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Proposal to determine the carbon and ecological footprint of seawater reverse osmosis desalination in the Canary Islands plants considering the energy mix

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ABSTRACT

This study focuses on seawater reverse osmosis (SWRO) desalination plants in the Canary Islands (Spain) where there are more than 320 private and public units of varying size. The objective is to provide proposals to optimize the operation of these plants, improving energy consumption, water quality, costs and emissions, and making the desalination process more efficient and sustainable. An analysis is undertaken in this study of the carbon footprint ratios (per m^3 and type of inhabitant or per m^3 and type of productive activity) for each of the islands as a contribution to the decision-making process on the inclusion of renewable energy in the energy mix. The conditions for the production of freshwater in each of the islands vary due to differences in the available power technologies and the energy costs. The ecological footprint is also studied for each island. This work shows the results of an analysis of energy efficiency and environmental footprints. The conclusions of the study can serve as a tool to improve energy efficiency in SWRO plants. For an annual desalinated water production in the Canary Islands of 660,000 m^3/d, and considering an energy consumption of about 3.04 kWh/m^3, the calculated carbon footprint per year is 439,402 t CO_2 and the ecological footprint 219,701 ha/y. Given a total population in the islands of 2,207,225 inhabitants, the ecological footprint is 0.1 ha/person/y, and the carbon footprint 0.2 t CO_2/person/y.

Keywords: Reverse osmosis; Desalination; Energy mix; Energy consumption; Carbon footprint; Ecological footprint

1. Introduction

Seawater desalination in water treatment plants has evolved considerably over the past five decades in terms of the processes and technologies applied and their efficiency. Initially, the water desalination process was a thermal-based process, but the scientific-technological advances that have taken place today see the seawater desalination market dominated by the process known as the reverse osmosis (RO) process which today accounts for 65% of the world's desalination water production [1,2].

The main objective of the present work is to consider potential improvements in seawater desalination based on the reduction of energy consumption in freshwater production. In this regard, RO is the most suitable process due to its low energy consumption per cubic meter of water product and, as a result, it occupies a privileged position in the sector. Research efforts in water desalination thus far in the 21st century have focused on advances in RO membranes,

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especially in terms of higher surface area and lower energy consumption, as well as energy recovery systems (ERSs) to recover the brine pressure and reintroduce it in the system with the aim of reducing the energy consumption of the desalination process. The operation, maintenance, and handling of membranes have been studied in detail due to their importance for energy savings, with different works showing how all the processes in which they are involved can be optimized in order to improve energy efficiency [3–5].

Energy efficiency in desalination plants depends on the quality of the permeate water required. In the particular case of the Canary Islands, the following permeate flows can be confirmed, this is determined following the health criteria for water for human consumption which are set out in Royal Decree 140/2003 dated February 7. Of the different ions, the highest restrictions are placed on the presence of boron, which must be lower than 1 ppm [6–9].

In the case of the Canary Islands in terms of seawater desalination plant production, the following current permeate flows can be confirmed: Gran Canaria (220,870 m^3/d), Tenerife (106,034 m^3/d), Fuerteventura (90,755 m^3/d), and Lanzarote (87,480 m^3/d). This produces a significant carbon footprint with respect to the overall footprint of each island, especially on Fuerteventura and Lanzarote. With this in mind, the possibility of introducing renewable energies, especially wind and solar photovoltaic (PV), for the supply of electricity to the seawater desalination plants of the Canary Islands is currently being studied to reduce this carbon footprint and the ecological footprint of the sector throughout the archipelago [2,5].

The electrical systems of the Canary Islands differ considerably from typical continental systems in a number of respects:

- The isolated (insular) electrical systems are small in size. There are six different subsystems, one for each island except for Fuerteventura and Lanzarote which are interconnected by an underwater cable, which is an added complication for the correct of renewable energies.
- This, together with the scarcity on the islands of conventional resources, generates a high external dependence which, in turn, increases the vulnerability of the sector to the continuous fluctuations in the price of oil, above all for lighter fuels (gas oil), which are more expensive than heavy fuels (fuel oil).
- The two biggest islands (the provincial capitals Gran Canaria and Tenerife) are the only ones with steam and combined-cycle units, while the other islands are dependent on diesel-only units.
- The current energy model in the islands does not meet the environmental requirements of the European Union, particularly regarding the reduction of greenhouse gas (GHG) emissions and the increase in the presence of renewable energy sources.
- The high cost of conventional electricity generation on the islands results in increases in the already high tariff deficit, compensated by state-level subsidies.
- A lack of coordination between the different agents responsible for energy, environmental, and territorial matters and little collaboration between the Central Government, the Autonomous Government, and the different Island Governments.
- The highest energy consumption occurs in the transport sector (land, sea, and air).
- An absence of energy storage systems in the archipelago (except for some enclaves such as the hydroelectric plant of La Gorona del Viento, on El Hierro island).
- A lax legislative body on environmental issues.
- Long and complex administrative procedures that delay the implementation of energy projects, affecting above all the installation of renewable-energy-based facilities.

The production of freshwater by an RO plant requires the consumption of electrical energy and, in a conventional network, when this energy is generated a certain quantity of emissions is released in the form of GHGs [5].

With respect to energy consumption, calculation of the carbon footprint, based on the quantity of GHG emissions, has been carried out for decades as part of life cycle assessments in the global warming potential (GWP) impact category [10].

Application of the carbon footprint in the public and private sector has now overtaken the so-called ecological footprint. Several standardization processes [10] and a huge number of publications [12–16] have raised awareness of the carbon footprint and there are many methods to calculate it [11,17–20]. Essentially, carbon footprint calculations use tons of CO_2 equivalents as a measure to compare GHG emissions on the basis of their GWP. There are many advantages to translating tons of CO_2 (carbon footprint) into global hectares (ecological footprint), as it allows comparison with other demands on productive land [21].

With the aim of reducing GHG emissions, the use of hybrid energy systems has been proposed to generate the electrical energy required for freshwater production in the same facility. Such hybrid systems can be based on several types of technology, but the main objective is to obtain as much energy as possible from renewable sources with the back-up support of an energy storage system or a conventional technology such as a diesel engine [20–24]. By way of example, a solar PV energy generating system operating with the back-up of a high-efficiency diesel engine could be used to power a small SWRO plant, thus reducing the GHG emissions associated with freshwater production. A system of such characteristics would be very useful in hotel complexes, private facilities, industries, isolated areas, etc. [25].

This study focuses on seawater reverse osmosis (SWRO) desalination plants with feed salinities of between 38,000 and 40,000 mg/L water. The aim is to provide proposals to optimize plant operation and increase the product water quality while at the same time reducing energy consumption, costs, and emissions, thus making the plant more efficient and sustainable. The analysis will consider different design parameters of the plant and its operation, including standard RO membrane boron rejection, depth of water intake, temperature, working pressure, and plant conversion and production rate. Consideration is also given to the use of special tools or pilot systems in the plants. The above is undertaken always taking into account and complying with the quality criteria established by national and European regulations on desalinated water for human consumption, as well as the recommendations of the World Health Organization (WHO) [5–6].

2. Methodology

The methodology employed in this study is divided into three subsections: energy consumption, CO_2 emission factor (carbon footprint), and ecological footprint. In each section, a formula is presented for each parameter, which will subsequently be used in the Results section.

The possible improvements to the RO seawater desalination process are analyzed in this paper not only on the basis of certain very specific cases, as in the desalination plants which will be described below but also considering a very wide range of validity in terms of seawater salinity and temperature, even at the level of a group of installations in a territory.

The methodology that has been developed is based on the use of a comprehensive model for the study of energy efficiency and potable water production in public (urban) and private (hotel and agricultural) SWRO desalination plants, always taking into account the quality parameters of the permeate established in Spanish Royal Decree 140/2003.

The Toray DS2 software is employed in the SWRO desalination plant design to run hypothetical projections under different scenarios, using a calculator tool to obtain all the required parameters.

The following input parameters were introduced into the software: feedwater intake, type of membrane, feed temperature, feed salt concentration, recovery, and production rate. The output parameters were as follows: feed pressure of the RO system, permeate quality, and power and energy consumption (energy evaluation), which were subsequently used to calculate the carbon and ecological footprints.

2.1. Energy consumption

The calculations are performed on the basis of the use of state-of-the-art RO membranes whose low energy consumption and high salt rejection improve the environmental impact of the process and therefore contribute to reducing its footprint. In addition, high salt rejection means an improvement in the quality of the product water at the usual working pressures. In this sense, Spanish Royal Decree 140/2003 dated February 7, which establishes the health criteria for the quality of water for human consumption, is amply complied with.

A key factor in the quality of the water produced in desalination plants is boron rejection efficiency, which can be increased by working with high rejection membranes, normally at higher pressure. Using state-of-the-art RO membranes, permeate water can be produced with less than 1 ppm of boron in more efficient and sustainable conditions than with standard membranes.

The formula for total energy consumed, which considers renewable and non-renewable energy taken from the main grid and locally generated (off-grid) renewable energy [3,5,8], is shown in Eq. (1):

$$E_{\mathrm{Tc}} = E_{\mathrm{Rg}} + E_{\mathrm{NRg}} + E_{\mathrm{LR}} \tag{1}$$

where E_{Tc} is the total energy consumed, E_{Rn} is grid-sourced renewable energy, E_{NRg} is non-renewable grid-sourced energy, and E_{LR} is locally sourced renewable energy.

The carbon and ecological footprints will vary depending on the contribution of E_{LR}, decreasing as the contribution of locally sourced renewable energy rises. The energy from the electric system can be both non-renewable (diesel, gas turbine, steam turbine, or combined cycle) and renewable (mainly wind and PV). This equation will be used in the Results section to calculate the energy consumption [21–25].

2.2. CO_2 emission factor (mix factor)

In accordance with the specific environmental impact indicator model [10–13,21] and the formula used by Red Eléctrica Española (the transmission system operator for electricity in Spain) for emissions and the CO_2 emission factor in non-renewable generation in the electricity system for 2020, a second formula is used (Eq. (2)) to calculate the mix factor considering all the CO_2 emission factors in non-renewable technologies [25]. This will subsequently be used in the Results section to calculate the mix factor of each island and compare them:

$$\mathrm{MF} = \mathrm{MF}_{\mathrm{md}} + \mathrm{MF}_{\mathrm{gt}} + \mathrm{MF}_{\mathrm{st}} + \mathrm{MF}_{\mathrm{cc}} \tag{2}$$

where, as defined by the Spanish Ministry of Ecological Transition, MF is the emission factor of the electric mix (tCO_2/kWh), $\mathrm{MF}_{\mathrm{md}}$ is the diesel motor mix factor (tCO_2/kWh), $\mathrm{MF}_{\mathrm{gt}}$ is the gas turbine mix factor (tCO_2/kWh), $\mathrm{MF}_{\mathrm{st}}$ is the steam turbine factor mix (tCO_2/kWh), and $\mathrm{MF}_{\mathrm{cc}}$ is the combined cycle factor mix (tCO_2/kWh).

The MF is calculated for each technology and island on the basis of total energy consumption per island, which is associated with the carbon footprint, and the percentage of a particular technology in the energy mix, including renewable and non-renewable energies. In consequence, the MF of a particular technology "*i*" per island is calculated as follows (Eq. (3)) [10–14]:

$$\mathrm{MF}_i = \frac{P_{\mathrm{ti}}}{100}\frac{\mathrm{CF}_i}{E_i} \tag{3}$$

where P_t is the percentage use of each technology in the energy mix, CF_i is the carbon footprint of technology "*i*" (tCO_2), and E_i is the energy consumed by each technology (kWh).

In this way, the carbon footprint of the current energy mix can be calculated, considering the sum of the energy consumption of each technology and their emissions mix factor [25]. Eqs. (3) and (4) are also used in the Results section to calculate the mix factor and carbon footprint per island and technology [15–19].

$$\mathrm{CF}_{\mathrm{MIX}} = \sum E_i \mathrm{MF}_i \tag{4}$$

where $\mathrm{CF}_{\mathrm{MIX}}$ is the carbon footprint of the energy mix (tCO_2).

The current and future energy consumption of the technologies of the energy mix are calculated through Eqs. (5) and (6), respectively. However, they are not used in the Results section for this paper [3,5,19]:

$$E^1 t_{\text{MIX}} = \sum E_i \text{ in the initial moment} \tag{5}$$

$$E^2 t_{\text{MIX}} = \sum E_i \text{ in the final moment} \tag{6}$$

To reduce the carbon footprint of the current energy mix, renewable energies should be introduced into the mix as much as possible, the high performance of conventional technologies such as the diesel engine, combined cycles, or the steam turbine, should also be maintained as these consume less fuel to produce the same energy as other conventional technologies, and the efficiency of the electricity grid has to be improved [14–19,25].

With respect to the previous formulation which calculates the carbon footprint of the energy mix factor, this needs to be reduced by as much as possible through the contribution of renewable energy as its emissions mix factor is negligible compared to conventional technologies and tends to zero [10–14]. That is, whenever possible, the idea is to try to introduce a higher percentage of renewable energies in the energy mix to reduce emissions and the carbon footprint. It is even possible to introduce these renewable energies in the pilot membranes that will be discussed below to improve the overall energy efficiency performance of SWRO desalination plants. In the future, it is predicted that the lower the emissions, and therefore the carbon footprint, the lower the cost per m^3 of product water will be, as taxes can be waived when pollution is avoided in this way [14–19].

2.3. Ecological footprint

Finally, after the energy consumption, mix factors and carbon footprint, the ecological footprint is calculated on the basis of Eq. (7) [20–25] and the values are shown in Table 1.

As can be seen from Table 1, it is calculated that an equivalent hectare of the planet is capable of absorbing an average of 2 tons of CO_2 per year, understanding the concept of equivalent hectare as that which brings together in the described proportion all the types of land that make up the planet and which have been summarized as forest land, agricultural land, meadow and grazing land, oceans and seas, deserts, and others. The following formula (Eq. (7)) is obtained:

$$\text{EF} = \frac{\text{CF}_a}{2} = \frac{\text{CF}_d \times 365d}{2} = \frac{\text{EI} \times \text{PF} \times 365d}{2} \tag{7}$$

where EI is the environmental impact (tCO_2/m^3), PF is the permeate flow (m^3/d), CF_a is the annual carbon footprint (tCO_2/y), CF_d is the daily carbon footprint (tCO_2/d), and EF is the ecological footprint (ha/y).

We know that the dispersion of CO_2, a GHG, is heterogeneous and global, although the sources of production are more intense in certain land areas colonized by human population centers.

A new concept can be considered in reference to CO_2 absorption, which can be termed the useful surface area of the planet, comprising forest land, agricultural land, livestock land, surface waters, and marine and coastal vegetation (therefore excluding deep waters, deserts, and other types of the surface not cataloged), which are those that most contribute to the absorption of carbon.

If we estimate the world population at 7.2 billion people and consider that the useful surface area is 12,190.14 million ha, assuming that there is currently an acceptable population situation for the planet, by distributing the population evenly the useful surface area for each individual would be 1.69 ha/person/y [24].

3. Results

In a general analysis of energy consumption by plant components, it is well-known that if membrane replacement is not carried out energy consumption increases progressively. This can be seen in Table 2, constructed on the basis of the calculations and design specifications of the Toray membrane manufacturers. An average operating flow is estimated at 16 LMH, with beach well intake or pre-treatment with ultrafiltration membranes, along with a recovery rate of 45% and a feed salinity of 39 g/L, normal in the area.

Table 1
Average and equivalent CO_2 absorption per hectare of different surface categories of the planet using surface area equivalence factors [25]

Surface category	Average absorption (tCO_2/ha/y)	Surface area (million ha)	%	ABS. Equivalent hectares (tCO_2/ha/y)	Equivalence factor (f_i)
Forest	19.35	3,858.10	7.56	1.46	9.66
Crop	8.09	1,958.32	3.84	0.31	4.04
Meadow/grazing	2.44	3,363.72	6.59	0.16	1.22
Ocean	0.10	36,010.00	70.60	0.07	0.05
Desert	0.00	3,600.00	7.06	0.00	0.00
Other	0.00	2,217.06	4.35	0.00	0.00
Total		51,007.20		2.00	1.00

As commented in section Methodology, the Toray DS2 software was used to run hypothetical projections under different scenarios, using a calculator tool to obtain all the required parameters. The worst-case scenario of energy consumption is considered as the lowest feedwater temperature in the Canary Islands (17°C) and the TM820K-440 membrane. This element had high salt rejection (99.86%) and a permeate flow of 24.2 m^3/d under the test conditions of 55.2 bar, a recovery rate of 8%, and feedwater characteristics of 32,000 ppm NaCl. The other element used in the projections, the TM820V-440, resulted in lower energy consumption, with 99.80% of salt rejection and 37.5 m^3/d of permeate flow under the same test conditions. The pore of the flat sheet membrane in the TM820K-440 is smaller than in the TM820V-440 and, as a result, the former produces permeate water with higher quality while the latter has lower energy consumption.

Table 2
Pressure, power, and energy consumption at 17°C with the TM820K-440 membrane element

Year	Pressure (bar)	Power (kW)	Energy consumption (kWh/m^3)
0	71.11	23,511.23	5.643
1	72.77	24,060.57	5.775
2	74.56	24,650.69	5.916
3	76.13	25,171.11	6.041
4	77.62	25,662.76	6.159
5	79.06	26,140.34	6.274

It can be seen from Tables 2 and 3 that, in 5 y of operation, the working pressure is considerably higher at the lowest feedwater temperature (17°C) than at the highest (27°C) and that consequently, the energy consumption is also higher. In the lower energy consumption case (with the TM820V-440 element), the calculations incorporated an ERS to further reduce energy consumption at the highest temperature of around 27°C (Table 3).

To calculate the MFs of each island per technology (Table 4), it is necessary to first find the energy consumption through Eq. (1) (see section Energy consumption) and then use Eqs. (2) and (3) (see section CO_2 emission factor (mix factor)). Regarding energy consumption, in Gran Canaria 8.1% of the energy required to produce 1 m^3 of potable water comes from renewable energy sources which generate no CO_2 emissions. The corresponding value in Tenerife is 7.7%, in Lanzarote 4.6%, in Fuerteventura 5%, in La Palma 10%, in La Gomera 0.7%, and in El Hierro 45.4%. For the Canary Islands as a whole, renewable energy sources are responsible for 7.56% of the total energy consumed [3,6,25]. In Gran Canaria, 45.1% of the non-renewable energies come from steam turbine, 45.2% from combined cycle, 7.8% from diesel motor, and the other 1.8% from gas turbine technologies. Bearing in mind that 91.9% of the total energy is non-renewable, this means that 41.5% of the total energy consumed is generated by the island's steam turbine plant [25].

Table 5 shows the carbon footprints results calculated through Eq. (4) and the ecological footprint per m^3 of permeate water produced (EF_w) and for the lowest energy consumption with the TM820V-440 element. Table 6 shows the results of the same calculations, but for

Table 3
Pressure, power, and energy consumption values at 27°C with the TM802V-440 membrane element

Year	Pressure (bar)	High pressure pump power (kW)	ERS power (kW)	Booster (kW)	Energy (kWh/m^3)
0	57.69	9,168.26	7,908.69	479.10	2.200
1	58.07	9,226.44	7,962.37	480.20	2.214
2	58.45	9,285.33	8,016.83	481.30	2.229
3	58.77	9,334.34	8,062.14	482.10	2.240
4	59.06	9,378.71	8,103.15	482.90	2.251
5	59.34	9,420.35	8,141.62	483.70	2.261

Thus, Table 2 show at the lowest temperature (17°C) and after 5 y of operation, the highest energy consumption (6.274 kWh/m^3) with the high salt rejection element (TM820K-440), and Table 3 show at the highest temperature (27°C) and at start-up, the lowest energy consumption (2.200 kWh/m^3) with the low energy consumption element (TM820V-440).

Table 4
Mix factor for each non-renewable technology used in the Canary Islands and broken down by island. Year 2017

Mix factor (MF) per non-renewable technology in the Canaries (kgCO_2/kWh)								
Technology	Gran Canaria	Tenerife	Lanzarote	Fuerteventura	La Palma	La Gomera	El Hierro	Canary Islands
Steam turbine	0.3736	0.3370	–	–	–	–	–	0.2775
Gas turbine	0.0185	0.0421	0.0170	0.1632	0.0030	–	–	0.0382
Diesel motor	0.0468	0.0529	0.6098	0.5246	0.5847	0.6466	0.3561	0.1646
Combined cycle	0.2492	0.2566	–	–	–	–	–	0.1974
Total	0.6881	0.6886	0.6267	0.6878	0.5877	0.6466	0.3561	0.6776

Table 5
Carbon footprint and ecological footprint per cubic meter of permeate water produced for the lowest energy consumption case

Carbon footprint (CF) $kgCO_2/m^3$ and ecological footprint (EF_w) m^2/m^3 for lowest energy consumption case								
Technology	Gran Canaria	Tenerife	Lanzarote	Fuerteventura	La Palma	La Gomera	El Hierro	Canary Islands
CF 5 y 0%R	1.5558	1.5569	1.4170	1.5551	1.3288	1.4620	0.8051	1.5321
CF 5 y 10%R	1.5455	1.5466	1.4076	1.5448	1.3200	1.4523	0.7998	1.5219
CF 5 y 15%R	1.5400	1.5411	1.4026	1.5393	1.3153	1.4471	0.7970	1.5165
CF 5 y 20%R	1.5338	1.5349	1.3969	1.5331	1.3100	1.4413	0.7937	1.5104
EF_w 5 y 0%R	7.6234	7.6289	6.9431	7.6201	6.5111	7.1636	3.9452	7.5071
EF_w 5 y 10%R								
EF_w 5 y 15%R								
EF_w 5 y 20%R								
EF_w 5 y 0%R	7.5728	7.5783	6.8971	7.5695	6.4679	7.1161	3.9190	7.4573
EF_w 5 y 10%R								
EF_w 5 y 15%R								
EF_w 5 y 20%R								
EF_w 5 y 0%R	7.5458	7.5513	6.8725	7.5426	6.4448	7.0907	3.9051	7.4307
EF_w 5 y 10%R								
EF_w 5 y 15%R								
EF_w 5 y 20%R								
EF_w 5 y 0%R	7.5155	7.5210	6.8449	7.5122	6.4189	7.0622	3.8894	7.4008
EF_w 5 y 10%R								
EF_w 5 y 15%R								
EF_w 5 y 20%R								

Table 6
Carbon footprint and ecological footprint per cubic meter of permeate water produced for the highest energy consumption case

Carbon footprint (CF) $kgCO_2/m^3$ and ecological footprint (EF_w) m^2/m^3 for highest energy consumption case								
Technology	Gran Canaria	Tenerife	Lanzarote	Fuerteventura	La Palma	La Gomera	El Hierro	Canary Islands
CF 5 y 0%R	4.3171	4.3203	3.9319	4.3153	3.6872	4.0568	2.2342	4.2513
CF 5 y 10%R	4.1981	4.2011	3.8235	4.1963	3.5856	3.9449	2.1726	4.1340
CF 5 y 15%R	4.1362	4.1392	3.7671	4.1344	3.5327	3.8867	2.1405	4.0731
CF 5 y 20%R	4.0708	4.0738	3.7076	4.0690	3.4768	3.8253	2.1067	4.0087
EF_w 5 y 0%R	21.1540	21.1694	19.2664	21.1448	18.0674	19.8782	10.9474	20.8312
EF_w 5 y 10%R								
EF_w 5 y 15%R								
EF_w 5 y 20%R								
EF_w 5 y 0%R	20.5707	20.5856	18.7351	20.5617	17.5692	19.3300	10.6456	20.2568
EF_w 5 y 10%R								
EF_w 5 y 15%R								
EF_w 5 y 20%R								
EF_w 5 y 0%R	20.2672	20.2820	18.4588	20.2584	17.3101	19.0449	10.4885	19.9580
EF_w 5 y 10%R								
EF_w 5 y 15%R								
EF_w 5 y 20%R								
EF_w 5 y 0%R	19.9469	19.9614	18.1670	19.9382	17.0365	18.7439	10.3228	19.6425
EF_w 5 y 10%R								
EF_w 5 y 15%R								
EF_w 5 y 20%R								

Table 7
Energy consumed, carbon footprint, ecological footprint, and carbon factor per island and cubic meter of product water. Year 2013

Desalination capacity, energy consumption, carbon factor, carbon, and ecological footprint						
	Gran Canaria	Tenerife	Lanzarote	Fuerteventura	La Gomera	El Hierro
Desalination capacity m^3/d	221,009	106,185	87,457	90,644	2,000	5,454
kWh/m^3	3.28	2.27	3.23	3.38	3.04	3.08
Energy consumption kWh/d	724,910.80	241,038.60	282,486.42	306,377.10	6,080.00	16,798.00
Carbon footprint tons/d	498.79	165.98	177.04	210.74	3.93	5.98
Factor CO_2/m^3	0.0023	0.0016	0.0020	0.0023	0.0020	0.0011
Ecological footprint ha/d	244.41	81.33	86.75	103.26	1.93	2.93

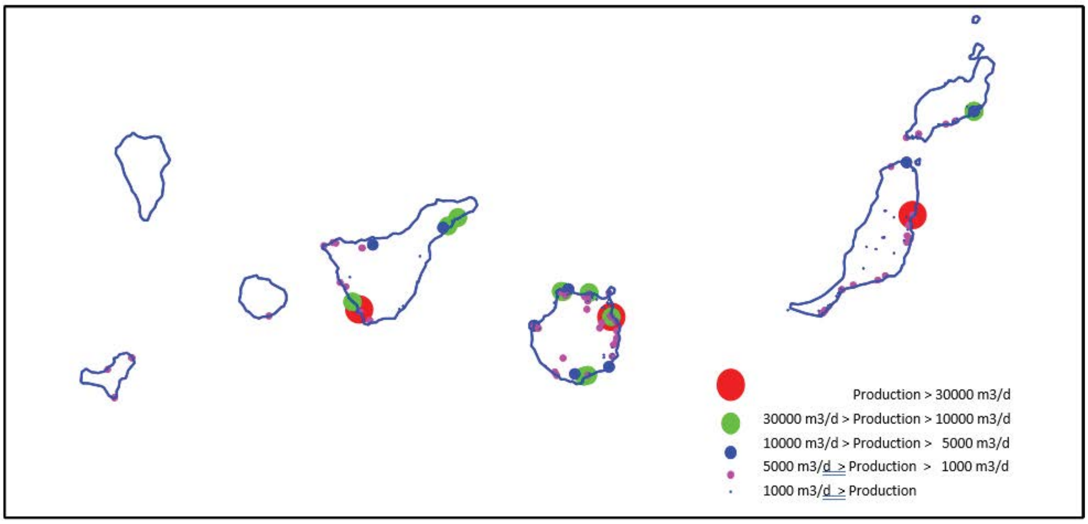

Fig. 1. Most significant seawater desalination plants in the Canary Islands (Spain) (2019).

the TM820K-440 element. In addition, partial replacements (ranging between 0% and 20%) of RO membranes per year are considered.

Table 7, using the SWRO plant production values of Fig. 1 and the results given above, shows the energy consumed (kWh) per m^3 of product water in each island, the carbon footprint, ecological footprint, and the carbon factor per island and m^3 produced [3,5,25].

Energy consumption was calculated by multiplying the desalination capacity of each island by the consumption per kWh/m^3 of permeate water. This consumption value (kWh/m^3) was obtained after considering the characteristics of the desalination plants in each island and the different ERSs installed (http://www.fcca.es).

For an annual desalinated freshwater production in the Canary Islands of approximately 660,000 m^3/d and considering an average energy consumption of 3.04 kWh/m^3, with brine energy recovery devices, a carbon footprint is obtained of 1,203.84 tCO_2/d (439,402 tCO_2/y). Following this same criterion and using a global coefficient of the ecological footprint for its calculation [22–25], a value of 219,701 ha/y due to the production of desalinated water in the Canary Islands is obtained. Divided by the population of the Canary Islands (2,207,225 habitants), this ecological footprint corresponds to 0.1 ha/person/y and the carbon footprint to 0.2 tCO_2/person/y.

The carbon and ecological footprints calculated above correspond solely to desalination in the Canary Islands. If this calculation is extended to the total annual consumption of 8,878,271 MWh in all the sectors of the archipelago in 2019, and considering an average value of 0.6 tCO_2/MWh [25], it is estimated that 5,326,963 tCO_2/y can be emitted, which corresponds to 2.4 tCO_2/person/y. Fig. 1 shows the most important plants in the Canary Islands in terms of size that produce most of the aforementioned ecological footprint.

4. Conclusions

Both the cost and the energy required in the reverse osmosis desalination process depend on the water quality required, the type of membrane used, and the age of the elements. Due to this, it is very important to select the most appropriate membrane in the plant with low energy consumption and replacement rate.

The methodology proposed in this paper was divided into three sections: energy consumption, CO_2 emission factor (carbon footprint), and ecological footprint. A formula is presented in each section to calculate the corresponding parameter per island and technology. The proposed methodology can be used to achieve stable operation while reducing the greenhouse gas emissions associated with freshwater desalination production.

Energy consumption decreases with both increasing feedwater temperature and decreasing feedwater salinity. Whenever possible, it is of interest to introduce a higher percentage of renewable energies into the energy mix to reduce emissions and the carbon footprint. Energy consumption also decreases if low energy consumption RO membranes, along with partial replacements per year, and ERSs are incorporated.

The desalination-sourced carbon footprint (0.2 tCO_2/person/y) and ecological footprint (0.1 ha/person/y) in the Canary Islands are considerable for a surface area of 749,300 ha and a population of 2,207,225 inhabitants. These very high carbon and ecological footprints need to be lowered through the incorporation of more renewable-sourced energy to improve the environmental conditions of the archipelago.

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References

[1] E. Dimitriou, E. Mohamed, C. Karavas, G. Papadakis, Experimental comparison of the performance of two reverse osmosis desalination units equipped with different energy recovery devices, Desal. Water Treat., 55 (2015) 3019–3026.
[2] E. Dimitriou, E. Mohamed, G. Kyriakarakos, G. Papadakis, Experimental investigation of the performance of a reverse osmosis desalination unit under full-and part-load operation, Desal. Water Treat., 53 (2015) 3170–3178.
[3] J.J. Sadhwani, J.M. Veza, Desalination and energy consumption in Canary Islands, Desalination, 221 (2008) 143–150.
[4] F.A. Leon, A. Ramos, Analysis of high efficiency membrane pilot testing for membrane design optimization, Desal. Water Treat., 73 (2017) 208–214.
[5] J. Schallenberg-Rodriguez, J.M. Veza, A. Blanco-Marigorta, Energy efficiency and desalination in the Canary Islands, Renewable Sustainable Energy Rev., 40 (2014) 741–748.
[6] J. Kherjl, A. Mnif, I. Bejaoui, B. Humrouni, Study of the influence of operating parameters on boron removal by a reverse osmosis membrane, Desal. Water Treat., 56 (2015) 2653–2662.
[7] D.M. Davenport, A. Deshmukh, J.R. Werber, M. Elimelech, High-pressure reverse osmosis for energy-efficient hypersaline brine desalination: current status, design considerations, and research needs, Environ. Sci. Technol. Lett., 5 (2018) 467–475.
[8] S.K. Patel, C.L. Ritt, A. Deshmukh, Z. Wang, M. Qin, R. Epsztein, M. Elimelech, The relative insignificance of advanced materials in enhancing the energy efficiency of desalination technologies, Energy Environ. Sci., *13* (2020) 1694–1710.
[9] C. Boo, R.K. Winton, K.M. Conway, N.Y. Yip, Membrane-less and non-evaporative desalination of hypersaline brines by temperature swing solvent extraction, Environ. Sci. Technol. Lett., 6 (2019) 359–364.
[10] M. Finkbeiner, Carbon footprinting—opportunities and threats, Int. J. Life Cycle Assess., 14 (2009) 91–94.
[11] T. Wiedmann, J.A. Minx, Definition of Carbon Footprint, C.C. Pertsova, Ed., Ecological Economics Research Trends, Nova Science Publishers, Hauppauge NY, USA, 2008, pp. 1–11.
[12] Carbon Footprints in the Supply Chain: The Next Step for Business, Report No. CTC616, The Carbon Trust, London, UK, 2006.
[13] H.S. Matthews, C.L. Weber, C.T. Hendrickson, Estimating Carbon Footprints with Input-Output Models, Proceedings of the International Input-Output Meeting on Managing the Environment, Seville, Spain, 2008.
[14] J. Minx, K. Scott, G. Peters, J. Barrett, An Analysis of Sweden's Carbon Footprint—A Report to WWF Sweden, WWF, Stockholm, Sweden, 2008.
[15] C.L. Weber, H.S. Matthews, Quantifying the global and distributional aspects of American household carbon footprint, Ecol. Econ., 66 (2008) 379–391.
[16] T. Wiedmann, R. Wood, M. Lenzen, J. Minx, D. Guan, J. Barrett, Development of an Embedded Carbon Emissions Indicator—Producing a Time Series of Input-Output Tables and Embedded Carbon Dioxide Emissions for the UK by Using a MRIO Data Optimisation System, Final Report to the Department for Environment, Food and Rural Affairs by Stockholm Environment Institute at the University of York and Centre for Integrated Sustainability Analysis at the University of Sydney, Project Ref. EV02033, Defra, London, UK, 2008.
[17] H.S. Matthews, C.T. Hendrickson, C.L. Weber, The importance of carbon footprint estimation boundaries, Environ. Sci. Technol., 42 (2008) 5839–5842.
[18] J. Minx, T. Wiedmann, J. Barrett, S. Suh, Methods Review to Support the PAS Process for the Calculation of Greenhouse Gas Emissions Embodied in Goods and Services, Report to the UK Department for Environment, Food and Rural Affairs by Stockholm Environment Institute at the University of York and Department for Bio-Based Products at the University of Minnesota, Project Ref. EV2074, Defra, London, UK, 2008.
[19] B.P. Weidema, M. Thrane, P. Christensen, J. Schmidt, S. Løkke, Carbon footprint. A catalyst for life cycle assessment?, J. Ind. Ecol., 12 (2008) 3–6.
[20] M. Lenzen, Double-counting in life cycle calculations, J. Ind. Ecol., 12 (2008) 583–599.
[21] A. Carballo, Usefulness of the ecological and carbon footprint in the field of corporate social responsibility (CSR) and the ecolabeling of goods and services, DELOS, 3 (2010) 1–17.
[22] Ministry of the Environment of the Andalusian government, The Ecological Footprint of Andalusia, a Tool to Measure Sustainability, 2006.
[23] Ministry of the Rural and Marine Environment, Analysis of the Ecological Footprint of Spain, 2008.
[24] J. Llinares Pascual, Methodological Proposal for the Determination of the Ecological Footprint in the Hotel Sector. Application for the Canary Islands, Thesis, University of Las Palmas de Gran Canaria, 2015.
[25] Canary Islands Energy Yearbook 2017, Directorate General for Industry and Energy, Canary Islands Government, 2017.