Life cycle assessment of salinity gradient energy recovery by reverse electrodialysis
in a seawater reverse osmosis desalination plant

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Raquel Ibáñez, Inmaculada Ortiz’

Abstract

Salinity gradient energy capture by reverse electrodialysis (SGE-RED) can play a part in
the shift away from fossil fuels towards a carbon-neutral renewable energy supply;
however, likewise other renewable power technologies, SGE-RED environmental
soundness hinge on its whole life-cycle environmental loads. This study surveys the Life
Cycle Assessment of SGE-RED technology. We quantified (i) the environmental loads
per 1.0 kWh generated by a stand-alone RED unit and then, (ii) the environmental burdens
related to the energy provision from an up-scaled RED system to a seawater reverse
osmosis (SWRO) desalination plant per 1.0 m$^3$ of desalted water. The RED unit’s
assessment results show SGE-RED is environmentally competitive with other renewable
sources such as photovoltaics or wind. Regarding the component’s contribution analysis,
the spacer’s fabric material drives the RED environmental burden as the number of cell

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† Electronic supplementary information (ESI) available: RED stacks’ electric parameters; RED stacks’
inventory data; Gibbs free energy of mixing.
pairs is increased. The scaling-up of the RED unit, however, improves its full environmental profile. Preliminary results of SGE-RED combination with a SWRO plant suggest that the energy harnessed from SWRO’s concentrate streams by RED could enhance the environmental performance of the desalination industry. Further research is required to identify SWRO-RED design alternatives that minimize the life cycle burden while still yielding good technical and economic performance.
1. Introduction

Salinity gradient is an untapped renewable energy source envisaged as a candidate to advance the progressive decarbonisation of the current electric energy portfolio under particular technical conditions.\textsuperscript{1,2} Reverse electrodialysis (RED) stands out among membrane-based technologies to harvest salinity gradient energy (SGE).\textsuperscript{1} RED, the reverse of the conventional desalination process i.e. electrodialysis, is an electrochemical membrane process that makes use of ion-exchange membranes (IEM) to recover the energy released in the reversible mixing of two solutions with different salinities.\textsuperscript{2} A RED unit is assembled by stacking a series of repeating units or cell pairs in a plate-and-frame arrangement. Each cell pair is comprised of an anion- and a cation-exchange membrane, with net polymer spacers placed in between to form the channels within the dilute and concentrate salt feed solutions flow. The chemical potential difference between the concentrate and dilute salt solutions gives rise to an electric potential difference over each membrane and drives the migration and diffusion of ions across membranes with opposing-charge functional groups, resulting in an ionic flux that is converted into an electron flux through redox reactions at the electrodes. The DC electric current and voltage yielded by the RED pile are readily accessible to power an external electric load connected to the RED electrodes.

RED performance has improved over the last decades, moving from relatively small power densities of 0.05 W m$^{-2}$ reported in 1954 by Pattle\textsuperscript{3} to 6.70 W m$^{-2}$ recently obtained mixing synthetic NaCl solutions mimicking fresh or brackish water and concentrated brines at a temperature of 60 °C.\textsuperscript{4} Last research advances have stepped up RED Technology Readiness Level enabling the progress from lab-scale units\textsuperscript{5,6} to up-scaled prototypes\textsuperscript{7–10} and pilot plants.\textsuperscript{11,12}
SGE can be obtained from natural or anthropogenic streams. The reclamation of industrial effluents in osmotic power generation plants as SGE-RED is a promising alternative to provide energy savings from an otherwise waste stream. Several authors have examined the energy recovery from desalination’s concentrate effluents,$^{13–18}$ as well as secondary treated wastewater effluents.$^{7,19,20}$ Moreover, RED operation with high-salinity effluents delivers higher energy densities than seawater/river water pairs extensively tested in previous works.$^{4,21,22}$

The ever-growing water demand, along with the steady decline of conventional water resources$^{23}$ is propelling the adoption of different water enhancement alternatives, such as desalination or water reclamation and reuse.$^{24}$ Recent figures about desalination sector signify this trend. The global installed desalination capacity has been growing steadily at an average rate of 8% per year since 1965 accounting for 97.4 million cubic meters per day (Mm$^3$d$^{-1}$) in 2017 and over 20,000 desalination plants had been contracted so far around the world.$^{24}$

Among membrane technologies, reverse osmosis (RO) leads the global market for seawater desalination sharing 69% of the current volume of desalinated water produced worldwide in 2018.$^{25}$ The energy to drive desalination in SWRO plants has dropped significantly over the last four decades as a result of improvements in membrane technology, the installation of energy recovery systems and the use of more efficient pumps.$^{26–28}$ However, this technology remains an intensive-energy and costly freshwater source.$^{27,29}$ Indeed, the specific energy consumption (SEC) – the energy consumed per cubic meter of freshwater produced – of current state-of-the-art SWRO plants falls within the range of 2.5–6.0 kWh m$^{-3}$ depending on several site-specific factors$^{30}$ as feed’s composition and temperature, water quality standards, brine management, production
capacity\textsuperscript{31,32} and RO plant configuration\textsuperscript{33} contributing up to 40\% in the water cost of large-scale seawater desalination plants.\textsuperscript{26,34}

The minimum theoretical energy for desalination of seawater –assuming a feed salt concentration of 35 ppt (parts per thousand) and 50\% recovery rate–, is \(\sim 1.06 \text{ kWh m}^{-3}\).\textsuperscript{34} Hence, alternatives for further reduce the energy demand of RO process are limited since desalination plants’ size is finite and the actual separation process is thermodynamically irreversible. Given that a gradual increase of the global desalination capacity is forecasted in the coming years,\textsuperscript{29} and the electric energy portfolio is still dominated by fossil fuels,\textsuperscript{35} the search of sustainable renewable energy sources turns to be decisive for the previously mentioned decarbonisation.\textsuperscript{36,37}

Currently, desalination driven by renewables is in the application and advance R&D stage. In 2009, the installed desalination plants powered by renewables was below 1\% compared to the world's total capacity.\textsuperscript{36} The preferred renewable energy systems to drive –primarily low-to-medium capacity (50–2,000 m\textsuperscript{3} day\textsuperscript{-1})– RO desalination plants are solar photovoltaic (31\%) followed by wind energy (12\%).\textsuperscript{36} The main issue of these renewable sources is its intermittency since RO desalination requires a continuous energy supply that ensures its operability. Conversely, SGE-RED systems can provide continuous energy supply to power desalination. Research in RED has been devoted to improvements in stack design,\textsuperscript{1,38} membrane development,\textsuperscript{1,39} process analysis and optimization,\textsuperscript{40} fouling control\textsuperscript{41} and hybrid processes.\textsuperscript{1,38} Lately, the progress of SGE-RED systems to pilot plant scale has boost research in control processes in SGE-RED systems.\textsuperscript{11,12} Several works underline the synergetic benefits of SGE-RED integration in membrane-based desalination processes as RO; for instance, Li et al. conceptual modelling of RED-RO hybridization, reporting the optimal operating conditions of the
RED process alongside different integration schemes of a RED network, indicates RED could remarkably reduce the SEC while improves rejected brine management compared to conventional SWRO. Tufa et al. novel design which combines membrane distillation and RED to simultaneously produce water and energy from SWRO brine, supports low-energy and Near-Zero Liquid Discharge seawater desalination. Although SGE-RED technology co-located with a SWRO facility can provide an evident energy relief due to the SGE retrieved from waste streams, the full environmental consequences of such concept are barely studied in the reported literature. Since all renewable energy technologies have associated environmental burdens –mainly due to the environmental amortisation of the infrastructure– it is mandatory to objectively quantify the potential environmental benefits of SGE-RED integration.

Life Cycle Assessment (LCA), a comprehensive and internationally well-known standardized tool to evaluate the environmental performance of products and services throughout its entire life cycle, can help identify the hot spots of SGE-RED concept. Its use provides the decision-maker with coherent, transparent, reproducible, and quantitative information about the environmental consequences in the full life cycle, avoiding shifting burden across environmental compartments or regions. SGE-RED environmental burdens are primarily caused by the infrastructure of the stack as no relevant additional material or energy resources are needed to operate the system, likewise wind or solar energy systems. The lack of similar environmental studies may be related to the very few SGE-RED pilot projects built and operated for long periods. While the LCA tool is vastly used for the environmental assessment of the energy produced from non-renewable and renewable sources, to the best of our knowledge, this work presents the very first environmental assessment of the SGE-RED technology using LCA.
This study aims to provide relevant insight into the environmental performance of SGE-RED by quantifying its environmental burdens through an LCA study. Two study cases are assessed to characterise this technology: (i) a stand-alone RED unit (Case 1) and (ii) an up-scaled RED system integrated into a real working environment, specifically a SWRO desalination plant (Case 2). The remainder of this paper is organised as follows. Section 2 describes the methodology. We define the goal and scope, i.e. the system boundary of Case 1 and Case 2 and the source for the primary and background data used to build the corresponding life cycle inventories (LCI). The midpoint impact categories considered in the study are also justified. Section 3 presents the results for each case, examining both the LCI and the values for the chosen impact categories. Regarding Case 1, we performed a sensitivity analysis of the number of cell pairs and membrane area (up-scaled stack), the degradation rate of the membranes, and the spacer material to examine their influence on the RED environmental performance. In Case 2, the environmental improvements attained in the hybrid SWRO-RED scheme are analysed and properly discussed. Specifically, the impact reduction achieved when SWRO energy demand is partly supplied by RED instead of the Spanish energy grid mix, defined as the baseline scenario. Finally, Section 4 outlines the main conclusions with some indications for future work. The findings reported here show for the first time the environmental performance of an SGE-RED system. The insights gained from this study may be of assistance to future design improvements of this technology, outlining the promising outcomes of SGE-RED implementation in energy-intensive processes.
2. Methodology

2.1. Life cycle assessment methodology

The international standard series ISO 14040:2006 and 14044:2006 specify the LCA methodological framework followed in the present study, which involves four iterative phases: goal and scope definition, inventory analysis, impact assessment and interpretation.

The RED stack model and the analysed scenarios were implemented in the LCA software GaBi ts version 9.1 (thinkstep, Germany). We applied an attributional process-based approach, which accounts for relevant physical flows (i.e., resources, material, energy, and emissions) attributed to the provision of a specified amount of the functional unit across a product lifecycle.

2.2. Phase 1: Goal and scope definition

The LCA was conducted in two stages, which are defined by two study cases. The goal in the first stage (Case 1) was to evaluate the environmental burdens of a stand-alone RED stack unit, to identify the “hot spots” and the potential environmental improvements of this technology and to check if the SGE-RED system is environmentally competitive compared to other renewable energy systems. The definition of the SGE-RED environmental profile enabled the assessment of its implementation in a real operation scenario in the second stage (Case 2). The goal in this phase was to quantify the emissions and the energy savings that SGE-RED could provide to energy-intensive processes such as desalination.
2.2.1. Case 1: Stand-alone RED stack unit.

The intermediate energy and materials input flows in the RED system were identified and quantified along with the emissions released to the environment over the RED unit’s life cycle from the extraction of primary resources (such as oil or ore deposits) through the production phase (i.e. a cradle-to-gate approach, Fig. 1). Then, the data collected in the inventory analysis was translated into a set of impact indicators by characterization models in the impact assessment phase. The impact indicators, which were referred to the functional unit, quantified the environmental loads of the RED unit in the interpretation phase.

![Fig. 1 SGE-RED unit’s system boundary.](image)

The assessment encompassed three distinct RED stack sizes, two lab-scale units and a product-scale one (Table 1). The functional unit set in the first stage was 1.0 kWh of gross energy yielded by each RED stack unit (Table 1) in the operational scenarios reported in Table 2 (set based on RED unit’s size). The functional unit was defined
considering the design lifetime of the RED plant and the total electricity generated over
the lifespan of the system in the different scenarios addressed in the study. The RED
lifetime assumed in the assessment was 20 years.\textsuperscript{10} The auxiliary equipment needed in
RED operation such as pumps, pipes and electric power conversion systems and the
related external energetic losses, were neglected in this part of the study according to the
established cut-off criteria.

\textbf{2.2.2. Case 2. SGE-RED integration into a SWRO plant.}

The environmental loads per cubic meter of freshwater in the hybrid SWRO-RED
scheme, i.e. the functional unit in the second stage—system boundary depicted in \textbf{Fig. 2}—
were estimated assuming that RED supplies to the SWRO plant (i) the maximum
extractable thermodynamic energy —the energy released in the complete mixing of the
first pass SWRO concentrate effluent with the mixed stream produced by blending the
second pass SWRO concentrate and the wastewater treatment plant (WWTP) effluent—
; and (ii) the actual energy output from the RED plant. The environmental loads of RED
coupled with the SWRO plant were compared to the baseline scenario, where the Spanish
grid mix fulfils the energy requirements of the SWRO plant. The assessment is restricted
to the SWRO energy demand during the operational phase in the aforementioned
scenarios. The SWRO plant’s infrastructure and pretreatment of feed’s streams, involved
in operation phase were left out of the system boundary.
Fig. 2 System boundary of SGE-RED integration into a SWRO desalination plant. The SGE-RED plant recovers the energy released in the controlled mix of the 1st pass SWRO concentrate and the blended 2nd pass SWRO rejected stream with the WWTP effluent to partly power desalination in place of the Spanish energy mix.

2.3. Phase 2: Life cycle inventory analysis (LCI)

2.3.1. Case 1. Stand-alone RED stack unit.

The RED stack unit modelled in the assessment—depicted in Fig. 3—is made up of several cell pairs each with a cation exchange membrane (CEM) and an anion exchange membrane (AEM) kept apart by spacers. An additional cationic membrane placed next to the electrodes shield the outer feed compartments from the electrode chambers. The net polymer spacers are disposed between the membranes to alternatively distribute the concentrate and diluate streams, to keep the inter-membrane distance and to provide mechanical stability. The inlet and outlet manifolds shaped in the silicone gasket—framing the net polymer spacers—, force the high salinity and low salinity streams to flow through the stack in alternate channels. The cell pile is closed with an endplate on either
side and is compressed by stain-less steel bolts and nuts to limit leakages. The chambers drilled in each endplate contains the electrodes and the flowing electrolyte solution i.e. the electrode rinse solution recirculated over the electrode compartments.

![Diagram of RED stack components](image)

**Fig. 3** RED stack’s components considered in the LCA.

**Table 1** summarises the number of cell pairs and membrane size of the commercial RED stack units considered in the assessment. The relevant input material flows were identified and quantified dismantling a lab-scale module from Fumatech® (foreground data, RED unit #1). The inventory analysis from the up-scaled RED module #3, with higher membrane area and number of cells, was defined by extrapolation of the #1 lab-scale RED stack inventory analysis results. The number of cell pairs of the product-scale stack was assigned according to large-scale commercial RED stacks reported in the literature.7,54 The #2 lab-scale module is the same as the dismantled RED stack #1 except for the number of cell pairs, which were assigned based on the maximum number of cells
admitted by the lab-scale module type according to manufacturer’s specifications. The
membrane standard dimensions of the product-scale module were also extracted from
Fumatech®.

**Table 1.** Number of cell pairs and membrane size of the lab-scale and product-scale
RED stack units.

<table>
<thead>
<tr>
<th>RED stack</th>
<th>Cell pairs</th>
<th>Membrane area (m²)</th>
<th>Membrane size (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Effective</td>
<td>Total</td>
</tr>
<tr>
<td>Lab-scale</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#1</td>
<td>20</td>
<td>0.020</td>
<td>0.046</td>
</tr>
<tr>
<td>#2</td>
<td>250</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Product-scale</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#3</td>
<td>1000</td>
<td>0.175</td>
<td>0.252</td>
</tr>
</tbody>
</table>

Inter-membrane distance: 270 µm

The lab-scale RED stack #1 (module type FT-ED-200 Fumatech®, Germany) – used to
validate the RED mathematical model – contains 20 cell pairs. The homogeneous ion-
exchange membranes of 200 cm² active membrane area (total membrane area of 458 cm²)
and a thickness of 50 µm were also supplied by Fumatech®. According to the information
kindly supplied by the providing company, the FKS-50 CEM base polymer is SPEEK
(sulfonated poly(ether-ether-ketone)) and the FAS-50 AEM base polymer is BPPO
(brominated polyphenylene oxide). The assumed IEMs durability was 7 years. The
RED stack is also composed of 40 spacers, with two extra spacers adjacent to the anode
and cathode compartments to confine the salt solutions flow over the RED pile. The net
spacers with equal dimensions as IEMs and 270 µm thick were made of polyethersulfone
(PES). The porosity of the spacers was 0.825. The embedded gasket material was
silicone. A 10-year lifetime was assumed for the spacers. The stack was also equipped
with four dimensionally stable anodes (DSA®). Both anode and cathode are stretched
titanium mesh substrates coated with ruthenium/iridium metal oxides with an area of 96.1
cm² and 2.6 cm thick. A loading of 10 g m⁻² and RuO₂:IrO₂ ratio of 70:30 coating was assumed. The electrode lifetime, 10 years, was estimated based on the current density at maximum power output conditions. The endplates were assumed to be made of polypropylene (PP) and last 10 years.

The energy yield by the RED stack unit in the different scenarios reported in Table 2 was estimated with the mathematical model developed by Ortiz-Imedio et al. The RED high salinity influent corresponds to the rejected 1st pass RO brine of a SWRO desalination plant in the Mediterranean Sea. The optimum RED low salinity concentration in terms of energy density was identified with the RED mathematical model. The maximum linear flow velocity within the concentrate and diluate compartments, i.e. 3.0 cm s⁻¹, was assigned based on operational restrictions prescribed by the manufacturer (Fumatech®).

Under this scenario (Scenario a), RED delivers higher gross power densities at the expense of a greater pressure drop within the flow channels involving increased pumping power costs. Hence, besides this scenario, we evaluated product-scale RED operation at lower flow rates (Scenario b). In this case, we assigned the optimal concentrate and diluate cross-flow velocities in terms of RED net power –equal to RED gross power output less pumping power required to overcome the internal hydrodynamic losses– estimated with the RED model, i.e. 0.6 cm s⁻¹ and 1.2 cm s⁻¹.
Table 2. RED stack’s operational conditions under scenarios a and b.

<table>
<thead>
<tr>
<th>RED stack</th>
<th>Scenario</th>
<th>( v ) (cm s(^{-1}))</th>
<th>( Q ) (m(^3) h(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>HC</td>
<td>LC</td>
</tr>
<tr>
<td>#1</td>
<td>a</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>#2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#3</td>
<td>a</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>0.6</td>
<td>1.2</td>
</tr>
</tbody>
</table>

HC: high concentration (1 M NaCl); LC: low concentration (20 mM NaCl)

T = 297.15 K (24 °C)

Scenario a: Maximum cross-flow velocity in the feed compartments suggested by the manufacturer Fumatech®.
Scenario b: Optimum cross-flow velocity in terms of net power density estimated with the RED model.

Background data from the modelled upstream processes were taken from research and patent literature and the ecoinvent database 3.5. If available, average European conditions were assumed. Infrastructure and transport requirements were always included. The Spanish grid mix, PV solar power plant and wind energy power plant environmental metrics were retrieved from ecoinvent database 3.5.

2.3.2. Case 2. SGE-RED integration into a SWRO plant

In this scenario (Fig. 2), we assumed that the SGE-RED plant was installed in a medium to large-size two-pass SWRO desalination facility in the Mediterranean Sea (seawater salinity ranges from 37 ppt to 40 ppt). The desalination plant operational parameters reported in Table 3 were set based on average values of two-pass SWRO plants in the Mediterranean Sea reported in the literature. As shown in Fig. 2, the RED plant’s high and low salinity influents match the 1st and the 2nd pass concentrate effluents rejected by the SWRO desalination plant. These streams, already pretreated by the SWRO plant, exhibits better quality conditions for RED stable operation mitigating fouling issues. However, the 2nd pass rejected stream concentration (70 mM) is over optimum RED’s diluate influent one (20 mM). Hence, the 2nd pass SWRO rejected stream was diluted with...
the secondary WWTP effluent (2 mM). This measure is feasible as long as the WWTP is located close to the SWRO plant. The resulting mixed stream volume was 0.7 m$^3$ per cubic meter of freshwater. The pump energy needs were considered negligible, as far as the SGE-RED plant is installed in the SWRO plant and the two streams flow into the RED system at enough pressure to overcome the internal pressure drop.

Table 3. Two-pass SWRO desalination plant’s average operational conditions per cubic meter of freshwater assumed in the assessment.$^{28,62}$

<table>
<thead>
<tr>
<th></th>
<th>SEC (kWh m$^{-3}$)</th>
<th>Recovery rate (%)</th>
<th>Concentrate $^b$ (m$^3$ m$^{-3}$)</th>
<th>Concentrate $^b$ (mol L$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1$^{st}$ pass RO</td>
<td>3.0</td>
<td>45</td>
<td>1.4</td>
<td>1.00</td>
</tr>
<tr>
<td>2$^{nd}$ pass RO</td>
<td>0.9</td>
<td>85</td>
<td>0.1</td>
<td>0.07</td>
</tr>
<tr>
<td>Total plant $^a$</td>
<td>4.5</td>
<td>42</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

$^a$Including energy required for feed water intake and pre-treatment. $^b$Computed considering the overall RO configuration and the recovery rate of the desalination plant, as well as the product water’s and feed seawater’s salinity.

2.4. Phase 3: Life cycle impact assessment (LCIA)

The environmental performance of the RED stack unit (Case 1) and the hybrid SWRO-RED configuration (Case 2) was evaluated in terms of three midpoint impact indicators, which were referred to the functional unit in each case of study: Abiotic Depletion Potential of element resources (ADP-e) in units of mass of Sb-eq, Abiotic Depletion Potential of fossil resources (ADP-f) in MJ and Global Warming Potential (GWP) in units of mass of CO$_2$-eq. These three environmental indicators were those compiled within the impact assessment method CML 2001 (Centre of Environmental Science - Leiden University). The CML method restricts the assessment to early stages (midpoints) in the cause-effect chain to limit uncertainties.
2.5. Phase 4: Interpretation

A sensitivity analysis of the RED system relevant components and parameters was performed to assess their relative influence on the overall RED unit environmental impact.

3. Results and discussion

3.1. Case 1. RED stack’s environmental impacts

3.1.1. Life Cycle Inventory Analysis

Table 4 displays the quantities of each component in the lab-scale module (#1) and the estimated quantities of the up-scaled modules (#2 and #3). Table 5 shows the energy delivered by the RED units in the operational conditions reported earlier in Table 2.

<table>
<thead>
<tr>
<th>Component</th>
<th>Amount #1</th>
<th>Amount #2</th>
<th>Amount #3</th>
<th>Unit</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEM</td>
<td>0.916</td>
<td>11.45</td>
<td>252.5</td>
<td>m²</td>
<td>Total membrane area</td>
</tr>
<tr>
<td>AEM</td>
<td>0.916</td>
<td>11.45</td>
<td>252.5</td>
<td>m²</td>
<td>Total membrane area</td>
</tr>
<tr>
<td>Spacer</td>
<td>0.368</td>
<td>4.397</td>
<td>96.69</td>
<td>kg</td>
<td>Mesh fabric and gasket</td>
</tr>
<tr>
<td>Electrode</td>
<td>0.038</td>
<td>0.038</td>
<td>0.165</td>
<td>m²</td>
<td>@42.65 A m² electrode</td>
</tr>
<tr>
<td>Endplate</td>
<td>6.667</td>
<td>6.667</td>
<td>26.656</td>
<td>kg</td>
<td></td>
</tr>
</tbody>
</table>
Table 5 Energy yield by the commercial RED stacks in scenarios a and b.

<table>
<thead>
<tr>
<th>RED stack</th>
<th>Scenario</th>
<th>( P_{d,\text{gross}} ) (W m(^{-2}))</th>
<th>( P_{\text{gross}} ) (W)(^a)</th>
<th>( E_{\text{gross}} ) (MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lab-scale</td>
<td>#1</td>
<td>3.11</td>
<td>1.2</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>#2</td>
<td></td>
<td>15.6</td>
<td>2.73</td>
</tr>
<tr>
<td>Product-scale</td>
<td>#3</td>
<td></td>
<td>3.03</td>
<td>529.7</td>
</tr>
<tr>
<td></td>
<td>#3</td>
<td></td>
<td>2.44</td>
<td>425.5</td>
</tr>
</tbody>
</table>

\( P_{d,\text{gross}} \): Gross power density, gross power per effective membrane area per cell pair.

\( E_{\text{gross}} \): Gross energy yield per 20 years of operation (LT), operating 8760 h year\(^{-1}\) (\( E_{\text{gross}} = P_{\text{gross}} \times \text{LT} \times \text{Operational hours} \)).

\(^a\)Estimated with the RED’s mathematical model.\(^{40}\)

3.1.2. Influence of SGE-RED scaling-up

Fig. 4 displays the RED stack’s components contribution in the three impact categories according to the number of cell pairs and membrane area of the lab-scale RED stacks #1 (20 cells) and #2 (250 cells) as well as the product-scale RED unit i.e. #3 (1000 cells and larger membrane area per cell pair). Fig. 4 also shows the aggregated value of each indicator.

Regarding the lab-scale RED units, under equal operational conditions, the stack with a greater number of cells (RED unit #2) performs better than the one with fewer cells (RED unit #1) relating to the environmental burdens of the system. The effect of cell pair increase is twofold: (i) a proportional increase of the energy yield since the gross power density (i.e. the gross power per cell pair per membrane area) is equal in both systems and (ii) a greater share of the spacers in the three impact categories. The higher energy output of the 250-cells RED unit outweighs the environmental burdens derived from the increased number of IEMs and spacers, representing a decline of \( \sim 83\% \) in GWP and ADP-f and \( \sim 87\% \) in ADP-e. Concerning the RED stack’s components contribution in the
impact categories, the overall environmental impact of the RED stack #1 is governed by
the electrodes and endplates contributing up to ~90% to ~95% in the three impact
indicators. The impact contribution is shifted to the spacers when the number of cells is
increased. The spacer’s share in GWP, ADP-f and ADP-e moves from ~8%, ~9% and
~5% to ~49%, ~52% and ~34% when the number of cells is twelvefold. A focus on the
environmental loads of the lab-scale units’ key contributors – i.e. the electrodes and the
spacers in RED units #1 and #2 – indicate the environmental loads exerted by a spacer
(0.09 kg CO$_2$-eq, 1.92 MJ, and 3.95·10$^{-7}$ kg Sb-eq) are much lower than the ones of an
electrode (3.59 kg CO$_2$-eq, 36.61 MJ, and 4.69·10$^{-7}$ kg Sb-eq). Therefore, increasing the
number of cells offset the environmental loads of the system due to the higher energy
production and the relative contribution of the spacers in the 250-cells RED unit.
Although the up-scaled unit #3 requires larger absolute quantities of each component the
environmental performance is also improved. The energy output counterbalances the
environmental loads of the product-scale RED unit manufacture. Employing a greater
number of cell pairs and membrane size leads to a ~30%, ~35% and ~42% saving in
GWP, ADP-f, and ADP-e respectively comparing to the lab-scale unit #2. Overall, these
results denote the need for scaling-up to drive a cleaner development of SGE-RED
technology.
3.1.3. Product-scale module: Influence of the spacer material

Previous results highlighted the spacers’ dominant influence on the total environmental profile of the RED system as the number of cells was increased. Hence, we carried out a detailed environmental load analysis of the spacer’s components i.e. the gasket and the mesh fabric. The environmental metrics of each process and materials required in the spacer manufacture was retrieved from ecoinvent database. Examining the impact breakdown of a spacer, over half of the impact is caused by the fabric material (i.e. polyethersulfone, PES) followed by the gasket material. Consequently, we set different materials to the product-scale RED unit spacers’ fabric to analyze the potential environmental enhancement in SGE-RED technology in contrast to PES. Specifically, polypropylene (PP) as it exerts a reduced environmental load compared to other polymer alternatives suitable for RED operation.65
**Fig. 5.** Influence of the spacer fabric material. Relative contribution of the product-scale RED stack’s components in GWP, ADP-f and ADP-e and their aggregated value. (RED stack #3: 1000 cell pairs and effective membrane area per cell pair 0.175 m$^2$).

**Fig. 5** presents the product-scale RED components share in the three impact categories, as well as the total environmental metrics’ value. As the bar chart show, replacement of PES by PP could cut down GWP, ADP-f and ADP-e by ~34%, ~38% and ~43% respectively. These results prove the effectiveness of LCA to assist RED ecologically aware design.

### 3.1.4. Product-scale module: Influence of IEMs degradation rate

The IEMs robustness against fouling events, which depend on feed water’s composition, will determine SGE-RED deployment.\(^{66-68}\) IEMs are the most prone to fouling among RED stack components.\(^{67,69}\) Hence, to consider the effect of fouled IEMs on RED performance, we assume an annual decline in RED power output of 5%.\(^{55}\) It is also assumed that RED system initial power output is recovered when membranes are
replaced. It should be noted the assumed degradation rate is a conservative value
determined by membrane properties and feed water composition.

Table 6. Influence of IEMs degradation in the product-scale RED gross energy yield
and the three impact indicators.

<table>
<thead>
<tr>
<th></th>
<th>( E_{\text{gross}} ) (MWh)</th>
<th>( \text{GWP}_{100} ) (g CO(_2)-eq kWh(^{-1}))</th>
<th>( \text{ADP-f} ) (MJ kWh(^{-1}))</th>
<th>( \text{ADP-e} ) (mg Sb-eq kWh(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>No degradation</td>
<td>92.8</td>
<td>18</td>
<td>0.32</td>
<td>0.075</td>
</tr>
<tr>
<td>IEMs degradation</td>
<td>79.3</td>
<td>21</td>
<td>0.37</td>
<td>0.088</td>
</tr>
</tbody>
</table>

\( ^a \)Assuming a 5% RED power decline per year and a full recovery of the RED initial power output with every IEMs replacement (lifetime 7 years).

IEMs degradation impairs the environmental profile of SGE-RED technology since it hinders the energy delivered by the RED system under equal operational conditions. As Table 6 show, a 5% yearly decline in RED power leads to a ~15% full-life time energy loss. This energy drop causes a ~17% increment in all impact categories as their value is inversely proportional to RED energy delivered over its lifetime. These figures signify the relevant influence of SGE-RED long-run performance in the sustainability and feasibility of this technology.

3.1.5. SGE-RED stack environmental profile vs. other renewable energy systems

The three environmental metrics of the product-scale RED unit are compared to other renewable energy systems to assess RED’s environmental competitiveness.

Table 7 reports the environmental burdens of high voltage electricity production by a solar PV power plant and a wind power plant within the Spanish context as defined in the ecoinvent database along with the product-scale RED unit ones. Additional widely accepted references are also included for solar PV and wind power systems.
Table 7 Environmental impacts associated with electricity delivery to the grid from solar photovoltaic and wind power systems and the energy delivered by the product-scale RED unit.

<table>
<thead>
<tr>
<th></th>
<th>GWP&lt;sub&gt;100&lt;/sub&gt; (g CO&lt;sub&gt;2&lt;/sub&gt;-eq kWh&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>ADP-f (MJ kWh&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>ADP-e (mg Sb-eq kWh&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar PV</td>
<td>68</td>
<td>0.71</td>
<td>1.87</td>
<td>ecoinvent&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>6–58&lt;sup&gt;b&lt;/sup&gt;</td>
<td>-</td>
<td>-</td>
<td>UNEP (2016)&lt;sup&gt;70&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>2.9–20.7&lt;sup&gt;c&lt;/sup&gt;</td>
<td>-</td>
<td>-</td>
<td>Pehl et al. (2017)&lt;sup&gt;71&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>15–90&lt;sup&gt;d&lt;/sup&gt;</td>
<td>-</td>
<td>-</td>
<td>Miller et al. (2019)&lt;sup&gt;72&lt;/sup&gt;</td>
</tr>
<tr>
<td>Wind</td>
<td>14</td>
<td>0.16</td>
<td>0.03</td>
<td>ecoinvent&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>6–11&lt;sup&gt;f&lt;/sup&gt;</td>
<td>-</td>
<td>-</td>
<td>UNEP (2016)&lt;sup&gt;70&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>3.3–6.3&lt;sup&gt;c&lt;/sup&gt;</td>
<td>-</td>
<td>-</td>
<td>Pehl et al. (2017)&lt;sup&gt;71&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>5.0–6.0 (Onshore)</td>
<td>-</td>
<td>-</td>
<td>Bonou et al. (2016)&lt;sup&gt;73&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>7.8–10.9 (Offshore)</td>
<td>-</td>
<td>-</td>
<td>Bonou et al. (2016)&lt;sup&gt;73&lt;/sup&gt;</td>
</tr>
<tr>
<td>SGE-RED</td>
<td>18</td>
<td>0.32</td>
<td>0.08</td>
<td>This work</td>
</tr>
</tbody>
</table>

<sup>a</sup>electricity production, photovoltaic, 570 kWp open ground installation, multi-Si – ES (ecoinvent 3.5). Reference year: 2014.

<sup>b</sup>Functional unit: 1.0 kWh produced in Europe. Minimum and maximum values for 6 different PV technologies under 2010 and 2050 scenarios.

<sup>c</sup>Based on the integrated assessment method REMIND. Global 2050 average of lifetime emissions over lifetime electricity production for capacities built in 2050 in a 2 °C-consistent mitigation scenario.

<sup>d</sup>Functional unit: 1.0 kWh of AC electricity delivered to the grid. Maximum and minimum values of PV power systems installed in different locations for 3 different cell types. AC capacity > 1 MW. Reference year: 2015.

<sup>e</sup>electricity production, wind, 1-3MW turbine, onshore – ES (ecoinvent 3.5). Reference year: 2014

<sup>f</sup>Functional unit: 1.0 kWh produced in Europe. Minimum and maximum values for 3 different wind technologies under 2010 and 2050 scenarios.

<sup>g</sup>Functional unit: 1.0 kWh to the grid from four representative power plants in Europe. Onshore (2.3 and 3.2 MW turbine) and offshore (4.0 and 6.0 MW turbine) with 2015 state-of-the-art technology.

It must be noted that the function provided (the goal) and the scope of the assessments are not fully equivalent. The solar PV and wind power plants’ LCA is cradle-to-grave and the functional unit is 1.0 kWh of electricity delivered to the grid whereas the function provided in our assessment is 1.0 kWh of gross energy delivered by a RED stack under a
cradle-to-gate approach. However, as previous life-cycle assessments report, the components manufacture stage prevail in the total environmental burden of solar PV and wind power systems,\textsuperscript{70–76} thus enabling a consistent comparison between the RED unit environmental loads and the ones present in these renewable energy systems. Moreover, the end-of-life stages such as RED’s components recycling, and reuse could further reduce the environmental loads of the system offsetting the additional impact contribution of other life-cycle stages, side equipment and processes not accounted in the RED assessment.

3.2. Case 2. SGE-RED integration into a SWRO plant.

Case 1 results reveal SGE-RED technology could promote the transition to a low-carbon economy by recovering energy from waste streams of energy-intensive industries. To quantify the potential environmental benefits of SGE-RED in such processes, this study addresses the environmental loads avoided in a hybrid SWRO-RED configuration. The environmental loads per cubic meter of freshwater produced by the SWRO desalination plant were quantified in the following scenarios when the SWRO desalination facility is powered by (i) the Spanish electricity mix; (ii) the thermodynamic limit of the SGE-RED plant operating at (a) maximum flow rate, (b) optimum net power output flow rate; and (iii) SGE-RED plant actual power output in the scenarios (a) and (b), when the RED stack units required to power the desalination plant are in parallel hydraulic configuration, i.e. the concentrate and diluate streams are evenly fed to the RED units. The aforementioned scenarios are sketched in Fig. 6.
**Fig. 6** SGE-RED plant energy balance in SWRO-RED Scenarios 1 and 2 under two different RED operational conditions i.e. Scenarios a and b. Scenario 1: equal volume availability for concentrate and diluate RED’s feed streams i.e. 1st pass brine SWRO effluent 1.4 m$^3$. Scenario 2: RED’s low salinity influent volume restricted by 2nd pass brackish SWRO effluent availability, i.e. 2nd pass–WWTP mixed stream volume 0.7 m$^3$. Functional unit: 1.0 m$^3$ of freshwater. In: Gibbs free energy of mixing before RED energy conversion; out: Gibbs free energy of mixing not recovered by RED; retrieved: fraction of the SGE available for conversion (= in – out); produced: RED useful energy after SGE conversion (= retrieved – RED’s internal losses).

The mixing free energy per unit volume of freshwater sets the upper bound energy savings to drive SWRO desalination. The energy released in the complete mixing (thermodynamic equilibrium) of the 1st pass brine SWRO effluent and the diluted 2nd pass brackish SWRO–WWTP effluent is limited by the volume of each stream available for SGE conversion. The SWRO 2nd pass rejected volume is far lower than 1st pass rejected...
one (SGE-RED diluate volume is ~50% lower), hampering SGE potential to power desalination. If same volume of diluate is accessible for energy conversion, the SGE thermodynamic limit in Scenario 1.a (1.16 kWh m$^{-3}$), i.e. maximum flow rate in the concentrate and diluate RED compartments, could reach 25.8% of SWRO energy demand (4.50 kWh m$^{-3}$) while if 2$^{nd}$ pass–WWTP volume is assumed, i.e. Scenario 2.a, the energy exploitable by RED is halved (0.58 kWh m$^{-3}$) accounting for 13.0% of the SWRO energy consumption. RED operation under optimum net power conditions, i.e. Scenario b, requires smaller low and high saline influents volumes ($V_{HC}:V_{LC} = 0.58:1$, 1.58 m$^{3}$) than Scenario a ($V_{HC}:V_{LC} = 1:1$, 2.00 m$^{3}$). As a result, the maximum energy RED could harvest is cut by ~20% in both scenarios 1.b and 2.b, and so the upper energy bound to drive desalination.

Despite the Gibbs free energy in Scenario 1.b and 2.b is reduced, a greater salinity gradient energy fraction is retrieved for conversion (twice the energy consumed for conversion in Scenarios 1.a and 2.a). Providing RED efficiency $^{77}$, –defined as the fraction of mixing free energy consumed converted to useful work– in both operational scenarios is almost equal (~33%), RED working at lower flow rates supplies enhanced specific energy per m$^{3}$ of freshwater produced comparing Scenario a. Regarding SGE-RED energy recovery is irreversible, –due to RED internal energy losses– the actual power production diverges from the theoretical maximum extractable work, i.e. the chemical energy stored in salinity gradients cannot be completely harnessed for useful work. Thus, the real RED power output could only meet 1.2% and 2.4% of SWRO demand in scenarios 1.a and 1.b. As mentioned earlier, considering the diluate as a limited resource (Scenario 2: 0.7 m$^{3}$ m$^{-3}$) the thermodynamic limit is halved and so the RED useful work. Therefore, RED energy supply in Scenarios 2.a and 2.b drops to 0.6% and 1.2% of SWRO
energy demand. Even so, a significant amount of energy remains untapped. Unused SGE leaving the RED system can be further recovered by additional RED units installed in the plant, thus closing the gap between the theoretical thermodynamic limit and the overall energy retrieved by the SGE-RED plant.\textsuperscript{78} These results denote SGE-RED plant layout should be thoroughly optimised to make more efficient use of these waste streams, increasing the share of energy delivered to the SWRO plant, thus easing desalination environmental burdens.

As long as the Spanish electricity mix environmental indicators per kWh are higher than SGE-RED ones (\textbf{Table 8}), SWRO plant’s environmental burdens are enhanced when a greater fraction of grid-based electricity supply is replaced by SGE-RED. As was stated before, under Scenario 1.a assuming a full recovery of the theoretical SGE, RED could meet 25.8\% of the SWRO energy demand leading to a 24.7\%, 24.1\%, and 8.4\% maximum decrease in GWP, ADP-f and ADP-e in contrast to the Spanish electricity mix. Conversely, in Scenario 2.a assuming a RED reversible process, the free energy of mixing available for conversion is cut in half and so the enhancement of the SWRO environmental metrics, as it is depicted in \textbf{Fig. 7}. With regards to RED operation at lower flow rates, i.e. Scenarios 1.b and 2.b, the free energy of mixing is reduced by ~20\%. Therefore, the maximum SWRO burden mitigation in both scenarios is decreased accordingly in the same way as Scenarios 1.a and 2.a.
Table 8 Environmental metrics of the Spanish electricity mix and the product-scale RED stack in scenarios a and b. Functional unit: 1.0 kWh

<table>
<thead>
<tr>
<th></th>
<th>GWP$_{100}$ (g CO$_2$-eq kWh$^{-1}$)</th>
<th>ADP-f (MJ kWh$^{-1}$)</th>
<th>ADP-e (mg Sb-eq kWh$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spanish grid mix$^a$</td>
<td>434</td>
<td>5.04</td>
<td>0.11</td>
</tr>
<tr>
<td>SGE-RED</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario a</td>
<td>18</td>
<td>0.32</td>
<td>0.08</td>
</tr>
<tr>
<td>Scenario b</td>
<td>22</td>
<td>0.40</td>
<td>0.09</td>
</tr>
</tbody>
</table>


Fig. 7 Environmental metrics of SWRO-RED hybrid configuration in Scenario 1 and 2 under RED operation Scenarios a and b compared to SWRO desalination full-powered by the Spanish electricity mix. Functional unit: 1.0 m$^3$ of freshwater.
4. Conclusions

This study defines for the first time the environmental life-cycle loads of the SGE-RED technology through a cradle-to-gate LCA approach. Two study cases were assessed: (i) a stand-alone RED stack unit and (ii) SGE-RED plant integrated into a SWRO desalination plant. The mid-point environmental indicators GWP, ADP-f and ADP-e quantified the environmental loads of the aforesaid cases.

The first case study enabled the environmental characterisation of the RED unit. The 1st case outcomes revealed LCA as a valuable tool to assist RED design advancements. For instance, the analysis of the number of cell pairs and the membrane size influence on the three environmental metrics indicated SGE-RED scaling-up supports the sustainable development and deployment of this technology. It also assists in the identification of life-cycle RED “hot spots”. In our assessment, the main contribution to all environmental categories came from the spacers’ fabric material, which is PES. Replacement of this polymer by PP did improve the RED environmental profile. The SGE-RED’s LCA results also placed the environmental metrics of this technology within the range of other renewable power systems such as solar PV and on-shore and off-shore wind, thus proving its environmental competitiveness. Results concerning IEMs degradation impact on RED environmental performance evidenced long-term RED operation will determine the environmental feasibility of SGE-RED systems. The operation and design of a full-scale SGE-RED plant would enable an in-depth environmental load assessment of this technology under LCA framework.

Regarding the implementation of SGE-RED into a SWRO desalination plant, LCA results suggested SGE-RED could provide environmental benefits to the desalination sector by
reducing the grid mix share of its electric power demand, thus increasing the overall
environmental efficiency owing to the use of available still untapped energy resources.

However, SGE-RED plant layout should be optimised to increase the overall energy
recovery and efficiency.

Overall, the RED stack’s LCA may be useful in the prospective environmental decisions
regarding scale-up and commercialization of SGE-RED technology. Given the spacer’s
relative contribution to the overall environmental burdens of the RED stack, development
of spacer’s novel designs and materials with anti-fouling properties and low
environmental loads is needed. Improvements in membrane’s properties (high
permselectivity and low ionic resistance) are also relevant regarding energy efficiency
and environmental profile of the RED process operating with high saline waste streams
and wastewater treated effluents. Regarding RED integration in industrial processes, the
systematic process synthesis and design of up-scaled RED systems to recover energy
from industrial effluents are required to increase the overall process efficiency and market
competitiveness.

Conflicts of interest

There are no conflicts to declare.

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LCA of lab-scale and large-scale stand-alone RED stacks and an up-scaled RED system co-located with a SWRO desalination plant.