of land disposal of reject brine from desalination plants on soil and groundwater. Desalination 2005;182(1–3). https://doi.org/10.1016/j.desal.2005.02.035.

[25] Bhandary H, Sabarathinam C, Al-Khalid A. Occurrence of hypersaline groundwater along the coastal aquifers of Kuwait. Desalination 2018;436. https://doi.org/10.1016/j.desal.2018.02.004.

[26] Younos T. Environmental issues of desalination. J Contemp Water Res Educ 2009;132(1). https://doi.org/10.1111/j.1936-704x.2005.mp132001003.x.

[27] Chang JS. Understanding the role of ecological indicator use in assessing the effects of desalination plants. Desalination 2015;365. https://doi.org/10.1016/j.desal.2015.03.013.

[28] Alvarez-Silva O, Winter C, Osorio AF. Salinity gradient energy at river mouths. Environ Sci Technol Lett 2014;1(10). https://doi.org/10.1021/ez500239n.

[29] Alvarez-Silva O, Osorio AF. Salinity gradient energy potential in Colombia considering site specific constraints. Renew Energy 2015;74. https://doi.org/10.1016/j.renene.2014.08.074.

[30] APHA. Standard methods for the examination of water and wastewater. In: Standard methods; 2005. doi: ISBN 9780875532356.

[31] Hashemi F, Hashemi H, Abbasi A, Schreiber ME. Life cycle and economic assessments of petroleum refineries wastewater recycling using membrane, resin and on site disinfection (UF-IXMB-MOX) processes. Proc Safe Environ Protect 2022;162. https://doi.org/10.1016/j.psep.2022.04.027.

[32] Pazouki P, Stewart RA, Bertone E, Helfer F, Ghaffour N. Life cycle cost of dilution desalination in off-grid locations: a study of water reuse integrated with seawater desalination technology. Desalination 2020;491. https://doi.org/10.1016/j.desal.2020.114584.

[33] Altmann T, Das R. Process improvement of sea water reverse osmosis (SWRO) and subsequent decarbonization. Desalination 2021;499. https://doi.org/10.1016/j.desal.2020.114791.

[34] Luong VT, et al. Modular desalination concept with low-pressure reverse osmosis and capacitive deionization: performance study of a pilot plant in Vietnam in comparison to seawater reverse osmosis. J Environ Manage 2023;329. https://doi.org/10.1016/j.jenvman.2022.117078.

[35] Rodríguez González A. ESTUDIO OPERACIONAL Y DISEÑO DE UNA PLANTA OPR DE GENERACIÓN DE ENERGÍA ELÉCTRICA. Universidad Carlos III de Madrid; 2017 [Online]. Available: http://hdl.handle.net/10016/28049.

[36] Zoungrana A, Çakmakci M. Optimization of the reverse electrodialysis power output through the ratio of the feed solutions salinity. IET Renew Power Generat 2021;15(4). https://doi.org/10.1049/rpg2.12066.

[37] Najjar E, Al-Hindi M, Massoud M, Saad W. Life Cycle Assessment of a seawater reverse osmosis plant powered by a hybrid energy system (fossil fuel and waste to energy). Energy Rep 2021;7. https://doi.org/10.1016/j.egyr.2021.07.106.

[38] ISO. ISO 14040:2006. International Organization for Standardization; 2022.

[39] Jolliet O, et al. IMPACT 2002+: a new life cycle impact assessment methodology. Int J Life Cycle Assess 2003;8(6). https://doi.org/10.1007/BF02978505.

[40] Giacalone F, Papapetrou M, Kosmadakis G, Tamburini A, Micale G, Cipollina A. Application of reverse electrodialysis to site-specific types of saline solutions: a techno-economic assessment. Energy 2019;181. https://doi.org/10.1016/j.energy.2019.05.161.

[41] Maleki A, Pourfayaz F, Ahmadi MH. Design of a cost-effective wind/photovoltaic/hydrogen energy system for supplying a desalination unit by a heuristic approach. Solar Energy 2016;139. https://doi.org/10.1016/j.solener.2016.09.028.

[42] Okampo EJ, Nwulu NI. Optimal energy mix for a reverse osmosis desalination unit considering demand response. J Eng Design Technol 2020;18(5). https://doi.org/10.1108/JEDT-01-2020-0025.

[43] Alhaj M, Tahir F, Al-Ghamdi SG. Life-cycle environmental assessment of solar-driven multi-effect desalination (MED) plant. Desalination 2022;524. https://doi.org/10.1016/j.desal.2021.115451.

[44] Nasrollahi M, Motevali A, Banakar A, Montazeri M. Comparison of environmental impact on various desalination technologies. Desalination 2023;547. https://doi.org/10.1016/j.desal.2022.116253.