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Life cycle assessment for the novel integration of electrodialysis with bipolar membrane with reverse osmosis.

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1. Introduction

Water suitable for drinking is one that can be consumed by human beings without risking their health. According to the World Health Organization (WHO), this potable water should contain less than 500 mg/L of dissolved salts (Aamer et al., 2018). Yet, the major amount of water in the world is unavailable for drinking, as it contains high amounts of salts. Moreover, 97% of the total worldwide water is seawater (Wilf et al.,2007), containing varying quantity of total dissolve solids between 25000-45000 mg/L, which makes it unsuitable for human use. Only 1% of the total water on earth is inland fresh liquid water. In addition, just small portion of this freshwater is available for drinking without pre-actions like drilling, cleaning etc. These data show the problematic starting point of freshwater sources for human uses.

In addition to these given facts, there are many other factors that affect the availability of freshwater, for example population growth, climatic changes and pollution of natural water sources.

The above mentioned facts, pushed humanity toward technologies that will enable the use of un-conventional water sources like seawater, brackish water etc. In particular, the development of desalination technologies enable humanity to meet the global demand for fresh water. Figure 1 shows the sharp growth of the cumulative contracted and commissioned desalination capacity worldwide between 1965 – 2015.

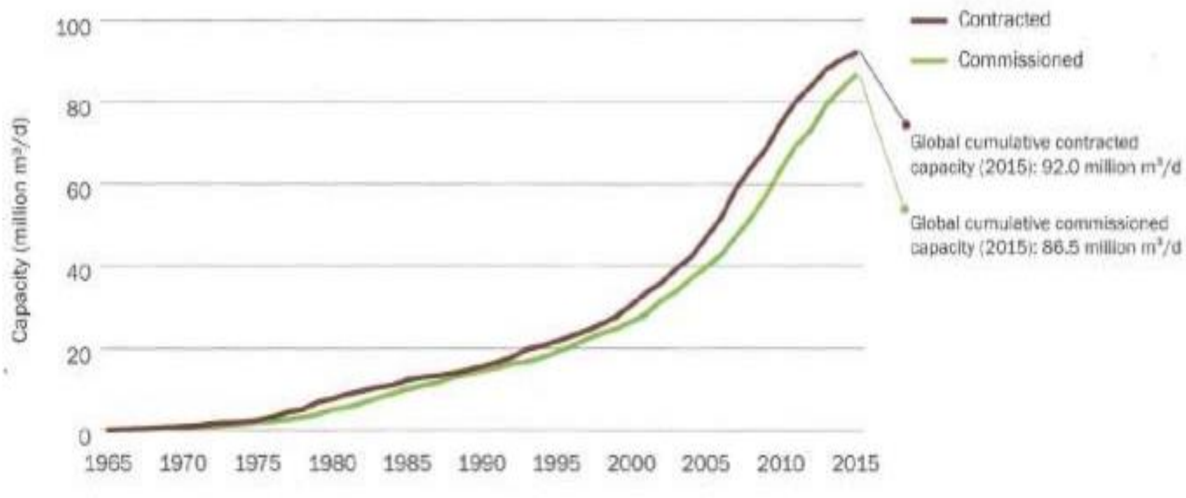


Figure 1:Worldwide desalination capacity (GWI Desaldata / IDA, 2015).

This great amount of desalination capacity, as for 2015 90 million m^3/day, is operated by about 18,000 desalination plants worldwide (IDA, 2015).

Two countries that suffer from a shortage of freshwater and as a result run a flourishing desalination industry are Spain and Israel. According to the Israel Water Authority as for May 2011, Israel desalinated 292 million m^3 /year of seawater and 28 million m^3 /year of brackish water and this volume is expected to grow by 2020 to 765 and 68 million m^3 /year for seawater and brackish water respectively (Harobbi et al., 2011), which means that by this time seawater is expected to be the main source of freshwater supply in Israel. As for Spain, which is the largest producer of freshwater by desalination in the European union, in 2009 about 3 million m^3 per day was desalinated. Also, the source of about 47% of the desalinated water in Spain is seawater (Meneses et al., 2010).

Today, two main technologies are used in water desalination: thermal processes and membrane processes. Among the thermal processes are: Multistage flash distillation (MSF), Multiple-effect distillation (MED) and Vapor compression (VC). The common membrane processes are: Reverse osmosis (RO) and Electrodialysis (ED).

The desalination capacity in the world is mainly attributed to reverse osmosis, with worldwide desalination capacity as for 2013 of 39.4 million m^3/day (Pérez et al., 2014). This is due to many advantages inherent in this method such as low energy consumption compared to other techniques in industry, low operation costs, industry in developed and low impact on the environment. Figure 2 presents the global online desalination capacity as for 2013 with distribution of desalination sources by reverse osmosis.

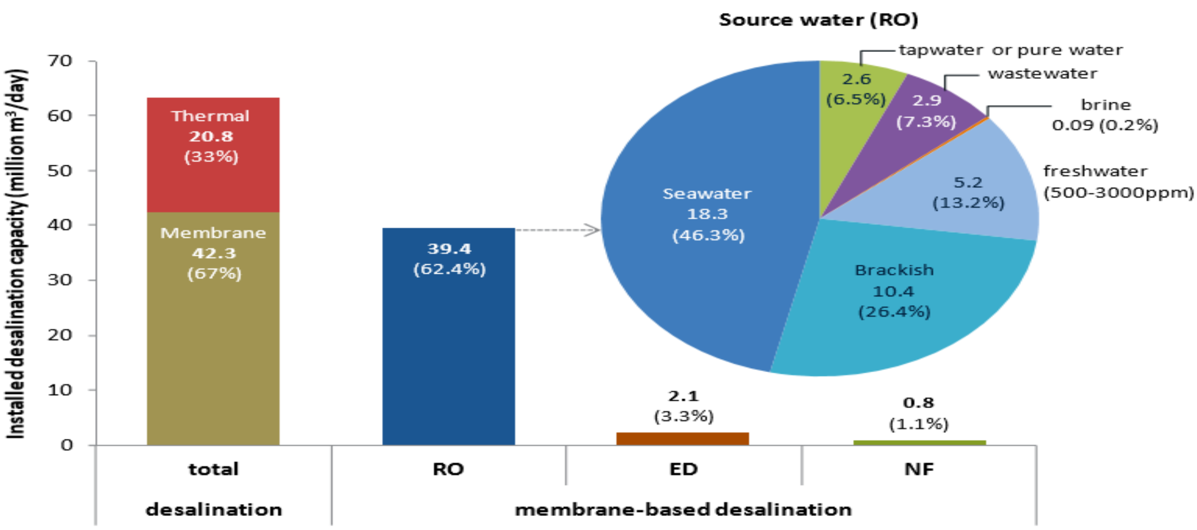


Figure 2: Distribution of desalination technologies worldwide (*Villacorte., et al 2014*).

It can be seen that reverse osmosis held 62.4% of installed desalination capacity worldwide while, 46.3% of this capacity is originated from seawater (Villacorte., et al 2014). As for any process, this process contains some operational drawbacks like low yield which limited to around 45% to prevent membrane fouling, a well know defect in membrane processes in which particles are adhesion to the surface of the membrane to a point that some of the pores are being blockage leading to decrease in the output (Panglisch et al., 2016). High frequency of fouling occurrence increases operation costs, as it requires cleaning treatments and membrane changes.

1.1. Reverse osmosis

The first use of pressure in favor of water desalination is not extennsively reviewed in literature, and in fact is not known for certainty till this day. Yet, it is well agreed that Reid and Breton conducted some scientific experiments at the University of Florida back at the 50s, which contributed to the development and advancement of this technology in years followed. But still, it was only in the 60s when the worlds first commercial RO plant was built (Glater et al., 1998).

The procces of reverse osmosis for desalination of seawater uses an external force to inverse the solvent direction flow. In the osmosis process, the solvent migrates from a dilluted solution (hypotonic) to a concentrated one (hypertonic) through a membrane. The process energy depends on the difference in osmotic pressure, which is related to the difference in the salt concentration. The greater the difference between the two solutions concentrations, the greater the osmotic pressure to overcome, which means that higher pressure must be exerted to allow the solvent migration through the semi-permeable membrane. For example, at 25 °C the osmotic pressure on the fresh water side is higher by 2.1 MPa over the seawater side (Wilf et al.,2007). Therfore water molecules will pass through the semi-permeable membrane from the seawater side to the other side only if greater force will by applied from the concentrated side. Finally, besided freshwater, a RO desaliation process yields also high concentarated salt solution, and when the source water is seawater this solution usually consist high amount of sodium chloride, named brine.

A reverse osmosis system consistes of five subunits: high pressure pump, pre-treatment unit, semi-permeable membrane, post treatment and turbine unit to recover energy from the brine stream. At first, seawater is pumped from the sea and enters to the pre-treatment unit. Then, the seawater goes through sand filters, micron filters and several chemicals are added to the solution to prevent membrane fouling by dirt or biological and chemical deposits.In the next step, high pressure pump generates the prussure that requiered to make the water molecules migrataion to the dilluted side. The pressure for seawater desalination ranges between 55-82 bars (Al-Karaghouli et al., 2013). The permeate water that passed through the membrane is then transferred to the post-treatment unit, there the pH is adjustmented and some other activities are performed to give the water the chemical characteristics it requirs to be suitable for drinking. The salty water comes out of the membrane is known as brine, and usually it is discharged back to the sea, but not before it goes through a turbine to recovere some of the energy invested in the process. Though the waste disposal of the desalination plants cotain a diverse of meterials,the brine consider to be the most influentail and important waste output due to it's hight volume and high salt concentration. Figure 3 presents a flow diagram of reverse osmosis plant.

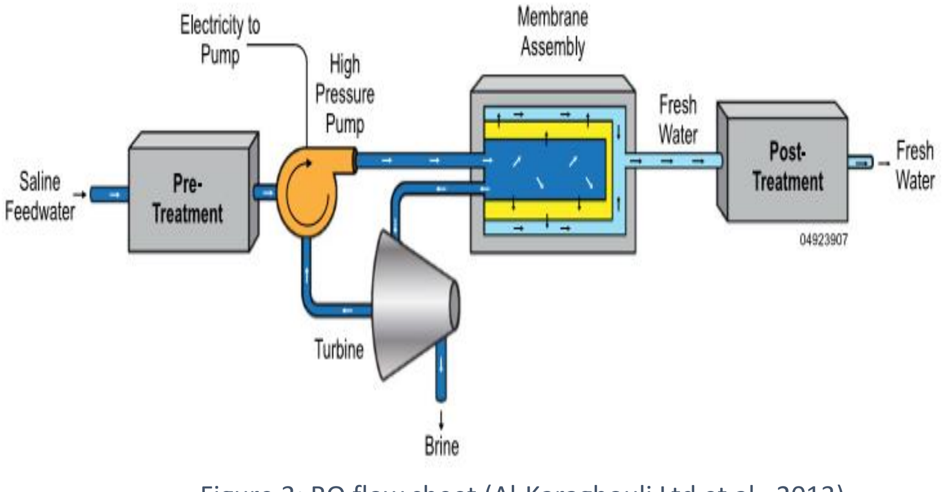


Figure 3: RO flow sheet (Al-Karaghouli Ltd et al., 2013).

As mentioned before, most of the brine is descharged to the sea, but there are some other methods found in the industry to traet the brine stream, like sewre discharge and solar ponds. However each method has environmental faults, capital costs and technical restriction. Therefor, discharge to the sea is the main solution for dealing with brine today.

1.2. Environmental impact of RO desalination

While seawater desalination seems to hold the solution for the world's water shortage problem, it is still a fly in the ointment, as the process accompanied by various environmental negative impacts. Every desalination technique has its own environmental effect (García-Rubio et al., 2012), and the following section will describe the main environmental effects caused by RO. The two main environmental impacts of RO desalination plants are:

1) Brine discharge: the main environmental effect of RO seawater desalination plants is the huge amount of brine discharge to the sea. As for 2015, the worldwide brine generation was between $29.3 \cdot 10^6$- $97.5 \cdot 10^6$ m^3/day (Fernandez et al., 2016). This brine is twice concentrated then seawater. In Spain, the concentration of salts in brine varies from 44 gr/L to 75.2 gr/L (García-Rubio et al., 2012). In addition to the high salt concentration, the brine also contains various chemicals that are added to the process in the pre-treatment and cleaning stages. The spread of brine in the sea depends on various factors such as oceanographic (waves, currents etc.) and production capacity. Since brine is denser then seawater it tends to sink in the seabed, which can cause dehydration of some marine organism. In addition, the presence of great amount of brine in sea may cause turbidity, which can interrupt to the proper process of photosynthesis (Fernandez et al., 2015). For these and other reasons, empty areas of vegetation are good places to unload the brine (Einav et al., 2002).
2) Greenhouse gas emissions: electricity is the main energy source in RO processes (Al-Karaghouli et al., 2013). Since RO is an intensive energy consumer, high amount of fuel is burned which is the typical way for producing electricity. This energy usage causes indirect effects over the environment and release different air pollutants from the production of electricity, such as CO_2, N_2O and CH_4 which also responsible for climate change (Biswas et al., 2009). As for 2015, it is estimated that desalination plants worldwide responsible for 76 million of tones of CO_2 emitted per year (Masdar

et al., 2015). This environmental impact can be minimized by powering RO processes with renewable energy sources which can reduce about 90% of greenhouse gases emitted (Shahabi et al., 2014).

To sum, the production of freshwater from seawater by RO has direct and indirect environment effects. Indirect negative effect caused because of massive consumption of energy leads to the emission of greenhouse gases.

The volume of global brine production every year is enormous and unloading it to the sea is costly. For instance, the cost of brine disposal to surface water is around 0.02-0.2 €/m^3 (Fernandez et al., 2015). This massive amount of brine production requires a comprehensive research to find new technology that meet the above-mentioned challenges.

1.3. EDBM a possible future solution for brine treatment

Electrodialysis with bipolar membrane (EDBM) is a promising technology that gained over the last years high attention for treatment and valorization of desalination brine to acids and bases. Since this wastewater contains high concentration of NaCl, it can be used to produce HCl and NaOH. These products are useful chemicals for a wide range of industries, including the desalination industry itself. For example, one of the stages of reverse osmosis is the pre-treatment phase, which include pH control by addition of acid solution (sulfuric acid or hydrochloric acid (Yang et al., 2013)) to prevent scaling occurring at neural pH. Fernandez et al. (2015) reported that seawater desalination plant with RO technique utilizes between 15-97 mg/L of sulfuric acid for the pre-treatment stage. That means that a plant with a capacity of 24000 m^3/day consumes between 0.36-2.28 ton of acid per day. In addition, transporting and storing of acid in large quantities can pose safety problems along with environmental burdens such as CO_2 emission during acid transporting and leakage from the storage tanks. Yet, Sulfuric acid can be replaced by hydrochloric acid and the number of protons obtained by sulfuric acid can be converted to a quantity of hydrochloric acid that will produce the same number of protons.

These calculation shows that a dose of 15-97 mg/L of sulfuric acid can be replaced by 11-72 mg/L of HCl, which can be obtained by internal production of desalination plants.

1.4. EDBM Processes

The core of EDBM technology is the integration of bipolar membrane within electrodialysis process. While electrodialysis is a desalination technique in which ions are transported through a semi-permeable membrane under the influence of an electric potential, leading to the creation of two streams, concentrated and freshwater, the addition of bipolar membrane enables the production of acid and base according to the salt solution, and therefore valorizing the desalinated brine. The principle that stands behind the creation of acid and base is water molecules dissociation thanks to the presence of a bipolar membrane as shown in figure 4.

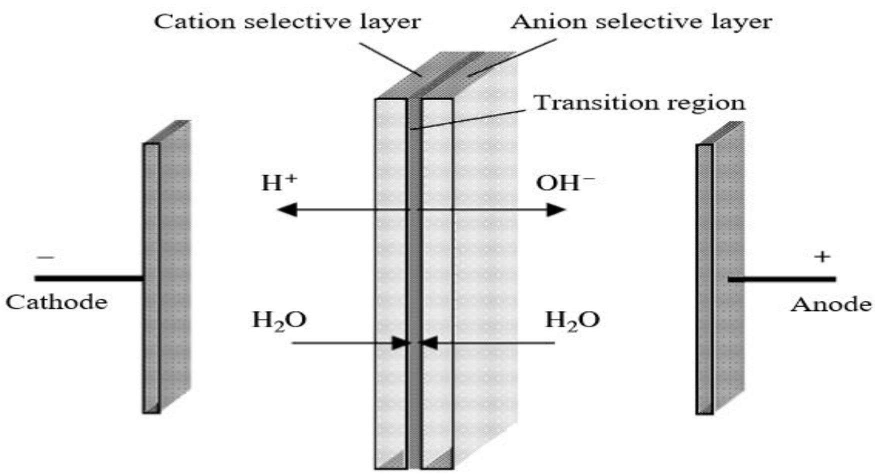


Figure 4: bipolar membrane structure (Pourcelly et al., 2002).

The bipolar membrane is located in the middle of the cell, and each side has an electrode, whereas water is diffused through the bipolar membrane (BPM). Yet, if potential difference is applied between the two electrodes, water molecules at the transition layer (interphase) are being dissociated into H^+ and OH^-, which in turn migrate to the corresponding side according to their electric charge. Pourcelly et al., (2002) reported that the water dissociation in the BPM is accelerated up to 50 million times compared to the rate of water dissociation in aqueous solutions.

As previously mentioned, the BPM is located in the middle of the electrodialysis cell, which composed of 3 mains component: anion exchange membrane (AEM), cation exchange membrane (CEM) and electrodes, as shown in figure 5.

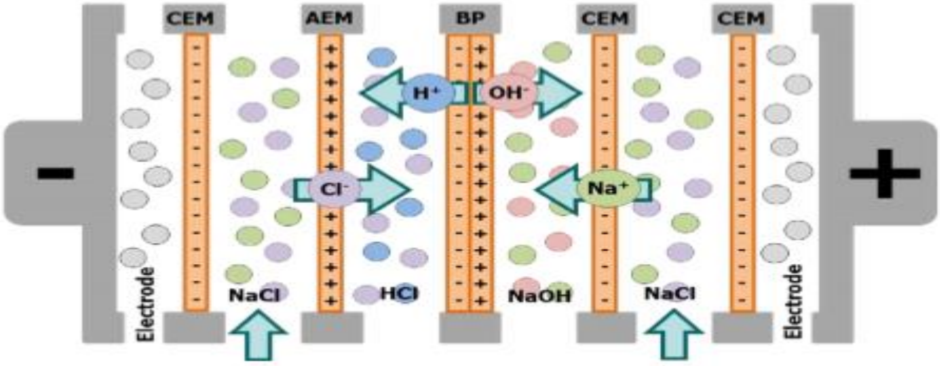


Figure 5: EDBM structure (Herrero-Gonzalez et al., 2017).

As can be seen in the illustrate there are three input streams: brine, diluted HCl solution and diluted NaOH solution. The use of acid and base diluted solutions is for safety reasons only. The gold is to prevent accumulation of electrical charge in the EDBM which can lead to warming and explosion. The contents of both external compartments are brine, and the content of the two internal compartments are diluted acid and base solutions. When electric current is being applied, salt and water dissociation is occurring. Then chlorine ions are migrating through the AEM, combining with the hydrogen ions to produce concentrate HCl solution, while sodium ions are migrating through the CEM, combining with the hydroxide ions to produce concentrated NaOH solution.

The chemical reactions that occur in the electrodialysis cell are (Yang et al., 2013):

1. $H_2O \rightarrow H^+ + OH^-$
2. $H^+ + Cl^- \rightarrow HCl$
3. $OH^- + Na^+ \rightarrow NaOH$

Limitation:

Though EDBM has high potential, today this technology faces number of technical and economical limitation, which should be overcome before it is implemented in desalination industry. One of the main obstacles is the low concentration of the obtained acid and base. The commercial HCl and NaOH concentrations are around 35% wt. (Glowacki et al., 2012) and 50% wt. (Bittner et al., 2012), respectively. The products attained in this method are about 1.2 M, which is about 4% wt for both products, and since those two diluted solutions have low commercial value, they cannot be traded in the market. The explanation attributed in the literature to the limit in the concentrations is due to water leakage to the product channels and the product diffusions to the brine channels (Fernandez et al., 2015).

1.5. Integration of RO and EDBM

The integrated process consists of two main sections, one of RO and the other of EDBM. There are two material input streams, seawater and chemicals, two energy inputs as electricity and six outputs materials streams: freshwater, concentrated brine, HCl, NaOH, treated brine, and table salt. The produced HCl and NaOH can be used for self-supply in both units. Since the produced HCl and NaOH solutions are at high concentration (typically 1.2 M), and the acid and base that are used in the system are usually at lower concertation (typically 0.1 M), freshwater was used to dilute the acid and base to a proper concentration. This in turn created another issue, as the fresh water produced contains residues of NaCl, which means that an accumulation of Na^+ will occur in the HCl produced. For this reason, an additional dummy separation unit was added, which supposed to remove all salt remain. Figure 6 present the proposed process.

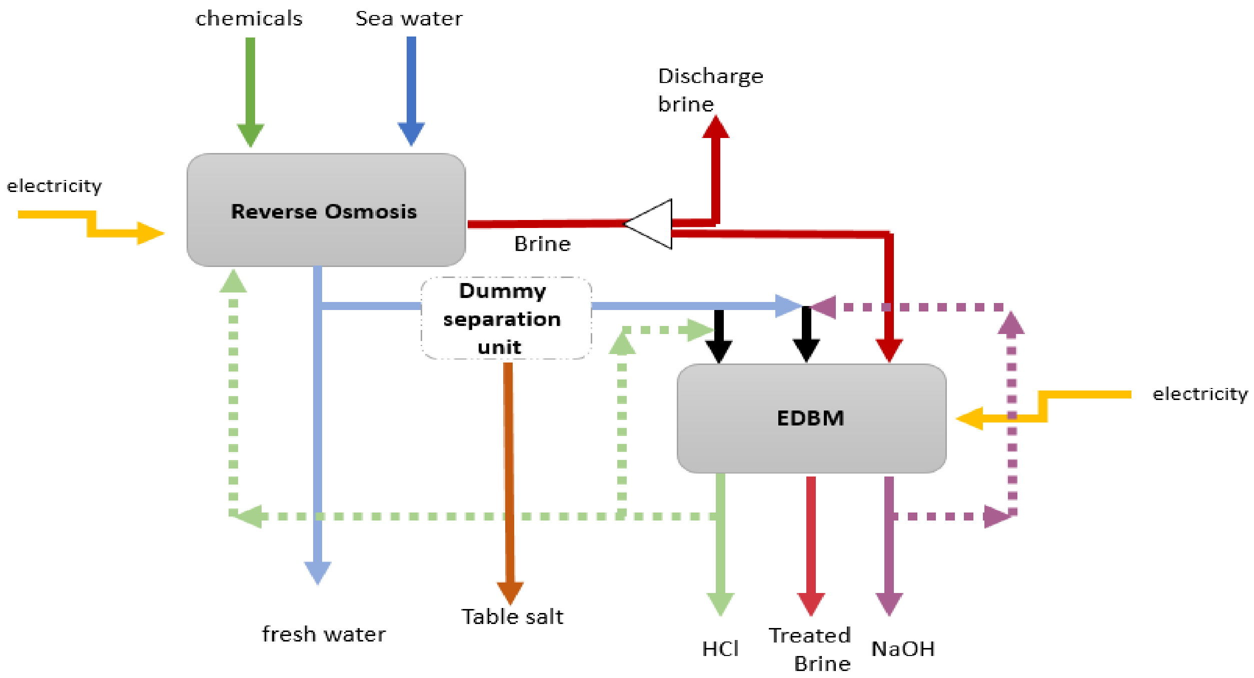


Figure 6: Process flow sheet.

1.6. Application of life cycle analysis

Life Cycle Assessment (LCA) aims to quantify the environmental impacts of products, services and production process throughout their entire life cycle: extraction of raw materials, production, distribution, use and disposal of waste (cradle to grave). The analysis examines alternative possibilities and compares technological combination, in order to recommend the optimal production method.

At first, LCA was used for energy analysis, but later on in the 1960s, two organizations began formulating what we know today as LCA. The Society of Environmental Toxicology and Chemistry (SETAC) shape the framework terminology and methodology, while the International Organization for Standardization (ISO) standardized the methods and procedures. According to the ISO 14040 and 14044 standards, a LCA study is consisted of four stages:

1. Goal and Scope definition: the first step carried out is goal definition and reasons for assessment. This part includes the determination of unit function and system boundaries.
2. Life Cycle Inventory (LCI) Analysis: collection of inventory of all input and output flows data within the system boundaries. Inputs refer to materials, energy and

chemicals which supplied to the system, while outputs are emissions into air, water and land solid wastes. The LCI is usually presents by a flow chart or a table that include all the collected data. This part is the main phase of LCA, since the conclusions will be affected by the data's nature.

3. Life Cycle Impact Assessment: in this stage, the contribution of the results of the previous stage to the impact category is evaluated. The inventory data are transformed into environment effects by multiplication the flow rate from the inventory table with the impact category indicator. Basically, this stage consists of 3 sub-stages: classification, characterization and valuation. Classification is assigning of inventories into impact categories, characterization is aggregating the inventories within the impact categories, valuation is calculating the impacts according to the selected categories indicators.
4. Interpretation: analysis, interpretation, summary of results and recommendations. The goal of this phase is to locate hot spots, improve system performance and suggests solutions and possible changes.

In the early 2000s, there was an increase in LCA studies published for drinking water production techniques. Most of the studies focused on the comparison between different methods of water treatment and desalination, and some focused on identifying "hot spots" in the varied processes. Many of the studies that were carried out were related to the issue of massive energy consumption caused by the process, and marked the brine disposal as a problematic solution. Some representative of the mentioned studies are listed below:

2001: LCA was conducted for treating and suppling of drinking water and for treatment of wastewater in Bologna city. This research identified the pumps use for the water pumping in the plant as the most problematic unit by all impact category as a result of high energy consumption. (Tarantini et al.,2001)

2005: LCA was used to assess the most environmentally friendly technology with the present state of the art technology for the most important commercial desalination technologies (MSF, MED and RO). In addition, an approximation of potential environmental loads in the future for each method was applied. This study concluded that the RO desalination technique has the lowest environmental load (Raluy et al., 2005).

2016: A study of the carbon footprint associated with the production of fresh water from groundwater treatment plant, surface water treatment plant and seawater desalination plant by ED was performed. The research results showed that the highest carbon footprint is caused by seawater electrodialysis. Moreover, it was reported that the carbon footprint can be reduced by integrating renewable sources for the three methods (Biswas et al., 2016).

1.7. Objectives

The goal of this study is to assess how the novel integration of EDBM with RO influences the two main environmental impacts of RO desalination: GHG emissions and discharged of brine to the sea. Each category will be assessed in a different manner, whereas quantity and concentration will be attributed to discharge of brine, the carbon footprint will be attributed to GHG emissions. A LCA approach was used according to ISO standards and mass and energy balances calculation were carried out. Four scenarios were assessed as later described. The functional unit selected is 1 m^3 of seawater, as the combined products can change between scenarios. Different sources for the electricity production was considered for the sensitivity analysis: PV solar energy, Israel Grid Mix and Spain Grid Mix. The actions that were carried out to accomplish the goal were:

1. Definition of functional unit (FU) as well as boundaries determination.
2. Collection of all input and output flows, starting from raw materials, and energy consumption to products and wastes.
3. Calculation of mass and energy balances.
4. Collection of GWP values for the use of resources.
5. Results interpretation.

2. Methodology

2.1. Goal and scope

This study has two main goals, the first one is to assess the carbon footprint (CF) associated to a desalination process operated by RO integrated with EDBM unit. The second main goal is to assess the environmental loads caused by brine discharge in each scenario. The FU is defined as the quantification of a system input and output for reference uses according to a pre-selected quantity of product or service (ISO 14040, 2006). In this study, the FU is defined as 1 m^3 of seawater. In this case, seawater is the FU, and not the freshwater, as it is usually applied in LCA for water treatment, since the amounts of all products changes in each of the scenarios examined. Choosing FU as an input instead of output is acceptable in LCA and is usually applied in the waste management field. Also, choosing the FU as seawater sparing the treatment of allocation problem, which is by definition relevant for products. In the next stage, four scenarios were selected, once the amount of brine discharge is determined to each of the four scenarios presented below, the GHG emissions of treating seawater will be calculated for three different mix grids: Spain grid mix, Israel grid mix and PV solar energy to create 12 sub-scenarios overall.

The system composed of two main sectors: desalination unit by RO and EDBM unit. The desalination unit is identical in all the tested scenarios, while for the EDBM concern the saline flow changes. The system boundaries include only operation stages, due to the negligible impact of other stages such as construction and dismantling, as reported in literature (Muñoz et al., 2008). The assessment takes into account all emissions caused by compounds often consume like chemicals and energy. Transports action were not included in the boundaries. Illustration of system boundaries is shown in figure 7.

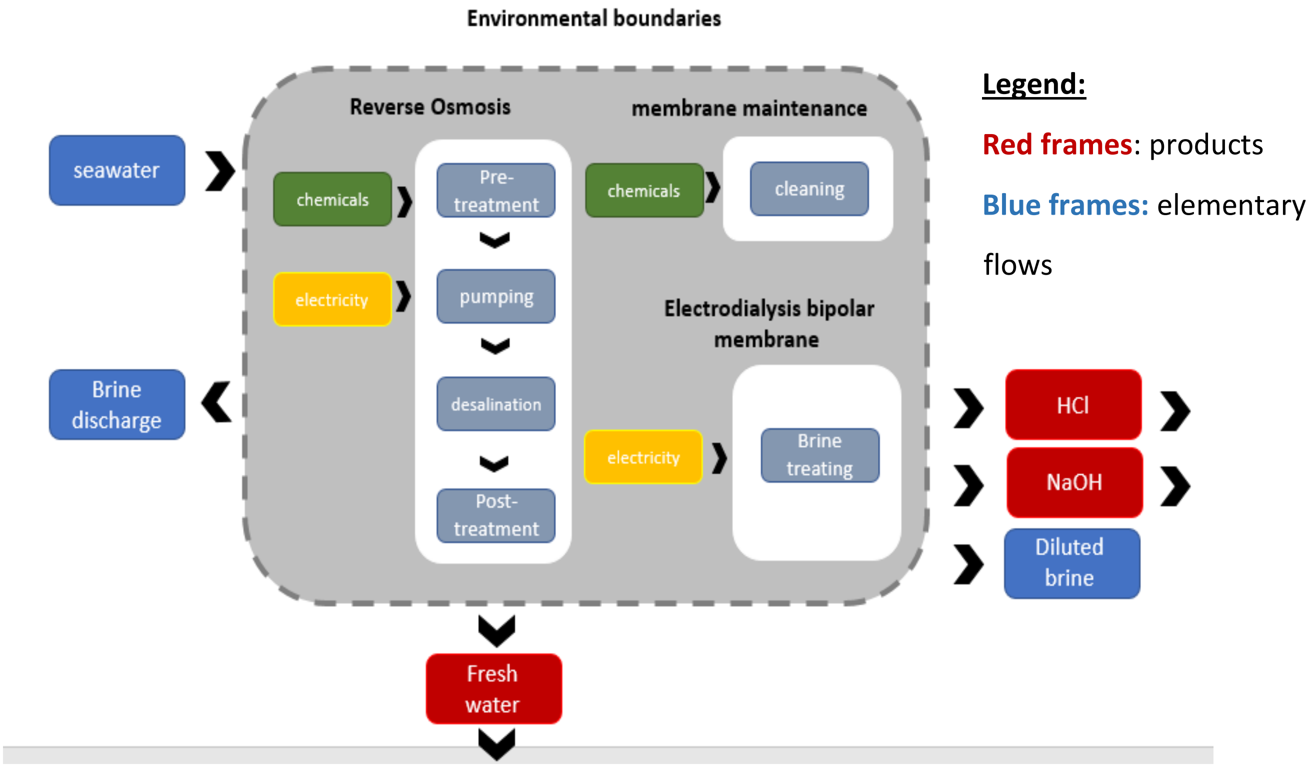


Figure 7: system boundaries

Scenario 1: the process consists the treating of 1 m^3 of seawater by RO unit only, which includes the pre-treatment stage, high pressure pump, selective membrane, post-treatment and membrane cleaning. This scenario is the reference case of this work and consider to be an end scenario. Furthermore, it is important to note that this case has been study extensively by the academia members in the last years.

Scenario 2: the process consists the desalination unit and the EDBM, which includes all RO stages mentioned above and the production of HCl and NaOH by EDBM for self-supply only. This scenario is located between the two end scenarios.

Scenario 3: another intermediate case analyzed, that includes RO and EDBM units. Here only half of the produced brine sent to be treated by the EDBM and another half was discharged to sea. All acid, base and freshwater remain after supplying the plants needs are for sale.

Scenario 4: the second end scenario, all the produced brine that can be treated is sent to the EDBM unit. As in the previous case, all products remain after supplying the plants needs are for sale.

3. Result and discussion

3.1. Life Cycle Inventory

The inventory data for the RO is based on literature, whereas the EDBM inventory obtained from previous experiments completed in lab scale plant (Herrero-Gonzalez et al., 2017). Table 1 summarized all inputs and outputs for treating 1 m^3 of seawater. All four scenarios are present, showing the difference between energy consumption with the use of EDBM.

Table 1: *Inputs and outputs of the process*

Component	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Unit	Ref.
Inputs for treating 1 m^3 of seawater						
Pre-treatment						
NaClO	6.0E-06	6.0E-06	6.0E-06	6.0E-06	ton	Harobbi et al., 2011
H_2SO_4	3.0E-05	0.00	0.00	0.00	ton	Harobbi et al., 2011
SHMP*	6.0E-06	6.0E-06	6.0E-06	6.0E-06	ton	Harobbi et al., 2011
$FeCl_3$	4.0E-06	4.0E-06	4.0E-06	4.0E-06	ton	Harobbi et al., 2011
$NaHSO_4$	4.0E-06	4.0E-06	4.0E-06	4.0E-06	ton	Harobbi et al., 2011
Membrane cleaning						
$C_6H_8O_7$	7.67E-09	7.67E-09	7.67E-09	7.67E-09	ton	Harobbi et al., 2011
$Na_5P_3O_{10}$	5.48E-09	5.48E-09	5.48E-09	5.48E-09	ton	Harobbi et al., 2011
EDTA**	3.3E-09	3.3E-09	3.3E-09	3.3E-09	ton	Harobbi et al., 2011
Post treatment						

CO_2	4.0E-05	4.0E-05	4.0E-05	4.0E-05	ton	Harobbi et al., 2011
Power						
RO electricity	4	4	4	4	kW·h	Al-Karaghouli Ltd et al., 2013
EDBM electricity	0.0	1.07E-01	2.62E+01	4.69E+01	kW·h	Herrero-Gonzalez et al., 2017
Outputs						
Products						
Fresh water	465.75	464.68	205.58	0.00	ton	Calculation
HCl 1.2 M	0.00	0.00	133.72	239.80	ton	Calculation
NaOH 1.2M	0.00	0.55	134.61	240.98	ton	Calculation
Waste						
Con. Brine 65 mg/L	569.30	568.10	284.64	59.73	ton	Calculation
Treated brine 33 mg/L	0.00	1.13	275.89	493.89	ton	Calculation

* Sodium hexametaphosphate, ** Ethylenediaminetetraacetic acid.

Electricity is the major energy form required for the entire process, and thus its production is the main cause for environmental impacts. For the RO unit, electricity is needed for pumping water from the sea, for the high-pressure pump and for the energy recovery system. For the EDBM unit, electricity is needed for creating an electric potential difference. As regarding to the waste produced in the process, brine is the main effluents. The amounts of outputs generate as a result of treating 1 m^3 of seawater were calculated by mass balance.

3.2. Life cycle impact assessment

This stage was carried out with Gabi 6 software, which is linked to 'Ecoinvent' database. The environmental impact category used in this study is 'Climate Change' and brine discharge (BD). We used this category since no characterization factor suitable for brine discharge usage was found in literature that takes into account both amounts and concentrations. Considering the concentration of released brine is of great importance, since the effect of brine discharge on the environment is not caused only by the volume of the brine but also by its concentration.

The reasons for choosing the above categories are:

1. Climate change – as mentioned before, previous studied identified that energy consumption is the main cause for environmental impacts (Meneses et al., 2010). The energy that was used in this process is electricity, and since electricity generation is assumed to be a major contributor for greenhouse gases emissions, it seems logical to consider this category. In addition, climate change is a contemporary issue which vigorously occupied by many in the scientific community.

2. Brine discharge - brine is the main residue of RO plant and therefore it is an important issue since high volume of brine discharge is not only an unsolved environmental burden but also an economic one.

The environmental impact categories used for this study described in table 2.

Table 2: impact categories

Impact category	method	units	Description
Global warming potential (GWP)	IPCC	kg CO_2- eq	Amount of GHG emitted
Brine discharge (BD)	Calculation (mass balance)	Kg	Amount of the total brine discharge

3.3. Assumptions and Limitations

The methodology applied in this research facilitates the assessment of treating 1 m^3 of seawater; however, during the analysis following of compromises were made:

1. Since the integration of EDBM with RO process is still in a research stage, no attempt has been made to find a unit suitable for treating the freshwater for the dilution of the acid and base streams. Therefore, during the assessment, a dummy ideal process whose impact over the environment is negligible was used.
2. As the obtained acid and base are at low concentration that does not allow their distribution, an additional unit equipment should be added, with the aim of concentrating each of the products. As in the previous case, the nature of such unit is still not defined.

3.4. Life cycle interpretation

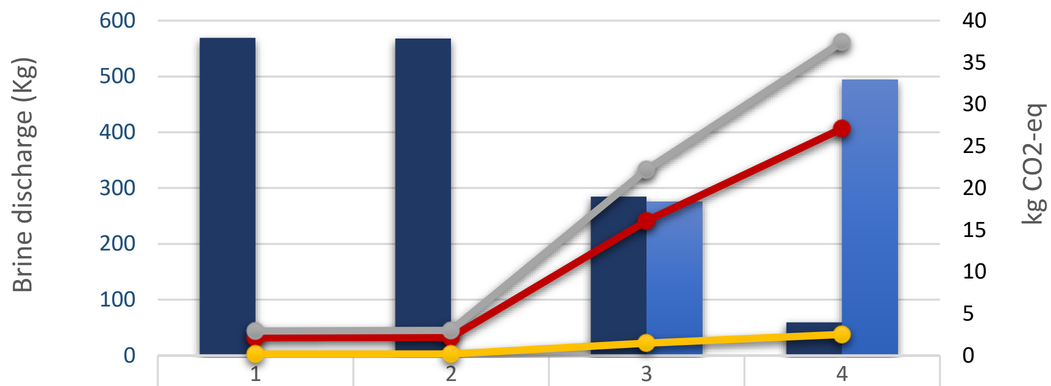
Table number 3 shows the results of the mass balance calculation for all four scenarios.

Table 3: Mass balance results- brine discharge

Scenarios	Rate of treated brine (%)	Concentrated brine discharge (65 gr/L) (kg)	Treated brine discharge (33 gr/L) (kg)	Total brine discharge (kg)	Total brine discharge concentration (gr/L)
Scenario 1	0	569.3	0	569.3	65
Scenario 2	0.2	568.10	1.13	569.23	64.9
Scenario 3	50	284.64	275.89	560.53	49
Scenario 4	89.5	59.73	493.89	553.62	36

It can be seen that the EDBM unit can reduce the total brine generated between 0.15-2.75%; however, this range can be misleading since the composition of the brine should be considered as well. As previously said, the waste generated by RO mostly consists of concentrated brine (65 gr/L) and some chemicals residues from the pre-treatment. On the other hand, after integrating RO with EDBM, the waste consists of concentrated brine, chemicals residues and treated brine. The treated brine has a concentration of 33 gr/L, which means that it has similar properties as seawater and therefore discharging it back to the sea should not cause an environmental hazard. EDBM can reduce the total brine discharge concentration to a range between 65-36 gr/L depending on the percentage of concentrated brine treated. The greater the amount of concentrated brine treated by the EDBM, the lower the concertation of the total brine discharged. In scenario number 4, the total brine discharged concertation is 36 gr/L, all the freshwater produced is utilized for the benefit of producing HCl and NaOH. In this case, the purpose of the plant is diverted from a desalination plant to a plant producing HCl and NaOH. However, this scenario (scenario no. 4) is not the goal of integrating EDBM with RO. The corresponding range of treated brine percentage is 0.2-89.5%, which in other words means that the integration of EDBM unit with RO process is limited in scope. Hence, it can be concluded that running a RO process with no concentrated brine discharge is impossible through the use of EDBM without the external purchase of water under the previous hypothesis. In addition, treating less than 0.2% of the concentrated brine will not be sufficient for self-supplying needs.

Figure 8 shows the environmental performance of the process regarding the categories were selected, carbon footprint and brain discharge, to each of the grid mixes: Spain, Israel and 100% PV.



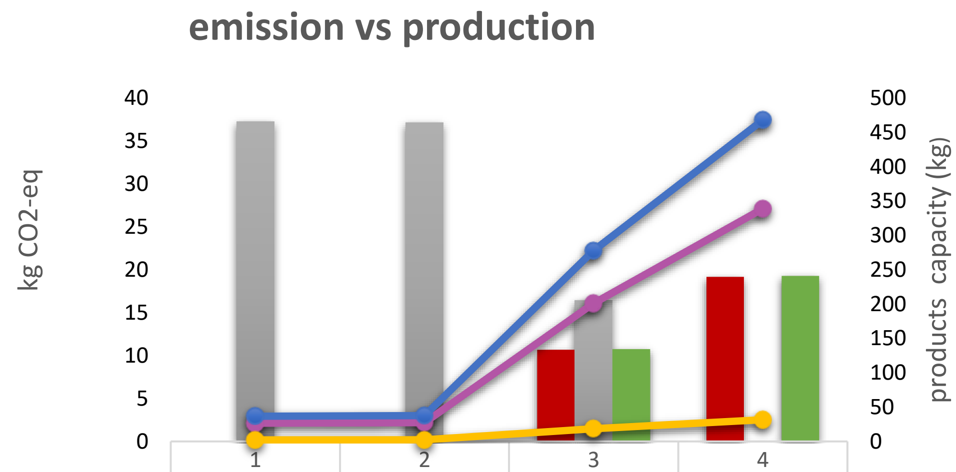
	1	2	3	4
Brine discharge 65 mg/L (kg)	569.30	568.10	284.64	59.73
Brine discharge 33 mg/L (kg)	0.00	1.13	275.89	493.89
Spain Kg CO2-eq	2.12	2.17	16.08	27.11
Israel Kg CO2-eq	2.94	3.01	22.21	37.45
PV Kg CO2-eq	0.19	0.19	1.49	2.53

Figure 8: The carbon footprint associate with the treatment of 1m^3 of seawater in the three different mix grids.

First, in order to validate this study, we checked that the carbon footprint of our process, without the integration of the EDBM, is within the range of the carbon footprint found in literature for producing 1 m^3 of fresh water. The energy consumption is ranging between 3-10 Kw·h/m^3 of seawater (Dashtpour et al., 2012). As for 2014, Spain and Israel CF values, were between 0.533-0.563 Kg CO_2 /kW·h and 0.736-0.746 Kg CO_2/kW·h respectively (IEA 2016). That means that the acceptable ranges for producing 1 m^3 of freshwater are: 1.599-5.63 Kg CO_2-eq and 2.208-7.46 Kg CO_2-eq, respectively. The values for producing 1 m^3 of freshwater in this work are 4.5 Kg CO_2-eq and 6.22 Kg CO_2-eq and therefore they are valid.

The carbon footprint obtained for treating 1 m^3 of seawater for Spain, Israel and PV are between 2.17-27.11, 3.01-37.45 and 0.19-2.53 Kg CO_2-eq respectively. In general, as accepted it can be seen for the three grid mixes, that as the amount of brine treated by the EDBM increases the carbon footprint increases as well. For all the three grid mixes, the CF increased by 13 between the two end scenarios, 1 and 4. In addition, in each scenario Israel grid mix has the largest CF followed by Spain and of course the PV solar energy. This was expected, as it is obvious that the combination of renewable energy sources reduces the emission of GHG to the atmosphere. Operation of each of the scenarios with PV can reduce Spain and Israel carbon footprint by 91% and 93% respectively. Also, in can be seen that the CF associated to scenario number 4 and is operated by PV, 2.53 Kg CO_2-eq, is 14% lower than the CF in scenario number 1 and operated by Israel mix grid, 2.94 Kg CO_2-eq. As of Spain, similar environmental performance between scenario number 1 to PV is somewhere between 50%-89.5% treated brine.

Figure 9 shows the carbon footprint associate to each mix grid in each scenario against the process products capacity.



	1	2	3	4
HCl (1.2 M) for sale (Kg)	0.00	0.00	133.72	239.80
Fresh water for sale (Kg)	465.75	464.68	205.58	0.00
NaOH (1.2 M) for sale (Kg)	0.00	0.55	134.61	240.98
Spain Kg CO2-eq	2.12	2.17	16.08	27.11
Israel- Kg CO2-eq	2.94	3.01	22.21	37.45
PV Kg CO2-eq	0.19	0.19	1.49	2.53

Figure 9: The carbon footprint against products capacity.

Another aspect that should be considered is the number of products compared to the CF and their amount. It can be seen that as the HCl and NaOH capacity is increased, the freshwater capacity is decreased. This is as a result of the freshwater consumption by the EDBM to dilute the acid and base streams. Thus, it can be expected that when the products will be obtained at commercial grad the amount of freshwater for sale will be higher. Also, treating about 90% of concentrated brine produce the maximum acid and base capacity, while treating 50% of concentrated brine produce about 55% of HCl and NaOH maximum capacity. Therefore, it can be roughly said that there is a linear relationship between the two.

Apart from that, the size of the different production units was compared in order to estimate the ratio between RO, EDBM and PV units. The extensive magnitude of the RO and EDBM unit is the ratio between the membrane area to the input/output volume. As for the PV panels, it's the ratio between the panels area to the amount of electricity consumed. The standard commercial membrane area is about 40 m^2, and will desalinate at operation conditions 13 m^3/day of fresh water (Wilf et al.,2007). The membrane area used in the lab experiments is 0.01 m^2 and treats 0.01152 m^3/day of concentrated brine (Herrero-Gonzalez et al., 2017). As for the PV panels, area of 1.125 m^2 is creating the 0.8329 kW·h/day of electricity which is consumed by the process (Herrero-Gonzalez et al., 2017).

After considering each scenario capacity and energy consumption the followed ratios obtained as for RO: EDBM: PV m^2

Table 4: Ratio of unit equipments

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
RO m^2	1.43	1.43	1.43	1.43
EDBM m^2	00.0	1.01E-03	0.25	0.44
PV m^2	5.4	5.5	40.8	68.8

These ratios show that PV panels have the largest operation area, ranging between 3.78-48.1 times from RO membrane area. The smallest unit is the EDBM membrane, which is smaller by at least one order of magnitude then RO membrane.

4. Conclusions

The integration of EDBM with RO process influences two main environmental impact of RO process. As regard to the environmental loads caused by brine discharge, they can be well treated and reduced significantly by EDBM. Moreover, EDBM can deal with both problematic characterization of brine discharge, mass and concertation. EDBM can reduce between 0.15-2.75% of the total brine discharge in addition, the overall brine concentration can drop between 65-36 gr/L. This is due to the treated brine produced by the EDBM, which has concentration of 33 gr/L. This treated brine has similar properties as seawater and therefore it can be discharged back to the sea, having very low environmental impact. The corresponding range of treated brine percentage is between 0.2-89.5% of concentrated brine. This operation range is for producing HCl and NaOH with a concentration of 1.2 M, (about 4% wt) which has no commercial value. Producing HCl and NaOH in commercial standard will lead to higher operation range as a reduction in freshwater consumption and higher freshwater for sale. As for the emission of GHG, integration of EDBM with RO process increased the energy consumption that eventually increased the carbon footprint. The carbon footprints obtained for Spain, Israel and PV are between 2.17-27.11, 3.01-37.45 and 0.19-2.53 Kg CO^2-eq respectively. The carbon footprints were multiplied by 13 between the end scenarios. EDBM is an intensive energy consumer, 4.4 Kw·h/Kg HCl, and thus combination of renewable energy sources in the national mix grids of Israel and Spain will lead to a meaningful reduction of the carbon footprint, about 91% and 93% respectively. Moreover, the carbon footprints associate to scenario 1 operated by Israel or Spain mix grids are close to the carbon footprint associate to scenario 4 and is operated by PV. The carbon footprints profiles present in this work constitute the best performance can be achieve since the dummy-process has zero GHG emission, which is something that can never be accomplish. Apart from that, it is concluded that a roughly linear relation is existed between the concentrated brine treated percentage to the HCl and NaOH capacity production. Finally, the estimation of the mains units size showed that the PV panels have the most extensive area occupied, which can reach about 50 time more than RO membrane area. In addition, the EDBM membrane area is negligible comparing to the other units, and it can reach up to one order of magnitude less than RO membrane area when 90% of brine is treated. In conclusion, integration of EDBM with RO process can reduce both, amount and concentration of brine discharge to the sea, and thus reduce the environmental impact of the process. Moreover, operating the novel process with PV energy can has at least better carbon footprint performance or in the worst scenario a similar one.

This works aims to assist in the assessment of the environmental impact of the novel integration of EDBM within the RO process and to evaluate whether it helps in reducing the major environmental hazards associate with RO. For future work it is recommend to preform a comprehensive LCA with all impact categories usually applied in wastewater management for wider understanding of the impacts caused as a result of the novel process.

As for today, it is impossible to compare the carbon footprint associate to the production of HCl and NaOH in this process to the conventional processes in the industry, since HCl and NaOH obtained in the industry are different products with other concertation. Yet, in the future when the commercial concertation will be obtained a comparison should be made.

In addition, it is recommended to search for a suitable separation unit that will meet the requirements of the dummy process and to include its performance in the environmental profile of the process.

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