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Climate Change Mitigation Strategy through Membranes Replacement and Determination Methodology of Carbon Footprint in Reverse Osmosis RO Desalination Plants for Islands and Isolated Territories

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Abstract: This article shows a climate change mitigation strategy by means of membranes replacement and determination methodology of carbon footprint in reverse osmosis (RO) desalination plants, valid for all the islands, and even isolated territories in the continent. This study takes the case of study of Canary Islands, where there are more than 320 desalination plants with different sizes, private, and public. The objective is to propose a new method which integrates this analysis with the replacement of membranes, from 0% to 20% per year in sea water reverse osmosis desalination plants, to reduce the carbon footprint and ecological footprint. If it is considered a replacement of 20% of the elements per year, the carbon footprint could be reduced to between 5% and 6% and even more if it is introduced low energy consumption membranes instead of high rejection elements. The factor mix in Canary Islands, according to the technological structure of the generation park that uses oil products, is around 0.678 $kgCO_2/kWh$, much higher than in the Spanish mainland where it is 0.263 $kgCO_2/kWh$. Therefore, it is estimated in Canary Islands 5,326,963 t CO_2/year can be emitted, which represents 2.4 tCO_2/person/year, 12 times more the admissible admissions per inhabitant in the Canary Islands, only considering the seawater desalination sector. This document shows the different results of the analysis of energy efficiency and the environmental footprints. This study may serve as a tool for the decision-making processes related to how to improve energy efficiency in desalination plants.

Keywords: carbon footprint; ecological footprint; reverse osmosis; desalination; energy consumption; energy mix

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1. Introduction

A reduction in energy consumption will have a direct impact on environmental improvement and we study this through the carbon footprint produced by these desalination plants and their ecological footprint, the latter as a future line of action [1–5]. To produce a quantity of water from a reverse osmosis plant, a quantity of electrical energy must be consumed, and to generate this energy, in a conventional electrical network, a quantity of emissions in the form of greenhouse gases is emitted [6–12]. The magnitude of these emissions depends on the set of technologies that make up the energy generation system of the electrical network to which the water production plant is connected. The energy produced by this set is often referred to as the energy mix, which tends to depend largely on the territory and energy policy [13–19].

In relation to territorial dependence, electricity networks generally have energy mixes that cause higher greenhouse gas emissions, typically in insular and isolated systems as opposed to large interconnected continental systems [20], as they generally have systems based on lower performance technologies. These electrical energy production technologies can be classified, mainly, in two types: conventional and renewable. Within the conventional technologies, which have a direct impact on the carbon footprint of the installations, several can be considered: diesel engines, gas turbines, combined cycles, and steam turbines, which generally have different performance and quantity of emissions. On the other hand, there are technologies based on renewable energies, such as solar photovoltaic, wind, waves, etc. [20–25].

This paper is focused on reverse osmosis (RO) desalination process, which currently accounts for 65% of the total in the world [26–29]. The main objective is to study the improvements in seawater desalination RO with regard the reduction of the CO_2 emissions, based on the reduction of energy consumption in the production of fresh water, due to RO being the lowest energy consumption desalination process. The operation and membranes replacement have been studied, due to their importance in energy savings, and with the consequent decrease in CO_2 emissions, showing how to optimize all the processes in which they are involved to improve the energy efficiency [30–34]. It is recommended to replace at least one element per vessel per year. The lead element usually is more damaged than the others due to the fouling, so it should be replaced for a new one to be located at the end of the vessel.

Membrane replacement is around 4% of the operating cost of a seawater desalination plant and the energy consumption of the pumps is around 62%. It has been also introduced other references with higher values, so it has been considered a conservative value following the local original equipment manufacturers OEMs sources. Due to this, it is justified the membranes replacement to improve the energy recovery in the RO desalination plants [21–24]. Moreover, it is of interest that the use of new generation membranes from graphene/carbon nanoparticles or zeolites for commercial and industrial RO applications is under development as their scalability is still a challenge. Polymeric membranes, such as polyamide, and their integration with other polymers or nanoparticles have also been considered. The choice of membrane materials for future RO processes would depend on the required permeability and the targeted foulants [35].

Energy efficiency in desalination plants depends on the quality of permeate water required, in this case in Spain according to the Real Decreto 140/2003 of 7 February, following the sanitary criteria of the quality of the water of human consumption established. Boron is the highest restriction issue of all the ions, and it must be lower than 1 ppm. Therefore, sometimes it requires a second pass of the permeate water, so practically double the number of plant membranes, if the second pass is required, in total. The permeate water has to feed a new reverse osmosis system, which is very expensive, or the system has to work with high rejection membranes in a single pass with higher pressures, i.e., consuming more energy and increasing this cost which is also one of the most significant of the variable costs of the installation [9–12].

2. Materials and Methods

To propose an integral methodology of calculation, the initial and final parameters to be reached are described below. The possible improvements in the seawater desalination process are studied, using reverse osmosis technology, not only for certain very specific cases, as shown in the desalination plants to be comment later, but the study is carried out with a very wide range of validity in terms of salinity, seawater temperatures in installations, or even at the level of a group of installations in a territory.

This article is focused on seawater desalination plants with feed salinities between 38,000 and 40,000 mg/L water. Furthermore, the aim is to provide proposals to optimize the operation of the plants by influencing energy consumption, water quality, costs, and emissions, thus making their operation more efficient and sustainable. The indicated analysis methodology will be achieved from the incidence in different design parameters of the plant or operation, such as the standard reverse osmosis membranes for seawater and high boron rejection, the depth of the water intake, the temperature, working pressure, the conversion, and the production of the plants. Of special mention is the use of tools or pilot systems in plants. All of this must comply with the parameters for the quality of the water at the end of the process, which must have values below the maximums permitted by the National and European regulations on water for human consumption, as well as the recommendations of the World Health Organization (WHO) [13–15].

A methodology has been developed, by means of an integral model, Figure 1, for the study of the energy efficiency and drinking water in public (urban) and private (hotel and agricultural) seawater desalination plants, also taking into account the quality parameters of the permeate in relation to the rejection of boron, in Spain the Real Decreto 140/2003, and the energy consumption through large-scale pilots with the necessary instrumentation and monitoring of the data for its study up to 2000 days of operation. All of this is aimed at reducing the operating costs of the facilities and their energy consumption.

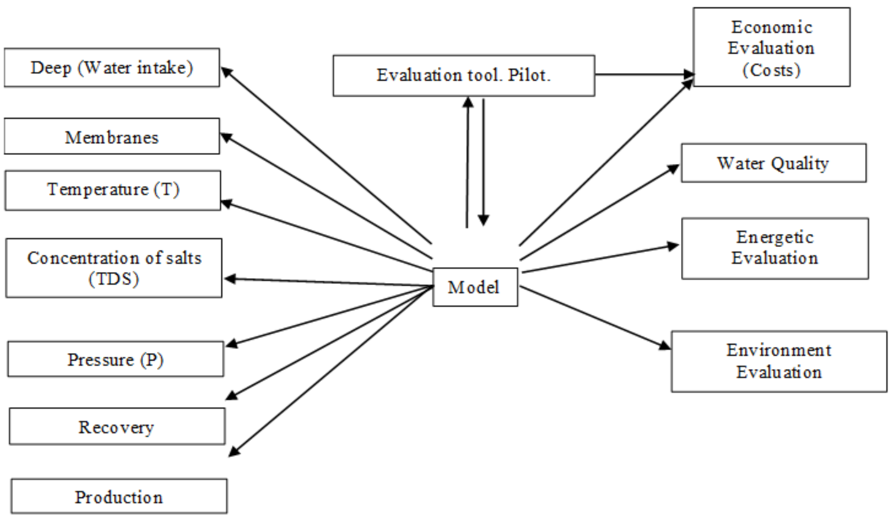

Figure 1. Block diagram of the integral model.

Toray DS2 (Toray Industries, Tokyo, Japan) is used as software for RO design and methodology following the Equation (1), to run hypothetical projections under different scenarios. A calculator tool is used to get all the parameters of the desalination RO design.

The following parameters in the software are introduced: intake, type of membranes, feed temperature, feed concentration of salts, recovery, and production; also obtained is the feed pressure of the reverse osmosis system, the permeate quality and an energetic evaluation (power and energy consumption), which it is used to calculate the carbon footprint and ecological footprint.

2.1. Permeate Quality–Cost Ratio

As indicated in the introduction, we are working with high-reject boron reverse osmosis membranes that usually operate at high pressures, which means a higher energy consumption of the system, and therefore an increase in the economic cost. These parameters are directly proportional and appear in Figure 1 due to their importance [16–18].

Therefore, the cost and energy required in the process are a function of the quality of water required and the type of membrane used.

The 62% of the economic cost per m^3 of water produced in a seawater desalination plant comes from the energy consumption of the pumps (high pressure pump and booster pump). On the other hand, membrane replacement is around the 4% of the operating cost of a seawater desalination plant. Other authors considered even higher values of the energy consumption in the pumps, so these values, following the local OEMs sources, have been considered as conservative values. Due to this it is justified the membranes replacement to improve the energy recovery in the RO desalination plants [21–24].

For example, the high-pressure pump may be at about 2.64 kWh/m^3 and the booster pump at 0.11 kWh/m^3 [3–5,9].

If we consider a price of 0.16 €/kWh the consumption will be 0.16 €/m^3 for the high-pressure pump and 0.01 €/kWh for the booster pump, in total 0.17 kWh/m^3 of produced water.

The choice of the right diaphragm can optimize the energy consumption of the pumps, especially the high pressure one, which represents 94% of it. A state-of-the-art high-flow, low-pressure membrane can reduce this consumption by up to 20%, which represents a significant economic, energy and environmental saving.

In this sense, there is an opportunity cost between choosing the option of making the partial replacements considered in the operation cost and commented on in the previous section or not carrying them out.

This mathematically represents the expression of the following equation in an approximate way:

$$h_{b(\text{year } 1\text{–}5)} = (1.2 \cdot t_m + 0.6) + h_{b(\text{year } 0)} \tag{1}$$

In the same way, the real power of the pump is calculated by dividing the theoretical power by its efficiency and the energy in kWh working 24 h a day [10–13].

$$P_{realb} = P_b \;/\; \eta \tag{2}$$

$$P_b = \rho\, g\, Q\, h_b \tag{3}$$

where

- t_m is the age of the membrane
- P_{realb} is the real power of the pump
- P_b is the theoretical power of the pump (in Watts; 1 Hp = 745.7 W)
- ρ is the density of the fluid (1000 kg/m^3 in the case of water)
- g is the acceleration of gravity (generally adopted: 9.81 m/s^2)
- η is the performance of the pump
- Q is the flow rate (m^3/s)
- h_b is the pump head (m)

In any case, it is necessary to comply with the quality of water required for its use as drinking water, so it is possible to optimize our energy consumption with state-of-the-art membranes but only if the water quality requirements are met, as indicated before specifically for the boron allowed in the permeate, which according to Real Decreto 140/2003 must be less than 1 ppm while the World Health Organization (WHO) allows 2.4 ppm maximum. In addition, when the temperature of the feed water rises, energy consumption and working pressure fall, but salt rejection worsens, so we must consider the different scenarios for meeting permeated water requirements.

For this reason, before making a considerable investment in membranes, it is proposed to carry out small-scale pilots of a membrane or a membrane tube, in the working conditions of each plant, to ensure the proper functioning of the same and success when it is to be carried out at an industrial level in the installation, in order to evaluate economic and energetic conditions. Therefore, the decision to change the membranes is a very important factor in the life of the installation and many variables must be taken into account, such as working pressure, water quality at the entrance, and exit of the reverse osmosis system, conversion, temperature, etc.

In this way, by introducing membranes with low energy consumption and greater permeability, more water is produced at lower working pressure, which results in lower energy consumption (kWh) per cubic meter of water produced, and therefore improves the economic supply of the water produced.

Similarly, the increase in water temperature, especially in winter, with deeper water intakes, as occurs in the plants that will be studied in the following sections, also has an impact on lower energy consumption to maintain the same production or an increase in it if we maintain the pressure of supply to the membranes constantly.

The depth of the seawater intake also represents a parameter or variable for the energy and economic evaluation of the system, since the deeper the intake, the more stable the temperature range of the supply water [14,15]. This means that the temperature of the intake does not rise so much in summer and low energy consumption membranes can be introduced, complying with the water quality required in the permeate, which previously, at higher temperatures, we only achieved with high rejection membranes and greater energy consumption.

2.2. Energy Consumption

With regard to energy consumption in kWh/m^3 of water produced, the following formula is arrived at based on the different energy recovery systems available in seawater desalination plants, the power being [36,37].

2.61 kWh/m^3 if there are isobaric chambers (ERI, DWEER, etc.)
3.04 kWh/m^3 if a pelton turbine or similar is available
3.50 kWh/m^3 with francis or other turbine type systems

The introduction of latest generation membranes, which at low energy consumption and high salt rejection, manages to improve the environmental conditions of the process, and therefore a reduction in its footprint. In addition, the high salt rejection means an improvement in the quality of the product water at the usual working pressures. In this sense, Royal Decree Law 140/2003 of the 7th of February, 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 the rejection of boron, which is achieved by working with high rejection membranes, normally at higher pressure. With the introduction of latest generation membranes with low energy consumption and high salt rejection, we can produce water with less than 1 ppm of boron in more efficient and sustainable conditions than with standard membranes.

Total energy consumed depends on the renewable and non-renewable energy from the electrical system and the local renewable energy produced by themselves. Due to this, the equation which representatives it is the following:

$E_{Tc} = E_{Rn} + E_{NRn} + E_{LR}$ being
E_{Tc}: Total energy consumed of the system
E_{Rn}: Renewable energy from the net
E_{NRn}: Non-renewable energy from the net
E_{LR}: Local renewable energy

Depending on the local renewable energy, the carbon and ecological footprint will vary. They will decrease as much as local renewable energy is produced. As you can see in item 3.5 the energy from the electric system could be non-renewable energy (diesel, gas turbine, vapor turbine, and combined cycle) but also renewable mainly from Eolic and photovoltaic energies.

2.3. CO_2 Emission Factor (Mix Factor)

In this sense, following the specific environmental impact indicator model [16] and the formula used by Red Eléctrica Española for emissions and CO_2 emission factor in non-renewable generation in the electricity system for 2020.

$$FM = FM_{md} + FM_{tg} + FM_{tv} + FM_{cc} \tag{4}$$

where we can define according to the Ministry of Ecological Transition:

FM: Emission Factor of the Electric Mix (tCO_2/kWh)
FM_{md}: Motor Diesel Factor Mix (tCO_2/kWh)
FM_{tg}: Gas Turbine Factor Mix (tCO_2/kWh)

FM_{tv}: Vapor Turbine Factor Mix (tCO_2/kWh)
FM_{cc}: Combined Cicle Factor Mix (tCO_2/kWh)
RE: Energy efficiency (kWh/m^3)
HC_{MIX}: Carbon Footprint of the energetic Mix (tCO_2)
E^1t_{MIX}: Actual Energy of the energetic Mix technologies (kWh)
E^2t_{MIX}: Future Energy of the energetic Mix technologies (kWh)
E_i: Energy of each technology (kWh)
P_t: Percentage of use of each technology in the energetic Mix

FM is calculated for each technology and island with the total consume of energy per island, associated to the carbon footprint and the percentage of one technology in the energetic mix, including renewable and non-renewable energies. In consequence, the FM of a determinate technology "i" per island is the following:

$$FM_i = P_{ti} \ / \ 100 \cdot HC_i \ / \ E_i \quad (5)$$

In this way, it is calculated the carbon footprint of the current and future energy mix, considering the sum of the energies of each technology and its emissions mix factor.

$$HC_{MIX} = \Sigma \, E_i \, FM_i \quad (6)$$

The current energy and future energy of the technologies of the energy mix are the following:

$$E^1t_{MIX} = \Sigma \, E_i \text{ in the initial moment} \quad (7)$$

$$E^2t_{MIX} = \Sigma \, E_i \text{ in the final moment} \quad (8)$$

To reduce the carbon footprint of the current energy mix, we introduce renewable energies as much as possible and, failing that, maintain the higher performance conventional technologies such as the diesel engine, combined cycles, or the steam turbine, since these consume less fuel to produce the same energy as other conventional technologies, or improve the efficiency of the electricity grid.

Taking into account the previous formulation that calculates the carbon footprint of the energy mix factor, to reduce it by a certain percentage with an equivalent contribution of renewable energy as its emissions mix factor is negligible compared to conventional technologies and tends to zero. Therefore, whenever possible we try to introduce a higher percentage of renewable energies in the energy mix to reduce emissions and carbon footprint. It is even possible to introduce these renewable energies in the membrane pilots we discuss below to improve our overall energy efficiency performance of seawater desalination plants. In the future, it is predicted that the lower our emissions, and therefore our carbon footprint, the lower the cost per cubic meter of water produced will be, since taxes can be levied for pollution that is avoided by working in this way [20].

2.4. Ecological Footprint

Similarly, to calculate the ecological footprint we use the following methodology [20]. It is thus determined that an equivalent hectare of planet Earth 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 forests, agricultural crops, meadows, pastures, oceans, seas, deserts, and others. Therefore, the following formula is obtained:

$$HE = HC_a \ / \ 2 = HC_d \times 365 \text{ days} \ / \ 2 = IA \text{ m}^3/\text{days} \times 365 \text{ days} \ / \ 2 \quad (9)$$

where

I_2A: Enviroment impact (tCO_2/m^3)
HC_a: Carbon footprint (tCO_2/year)
HC_d: Carbon footprint (tCO_2/day)

HE: Ecological footprint (ha/year)

We know that the dispersion of CO_2, a gas defined within the typology of greenhouse gases, is heterogeneous and global, although the sources of production are more intense in a large part of the land areas colonized by human population centers.

A new concept arises in reference to the absorption of CO_2 and it is what is called the useful surface of the planet, which is formed by forests, agricultural crops, livestock, surface waters, and marine and coastal vegetation (therefore excluding deep waters, deserts, and other types of surface not catalogued), which are those that we consider contribute mainly to the absorption of carbon.

If we estimate the world population at 7.2 billion people and taking into account that the useful surface is about 12,190.14 million hectares, assuming that there is currently an acceptable population situation for the planet, by distributing the population evenly over the land we would obtain the available land for each individual, which is 1.69 ha/person/year.

2.5. Analysis per Specific Number of Inhabitants

Similarly, it can be studied whether concentrated production in a public plant is more efficient than distributed production in small, localized plants at the site of demand. In this way, with distributed production the introduction of on-site renewable energies, both wind and solar, is more flexible and we avoid the problem of transporting electrical energy and even water. This reduces costs, CO_2 emissions and the ecological footprint, which can also be studied according to the specific number of inhabitants N_e, being:

$$N_e = N_{hab} \ / \ km^2 \tag{10}$$

$$N_i < N_{hab} \ / \ km^2 < N_s \tag{11}$$

N_e: Specific number of inhabitants
N_{hab}: Number of inhabitants
N_i: Lower than average number of inhabitants
N_s: Number of inhabitants above averagee

3. Results and Discussion

In line with the above, regarding the general analysis of energy consumption by elements in the plants, if this replacement of membranes is not carried out, our consumption will increase progressively as can be seen in the Table 1 made using the calculations and design specifications of the Toray membrane manufacturer's reverse osmosis systems. The TM820K-440 high rejection seawater membrane, from the same supplier, has been used for these calculations. It is estimated an average operating flow of 16 lmh, a beach well intake or a pre-treatment with ultrafiltration membranes, an average temperature of 22 °C usual in the Canary Islands, a current recovery of 45% and a feed salinity of 39 g/L, also normal in the area. Considering these parameters, a typical production of a seawater plant of 100,000 m^3/d, divided in 10 trains of 10,000 m^3/d. In Table 1 (10%R) means a RO membranes replacement of a 10% of the total number of elements in the sea water plant per year, (15%R) is a 15% replacement per year and (20%R) is a 20% replacement per year. The best time to replace the membranes is before the high season which is in Canary Islands after summer, when the demand of water and the cost of the energy increase. It is recommended to replace at least one element per vessel per year. The lead element usually is more damaged than the others due to the fouling, so it is replaced for a new one to be located at the end of the pressure vessel (brine side). All the other elements go back to the front, i.e., the second membrane is going to be the first, the third the second, etc. As it is explained above, and using the reverse osmosis membrane software, it is obtaining the following common results in Table 1.

Table 1. Pressure, Power, and Energy consumption at 22 °C.

Year	Pressure (bar)	Power (kW)	Energy (kWh/m^3)
0	66.79	22,074	5.298
1	68.39	22,602	5.425
2	69.82	23,075	5.538
3	71.07	23,488	5.637
4	72.24	23,877	5.731
5	73.38	24,254	5.821
5(10%R)	71.66	23,685	5.684
5(15%R)	70.77	23,389	5.613
5(20%R)	69.82	23,075	5.538

It shows that the pressure difference grows more in the first years and feed pressure is increasing with the age of the elements. Consequently, it is obtained, Figure S1 in Supplementary Materials, how the pressure varies over five years without replacing the membranes, where the power consumed by the high-pressure pump increases proportionally. It also shows the energy needed to work 24 h a day and the daily economic cost if we do not replace the membranes. Moreover, it is shown in Table 2 the power and energy consumption per day in all the scenarios increasing them with the age of the membranes.

Table 2. Pressure, Power and Energy consumption at 17 °C.

Year	Pressure (bar)	Power (kW)	Energy (kWh/m^3)
0	71.11	23,511	5.643
1	72.77	24,061	5.775
2	74.56	24,651	5.916
3	76.13	25,171	6.041
4	77.62	25,663	6.159
5	79.06	26,140	6.274
5(10%R)	76.88	25,420	6.101
5(15%R)	75.75	25,045	6.011
5(20%R)	74.56	24,651	5.916

By varying the temperature of the feed water to a minimum of 17 °C and a maximum of 27 °C, the following result Tables 2 and 3 are obtained.

Table 3. Pressure, Power, and Energy consumption at 27 °C.

Year	Pressure (bar)	Power (kW)	Energy (kWh/m^3)
0	63.70	21,050	5.052
1	65.26	21,568	5.176
2	66.44	21,955	5.269
3	67.44	22,288	5.349
4	68.38	22,598	5.424
5	69.29	22,898	5.496
5(10%R)	67.92	22,445	5.387
5(15%R)	67.20	22,208	5.330
5(20%R)	66.44	21,955	5.269

It can be seen from Table 2 that as the temperature decreases, the working pressure increases, and this leads to greater energy consumption. However, the opposite occurs when the temperature rises, since as shown in Table 3 the pressure drops, and energy consumption is considerably reduced.

The element TM820K-440 has been selected due to it has the highest boron rejection to be sure to get potable water and boron less than 1 ppm in all the cases. However, for irrigation of bananas and tomatoes is not mandatory to have the boron issue lower than

1 ppm, so we can use a low energy consumption element like the TM820V-440. Therefore, you can find the following Tables 4–6 with all the data regarding this scenario at 22 °C, 17 °C, and 27 °C for the same permeate flow, recovery, and feed salinity.

Table 4. Pressure, Power, and Energy consumption at 22 °C.

Year	Pressure (bar)	Power (kW)	Energy (kWh/m^3)
0	57.90	19,135	4.592
1	58.12	19,211	4.611
2	58.51	19,338	4.641
3	58.84	19,448	4.668
4	59.16	19,553	4.693
5	59.48	19,658	4.718
5(10%R)	59.01	19,502	4.681
5(15%R)	58.76	19,422	4.661
5(20%R)	58.51	19,338	4.641

Table 5. Pressure, Power, and Energy consumption at 17 °C.

Year	Pressure (bar)	Power (kW)	Energy (kWh/m^3)
0	60.24	19,916	4.780
1	60.55	20,021	4.805
2	61.08	20,194	4.847
3	61.52	20,341	4.882
4	61.93	20,474	4.914
5	62.31	20,600	4.944
5(10%R)	61.73	20,410	4.898
5(15%R)	61.42	20,307	4.874
5(20%R)	61.08	20,194	4.847

Table 6. Pressure, Power, and Energy consumption at 27 °C.

Year	Pressure (bar)	Power (kW)	Energy (kWh/m^3)
0	56.47	18,661	4.479
1	56.79	18,766	4.504
2	57.15	18,886	4.533
3	57.45	18,986	4.557
4	57.73	19078	4.579
5	57.99	19,163	4.599
5(10%R)	57.60	19,034	4.568
5(15%R)	57.38	18,963	4.551
5(20%R)	57.15	18,886	4.533

Moreover, the calculations are also made including an energy recovery system (ERI) to reduce even more the energy consumption in all the cases before and with both elements. You can find them in the following Tables 7–12. Firstly, with the high rejection elements TM820K-440.

Table 7. Pressure, Power, and Energy consumption at 22 °C.

Year	Pressure (bar)	Power (kW)	ERI Power (kW)	Booster (kW)	Energy (kWh/m^3)
0	68.26	10,796	9402	514	2.591
1	70.05	11,067	9658	516	2.656
2	71.55	11,295	9872	518	2.711
3	72.85	11,492	10,058	519	2.758
4	74.07	11,677	10,233	520	2.803
5	75.27	11,859	10,405	521	2.846
5(10%R)	73.46	11,586	10,147	520	2.781
5(15%R)	72.53	11,444	10,014	519	2.747
5(20%R)	71.55	11,295	9872	518	2.711

ERI: Energy Recovery Inc.

Table 8. Pressure, Power, and Energy consumption at 17 °C.

Year	Pressure (bar)	Power (kW)	ERI Power (kW)	Booster (kW)	Energy (kWh/m^3)
0	72.67	11,494	10,017	543	2.759
1	74.55	11,779	10,286	545	2.827
2	76.43	12,064	10,555	547	2.895
3	78.06	12,311	10,789	548	2.955
4	79.59	12,542	11,008	549	3.010
5	81.07	12,766	11,219	551	3.064
5(10%R)	78.83	12,428	10,899	549	2.983
5(15%R)	77.67	12,251	10,732	548	2.940
5(20%R)	76.43	12,064	10,555	547	2.895

Table 9. Pressure, Power, and Energy consumption at 27 °C.

Year	Pressure (bar)	Power (kW)	ERI Power (kW)	Booster (kW)	Energy (kWh/m^3)
0	65.11	10,296	8968	489	2.471
1	66.83	10,557	9214	492	2.534
2	68.06	10,744	9390	493	2.579
3	69.11	10,903	9540	494	2.617
4	70.09	11,052	9680	495	2.652
5	71.03	11,195	9815	496	2.687
5(10%R)	69.61	10,979	9611	495	2.635
5(15%R)	68.86	10,865	9504	494	2.608
5(20%R)	68.06	10,744	9390	493	2.579

Table 10. Pressure, Power, and Energy consumption at 22 °C.

Year	Pressure (bar)	Power (kW)	ERI Power (kW)	Booster (kW)	Energy (kWh/m^3)
0	59.06	9398	8087	502	2.256
1	59.31	9438	8124	503	2.265
2	59.77	9507	8188	504	2.282
3	60.17	9568	8245	505	2.296
4	60.53	9624	8297	506	2.310
5	60.88	9678	8347	506	2.323
5(10%R)	60.35	9597	8271	505	2.303
5(15%R)	60.07	9553	8231	505	2.293
5(20%R)	59.77	9507	8188	504	2.282

Table 11. Pressure, Power, and Energy consumption at 17 °C.

Year	Pressure (bar)	Power (kW)	ERI Power (kW)	Booster (kW)	Energy (kWh/m^3)
0	61.41	9784	8406	530	2.348
1	61.73	9833	8452	531	2.360
2	62.26	9914	8527	532	2.379
3	62.71	9982	8591	532	2.396
4	63.12	10,044	8649	533	2.411
5	63.50	10,102	8704	534	2.425
5(10%R)	62.92	10,014	8621	533	2.403
5(15%R)	62.60	9966	8576	532	2.392
5(20%R)	62.26	9914	8527	532	2.379

Table 12. Pressure, Power, and Energy consumption at 27 °C.

Year	Pressure (bar)	Power (kW)	ERI Power (kW)	Booster (kW)	Energy (kWh/m^3)
0	57.69	9168	7909	479	2.200
1	58.07	9226	7962	480	2.214
2	58.45	9285	8017	481	2.229
3	58.77	9334	8062	482	2.240
4	59.06	9379	8103	483	2.251
5	59.34	9420	8142	484	2.261
5(10%R)	58.92	9357	8083	483	2.246
5(15%R)	58.70	9323	8051	482	2.238
5(20%R)	58.45	9285	8017	481	2.229

Secondly, with the low energy consumption elements TM820V-440.

Therefore, it is shown in Table 5 at lowest temperature (17 °C) and five years operation the highest energy consumption 6.274 kWh/d with the high rejection element (TM820K-440); and in Table 12 at highest temperature (27 °C) and start up the lowest energy consumption 2.200 kWh/d with the low energy consumption element (TM820V-440).

In this sense, several energy-efficient solutions are proposed depending on the characteristics of the seawater desalination plants where they are to be installed. For example, a classification can be made with the most appropriate solution for the introduction of renewable energies, depending on whether there is considerable wind in the area, sufficient solar radiation, space to place the solar panels or wind turbines, etc., as shown in Table 13. With the introduction of photovoltaics, up to 30% of the energy required by the plant can normally be obtained, and the remaining 70% is supplied through wind energy when it is possible.

Table 13. Production of the existing seawater desalination plants in the Canary Islands, useful area, production per area, and number of habitants per area (2013).

N_{hab}	Island	Production (m^3/d)	Surface (km^2)	P/S (m^3/d/km^2)	Ne (hab/km^2)
10,968	El Hierro	5450	268.71	20.28	41
82,671	La Palma	-	708.32	-	117
21,503	La Gomera	2000	369.76	5.41	58
917,841	Tenerife	106,034	2034.38	52.12	451
851,231	Gran Canaria	220,870	1560.10	141.57	546
116,886	Fuerteventura	90,755	1659.00	54.71	71
152,289	Lanzarote	87,480	845.94	103.41	180

N_e: Specific number of habitants per km^2.

The number of inhabitants supplied with drinking water by each plant can be calculated as a specific number of inhabitants divided by the surface area, as explained above through Equation (11).

This calculation by island, is made in Table 13. The highest population density is found on the island of Gran Canaria, followed closely by Tenerife, which is far removed from the rest of the islands. In the same way it is compared the production of permeated water by surface of each island (P/S) with the specific number of inhabitants, where all the islands of the eastern province have greater values headed by Gran Canaria.

Recalling the previous absorption data of one equivalent hectare (2 tCO_2/ha/year) and crossing these last two values, the admissible CO_2 emissions per inhabitant/year can be calculated at 3.38 tCO_2/person/year. The values are shown in the following Table 14.

Table 14. Useful area, sustainable ecological footprint, and sustainable CO_2 emissions. (Llinares, 2005; Gobierno de Canarias, 2017).

Category Surface	ABS. Average (tCO_2/ha/Year)	Surface (Millions ha)	Ecological Footprint (ha/hab/Year)	Sustainable Emission CO_2 (tCO_2/hab/Year)
Forests	1.46	3858.10	0.54	0.79
Crops	0.31	1958.32	0.27	0.09
Meadows and Pastures	0.16	3363.72	0.47	0.08
Marine Vegetation	0.02	90.00	0.01	0.00
Surface Water	0.56	2920.00	0.41	0.23
Useful Area	2.50	12,190.14	1.69	3.39
Land Area	1.93	14,997.2		
Planet Surface	2.00	51,007.20		

ABS: sustainable CO_2 emissions per surface and year.

Table S1 of Supplementary Materials shows the existing seawater desalination plants in the Canary Islands, according to the calculations explained before, where the different energy consumption of each one of them can be appreciated, starting almost all of them with a very similar salinity of supply, so that they are susceptible to improvement by applying the same studies carried out in Alicante or Carboneras, being able to reduce these current energy consumptions by around 3.50 kWh/m^3 up to values of 2.61 kWh/m^3 if we combine these studied energy improvements by introducing energy recovery systems for the brine of these installations.

In this sense, it can be confirmed that for an annual production of desalinated water in the Canary Islands of approximately 660,000 m^3/day and considering an average energy consumption of 3.04 kWh/m^3, introducing equipment to recover energy from brine, we have a carbon footprint of 1203.84 tCO_2/day, which means that there are 439,402 tCO_2 per year, as commented on in Section 3. On the other hand, following this same criterion and using a global coefficient of the ecological footprint to calculate it [17–20], a value of 219,701 ha/year of surface area is obtained to compensate for the ecological footprint that we have due to the production of desalinated water in the Canary Islands, the surface area of the Canary Islands being 749,300 ha. This ecological footprint per person, as explained in Section 3 and taking into account that the Canary Islands have a population h_{RE} of 2,207,225 habitants, supposes a value of 0.1 ha/person/year and the emissions per inhabitant and year are 0.2 tCO_2/person/year as opposed to 3.38 tCO_2/person/year at the world level, being

h_{RE} = number of habitants or persons in the region
h_{PR} = number of habitants or persons in the province
h_{MU} = number of habitants or persons in the municipality
h_{PA} = number of habitants or persons in the country

In this way, taking into account the annual consumption in 2019 of 8,878,271 MWh in non-renewable generation of the current energy mix (diesel, gas, steam and combined cycle) of the Canarian electricity system, since in renewable generation no emissions are produced and according to the technologies that met the demand, an average value of 0.6 tCO_2/MWh is obtained. Therefore, from the total installed above, it is estimated that 5,326,963 tCO_2/year can be emitted, which represents 2.4 tCO_2/person/year. This last value exceeds 12 times the admissible admissions per inhabitant in the Canary Islands, only taking into account the seawater desalination sector.

Taking into account the model of specific environmental impact indicators [18–20] presented before, we can get the carbon footprint according to the technological structure of the generation park that uses oil products in the Canary Islands in Table S2. Similarly, we can calculate the CO_2 footprint per MWh considering the thermal consumption by technology and island in the Table S3.

To calculate the ecological footprint, it is used the following methodology [18–20] that is expressed in Table 14 and Table S2. Summarizing in Gran Canaria, the 8.1% of the energy to produce 1 m^3 of potable water comes from renewable energy and it does not produce any CO_2 emissions. In Tenerife it is a 7.7%, in Lanzarote 4.6%, in Fuerteventura a 5%, in La Palma a 10%, in La Gomera a 0.7%, and in El Hierro a 45.4%. In total in Canaries, the renewable energy is a 7.56% of the total energy consume [20].

Moreover, in Gran Canaria Island the 45.1% of the non-renewable energies comes from the technology of vapor turbine, the 45.2% from combined cycle, the 7.8% from diesel motor and the other 1.8% from gas turbine. Applying Equation (4), this 45.1% of the non-renewable energies from the vapor turbine times 91.9%, which is the percentage of non-renewable energies of the total, means that the 41.5% of the total energy consumed comes from the vapor turbine in this island. Considering the carbon footprint of each technology per island in Table S2 and Table S3 Considering the carbon footprint of each technology per island in and the total consume of this one [18–20], you can find below Table 15 with the factor mix per technology and island.

Table 15. Factor Mix according to the technological structure of the generation park that uses oil products in the Canary Islands and broken down by islands. Year 2017.

Technology	Gran Canaria	Tenerife	Lanzarote	Fuerteventura	La Palma	La Gomera	El Hierro	Canary Islands
Vapor Turbine	0.374	0.337	-	-	-	-	-	0.278
Gas Turbine	0.019	0.042	0.017	0.163	0.003	-	-	0.038
Diesel Motor	0.047	0.053	0.610	0.525	0.585	0.647	0.356	0.165
Combined Cycle	0.249	0.257	-	-	-	-	-	0.197
Total	0.688	0.689	0.627	0.688	0.588	0.647	0.356	0.678

In this way, it is calculated the carbon footprint and ecological footprint for the lowest energy consumption case (Table 16) and highest energy consumption (Table 17). You can find it below.

Table 16. Carbon Footprint (CF) and Ecological Footprint (EF) for lowest energy consumption case in the Canary Islands. Year 2017.

Technology	Gran Canaria	Tenerife	Lanzarote	Fuerteventura	La Palma	La Gomera	El Hierro	Canary Islands
CF 5 years 0%R	1.5558	1.5569	1.4170	1.5551	1.3288	1.4620	0.8051	1.5321
CF 5 years 10%R	1.5455	1.5466	1.4076	1.5448	1.3200	1.4523	0.7998	1.5219
CF 5 years 15%R	1.5400	1.5411	1.4026	1.5393	1.3153	1.4471	0.7970	1.5165
CF 5 years 20%R	1.5338	1.5349	1.3969	1.5331	1.3100	1.4413	0.7937	1.5104
EF 5 years 15%R	7.6234	7.6289	6.9431	7.6201	6.5111	7.1636	3.9452	7.5071
EF 5 years 15%R	7.5728	7.5783	6.8971	7.5695	6.4679	7.1161	3.9190	7.4573
EF 5 years 20%R	7.5458	7.5513	6.8725	7.5426	6.4448	7.0907	3.9051	7.4307
EF 5 years 20%R	7.5155	7.5210	6.8449	7.5122	6.4189	7.0622	3.8894	7.4008

Table 17. Carbon Footprint (CF) and Ecological Footprint (EF) for highest energy consumption case in the Canary Islands. Year 2017.

Technology	Gran Canaria	Tenerife	Lanzarote	Fuerteventura	La Palma	La Gomera	El Hierro	Canary Islands
CF 5 years 0%R	4.3171	4.3203	3.9319	4.3153	3.6872	4.0568	2.2342	4.2513
CF 5 years 10%R	4.1981	4.2011	3.8235	4.1963	3.5856	3.9449	2.1726	4.1340
CF 5 years 15%R	4.1362	4.1392	3.7671	4.1344	3.5327	3.8867	2.1405	4.0731
CF 5 years 20%R	4.0708	4.0738	3.7076	4.0690	3.4768	3.8253	2.1067	4.0087
EF 5 years 15%R	21.1540	21.1694	19.2664	21.1448	18.0674	19.8782	10.9474	20.8312
EF 5 years 15%R	20.5707	20.5856	18.7351	20.5617	17.5692	19.3300	10.6456	20.2568
EF 5 years 20%R	20.2672	20.2820	18.4588	20.2584	17.3101	19.0449	10.4885	19.9580
EF 5 years 20%R	19.9469	19.9614	18.1670	19.9382	17.0365	18.7439	10.3228	19.6425

Regarding the data base of sea water reverse osmosis (SWRO) Plants in Canary Islands in Table S4 and Figure 2, it is calculated the following Table 18 including the energy consumed (kWh) per cubic meter produced in each island, the carbon footprint, ecological footprint, and also a carbon factor per island and cubic meter produced.

Table 18. Energy consumed, carbon footprint, ecological footprint, and carbon factor per island and cubic meter produced in Canaries. Year 2013.

	Gran Canaria	Tenerife	Lanzarote	Fuerteventura	La Gomera	El Hierro
Energy Consumption kWh/d	724,910.80	241,038.60	282,486.42	306,377.10	6080.00	16,798.00
kWh/m^3	3.28	2.27	3.23	3.38	3.04	3.08
Carbon Footprint (tons/day)	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/day)	244.41	81.33	86.75	103.26	1.93	2.93

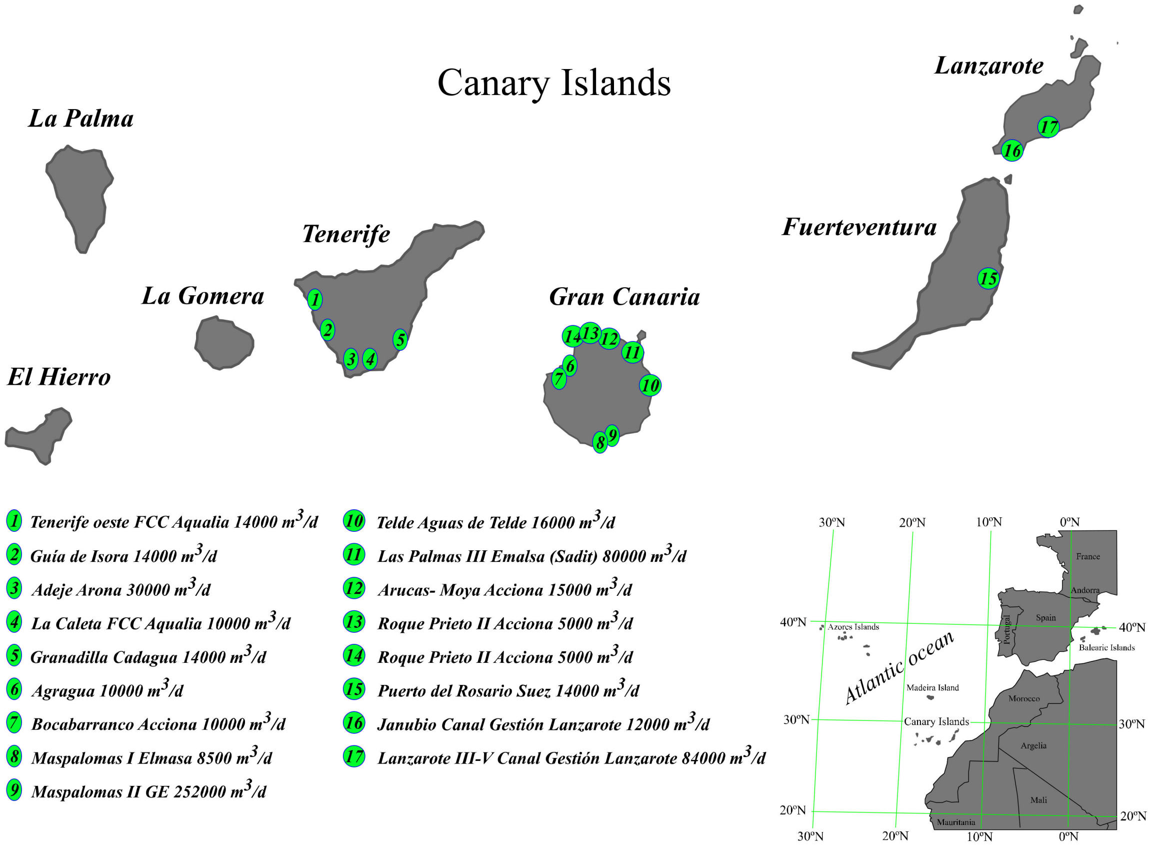

Figure 2. Most significant seawater desalination plants (2019).

In addition, the percentages of water consumed in the different sectors and for all the islands can be added, as shown in Table S5. They can also be compared with the number of tourists and residents on each island per year. This information is shown in Table 19.

Table 19. Population by island divided into tourists and residents per year [20].

Islas	Lanzarote	Fuerteventura	Gran Canaria	Tenerife	La Gomera	El Hierro	La Palma
Tourists	2,929,000	2,219,000	4,478,000	5,928,000	700,000	23,000	294,000
Residents	144,140	112,299	855,496	908,644	21,398	10,770	82,956
Medium Stay (Day)	8.79	9.49	10.02	9.56	11	4.6	10.87

To further emphasize this idea, if we consider what is the average water expenditure per person per day (INE, 2014) in the Canary Islands, which is 143 per liter per day, and tourists, which is between 300 and 400 L, we consider that the figure of 350 L can fit well into the average. This consume includes any act that involves the demand of water, either for personal consumption, or in any washing work or scrubbing.

Following this approach, the number of liters spent by the people of each island, multiplying the number of inhabitants of each island by 365 (days of the year) and the average amount of water spent per day. In the case of tourists it will be similar, by substituting the data of residents by tourists and that of 365 days by the average number of days spent on each island.

Therefore, water consumption among tourists and residents of the Canary Islands is studied, as shown in Table 20, highlighting the higher water consumption in the capital islands due to the latter compared to the former.

Table 20. Water consumption, Carbon, and Ecological Footprints by islands for tourists and Canary residents in one year (m^3) [20].

	Lanzarote	Fuerteventura	Gran Canaria	Tenerife	La Gomera	El Hierro
Tourists (m^3)	9011	7370	15,704	19,835	2695	37
Residents (m^3)	7516	5845	44,626	47,445	1096	521
Tourists Carbon Footprint	18.24	17.11	35.46	31.05	5.30	0.04
Residents Carbon Footprint	15.21	13.57	100.78	74.27	2.15	0.57
Tourists Ecological Footprint	8.94	8.39	17.38	15.22	2.60	0.02
Residents Ecological Footprint	7.46	6.65	49.40	36.41	1.06	0.28
Carbon Footprint per Tourist (kg CO_2)	0.0062	0.0077	0.0079	0.0052	0.0076	0.0018
Carbon Footprint per Resident (kg CO_2)	0.1055	0.1209	0.1178	0.0817	0.1007	0.0531
Ecological Footprint per Tourist (m^2)	0.0305	0.0378	0.0388	0.0257	0.0371	0.0087
Ecological Footprint per Resident (m^2)	0.5173	0.5925	0.5775	0.4007	0.4935	0.2603

Two different results can be seen for the Canary Islands: the eastern and western zone (except for La Gomera). In the west you can see a situation that should be normal and logical, as it is the fact that people who live in the territory use more water than tourists for the mere fact that the former live there 365 days of the year; on the contrary, the vast majority of tourists do not exceed one month, and half of them do not even stay 10 days on average.

In the east (Fuerteventura and Lanzarote) has the preponderance of the tourism industry as opposed to other areas, which, in the case of these islands, has changed a lot the landscape with the appearance of golf courses and urbanizations, where it would be impossible with the water naturally present in this environment. The other case is that of La Gomera, which is mainly because the island is quite sparsely populated, and yet it does receive quite a few tourists.

4. Conclusions

The cost and energy required in the 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 adequate membrane in the plant with low energy consumption and the replacement rate.

The amount of the membranes in a seawater desalination plant represents approximately a 13% of the total investment in the facility's equipment. Furthermore, membrane replacement is around the 4% of the operating cost of a seawater desalination plant and the energy consumption of the pumps is around 62%, which is the reference data considered in Canary Islands by the RO desalination plants constructors (OEMs) to compare with the cost of the membranes. Other authors considered even higher values of the energy consumption in the pumps, so these values, following the local OEMs sources, have been considered as conservative values. Due to this it is justified the membranes replacement to improve the energy recovery in the RO desalination plants. Due to these issues, the cost of membranes replacement is very low comparing with the energy costs we can save. Moreover, it is around a 20% of the energy consumption.

Energy consumption decreases when the feed temperature increases and when the feed salinity decreases too. Whenever possible it is interesting to introduce a higher percentage of renewable energies into the energy mix to reduce emissions and carbon footprint. With the introduction of photovoltaics, normally up to 30% of the energy needed by the plant can be obtained, and the remaining 70% is supplied by wind power when possible.

Canary Islands desalination carbon footprint is around 1203.84 tCO_2/day, and the annual total is 439,402 tCO_2. Therefore, the ecological footprint due to this is 219,701 ha/year. It means 0.1 ha/person/year and the emissions per habitant and year are 0.2 tCO_2/person/year, compared to 3.38 tCO_2/person/year at the world level.

Supplementary Materials: The following are available online at https://www.mdpi.com/2073-4441/13/3/293/s1. Table S1: Existing seawater desalination plants in the Canary Islands. consumption and solution of renewable energies. (Source FCCA 2013. REE 2020 and own elaboration); Table S2: Carbon footprint according to the technological structure of the generation park that uses oil products in the Canary Islands and broken down by islands.; Table S3: CO2 footprint of each non-renewable technology per MWh in the Canary Islands (tCO2/MWh); Table S4: Existing seawater desalination plants in the Canary Islands. (Source FCCA 2013 and REE 2020); Table S5. Percentages of water consumption by islands and sectors (%); Figure S1. Pressure, Power, Energy and Cost vs. Time (years).

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