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Mitigation of climate change through the analysis and reduction of greenhouse gases in desalination plants

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ABSTRACT

Within the lines of work currently being proposed concerning the water-energy nexus, this work focuses on energy consumption in the desalination process and the consequent emission of greenhouse gases (GHGs). To demonstrate this crucial problem, a life cycle assessment was developed and applied to a real plant located in the Canary Islands, Spain. In the analysis, the environmental consequences of each phase of the process were quantified. Prior to this, a review of the different calculation tools was undertaken with the intention of selecting the one that best matches the plant in order to obtain the most reliable results possible. The plant was selected for analysis on the basis of its size, with an average supply capacity in the island territory, as well as the availability of renewable energy resources. Calculation of the GHG emissions generated by the plant's energy consumption confirmed its contribution to climate change. To mitigate this contribution, a methodology is developed to determine the feasibility of renewable energy synergies to obtain a clean energy mix. This methodology, applicable to any reverse osmosis desalination system, was applied to the plant under study, with a resulting proposal for a sustainable energy system that avoids the emission of 21,781 tons of GHGs. By extending the application of the proposed methodology to other reverse osmosis desalination plants on the island, a considerable reduction in GHG emissions and its impact on climate change could be achieved at this stage of the water cycle.

Keywords: Desalination; Energy; Life Cycle Assessment; Renewable energy; Greenhouse gases; Water-energy nexus

1. Introduction

As a consequence of population growth and economic development, global water consumption has increased six-fold in the last 100 y, with a steady growth of 1% per year today [1]. This, in turn, contributes to the growing problem of freshwater scarcity, which has resulted in two-thirds of the world's population living in severe water scarcity conditions for at least 1 month of the year, while 500 million people in the world face severe water shortages throughout the year [2]. For this reason, the search for and development of systems to generate freshwater and mitigate the current water stress represents one of the greatest challenges of this century [3].

One of the best alternatives to tackle the constant increase in water consumption, improve its quality, and reduce its scarcity in regions that lack the resources to obtain sufficient surface water is the desalination of both brackish water and seawater [4,5]. However, due to the high osmotic pressures used, desalination is a process with a significant energy demand, which often comes from conventional energy sources such as fossil fuels [6–8].

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Water and energy are closely related. Water is essential for energy production (hydroelectric energy, fossil fuel extraction, refrigeration, etc.), while energy is essential in the different stages of the integral water cycle (transport, treatment, extraction, etc.). This link is known as the water-energy nexus [9–11].

Demand for water in the energy sector is increasing, and an ever-growing interrelationship between water and energy is expected in the coming years. With respect to water demand, it is important to distinguish the concepts of water consumption and water extraction. According to Vickers [12], water extraction can be defined as "water diverted or withdrawn from a surface water or groundwater source", and water consumption as "water use that permanently withdraws water from its source; water that is no longer available because it has evaporated, been transpired by plants, incorporated into products or crops, consumed by people or livestock, or otherwise removed from the immediate water environment". In this sense, the energy sector is an intensive water consumer.

Around 10% of water extractions worldwide are attributable to the energy sector, and this is expected to increase to 12% by 2040, reaching 400 billion m^3. Water consumption by the energy sector represents around 12% of the extracted water [13]. For this reason, the water footprint in the energy sector has been widely studied for different energy production systems [14–17].

In conventional energy generating systems, the highest consumption is due to the cooling systems [11], with approximately 90% of the total consumption of water in power generation plants spent on cooling the steam from the turbine [18]. To improve the use of water in the energy sector, it is necessary to implement advanced technologies and modernize cooling systems [19], introducing systems like hybrid cooling or closed circuit systems that allow the reduction of water consumption [20,21]. However, there is no doubt that the use of renewable energies such as solar, wind, wave, and geothermal energy produces a lower water footprint compared to conventional energy production systems [11,17,22].

On the other hand, energy consumption in the water cycle also has a growing trend. About 4% of global electricity consumption can be attributed to the water sector, with 40% used for extraction, 20% consumed during water treatment, and 25% during distribution. It is expected that by 2040, the energy consumption of the water sector will double [13]. Although the highest energy consumption is due to the extraction of groundwater, which provides between 20% and 40% of drinking water worldwide [23], the projected increase in energy consumption is mainly due to the growing importance of the desalination process as a water supplier. While today desalination is responsible for 5% of the total energy consumed by the water sector, that value is expected to rise to 20% by 2040 [13].

Within the water cycle, the desalination process has the highest unit energy consumption compared to any other stage of the integral water cycle. Desalination consumes between 2.4 and 8.5 kWh/m^3, compared to the consumption of 0.38–1.122 kWh/m^3 in wastewater treatments, 0.37–1.44 kWh/m^3 in groundwater extraction, and 0.18–0.63 kWh/m^3 in water reuse [24]. On a global scale, most of the energy used in the desalination process comes from conventional energy production systems, based on fossil fuels, while less than 1% of the energy consumed in desalination comes from renewable energies [25].

This situation leads to the emission of greenhouse gases (GHGs), which in turn contribute to the worsening of global warming [5,26]. Several research studies on the carbon footprint of desalination plants and possible ways to reduce their emissions have been conducted. Jia et al. [27] analyzed the evolution over 11 y of GHG emissions in China. Due to the development and increasing rate implementation of desalination plants, the authors reported a 180% increase in emissions, rising from approximately 85 to 1,628 Mt CO_2eq/y. Stokes and Horvath [28] highlighted the operation phase as predominant in the energy consumption of the process, compared to the construction and maintenance phases, while the impact of extraction, distribution, and treatment processes on energy consumption varies depending on the water source used. Liu et al. [29] estimated that the carbon footprint of the construction phase, mainly due to the consumption of energy and raw materials during the manufacturing process of the equipment, is just one-tenth of that consumed in plant operation. Finally, Bitaw et al. [30] analyzed various hybrid systems which combined nanofiltration and electrodialysis processes with reverse osmosis (RO) as an alternative to conventional RO desalination processes, obtaining reductions of 63% in GHG emissions in exchange for an increase in operating costs.

In islands, which are the main focus of this research, the situation of the water cycle is of particular concern. In several island regions, the scarcity of freshwater resources is aggravated by natural limitations of accessibility and distribution, resulting in their overexploitation [31]. This is the case of the Canary Islands (Spain), where population growth and the overexploitation of freshwater resources, which are particularly scarce in the eastern islands, have led to the incorporation of water treatment processes such as desalination to reduce water stress in the region [32]. In fact, the Canary Islands have been the forerunners of water desalination processes in Europe, including its first desalination plant which was installed on Lanzarote island in 1964 [33]. There are currently 337 desalination plants in the Canary Islands, 31 of which are public. The easternmost islands (Lanzarote and Fuerteventura) have a strong dependence on desalination, with almost 100% of their freshwater demand met by this technology. In El Hierro, the corresponding value is 90%, in Gran Canaria 86% and in Tenerife 47% [34].

Moreover, if viewed from an energy perspective, the islands' water-energy nexus aggravates its already complicated environmental situation, with 84.14% of its energy production based on fossil fuels [35]. Therefore, the dependence on desalination processes in the Canary Islands makes it necessary to carry out an exhaustive study of the GHG emissions that this process generates and its consequent impact on climate change. To do so and for the purposes of this study, a real desalination plant of average capacity was selected on Gran Canaria, and its carbon footprint was determined throughout its life cycle. In this way, the main contributors to GHG emissions can be located and quantified. A methodological plan was then drawn up to achieve a more sustainable desalination system based on renewable energy potentials.

This work aims to contribute to the analysis of the water-energy nexus from the perspective of energy consumption in desalination plants and the GHG emissions that this generates. The focus is on isolated regions where this problem is aggravated on both sides of the nexus (water and energy). A path is proposed towards achieving a sustainable system that contributes to the mitigation of climate change through the management and treatment of both these vital resources. This study is part of a global analysis of the contribution to climate change of the water cycle, in which the contribution of wastewater treatment plants was previously evaluated by the authors [36].

2. Methodology

The methodology implemented follows the steps shown below:

- Selection of the practical case.
- Definition and selection of the different protocols for the calculation of the carbon footprint.
- Data calculation in terms of the emission factors of the different phases of the life cycle assessment (LCA).

2.1. Practical case

On the island of Gran Canaria, water desalination technology consumes around 10% of the total energy demand [37], with only 15.5% of this demand supplied by renewable energy sources [35]. The most widely used technology in seawater desalination in Gran Canaria is RO due to its low production costs. Total seawater desalination production on the island is 121.96 hm^3/y. There are more than 120 public and private desalination plants on the island, with production capacities that in some cases exceed 10,000 m^3/d [38]. One such complex is the Arucas-Moya desalination plant, with a production capacity of 15,000 m^3/d. It is a key desalination plant for the northern region of the island, supplying 90% of the consumption of Arucas, 70% of Moya, and 20% of Firgas [39].

The Arucas-Moya desalination plant is one of the few desalination plants on the island capable of producing desalinated water below 4.0 kWh/m^3 [37], thanks in part to efforts made to reduce the consumption of energy produced by conventional technologies through the incorporation of a photovoltaic plant that has improved the energy management of the plant by 40% [39]. The complex is located in the northern part of the island on the coast of the municipality of Arucas, covering an area of 7,000 and 2,890 m^2 of which have been constructed. The current design of the Arucas-Moya desalination plant consists of two RO racks and 1,162 membranes, with maximum daily plant production distributed evenly at 7,500 m^3/d per rack. With a recovery rate of 45%, the product water intended for human consumption and irrigation obtains a quality of 400 ppm in terms of total dissolved solids. The contracted power of the plant is 2.7 MW.

2.2. Protocol selection

The concern in modern society about the causes and consequences of climate change has led many organizations, companies, and institutions to investigate the problem and delve into the many adverse effects that GHG emissions entail. Some of the examples include the United Nations Framework Convention on Climate Change (UNFCCC), whose efforts led to the signing of the Kyoto Protocol in 1998 [40] and the Paris agreement in 2015 [41] with clear objectives to slow the rise in global warming or the Intergovernmental Panel on Climate Change (IPCC) as a reference in the field of studying the impact of climate change together with its evolution and mitigation [42]. The carbon footprint has emerged as a tool for estimating the direct or indirect GHG emissions of an individual, organization, event, or product. As a result, the dynamics of these gases can be better understood and adopted as another factor to be considered in decision-making at the individual, company, regional, or country level. By measuring the carbon footprint, it is possible to control, reduce and/or mitigate the emissions sent to the atmosphere and the impact they create [42,43].

Estimation of the carbon footprint can be performed using several methods that can basically be classified as either "bottom up" (or process LCA), "top down" (or input-output (IO)) assessments, or as a hybrid of the first two methods (IO-LCA). In all three cases, a multi-criteria evaluation of the process is necessary at each stage of the life cycle. The limitations of the evaluation in each case are related to the main distinguishing characteristics of the estimation methods [44,45]. The "bottom up" or LCA method performs a division by categories to treat each emission source individually. This method requires detailed information on each stage, which is very suitable for estimating smaller systems, specific processes, or consumer goods, as in the case study presented here. The "top-down" or IO method, on the other hand, addresses a more generalized perspective that relies on an entry-exit economic model that reflects the interconnections between sectors, which is why it is commonly used for regions, sectors, or countries. The hybrid method tries to combine the strengths of both methods (LCA and IO), and is still being studied and developed. This method uses matrices of economic inputs and outputs from specific regions such as the US and China, which are difficult to extrapolate to situations in other regions [46–48].

There are several calculation tools based on the methods mentioned above, four of which were initially selected for the present case study given its characteristics and the scope of the tools. Table 1 presents a comparison of the four tools.

The emission factors of the O2C tool, selected for the study, come from both public sources (Ademe–Bilan Carbone® or Carbon Balance, ASTEE, etc.) and research carried out by CIRSEE (International Agency for Research on Water and the Environment). The tool is based on international guidelines for LCA and GHG quantification (ISO 14040 Standard). It integrates the Bilan Carbone® (Carbon Balance) methodological standards of the French Environment and Energy Management Agency (ADEME) in France and is based on the guidelines published by the Scientific and Technical Association for Water and the

Environment (ASTEE). This was the tool finally selected for the present study, on the one hand, because of the advantages set out in the table and on the other because of its versatile use in other stages of the integral water cycle of the islands (its ability to discern between wastewater, desalination, and drinking water treatment plants). Also, this dynamic and scalable online tool allows the generation of several scenarios in a confidential manner.

2.3. Data calculation

Estimation of the carbon footprint is based on the calculation of carbon emissions of the energy consumption in two main stages: infrastructure and exploitation.

2.3.1. Infrastructure stage

The emissions calculated in this section are those generated through the manufacture of construction materials, as well as those generated by transportation from their companies of origin to the construction area of the desalination plant. Likewise, the manufacture of the equipment required for the construction and operation of the plant is also considered. Table 2 shows a classification of the emission factors associated with each of the two parameters (construction materials and equipment) of the infrastructure stage.

2.3.2. Exploitation stage

In this stage, the GHG emissions related to the inputs necessary over a year-long period for plant operation are quantified. The consumables required for plant operation correspond to the purchase of reagents and other consumables, the purchase of services, etc. In turn, this stage also considers the emission factors associated with the purchase of the energy necessary for the operation of the desalination plant for 1 y.

The electricity consumed by the installation in 1 y is also taken into account. This is the electricity produced off-site (corresponding to the total needs subtracted from the self-produced electricity consumed on-site). In this case study, the energy generated by the solar photovoltaic (PV) system available to the plant is considered, however in other cases the presence of boilers, anaerobic digestion systems or renewable technologies, etc., which reduces the purchase of external electricity, has to be taken into account.

The objective is to quantify the indirect emissions generated as the result of the need to purchase electricity produced outside the plant. If a conventional energy production system is available, this emission factor is accounted for separately.

At this point, it should be noted that the energy generated in any region is due to an energy mix made up of both conventional and renewable resources. In the case of Gran Canaria, 84.54% of electricity generation is due to conventional technologies, which use fossil fuels, and the remainder to renewable technologies, of which 13.9% is wind energy-based and 1.55% PV solar energy-based [35]. Table 3 shows the breakdown of the emission factors associated with the three points discussed above.

3. Results and discussion

The results obtained for the different phases of the LCA of the desalination plant are presented below, both globally and in detail, depending on the construction and exploitation stages. Subsequently, solutions are proposed to reduce GHG emissions and a methodological plan for the penetration of renewable energies is established.

3.1. Overall balance

Table 4 shows the overall balance of the total CO_2 emissions that result from the construction and exploitation stages of the plant. An average desalination plant useful life of 25 y is assumed. The third column of the table shows the annual distribution of the tons of gases emitted during the exploitation phase. In this study, it is assumed that plant construction takes place in the first year of the plant's useful life, while the remaining years correspond to plant operation/exploitation. It can be seen how a year of plant operation generates a

Table 1
Comparison of carbon footprint estimation methodologies

Method	Advantages	Disadvantages
O2C	LCA method Easy to use Free access Based on international LCA guidelines Water treatment application tool Extensive input data requirements	Maintenance actions are not clearly specified inside the operation phase
WEST	Extensive input data requirements Water treatment application tool	Upon request Not applicable in Europe
WEST-web	Free access Extensive input data requirements Water treatment application tool	Less complete than full version
Tampa Bay Water Model	Easy to use Water treatment application tool	Upon request Poor input data requirements

Table 2
Infrastructure emission factors

Construction materials		
Material	Emission factor	Unit
Industrial building	0.823	teq CO_2/m^2
Road surface	0.168	teq CO_2/m^2
Aluminum window frame	0.491	teq CO_2/m^2
Double glazing	0.033	teq CO_2/m^2
Equipment		
Material	Emission factor	Units
Pumping/dosing pump	1	teq CO_2/t
Network/stainless steel pipes	5	teq CO_2/t
Network/PVC pipes	2	teq CO_2/t
Network/cast iron pipes	3	teq CO_2/t
Membranes/cellulose acetate	0.367	teq CO_2/kg
Pumping/stainless steel pump	6	teq CO_2/t

Adapted from [49,50].

Table 3
Exploitation emission factors

Consumables		
Material	Emission factor	Unit
Provision of services with materials	98.571	teq CO_2/k$
Pure sulfuric acid (H_2SO_4)	0.147	teq CO_2/t
Sand	0.011	teq CO_2/t
Drinking water	0.00031	teq CO_2/t
Calcium hydroxide ($Ca(OH)_2$)	0.804	teq CO_2/t
Sodium hypochlorite (NaClO)	0.887	teq CO_2/t
Carbon dioxide (CO_2)	0.815	teq CO_2/t
Power purchase		
Electricity (petroleum)	0.997	teq CO_2/MWh
Electricity (wind power)	0.028	teq CO_2/MWh
Electricity (solar power)	0.091	teq CO_2/MWh
Energy production		
Electricity (solar PV power)	0	teq CO_2/MWh

Adapted from [50,51]

Table 4
Overall balance of CO_2 emissions

Stage	Total teq CO_2	teq CO_2/y	%
Infrastructure	17,056	17,056	41%
Exploitation	579,072	24,128	59%
Total	596,128	41,184	100%

greater amount of emissions than the year of plant construction (59% vs. 41%, respectively), which may be due in part to the savings in emissions associated with the transport of construction materials due to proximity to suppliers, vs. the consumables associated with the exploitation phase, which often come from outside the country.

3.2. Infrastructure stage emissions

The emission values associated with construction materials used in the desalination plant can be seen in Fig. 1. The most significant impact in this stage is due to the manufacture of the plant equipment (14,473 teq of CO_2). Figs. 2 and 3 represent in more detail the emissions associated with the infrastructure construction stage. With respect to the construction materials, concrete is associated with the highest value as it is the most widely used material in the construction of the plant. Regarding the manufacture of the equipment, the high values corresponding to

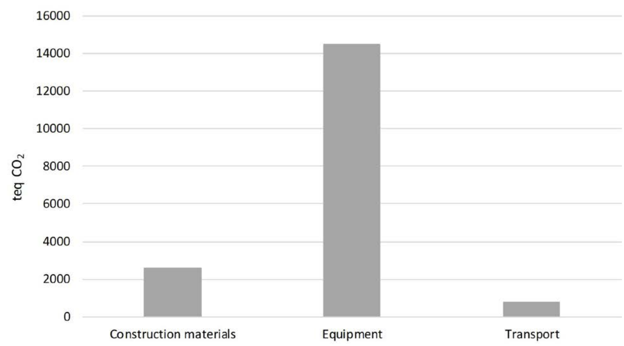

Fig. 1. Construction stage emissions.

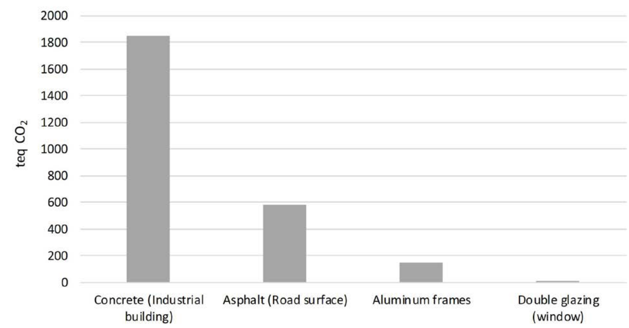

Fig. 2. Construction materials emissions.

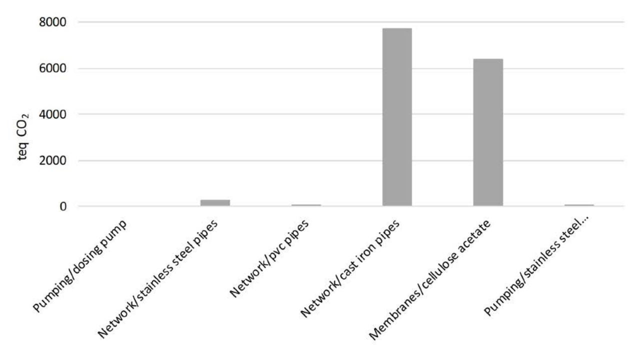

Fig. 3. Equipment emissions.

cast iron pipes are due to their high energy consumption and the extensive use of this material for the final distribution of drinking water to the municipalities of Arucas, Moya, Firgas, Teror, and Gáldar. Likewise, the manufacture of cellulose acetate membranes involves high energy consumption, which is reflected in the high CO_2 emission values.

3.3. Exploitation stage emissions

The detailed values of the CO_2 emissions from the operation or exploitation phase of the desalination plant are presented in Fig. 4, where the predominance of the emissions corresponding to the purchase and production of energy can be observed. The value of 21,781 teq CO_2 corresponds to 90% of all emissions associated with the operation phase, in addition to being the highest value attributable to a variable within the study. The remaining 10% are due to plant consumables, 80% of which correspond to the materials used for the remineralization of the treated water in the plant, whose emission values can be seen in Fig. 5.

3.4. Solutions for the reduction of the carbon footprint

Among the main solutions to achieve zero net carbon emissions in desalination plants, the direct integration of solar, wind, and marine renewable energies stands out. Renewable energies are clean and respectful with the environment and are able to significantly reduce the emissions of polluting gases into the atmosphere and thus improve the energy management of the water cycle. The Canary Islands present a high potential in this respect, especially for wind and solar energy. With appropriate energy management strategies, it has been calculated that a supply based exclusively on renewable energies could potentially meet the islands' power, heating, and land transport energy demands by 2050 [52]. In terms of wave energy, most of the coasts that bathe the Canary Islands could be exploited in this respect to reduce the dependence on fossil fuels. For this reason, there is increasing interest in studying its availability and applicability on the coasts of islands such as Gran Canaria or Tenerife [53,54]. The island of Gran Canaria is an ideal place for the application of wind energy, due to a favorable geographical location that allows the generation of large amounts of wind and the availability of land for the installation of wind farms. Thanks to the good weather in the region, there are many hours of sunshine, as well as little rainfall and few cloudy days, which translates into large amounts of radiation that can be exploited by PV solar panels. Rosales-Asensio et al. [55] analyzed the feasibility of implementing renewable solar PV and wind energy, with good results for desalination systems on the island of Gran Canaria.

The improvements that have been made in the field of membranes can also contribute to reducing the energy consumption of the process. Ultra-low energy membranes allow greater production of desalinated water at constant feed pressures, with lower working pressures compared to conventional membranes [56]. Likewise, biomimetic membranes used in emerging technologies such as forward osmosis, and specifically those that incorporate aquaporin, have been shown to improve the permeability and selectivity of the process at a laboratory scale. These types of membranes, along with those that introduce nanomaterials, are in the middle of the research and development phase [56,57].

Another process of interest is the capture and storage of CO_2. This method consists of the separation of CO_2 from the combustion gases of thermal power plants for its subsequent storage in reservoirs. This would help allow a transition from the use of conventional energies to cleaner energies, such as solar, wind, wave energy, etc. It should be noted, however, that this is not a reduction in CO_2 emissions, but a reduction in atmospheric pollution by GHGs [58]. It should also be noted that this system is applicable to the thermal power plant that generates the electricity consumed by the desalination plant and not to the actual desalination plant. Several documents and publications identify this line of research as crucial to achieve the objective of reducing GHG emissions [59–61].

Due to the relevance and applicability of renewable energies in the region and their contribution to zero net carbon in water treatment systems, this section presents a methodological plan that serves as a roadmap for the further penetration of renewable energies in desalination plants.

3.5. Methodological plan to penetrate renewable energies

The following logic diagram presents an easy methodology to integrate renewable energies in a desalination plant (Fig. 6). The first step is to find out if there are renewable

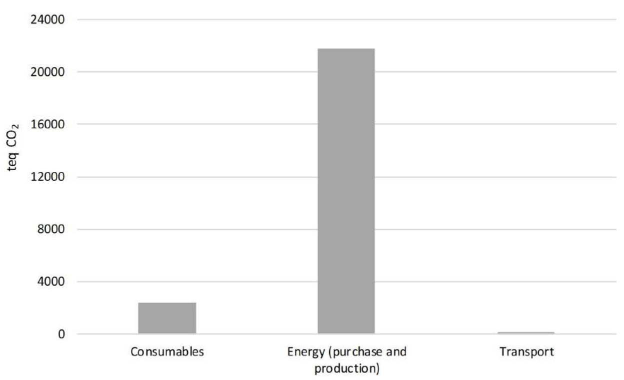

Fig. 4. Exploitation stage emissions.

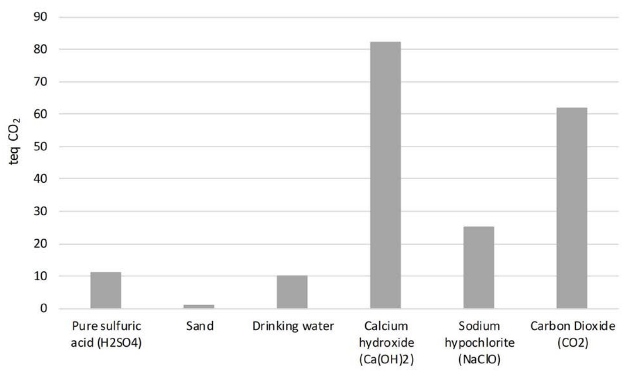

Fig. 5. Water remineralization products emissions.

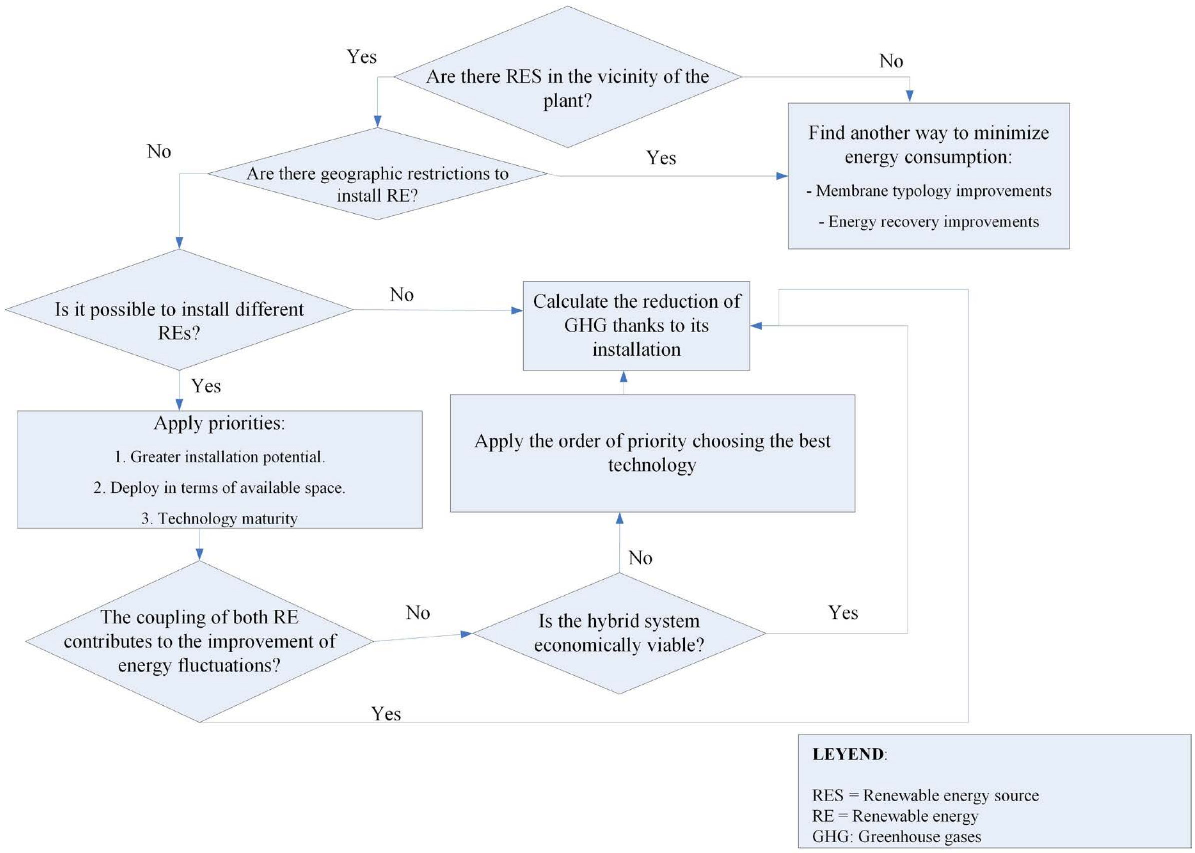

Fig. 6. Logic diagram of the methodological plan for the penetration of renewable energies in desalination plants.

energy sources near the plant. Following this, there are three options. If the desalination plant has no renewable resources in its vicinity, attempts should be made to lower energy consumption using more efficient and state-of-the-art technologies, including membranes or energy recovery systems. If only one resource is available, the technology to take advantage of that resource should be installed. Finally, if there are multiple available resources, a comparison should firstly be made between them.

The resources evaluated are wind, solar PV, and marine renewable energy as waves and offshore wind. As such, they will generally cover different areas that must be previously analyzed to verify their possible use. Any restrictions applied to areas destined for socio-economic or military activities, or to natural reserves of flora and fauna, must also be carefully analyzed beforehand.

In relation to the possibility of installing multiple technologies, an order of priorities should be generated. This order will depend on the renewable potential available in the area (always complying with the minimum requirements of each technology), on the correlation between the space that is available and the space required for its correct deployment, and on the maturity of the renewable technologies under consideration. In this sense, renewable energies have different degrees of maturity, generally expressed in the form of their technological readiness level (TRL). By way of example, with respect to wave energy, prototypes are currently available at a pre-commercial scale.

Once the technologies have been classified, and if the installation of an energy mix continues to be feasible, an analysis should be undertaken of whether the coupling of these renewable technologies contributes to improving the energy fluctuations which are characteristic of renewable resources.

It is known that a constant flow of energy is important to ensure the membranes operate correctly and to not reduce their lifetime. For this reason, among others, it is useful to know whether particular renewable energy is capable of covering the valleys or energy deficits that are inherent to the other renewable technology, and vice versa. If so, greater network stability can be achieved.

In the event that this is not always possible, and an energy overlap occurs at certain points of the day, month or season, the next step will be to analyze whether the hybrid system could be economically viable. For this, two scenarios have to be considered. The first scenario consists of a stand-alone system with the use of energy storage, while the second involves the purchase/sale of electricity from/to the grid based on the needs of the plant. In terms of energy storage, for the selection of the appropriate technology, it is important to know the period of time. In this regard, if long-term storage is required the use of hydrogen storage has the potential as an emerging technology to solve the problem with great efficiency and adaptability. If the periods of time are short, depending on the energy resource that is being considered, batteries, flywheels, or ultra-capacitors all have a very adequate response time. If the system is found to be economically viable in either of the two scenarios, the installation of the various renewable technologies is feasible. Otherwise, renewable energy with the greatest potential will be used.

3.6. Practical case

The Arucas-Moya desalination plant is located in an area that is not affected by any Nature 2000 network, biosphere reserve or nature protection area [62]. It is consequently not subject to any environmental or socio-economic constraints.

Located just 80 m from the sea, the mean annual wave energy resource is about 19.3 kW/m [54], suitable for the installation of wave energy converters (WECs). A small solar-PV roof has recently been installed in the plant [63]. The 988 PV modules have a total power of 272 kW and produce ca. 420 MWh/y. This energy covers around 2% of the electricity demand. The consortium that runs the plant has plans to enlarge this PV facility in the near future. Wind is the only renewable energy resource with a low potential for exploitation (average wind speed in the area below 5.5 m/s at 80 m height).

In terms of wave energy, a pilot zone of 7.82 km^2 located next to the selected desalination plant was analyzed, beginning at the shoreline and extending seawards to an approximate depth of 350 m. A work previously carried out by the authors confirms the technological viability of the implementation of WECs in the area. It also compared four technologies which, despite different operating principles, are characterized by a high range of maturity. Most of them are able to obtain sufficient energy to cover the annual demand of the desalination plant. In the study, the appearance of seasonal fluctuations was also confirmed and analyzed in detail [64].

However, as wave energy is not available on a commercial scale, the next step is to consider the second position of priority, with PV solar energy heading the list. The currently operative PV facility was installed on the tank roof which stores the treated water next to the desalination plant. This roof has a surface area of 2,573.5 m^2. A similar PV facility could be installed on the desalination plant roof whose area is 2,889.2 m^2. The production of this second PV facility would be 467 MWh/y and the total production of both facilities would represent ca. 5% of the energy demand of the desalination plant. However, and by way of example, to reach a target of 20% PV coverage of energy demand, the area covered by this technology would still need to be increased by a factor of 4.3 (to approximately 23,489.6 m^2). In principle, this could be attainable if the parking area and unused land near the desalination plant were exploited, although a prior adaptation of the spaces would also be required.

Finally, the potential benefits of installing a wave-solar PV hybrid system were investigated. The results showed that, as expected, such a system could contribute to reducing the number of hours with zero or very low renewable energy production in a year, depending principally on the WEC that is selected and how it can be adapted to the wave resource of the area. An analysis was also undertaken of whether the incorporation of solar PV energy could improve the hourly match between supply and the energy demand of the plant. In some cases, no improvement in the accumulated surplus and deficit was obtained, while in others the hybrid system was found to be capable of lowering the accumulated surplus by 11.8% and the accumulated deficit by 16.5% [64]. It is thus concluded that an hourly analysis of the specific technologies is needed in order to install a combination that allows greater network stability.

4. Conclusions

This work presents a methodology for the quantification and possible reduction of the carbon footprint generated in the life cycle of desalination plants.

To this end, an analysis of the protocols and specific calculation tools for the desalination process was carried out, highlighting the advantages and disadvantages of each tool with the intention of helping in the appropriate selection for each case study.

After analyzing the scope and emission factors in the various stages that comprise these plants, a strategic plan for the reduction or even eradication of their carbon footprint is described. This roadmap proposes solutions that involve different alternatives such as reducing energy consumption using ultra-low energy membranes or emerging technologies like forwarding osmosis. It also introduces the possibility of capturing the CO_2 emitted for later use as a second-generation product, and finally proposes a methodology for the analysis, management, and validation of possible renewable energy resources that are available near desalination plants. The methodology can be extrapolated to any desalination plant, managing to substantially reduce the indirect emissions of the process in its energy consumption.

Finally, a case study of a real plant located in the northern region of the island of Gran Canaria (Spain) is described. Total emissions amounted to 596,128 teq CO_2 during the 25 y average life of the plant. Of these, the overwhelming contribution was in the exploitation phase, and more specifically on the consumption of energy by the plant which is supplied mostly by conventional thermal power plants that contribute 84.54% to the total electricity generation of the island. In this case, around 21,781 teq of CO_2 emissions can be avoided annually using a hybrid wave and solar PV energy system. In order to reach a zero net carbon footprint, an hourly analysis of the energy fluctuations of the renewable system must be carried out and of their potential management using an energy storage system.

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