Monetizing environmental footprints: Index development and application to a solar-powered chemicals self-supplied desalination plant

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KEYWORDS

Monetized Footprint Index (MFI); carbon footprint (CF); land footprint (LF); water footprint (WF); seawater reverse osmosis (SWRO); desalination; electrodialysis with bipolar membranes (EDBM); brines

ABSTRACT

The assessment of the environmental greenness in the process industry has been quantified by means of the development of an integrated index, i.e., Monetized Footprint Index (MFI), based on

the compilation and the integration of land, water and carbon footprint indicators. The MFI has been applied to assess the case study of a seawater reverse osmosis desalination with an integrated electrodialysis with bipolar membranes brine treatment. The MFI enables the evaluation of environmental burdens related to the chosen functional unit based on a weighting procedure, which integers land, water and CO_2 prices. It is neither a tool for the calculation of the production cost nor a sustainability analysis tool as it does not include social or economic indicators. Comparison between selected scenarios, based on the different sources of the requested electricity, grid mix (Spain and Israel, as examples) and photovoltaic solar energy (under a fixed solar irradiation), has been carried out. Maximum values of 0.30 $€\cdot m^{-3}$ and minimum values of 0.11 $€\cdot m^{-3}$ for the different scenarios have been obtained in the calculation of the MFI. Moreover, uncertainties in land, water and CO_2 prices have been analyzed under a Monte Carlo simulation. This study concludes that MFI, being based on well-known environmental footprint indicators, can simplify and support the decision-making process.

TEXT

Introduction

Many attempts to obtain appropriate environmental sustainability index have been made over the years. Literature provides a comprehensive background of references that aggregate different environmental indicators in order to obtain an integrated index that can easily be used to compare different scenarios.[1–10] However, there is not yet one indicator that could catch the various environmental effects of anthropogenic activities and be considered as the “golden standard”.[11] Moreover, developing a novel monetized index, which can also be combined with economic objectives, is of major interest.

With this regard, several environmental studies, based on life cycle assessment (LCA), have been reported, analyzing freshwater supply.[12–18] Among them, the damage to human health has been quantified through Disability Adjusted Life Years (DALYs),[15–18] while others reported on an economic evaluation based on life cycle costing (LCC).[19–21] Moreover, compilation of indicators into a composite index was proposed and applied by Lior[22] and Lior and Kim[23], however, these proposals requires an exhaustive knowledge of the process leading into complexity in its calculation.

Land, water and carbon footprints have been proven to be adequate reference tools to evaluate the environmental sustainability of different processes, products and/or services,[24] considering the land requirements, water consumption and greenhouse gas equivalent emissions regarding to the functional unit of a system. Thus, the allocation of the economic utilization cost of land (€$\cdot$m$^{-2}\cdot$y^{-1}), water (€$\cdot$m^{-3}) and CO_2 emissions (€$\cdot$ton^{-1} CO_2), can comprehensively compile and integrate the useful environmental information given by these footprints into a Monetized Footprint Index (MFI). In addition, this index could serve as a robust nexus between the environmental and the economical pillars of sustainability. We thus propose a methodology to quantify a MFI, which translate the environmental information into a monetized value in terms of the chosen reference unit for a specific process, product or service. Figure 1 conceptualizes the framework and methodology for MFI, which will be obtained for a specific case study. Yet, as MFI is a tool for an economic evaluation of environmental burdens, the calculus of the production cost is not included on its scope.

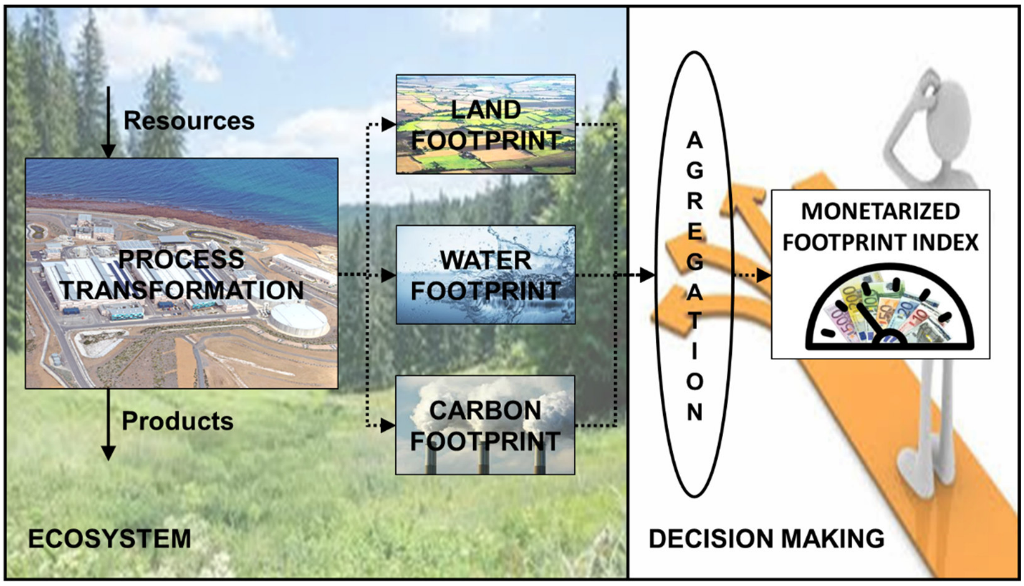

Figure 1. Framework: A proper description for the process transformation used as a case of study is provided on Figure 2.

Land, Water and Carbon Footprint

The evaluation of the footprints is carried out from a life cycle perspective, in which all the stages of the production of a process, product or service are taken into consideration, such as the acquisition of the raw material, the manufacture, the use and end-of-life treatment and final disposal. All values will be referred to the chosen functional unit. In addition, references that were used for the assessment of the carbon footprint and the water footprint of the energy profiles fit the standards ISO 14067:2013[25] and ISO 14046:2014,[26] respectively. Moreover, no specific international standards as those presented in the ISO norms regarding the calculation of land footprint are available. Furthermore, through the life cycle approach, several authors have compiled the requirements of land (land footprint), water (water footprint) and emissions of greenhouse gases (carbon footprint) of the different energy sources that contributes to a national grid mixes. As a result, a compilation of the individual sources of data has been gathered in the SI.

Hence, the land, water and carbon footprints of the national grid mixes of Spain and Israel have been obtained.

Monetized Footprint Index (MFI)

The MFI is proposed as a novel strategy to compile a trade-off among given land, water and carbon footprints. This MFI will be calculated by the allocation of the economic costs of land (€·m^{-2}·y^{-1}), water (€·m^{-3}) and greenhouse gases equivalent emissions (€·ton^{-1} CO_2). The monetized cost will be determined by the scenario to be evaluated. Land price will be depended on the location, availability and sort of land (agricultural, industrial or urban) required; water price, which suffers from large variations, will be depending on the accessibility to water resources, even in the same nation; and CO_2 prices that normally vary between 5.0 €·ton^{-1} CO_2 and 10.0 €·ton^{-1} CO_2 in the European Union, will be adopted.

Case of Study: SWRO desalination plant coupled to an EDBM brine treatment

Water is a necessary good for society, nevertheless four billion people live facing severe water scarcity.[27] Thus, preventing, reducing or offsetting the use of water resources and/or avoiding the generation of waste and pollution, either by increasing the efficiency of processes or by replacing them with more sustainable alternatives,[28] are of high concern. One such route is using desalinated water, and the global desalination market is dominated by the seawater reverse osmosis (SWRO) technology with a share of 65% based on the installed desalination capacities.[29] SWRO is a suitable and well-established commercial level alternative for desalination, although some drawbacks can be pointed out. Among the environmental issues that SWRO presents, the main impacts are twofold: i) the energy consumption, which is directly associated with climate change and air pollution, and ii) the disposal of the waste effluent brine into the water bodies.[30]

A case of study corresponding to a SWRO desalination system with an integrated electrodialysis bipolar membrane (EDBM) brine treatment was selected. Fernandez-Gonzalez et al.[31] reviewed the current situation of renewable desalination worldwide, highlighting the environmental benefits of employing low-carbon energy resources such as photovoltaic (PV) solar energy. Although PV solar energy represents less than 1% of the world total primary energy supply,[32] it is recognized as a technical and commercially mature technology.[33]

SWRO process produces not only freshwater but also brines, discharged directly into the sea because other alternatives are technically, socially, economically or environmentally not feasible.[30] Although there is no evidence of discharge concentration limits in the regulation of the European Union, several studies have focused on the effect of brine disposal into the receiving media and they found damaging effects on marine ecosystems,[34] whereas, other studies suggested saline concentration limits.[30] As expected, the desired disposal concentrations are below the typical brine concentration, so a treatment of these brines will be required. Perez-Gonzalez et al.[35] reviewed the available treatment technologies of water RO concentrates, concluding that EDBM is an emerging technology for treatment and valorization of SWRO brines[34] that can be integrated into zero liquid discharge (ZLD) processes.

EDBM technology generates hydrochloric acid (HCl) and sodium hydroxide (NaOH) from two inputs: brines and energy. Both HCl and NaOH are chemicals of great interest in any desalination plant. Hence, the integration of a brine EDBM treatment to a desalination plant will not only have the environmental benefit of partially avoiding brine disposal, but also environmental and economic benefits due to the potential self-supply of these two chemicals, as suggested by the circular economy model.[36]

Therefore, the aim of the present work is to develop and apply a novel Monetized Footprint Index (MFI) based on the integration of land, water and carbon footprints to a desalination process. Thus it can help at decision-making process to support sustainable decisions at both public and private institutions. As a case of study to show the usefulness of the proposed index, a SWRO desalination system with an integrated EDBM brine treatment was chosen. The MFI allows to compare between selected scenarios based on the different sources of the requested electricity. Hence, a sensitivity analysis for the energy supply was carried in order to discuss a trade-off among options.

The present case of study will focus in two Mediterranean countries as examples: Israel and Spain. Both countries are in the top 10 countries by total installed desalination capacity[37] and also are SWRO technology exporters worldwide due to their widely research in this field. Additionally, both countries present vast regions in the Mediterranean Sea, thus solar irradiation conditions can be assumed similar (5.5 $kWh\cdot(m^2\cdot day)^{-1}$).[38] In this sense, the developed MFI is expected to support and to help decisions-makers with a much more comprehensive indicator. To the best of our knowledge, it is the first time that an economic composite index (MFI) has been developed and used as a mean to integrate different environmental impacts.

As a case of study, the present work evaluates the land, the water and the carbon footprints, as well as MFI, of a SWRO desalination plant with or without an EDBM process for brine treatment, using different energy sources as alternatives (Figure 2).

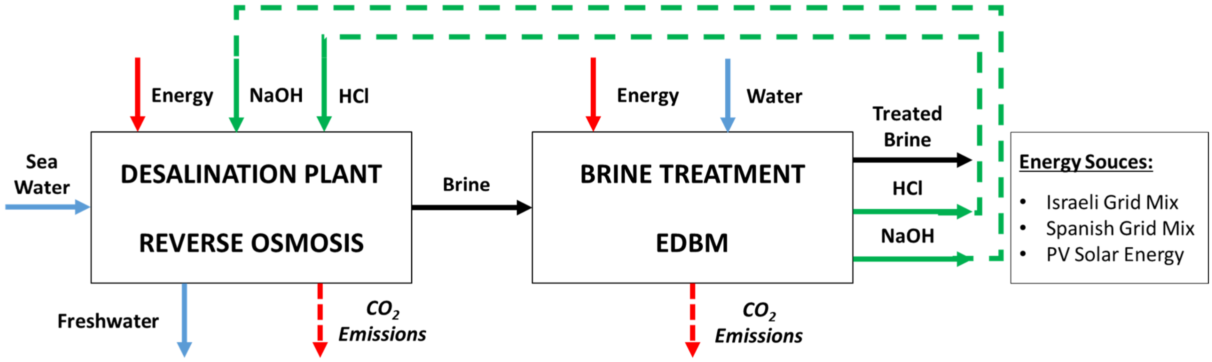

Figure 2. System flow chart. Dotted lines represent the equivalent indirect CO_2 emissions generated in energy production stages (not released in the processes) and the recirculation of HCl and NaOH produced by means of EDBM into the desalination plant.

Freshwater is the main product in desalination, accordingly, all data will be presented per 1.0 m^3 of freshwater produced as functional unit. Although any percentage of the brine to be managed could be potentially considered, two scenarios were analyzed: a) no brine treatment, and b) treatment that fulfills the requirements of HCl and NaOH for the self-supply in the SWRO plant.

The calculation of the percentage of brine to treat in order to obtain the required amount of HCl and NaOH for the self-consumption of the SWRO desalination plant (scenario b) is not straightforward. A review on the acid dosages[34] concluded that between 15 $mg \cdot L^{-1}$ and 100 $mg \cdot L^{-1}$ of H_2SO_4 are consumed. However, it can be replaced with a range between 11 $mg \cdot L^{-1}$ and 73 $mg \cdot L^{-1}$ of HCl, which is preferred over H_2SO_4, as the latter can increase the sulphate scaling potential.[39,40] On the other hand, a range from 2 $mg \cdot L^{-1}$ to 60 $mg \cdot L^{-1}$ of NaOH is required. As higher concentrations of HCl than NaOH are required, calculations will be made based on these products. Thus, between 0.2% and 1.3% of brine must be treated in order to produce enough products for the self-supply of the whole plant. In order to cover all reagent requirements, it has been assumed a treatment of 1.3% of the brines. While a fraction of the brine is directed to the EDBM process, the remaining one could be directly disposal.

As the power supply for the two scenarios (process flowcharts) is potentially the main contributor to the environmental effects of the processes, three different supply systems will be considered: the grid mix from Spain, the grid mix from Israel and the PV solar energy (assuming similar solar irradiation for the two countries). The following proposed main scenarios will then be compared for each alternative condition. A summary of the scenarios and alternatives and their conditions is presented in Table 1.

Table 1. Summary of scenarios and selected alternatives. A code is given to each alternative.

Codification	% Brine treated	Country	Energy source
a-S-GM	0.0	Spain	Grid mix
a-I-GM	0.0	Israel	Grid mix
a-S-PV	0.0	Spain	PV
a-I-PV	0.0	Israel	PV
b-S-GM	1.3	Spain	Grid mix
b-I-GM	1.3	Israel	Grid mix
b-S-PV	1.3	Spain	PV
b-I-PV	1.3	Israel	PV

Spanish and Israeli Grid Mix, and photovoltaic solar energy footprint indicators

Regarding the shares and the values of the indicators given in the SI, a global value for the land, the water and the carbon footprints for both countries grid mixes was calculated (Table 2), whereas in the land footprint, only the contribution of non-CO_2 sinks has been considered. Israel presents a higher consumption on fossil fuels than Spain. This fact leads to CO_2 emissions per person about 2.0 times higher in Israel than Spain. In contrast, both the water footprint and the land footprint present 3.2 and 4.2 times higher values, respectively, in Spain than in Israel. These values for Spain are attributed mainly to the use of nuclear, hydropower and biofuels, which are highly intensive in land and water energy sources. These sources are not so extended in Israel.

Table 2. Land, water and carbon footprints for the Spanish and Israeli grid mixes, and PV solar energy.

Indicator	Land footprint		Water footprint	Carbon footprint
	$m^2 \cdot year \cdot GJ^{-1}$		$m^3 \cdot GJ^{-1}$	$kg \cdot GJ^{-1}$
Grid Mix	**Min.**	**Max.**		
Spain	3.8	6.0	1.58	94
Israel	1.45	1.63	0.50	194
PV	0.725	4.41	0.25	10

Land, water and carbon prices for Spain and Israel

Prior to the allocation of costs, it is necessary to know the prices of land, water and CO_2 for each country, because initially they should not be considered equal. The estimation of an average price for the land occupation is not an easy task, since different classes of lands are involved in the conformation of the whole land footprint. However, due to the nature of the process, an industrial land can be considered as a benchmark. In addition, industrial land prices depend on multiple factors such as the region (country: Spain/Israel), its proximity to large cities or industrial complexes and/or the access to energy, water and transportation infrastructures. Annual cost of land occupation is proposed as an adequate approximation strategy, it can be calculated by the taxes payable for owning that extension of land. In the case of Spain, the corresponding tax is the so call "property tax", in which a certain percentage of the value of the land is paid, which depends on its type, differentiating between rural (not applicable), urban (applicable to the land footprint associated with the industrial plant) and special characteristics (applicable to the land footprint associated with energy production), being for the year 2017, 0.59934%, 0.62285% and 0.84917%

respectively.[41] Investments in land in the range between 400 €·m^{-2} and 450 €·m^{-2} (average 425 €·m^{-2}) can be considered as a basis for the calculation for Spain in year 2017. Hence, prices of 2.55 €·m^{-2}·y^{-1} and 3.61 €·m^{-2}·y^{-1} are given for urban land and special characteristics land, respectively. On the other hand, an equivalent cost of land occupation has not been able to be determined for the case of Israel, so it will be considered equal to the Spanish.

A similar case can be described for industrial water, whose price is highly influenced, among others, by the region and the season. Despite these difficulties, Israel Water Authority establish an average value of 2.0 €·m^{-3} (before VAT 17%)[42] for industrial water in year 2017. According to Brey et al.[43], 1.5 €·m^{-3} can be considered as an average price for industrial water in Spain in year 2011. For simplification, it has been considered that all water sources used both directly and indirectly have the same cost per unit of volume.

Regarding CO_2 footprint, it can be determined that, given the existence of an European market (under the regulation of the EU ETS[44]), the price could be assumed uniform for all the countries around the world. Therefore, the price reported by SENDECO2[45] of 5.83 €·ton^{-1} CO_2 (average for year 2017) could be considered for both Spain and Israel. For simplification, it has been considered that all CO_2 emitted directly in the process and indirectly on energy production stages has the same cost.

SWRO inventory

In this section, an inventory of the data required for the calculation of the SWRO process land, water and carbon footprints is presented. Einav et al.[46] reported that a SWRO plant with a 100 million m^3·$year^{-1}$ production requires 25 acres of area, which means a direct land use of $1.012 \cdot 10^{-3}$ m^2·year·m^{-3} of freshwater. The energy production area, dependent on the energy supply powering the system, must be added. In general, the production of 1 m^3 of freshwater from SW requires between 2.6 kWh and 8.5 kWh.[47] As a particular example, Las Palmas III-IV (Spain) SWRO desalination plant presents an energy consumption of 3.0 $kWh \cdot m^{-3}$,[48] while the average energy consumption in SWRO desalination plants in Israel is about 3.5 $kWh \cdot m^{-3}$.[49] These values will be taken as a preferred reference for Spain and Israel, respectively. Regarding the water footprint, it should be noted that the water production in a SWRO plant is about 50% of the seawater collected,[50] producing, in turn, an analogous volume of brines. Thus, for this particular case, 2 m^3 seawater are required for the production of 1 m^3 of freshwater, whereas additional 1 m^3 of brines are generated. However, taken into consideration the fact that the amount of fresh water produced can be balanced with the amount of brines,[51] the net water footprint in this particular case can be assumed to be zero (the production of freshwater is compensated with the production of brines). So, production of 1 m^3 of freshwater from seawater does not contribute to the water footprint (considering that the water footprint from the energy consumption is calculated aside).

SWRO-EDBM inventory

As noted above, while producing freshwater during the SWRO desalination process, approximately the same amount of brines are generated,[50] so 1.0 m^3 of brines are generated per 1.0 m^3 freshwater produced. In addition to the brine, 1.0 m^3 of water is required per m^3 of treated brine in order to generate the acid and the base; it is noteworthy that a relevant fraction of this volume of water could be recovered in the case additional concentration stages are installed. Herrero et al.[52] reported a lab-scale experimental EDBM process for acid and base production, both powered by the grid mix and a simulated PV solar energy source. In that particular work, 1.0 m^3 of HCl (1.0 $mol \cdot L^{-1}$) and 1.0 m^3 of NaOH (1.5 $mol \cdot L^{-1}$) were produced from 1.0 m^3 of brine and 1.0 m^3 of diluted acid and base, reducing the concentration of the brine from 1.0 $mol \cdot L^{-1}$ to 0.5 $mol \cdot L^{-1}$, a concentration value close to the average sea salinity. Thanks to a feedback loop control, only 74.9 kWh·m^{-3} of brine treated were consumed. Thereby, by means of the production of HCl and NaOH, the environmental burdens associated with the consumption of these reagents in the SWRO plant would be avoided.

Results and Discussion

Footprint results

The land, the water and the carbon footprints for the production of 1.0 m^3 of freshwater (FW) by SWRO powered by the Spanish and the Israeli grid mix or by the PV solar energy, with or without an EDBM brine treatment for HCl and NaOH self-supply, are summarized in Table 3.

Table 3. Summary of the footprint values of the studied scenarios and alternatives.

	Land Footprint	**Water Footprint**	**Carbon Footprint**
	m^2·yr·m^{-3} FW	**m^3·m^{-3} FW**	**kg·m^{-3} FW**
a-S-GM	0.044 – 0.068	0.022	1.177
a-I-GM	0.021 – 0.023	0.011	2.603
a-S-PV	0.011 – 0.050	0.008	0.270
a-I-PV	0.012 – 0.058	0.008	0.288
b-S-GM	0.055 – 0.087	0.023	1.344
b-I-GM	0.024 – 0.027	0.008	3.120
b-S-PV	0.011 – 0.064	0.004	0.143
b-I-PV	0.013 – 0.072	0.004	0.161

The differences in the land, the water and the carbon footprints for the production of 1 m^3 of FW by SWRO as a function of the grid mixes used (alternatives a-S-GM and a-I-GM) are essentially associated to the different contribution of the energy generation technologies in each grid mix. This is true due to the higher use of renewable energies in Spain (36%) compared to

Israel (1.9%). In addition, it is important to note that the carbon footprints per 1.0 m^3 of FW of the desalination plant are assumed to be negligible, even if its building and maintenance (e.g., concrete and steel production) it is not strictly zero. When PV solar is used as energy source (entries a-S-PV and a-I-PV), the difference between the two countries is not significant, and it is mainly attributed to the total energy demand per 1.0 m^3 of FW, which is higher by 17% in Israel.

As expected, the integration of renewable energy, i.e., the use of PV solar energy (entries a-S-PV and a-I-PV) instead of carbon-based fuels (entries a-S-GM and a-I-GM), dramatically reduces the carbon footprint. For the Spanish case, the carbon footprint value is more than 4 times lower (a-S-GM vs a-S-PV) and for the Israeli case it is more than 9 times (a-I-GM vs a-I-PV).

There is almost no difference in the water footprint, except for the slightly higher footprint in the case of the grid mix in Spain, which is associated to the use of hydroelectric power, nuclear energy and the use of biofuels. Furthermore, it is clear that the integration of PV solar energy leads to lower land, water and carbon footprint values. Otherwise, when the contribution of the reagents to the global computation of the footprints in scenario a (entries a-S-GM, a-I-GM, a-S-PV and a-I-PV) is analyzed different behaviors are reported. The reagents do not contribute in excess to the land footprint, being all below the 7.9% of the land footprint. Whereas, when the grid mix is employed, the contributions of the reagents in the water footprint are 22.8% and 44.5% for Spain and Israel respectively, being the differences caused by the highly water intensive character of the Spanish grid mix. When PV solar energy is used, the contributions of the reagents in the water footprint increases to 65.1% for Spain and 61.5% for Israel. As for the carbon footprint, reagents have low contributions when grid mix is employed, 13.8% and 6.2% for Spain and Israel (based on non-renewable energies) respectively, and high contributions when using PV, 60.1% and 56.5%, respectively.

SWRO process can be coupled to the treatment of brines by EDBM in order to reduce the environmental impact of the brine disposal and to produce valuable HCl and NaOH for self-consumption (entries b-S-GM, b-I-GM, b-S-PV and b-I-PV). In this case, the land, the water and the carbon footprints undergo diverse changes mainly due to not considering the external impacts of the footprints associated to the reagents, and, due to the highly energy intensive nature of the process, to the different power supplies studied. Again, although the facility itself presents small carbon and water footprints, the footprints per 1 m^3 of FW are assumed to be negligible. Regarding the relationship between the different alternatives analyzed, it seems that the behavior is analogous to the one in the previous section. Again, the difference between the two countries and the difference between the alternatives with and without PV solar energy is due to the different components of the grid mix. Land footprint is increased for every alternative analyzed, however carbon and water footprint are not. Water footprint decreases except for alternative b-S-GM that increases due to the high water footprint of the Spanish grid mix. Regarding the carbon footprint, when grid mix is assumed the value increases, and decreased when PV solar energy does. This means that the environmental behavior in terms of the water and the carbon footprint of the SWRO coupled to EDBM brine treatment is enhanced if PV solar energy is employed.

In addition, the fact that HCl and NaOH used in the pretreatment, the cleaning and maintenance, are also produced in the process is also reducing the overall environmental impact. Moreover, concentration stages for the diluted HCl and NaOH have not been considered, however, these products can be employed in a diluted form in the desalination plants. In addition, though brine treatment results in direct increase of the water footprint due to water that is used for the excess energy production and for the electrodialysis process, for example 1 $m^3 \cdot m^{-3}$ freshwater in the case of PV solar energy, this 1 m^3 can be recycled back in the form of HCl and NaOH solutions. To avoid this full fraction of the brines to be treated it is necessary: i) the products acid and base to be as much concentrated as possible, and ii) the integration of technologies to purify/concentrate the products until commercial values. This could eventually save fresh water that is not incorporated in the products so a net fresh water production is still possible.

Monetized Footprint Index results

If the footprint values given in Table 3 are normalized using a monetized base, the MFI can be obtained. MFI for the studied scenarios and alternatives are presented in Figure 3.

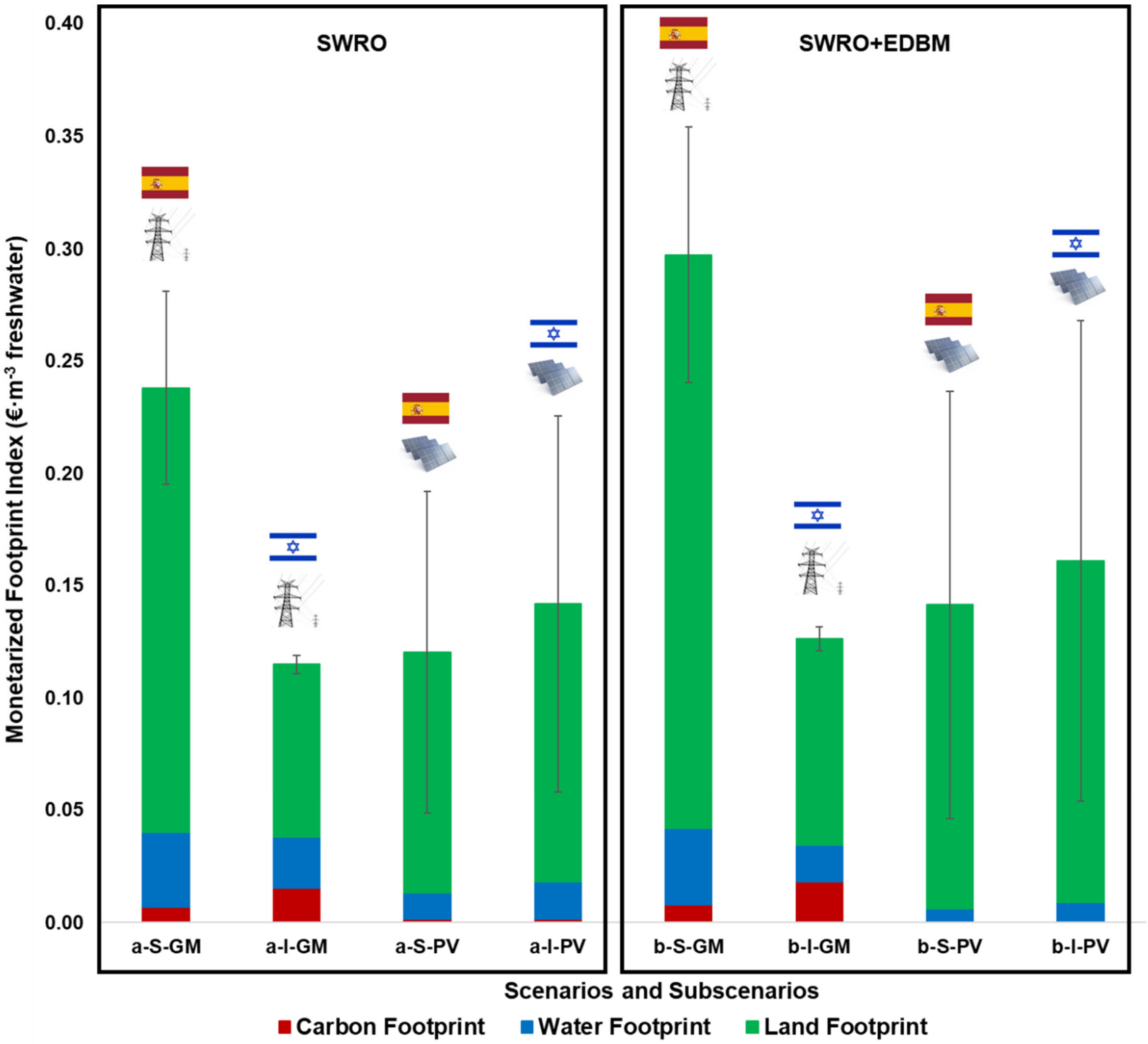

Figure 3. Monetized normalization of land, water and carbon footprints and Monetized Footprint Index for the studied scenarios and alternatives.

Maximum values of 0.24 €·m^{-3} for scenario a and 0.30 €·m^{-3} for scenario b have been obtained in the calculation of the MFI. The maximum value is always obtained for the Spanish grid mix while the minimum value is given by the Israeli grid mix, although values for the Israeli grid mix Spanish PV and Israeli PV are close to this minimum. The contribution of the land footprint to this index stands out, assuming more than 80% of the total value for every scenario except for the

Israeli grid mix that turns to be around the 70%. Values between 13.9%-19.7% for scenario a_GM and 9.7%-11.6% for scenario a_PV, and 11.4%-12.7% for scenario b_GM and 3.8%-5.0% for scenario b_PV are reported for the water footprint. These results demonstrate the important reduction in terms of water footprint that is achieved when EDBM brine treatment and PV solar energy is coupled to the process. The carbon footprint values represent less than the 3.0% of the value except for a-I-GM and b-I-GM alternatives (13.2% and 14.4%, respectively), due to the contribution of non-renewable energies to Israeli grid mix.

Alternatives in which PV solar energy is employed against Spanish grid mix, the MFI is halved. No such decrement is observed in the Israeli case, being PV values slightly higher. These differences are due to the configuration of the Spanish grid mix. As it has been said throughout the present work, the Spanish grid mix has much higher land and water footprints than the Israeli grid mix. The increase in LF and WF is essentially due to the weight that certain renewable energies have in the Spanish grid mix, such as hydropower and biofuels, and also, to a non-renewable energy source in the form of nuclear energy.

The MFI goes up in value when the brine is treated; however, this increment is reduced when PV solar energy is employed. Thus, the environmental behavior in terms of MFI is not improved. Moreover, even though a 1.3% of brine treatment seems a minor amount of treatment supposes huge savings in the external acquisition of the HCl and NaOH for SWRO plants. Assuming maximum HCl and NaOH dosages of 73 $mg \cdot L^{-1}$ and 60 $mg \cdot L^{-1}$ respectively, commercial prices between 190 $€ \cdot ton^{-1}$ and 265 $€ \cdot ton^{-1}$ of HCl (37%)[53] and between 195 $€ \cdot ton^{-1}$ and 205 $€ \cdot ton^{-1}$ of NaOH (50%),[54] and a total desalination market of 86.8 million $m^3 \cdot day^{-1}$,[55] a total saving of 2,185 million $€ \cdot y^{-1}$ is achieved worldwide (1,425 million $€ \cdot y^{-1}$ for HCl and 760 million $€ \cdot y^{-1}$ for NaOH). These figures provide an estimation on the impact of the development of the technology proposed.

Monte Carlo sensitivity analysis

Uncertainties in land, water and CO_2 prices will result in different values of MFI. Thereby, these variations in prices have been studied through Monte Carlo sensitivity analysis composed of 1,000 simulations, which generate the corresponding 1,000 scenarios of different prices combinations. In this sense, variations in prices have been considered through a set of triangular probability distributions. Prices for the previous case of study have been considered as mode. No monetary value (0 €) has been considered as minimum value for every price, whereas considered maximum values depend on the footprint. For the land footprint twice the reference value, for the water footprint three times the reference value, and 30 €·ton^{-1} for CO_2, top record value achieved in the market.[56] Please check Table S6 of the SI for more details.

As shown in Figure 4, whether or not the EDBM brine treatment is considered, the larger variations are found for the case of the Spanish grid mix, with the smallest variations for the Israeli grid mix. However, variations for the PV solar are also small. In addition, wider ranges seems to be found when EDBM is considered. While in the reference case MFI values for PV solar were over the values of the Israeli grid mix, when the analysis is applied it can be observed that there are numerous combinations in which the MFI value for PV solar in Spain is below the Israeli grid mix, especially if the scenarios with EDBM treatment of the brine is considered.

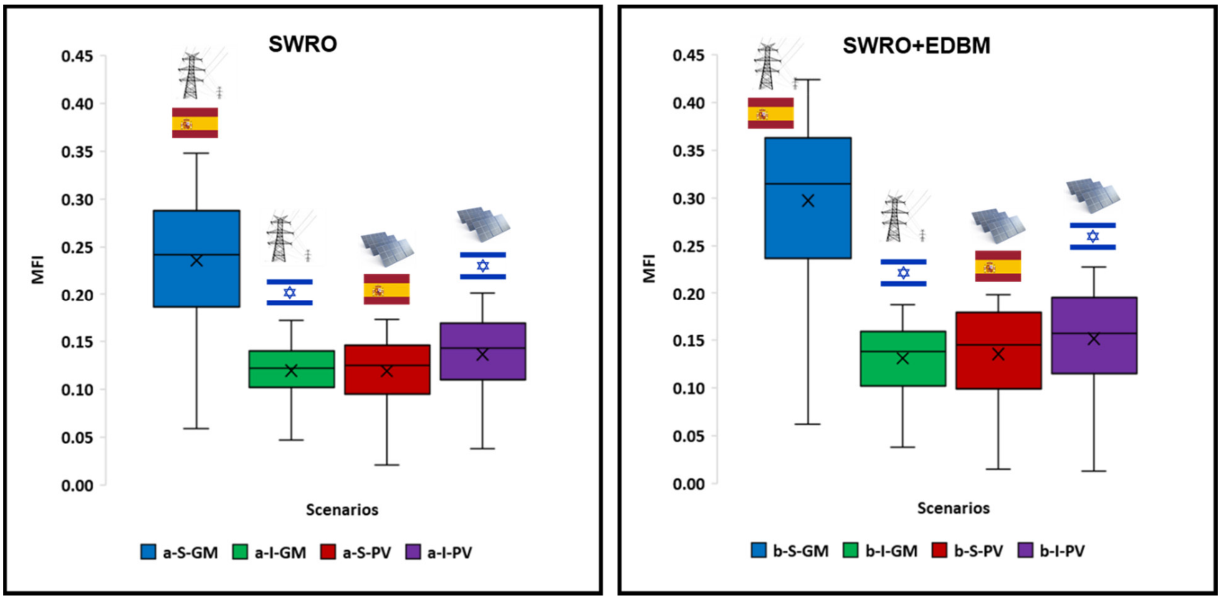

Figure 4. MFI sensitivity analysis.

Final remarks

The novel MFI developed as an integrated index for the assessment of the environmental greenness of an industrial process is based on the compilation and integration of land, water and carbon footprint indicators. The MFI simplifies and supports the decision-making process, allowing the election of the most environmentally sustainable alternative among proposed scenarios while taking into account economic criteria. MFI is a tool for the economic evaluation of environmental burdens, not being included on its scope the calculus of the production cost and it does not include social or economic indicators. To the best of our knowledge, this is the first time that an economic composite index (MFI) has been developed and used as a mean of measuring environmental sustainability based on footprints.

MFI has been applied to the case study of a SWRO desalination system with an integrated EDBM brine treatment. Even if EDBM is still at a low TRL, is a promising technology for brine management and it should be considered, among other technologies, to conform an integrated zero liquid discharge (ZLD) system. This work can be used to claim that the integration of the EDBM, can be a way to improve the environmental sustainability of desalination processes thanks to the integration of a renewable energy in the form of PV solar energy not only in the EDBM but also in the SWRO.

Comparison between selected scenarios based on the different sources of the requested electricity, grid mix (Spain and Israel, as examples) and PV solar energy (under a fixed solar irradiation), has been carried out. The latter is expected to play a key role in the near future and this work is an example of the overall advantages of the electrification of processes as a mean to curb global greenhouse gas emissions. This way, it is possible the improvement of the environmental sustainability of the electrified processes, having better results for every environmental indicator considered in this work. The expected larger value of land footprint for PV solar energy compared to the grid mix is not strictly intuitive.

Maximum values (for the Spanish grid mix) of 0.24 $€\cdot m^{-3}$ for scenario a and 0.30 $€\cdot m^{-3}$ for scenario b (self-supply) have been obtained in the calculation of the MFI. Alternatives in which PV solar energy is employed against Spanish grid mix, the MFI is halved. No such decrement is observed in the Israeli case, being PV values slightly higher. The MFI goes up in value when the brine is treated; however, this increment is reduced when PV solar energy is used as source of electrons. Even though a 1.3% of brine treatment is apparently an insignificant amount of treatment, this value means huge savings in the external acquisition of the HCl and NaOH for SWRO plants with an estimation of a total value worldwide of 2,185 million $€\cdot y^{-1}$. Moreover, uncertainties in land, water and CO_2 prices analyzed under a Monte Carlo simulation, concluded that there are several price combinations in which the MFI value for PV solar in Spain could be below the Israeli grid mix value, especially if the scenarios with EDBM treatment of the brine is considered.

ASSOCIATED CONTENT

Supporting Information

The following files are available free of charge:

Supporting Information (PDF)

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The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

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ABBREVIATIONS/ACRONYMS

CF	Carbon Footprint
DALYs	Disability Adjusted Life Years
EDBM	Electrodialysis Bipolar Membrane
E-PRTR	European Pollutant Emisión Register
FW	Freshwater
GM	Grid Mix
I	Israel
IChemE	Institution of Chemical Engineers
LF	Land Footprint
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCSD	Life Cycle Sustainability Dashboard
LCST	Life Cycle Sustainability Triangle
MFI	Monetized Footprint Index
PV	Photovoltaic
RO	Reverse Osmosis
S	Spain
SI	Supporting Information
SWRO	Seawater Reverse Osmosis
WF	Water Footprint
TRL	Technology Readiness Level
ZLD	Zero Liquid Discharge

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SYNOPSIS

A novel monetized index based on land, water and carbon footprints has been developed and applied in order to evaluate the environmental sustainability of a desalination plant.