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Calculation of greenhouse gas emissions in Canary Islands wastewater treatment plants

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ABSTRACT

This research analyzes the water-energy nexus contribution to climate change from the integral water cycle perspective. A prior analysis of the sectors involved in global warming showed that clear water/energy interdependence was a crucial factor in increasing greenhouse gas (GHG) emissions. Although the analysis of water consumption in the energy sector has been widely studied, global requirements of energy for water are still poorly understood as is their contribution to climate change. With this in mind, wastewater treatment plants (WWTPs) were chosen for the specific analysis conducted in the present study as they are one of the biggest GHG emitters in the water industry. They are located in the Canary Islands (Spain), an archipelago that, like many others, is characterized by its dependence on external water and energy resources. The methodology employed involved an initial analysis of the WWTPs in the islands and the selection of four full-scale WWTPs of varying capacity for further in-depth analysis. This was followed by consideration of the different protocols and tools that can be used to quantify direct and indirect GHGs emissions. The Intergovernmental Panel on Climate Change protocol was selected due to the great diversity of operational data and the emission factors proposed by experts when the data are not available for a specific region under analysis. The results show that the highest emission source is due to energy consumption (ranging from 165 to 2,716 Tm_{eq} CO_2/y for the smallest and largest size WWTPs, respectively). To solve the problem, the introduction of renewable energies is presented as a feasible and attractive option due to the specific characteristics of the analyzed territory. Likewise, the use of sludge as an internal energy resource (in anaerobic digestion) obviates the need for its transport and management, contributing to the circular technology and reducing emissions.

Keywords: Wastewater treatment plants; Greenhouse gas emissions; Global warming; Direct/indirect emissions; Climate change

1. Introduction

Climate change is no longer considered a possibility, but rather a reality caused largely by the humankind. Anthropogenic-induced warming has resulted in an increase in the global mean temperature of approximately 1°C compared to pre-industrial levels [1]. Innumerable research studies and policy changes in a wide range of fields (industrial, social, ecological, etc.) have been carried out with a view to limiting and reducing greenhouse gas (GHG) emissions [2–8].

From an ecological perspective, measures such as afforestation and sustainable agricultural intensification are being promoted as ways to ensure food production without compromising the Paris agreement on climate targets [2]. However, it should be borne in mind that urban trees are also affected by the harsher conditions found in urban environments [3] and that agriculture systems in different parts

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of the world need to be managed in accordance with the specificities of each ecosystem [4]. Similarly, when considering ways to limit climate change from a social perspective, a place-based approach can be useful to analyze the abstract entity of climate change as a whole or classified by its different independent sources [5,6].

There is no doubt that the industrial sector is leading GHG emitter. With this in mind, Wang and Feng [7] developed a decomposition framework which was used to quantify the impacts of both oriented technologies and economic factors on CO_2 emissions in China. Their results highlighted investment scale expansion as the leading factor in promoting the growth of emissions and confirmed the need to keep improving the energy structure to reduce emissions [7]. In another study, which aimed to develop a low-carbon scenario for the energy sector in less developed countries such as Brazil, it was again reported how the increase in energy consumption was a crucial factor in CO_2 emissions [5]. As far as Europe is concerned, while a lot of the research undertaken has focused on a similar transformation of the energy sector, it has also been reported that there has been a systematic overestimation in the literature of the consequent costs of the transition to a low carbon scenario [8].

Despite these problems, the goal of finding ways to reduce GHG emissions is one that must necessarily continue. One way to contribute to achieving this goal is to identify, analyze, and quantify the main emission points. Such research requires an understanding of the complicated scenario inherent to the management of water and energy, two essential resources for life that have been the focus of the World Energy Outlook (WEO) since 2016 [9]. The processes involved in water and energy generation and the intrinsic relationship between them are vital factors that need to be considered in a world of climate change.

Water consumption in the energy sector has been widely studied [10,11]. Most studies have prioritized the analysis of an energy transition in which fossil fuels give way to renewable technologies in terms of cost [12], GHG emissions reduction [13], and manufacturing and storage capacity [14]. In all of these cases, water consumption is a crucial factor. However, global requirements of energy for water are still poorly understood, which may result in biases in projections and consequently in policies adopted for its management [15].

The water cycle is an important player in global warming. This work focuses specifically on the water cycle in wastewater treatment plants (WWTPs), a major GHG emitter which produces 56% of GHG emissions in the water industry [16].

It was decided to use island regions as the scenario for this study given the problem of water/energy interdependency they typically have to deal with. This is the case of the Canary Islands (Fig. 1). This archipelago is one of the seventeen autonomous communities of Spain [17,18] and the southernmost region in the country. It has been granted special status by the EU as one of it is nine outermost regions [19,20].

Located in the transitioning area between the temperate and tropical zones, the climate in the islands is characterized by very scarce and irregular precipitations [21]. In some cases, this can mean a shortfall of as much as 90% in terms of water requirements [22]. One way to quantify the problem that this can generate is to compare the significant difference between the water capital of a resident in the islands (20 m^3/inhabitant/y) with that of a resident on the Spanish mainland (2,470 m^3/inhabitant/y) [23]. The major social concern of water scarcity is further exacerbated by the growing demand for an increase in life quality [24] and an expected rise in population which will shortly mean the need to guarantee domestic water supply for an estimated 2,150,000 inhabitants [22].

This problem has made the Canary Islands pioneers in satisfying demand with innovative techniques for water production [25]. However, in a territory characterized by its external energy dependence, water production plants tend to require high levels of energy consumption as a result of the technologies used in the desalination and wastewater treatment processes [26]. Almost inevitably, this high energy consumption increases the carbon footprint of the islands [27,28].

This work focuses on an analysis of the contribution to global warming by WWTPs. After identifying the problem, the main objective is to provide a numerical value for its quantification. To do so, an evaluation is made of the different sources of GHG emissions of the WWTPs. These trouble spots are differentiated according to whether the emissions are direct (produced by the different processes and equipment of the plant itself, as well as the sludge that

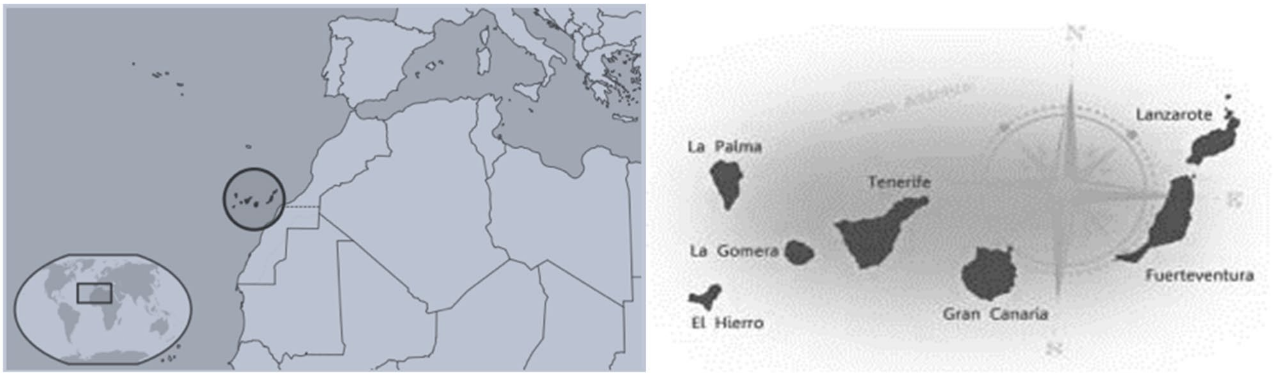

Fig. 1. Location of the Canary Islands.

it generates) or indirect (not produced directly through the mechanisms and equipment of the plant) [29].

This framework gives us a starting point to restructure the management of water resources in the Canary Islands, underlining the importance of the water-energy-environment nexus and the need to apply optimizations and improvements in both the water and energy sector.

2. Methodology

The methodology used in this research work can be divided into three subsections:

- *Subsection 2.1*: WWTPs analysis
- *Subsection 2.2*: protocol selection for calculating GHG emissions
- *Subsection 2.3*: data calculation

2.1. WWTPs analysis

In accordance with Directive 91/271/EC, since December 31 of 2005, any urban nucleus with a population of between 2,000 and 15,000 inhabitants has been required to have a collector system and a wastewater treatment process [30]. As a result, the number of WWTPs has increased in the different islands, causing a consequent decentralization of the treatment system [31].

Due to the wide range of WWTP sizes found in all the islands, a characterization procedure was established based on the treated water capacity. The range limits were established in a previous statistical survey which provided the various mode values. The classification ranges are shown in Table 1.

The 142 WWTPs in the islands were classified in this way at both island and archipelago level in order to evaluate their distribution throughout the region.

Table 1
WWTP classification

WWTP	Capacity (m^3/d)
Very small	<1,000
Small	1,000–5,000
Medium	5,000–10,000
Big	>10,000

Given the heterogeneity of the WWTPs and the territorial fragmentation of the Canary Islands, it was decided to evaluate one plant for each of the four established ranges in order to guarantee reliable results. The four plants are chosen (representative of each range) are shown in Fig. 2.

2.2. Protocol selection for calculating the GHG emissions

The global concern about the adverse effects and consequences of climate change [32] has triggered the development of various strategies to mitigate this change. Examples include the National Roadmap 2020 [33], Europe 2020 (the growth strategy) at the European level [34], and the guidelines set out in the "Mitigation Change 2014" document prepared by the Intergovernmental Panel on Climate Change (IPCC) [35].

With regard to the application methodologies for the quantification of GHG emissions (web-based platform, software tools, etc.), they are few in comparison with the regulations provided for them. There are two types of methodologies classified respectively as top-down and bottom-up. The difference between them lies in the strategy of information processing and knowledge ordering. The top-down methodology firstly considers the overall picture and is then broken down into smaller segments. Unit indicators are commonly analyzed, while, a detailed analysis of individual devices is less often performed. In the bottom-up methodologies, the individual base parameters of the system are first specified in detail and then linked together to form a complex system [36]. In this context, the difficulties in obtaining detailed data from the WWTPs considered in the present study suggested that a top-down methodological approach was the most appropriate for this work.

Due to the lack of established procedures at the regional level, the calculations of GHG emissions for this study were based on operational data and emission factors, using the protocol stipulated by the IPCC. This protocol was selected on the basis of a previous discussion about various possible tools derived mainly on the basis of four methodologies. Table 2 shows these methodologies and their main advantages and disadvantages.

The IPCC methodology lays the foundation for most of the aforementioned documents and consists of a great diversity of values and technical data evaluated by expert commissions. These data values are particularly necessary for application in the Canary Islands because of the absence of any information on this sector in the local territory.

Fig. 2. WWTP selection.

Table 2
Methodologies used to calculate GHG emissions.

Methodology	Advantages	Disadvantages
LGO[a]	Top-down methodology Free access and easy to use It provides several forms of calculation that allow it to be more precise depending on the availability of site-specific data	IPCC and USEPA approaches Standardized set of guidelines to assist US local governments
USEPA[b]	Different levels of data requirements, rigor and accuracy Free access and easy to use	National and state-level estimations using IPCC basis More appropriate method for the state of California
NERI[c]	Top-down methodology Free access and easy to use	Methodology follows the IPCC guidelines and the IPCC good practice guidance It does not provide a default operating database Country-specific data on the emission factor for direct N_2O
IPCC[d]	Internationally recognized Basis for subsequent protocols Top-down methodology Designed for macroscale evaluations Great contribution of revised data	Does not use facility-specific information

Adapted from [37–41].
[a] Local Governments Operations protocol (USA and Canada).
[b] United States Environmental Protection Agency. Wastewater treatment methodology.
[c] National Environmental Research Institute of Denmark methodology.
[d] Intergovernmental Panel on Climate Change protocol.

The other methodologies mostly try to use local/state data and sometimes modify some of the equations based on-site regulations to improve the accuracy of the calculation. To better understand the evolution of a methodology, the work prepared by the California wastewater climate change group and Bay area clean water agencies in 2007 provides a detailed analysis of the differences between the United States Environmental Protection Agency (USEPA) and IPCC methodologies [42].

2.3. Data calculation

For the purposes of this study, direct and indirect emissions were considered separately [43].

2.3.1. Indirect emissions

The main factor that needs to be considered is intensive energy consumption [44]. Conventional electricity, in most cases, is produced through an energy mix in which fossil fuels predominate [45], causing GHG emissions in the power plant that generates it [46]. To carry out this calculation, carbon dioxide emission factors and transition coefficients to primary energy, provided by the Spanish Institute for Energy Diversification and Saving were used [47]. Table 3 lists the treated wastewater treatment capacities and the energy consumption necessary for plant operation.

The second indirect emission factor considered is related to the transport of sludge from the WWTP to the corresponding biomethane plants or landfills [48]. For this purpose, an analysis was conducted of the distance between the two locations, truck engine capacities, type of journey, and the number of days of sludge removal [49]. Table 4 shows the distance traveled for each of the selected plants.

Table 3
WWTP energy consumption

WWTP	Capacity (m^3/y)	Energy consumption (kWh/y)
Sureste	4,380,000	3,349,255
Jinámar	3,650,000	1,554,719
Tazacorte	547,500	164,079
P. Hidalgo	232,140	203,632

2.3.2. Direct emissions

The direct emissions were classified into two clearly differentiated subdivisions. One considers the different processes used in treating the water, while the other corresponds to the emissions of the sludge itself [50].

2.3.2.1. Treatment process emissions

It should be noted that, within the components of the carbon footprint that are part of the biogenic source, CO_2 emissions were not included since they are considered part of the natural cycle [51]. CH_4 and N_2O, as they have a greater global warming potential, must be quantified [41]. Likewise, the null emission of these three components in the water

Table 4
Distance traveled for sludge removal

WWTP	Distance between locations (km)
Sureste	33
Jinámar	25.7
Tazacorte	45
P. Hidalgo	60

collection process is confirmed, because the entire Canary water collection is confined under the soil [52].

Anaerobic treatments produce higher emissions of these compounds than aerobic treatments. In this respect, as centralized aerobic systems predominate in the archipelago, GHG emissions should not be very noticeable. However, the Canary climate is within the temperature range that favors methane production processes (>15°C). In addition, there are a large number of plants ending their service life. These factors support the decision to calculate the emission of methane and nitrous oxide.

The CH_4 emission produced by anaerobic degradation and its quantification is a function of the degradable organic matter content of the wastewater, as well as the temperature and type of treatment. Emissions of CH_4 (kg CH_4/y) were determined through Eq. (1) [51].

$$\mathrm{CH_4 Emissions} = \left[\sum_{i,j}\left(U_i \times T_{i,j} \times \mathrm{EF}_j\right)\right]\left(\mathrm{TOW} - \mathrm{S}\right) - R \quad (1)$$

The equation parameters are shown in Table 5. Data values were either provided by the different WWTP owners or by incorporating the mean value of the corresponding IPCC protocol.

N_2O emissions are associated with the degradation of nitrogenous components in wastewater, namely urea, nitrates, and proteins. In this study, the N_2O emissions (kg N_2O/y) were determined through Eq. (2) [51].

$$\mathrm{N_2O\ Emissions} = \mathrm{N_{EFLUENT}} \cdot \mathrm{EF_{EFLUENT}} \cdot \frac{44}{28} \quad (2)$$

The same procedure used for calculating methane emissions was used. The equation parameters are shown in Table 6.

2.3.2.2. Emissions from sewage sludge

Two separate calculations were made to determine the emissions from sewage sludge, one for the biodegradable organic carbon and the other for the possible N_2O that remains and/or forms in the sludge.

According to the IPCC protocol, in the domestic sludge sector, the biodegradable organic carbon content is about 45% of the dry matter [53]. Using the data available and the stoichiometric ratio in the oxidation reaction, the emission value was obtained.

With respect to N_2O and considering the characteristics of the wastewater treatment in the islands applied in the selected protocol [51], Eq. (3) was obtained, as follows [54].

$$\mathrm{N_2O}_{(L)} - N = \left(F_{\mathrm{ON}} + F_{\mathrm{SOM}}\right) \cdot \mathrm{Frac}_{\mathrm{LIXIVIACION}-(H)} \cdot \mathrm{EF}_5 \quad (3)$$

The conversion of $N_2O_{(L)}$–N emissions to N_2O emissions was performed through Eq. (4).

Table 5
Parameters used in the calculation of CH_4 emissions

Parameter	Definition	Data value	Function
U_i	Fraction of population in income group "*i*"	By default	*Income group*: rural, urban high income and urban low income
T_{ij}	Degree of the utilization of treatment/discharge system, "*j*", for each income group fraction "*i*"	By default	*Income group*: rural, urban high income and urban low income
EF_j	Emission factor, (kg CH_4/kg BOD)	$B_0 \cdot MCF_j$	"*j*" = each treatment/discharge pathway or system B_0 = maximum CH_4 producing capacity, (kg CH_4/kg BOD) MCF_j = methane correction factor
TOW	Total organics in wastewater, (kg BOD/y)	$P \cdot BOD \cdot 0.001 \cdot I \cdot 365$	*P* = country population, (person) BOD = country-specific per capita BOD, (g/person/d) 0.001 = conversion from grams BOD to kg BOD *I* = correction factor for additional industrial BOD discharged into sewers (default value)
S	Organic component removed as sludge (kg BOD/y)	Value contributed by each plant	Type of system
R	Amount of CH_4 recovered, (kg CH_4/y)	Not applicable in the archipelago	–

Adapted from [51].

Table 6
Parameters used in the calculation of N_2O emissions

Parameter	Definition	Data value	Function
$EF_{EFLUENT}$	Emission factor for N_2O emissions from discharged wastewater, (kg N_2O–N/kg N]	By default	–
$N_{EFLUENT}$	Nitrogen in the effluent discharged to aquatic environments, (kg N/y)	$(P \cdot \text{Protein} \cdot F_{NPR} \cdot F_{NON\text{-}CON} \cdot F_{IND\text{-}COM}) - N_{SLUDGE}$	P = human population Protein = annual per capita protein consumption, (kg/person/y) F_{NPR} = fraction of nitrogen in protein, default = 0.16, (kg N/kg protein) $F_{NON\text{-}CON}$ = factor for non-consumed protein added to the wastewater $F_{IND\text{-}COM}$ = factor for industrial and commercial co-discharged protein into the sewer system N_{SLUDGE} = nitrogen removed with sludge (default = zero), (kg N/y)
44/28	Conversion of kg N_2O–N into kg N_2O	–	–

Adapted from [51].

$$N_2O_{(L)} = N_2O_{(L)} - N \cdot \frac{44}{28} \tag{4}$$

Table 7 shows the parameters used in Eq. (3).

3. Results and discussion

The various figures below synthesize the results that were obtained in the analysis of the WWTPs in the Canary Islands. Fig. 3 shows the distribution of the treated wastewater volume by island. At the same time, the 142 WWTPs of the archipelago were classified based on the volume range shown in Table 1. The big, medium, small, and very small plants are presented in percent terms in Fig. 4. To highlight the input of smaller plants, in the first circle diagram in Fig. 4 the percentage named "others" corresponds to the sum of the small and very small plants, with their corresponding percentages broken down in the second circle diagram to the right.

The distribution of the total treated wastewater volume by plant capacity range (Table 1) is shown in Fig. 4.

A more detailed analysis is found in Fig. 5, showing the number of WWTPs and their distribution according to the capacity range classification (Table 1) for each island.

The number of plants with a capacity below 1,000 m^3/d accounts for more than 50% of the total number of plants. In terms of the installed capacity range, the number of plants

Table 7
Parameters used in the calculation of N_2O sludge emissions

Parameter	Definition	Data value	Function
$N_2O_{(L)}$–N	Annual amount of N_2O–N produced from leaching and runoff of N additions (kg N_2O–N y^{-1})	–	–
F_{ON}	Annual amount of sewage sludge and other organic N additions applied to soils in regions where leaching/runoff occurs, (kg N y^{-1})	$F_{ON} = F_{SEW}$	F_{SEW} = annual amount of total sewage N that is applied to soils, (kg N y^{-1})
F_{SOM}	Annual amount of N mineralized in mineral soils associated with loss of soil C from soil organic matter as a result of changes to land use or management in regions where leaching/runoff occurs, (kg N y^{-1})	Null value	Not competent in the archipelago
$Frac_{LIXIVIACIÓN–(H)}$	Fraction of all N added to/mineralized in managed soils in regions where it is lost through leaching and runoff, [kg N (kg of N additions)$^{-1}$]	By default	Calculated by experts
EF_5	Emission factor for N_2O emissions from N leaching and runoff, [kg N_2O–N (kg N leached)$^{-1}$]	By default	Calculated by experts
$N_2O_{(L)}$	N_2O emissions from leaching and runoff	–	–

Adapted from [54].

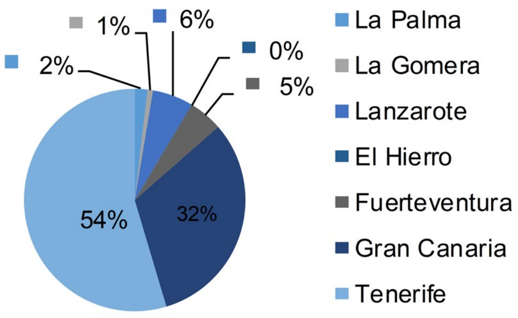

Fig. 3. Treated wastewater volume distribution in the Canary Islands (m^3/d).

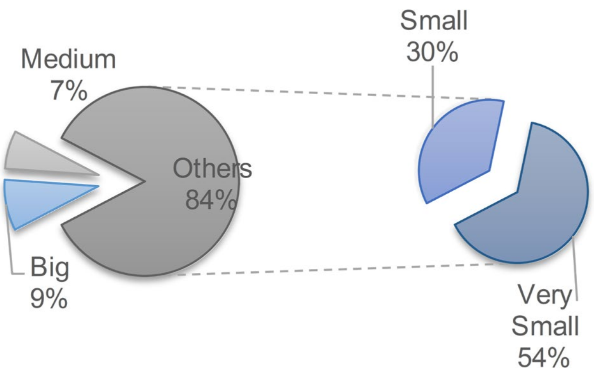

Fig. 4. Distribution of treated wastewater volume by plant capacity range (%).

built is inversely proportional to their size. The low number of big plants (capacity > 10,000 m^3/d), located in the two provincial capital islands (Gran Canaria and Tenerife) which are characterized by larger population centers, is due to the implementation of the previously mentioned Directive 91/271/EC [30].

Fig. 6 compares the number of inhabitants in each island with the theoretical number of people with access to wastewater sanitation according to the total installed wastewater treatment capacity. As can be seen, in some of the islands the installed capacity covers considerably more than the actual number of inhabitants. This is due to the oversizing caused by holiday resorts where the tourist sector doubles the number of inhabitants [55]. On the other hand, the more rural islands (La Palma, La Gomera) manage to reach the equilibrium of the inhabitant/ treated wastewater ratio with other kinds of wastewater treatment systems like filter wells or septic tanks, which are usually located in the most decentralized areas [56,57].

For the evaluation of GHG emissions, the following subsections provide the results obtained from the four plants under study expressed in equivalent annual metric tons of carbon dioxide (Tm_{eq} CO_2/y) for purposes of comparison [41]. Global warming potential conversion factors should be used for the respective components that make up the GHGs emitted by the WWTPs.

The results are classified according to the type of emission (direct or indirect) and the component of the emissions.

3.1. Indirect emissions

Energy consumption is the largest indirect emitter analyzed. As the vast majority of the WWTPs operate with aerobic secondary biological treatments, the most important factors are the pumping and aeration systems. The robust equipment required for the smallest WWTPs to operate results in them having a relatively high energy consumption (Table 8). Table 9 shows the relationship between energy consumption and treated wastewater volume.

With respect to transport emissions, the distance between the treatment plant and the landfill or sludge treatment area (Table 4) clearly has an important impact. Although sludge transport emissions are low in comparison to energy consumption emissions, they are a concern because of the increasing need for WWTP installation in smaller urban centers.

3.2. Direct emissions

The results of direct emissions of CH_4 and N_2O are shown in Table 10. Although the WWTPs use aerobic treatments, methane emissions are confirmed in all plant sizes, confirming the major influence of the climatic conditions (high

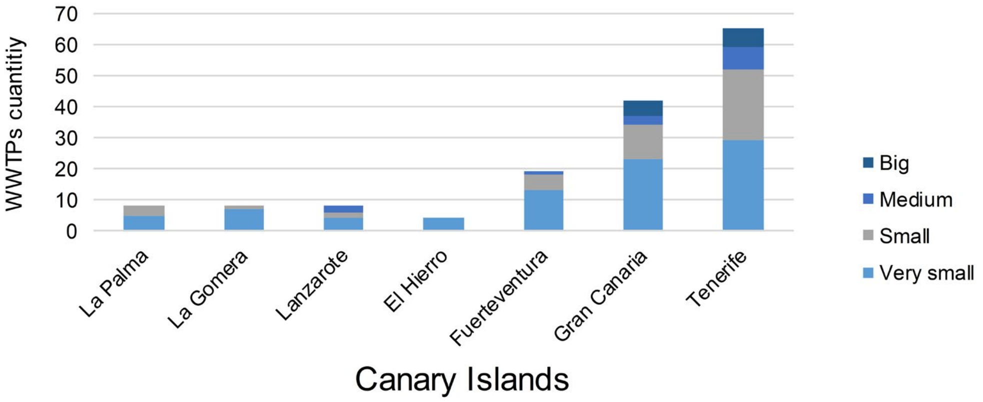

Fig. 5. Canary Islands WWTPs distribution.

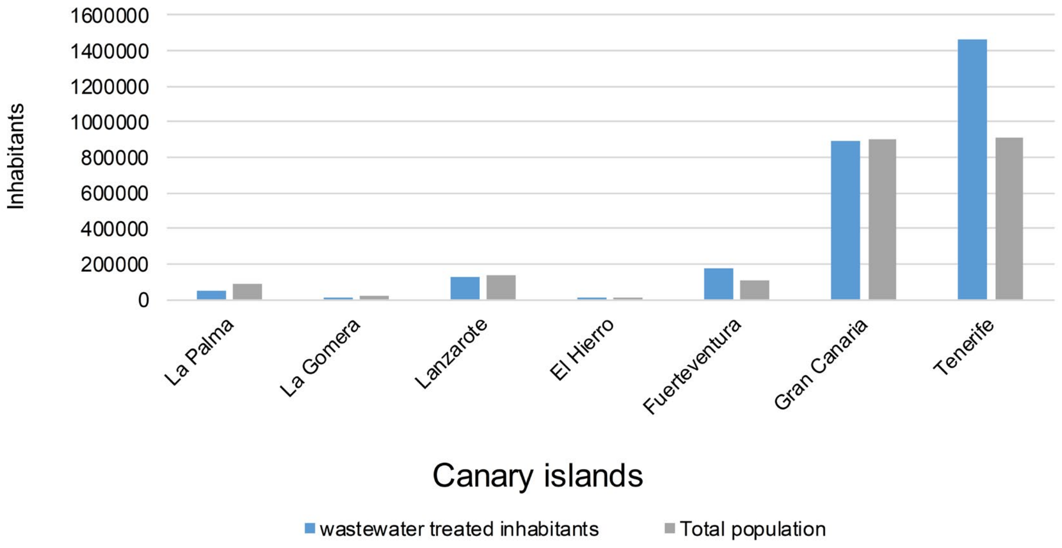

Fig. 6. Access to wastewater sanitation.

Table 8
Indirect emissions

WWTP	Energy consumption emissions (Tm_{eq} CO_2/y)	Sludge transport emissions (Tm_{eq} CO_2/y)
Sureste	2,716	4
Jinámar	1,259	3
Tazacorte	133	5
P. Hidalgo	165	7

temperature) in the islands. The degree of N_2O emissions tends to vary due to the installation of de-nitrification processes in some plants.

Finally, emissions from sludge biodegradation, whether in landfills or in confined spaces, have in most cases low values (Table 10). However, when the total amount of sludge produced in all the WWTPs is considered, as well as the corresponding sludge transport emissions, the resulting value would be a concern. In addition, the European Parliament has called for the progressive banning of landfills before 2020 [58].

3.3. Total emissions

Table 11 summarizes the emissions of the four plants used as case studies. As is widely known, no wastewater treatment plant can carry out its operation without emitting GHGs. However, the quantification of these emissions allows the problem to be considered in a tangible and real way. If the analysis is extended to cover the total emissions produced by a plant over its average useful life (25 y), the resulting values are alarming. As an example, and based on the values shown in Table 11, the smallest and largest size WWTPs considered in this study would emit an estimated total of 7,767 and 446,975 Tm_{eq} CO_2, respectively.

Fig. 7 shows how the respective percentages of direct and indirect emissions vary according to plant size.

Table 9
The ratio between treated wastewater volume and energy consumption (kWh/m^3) of the WWTP case studies

WWTP	Volume (m^3/y)	Energy consumption (kWh/y)	Ratio (kWh/m^3)
Sureste	4,380,000	3,349,255	0.76
Jinámar	3,650,000	1,554,719	0.42
Tazacorte	547,500	164,079	0.30
P. Hidalgo	232,140	203,632	0.87

Table 10
Direct quantified emissions

Treatment process emissions		
WWTP	CH_4 (Tm_{eq} CO_2/y)	N_2O emissions (Tm_{eq} CO_2/y)
Sureste	10,801	1,479
Jinámar	4,980	4,624
Tazacorte	13	9
P. Hidalgo	82	55
Sewage sludge emissions		
WWTPs	BOC emissions (Tm_{eq} CO_2/y)	N_2O emissions (Tm_{eq} CO_2/y)
Sureste	9	48
Jinámar	6	32
Tazacorte	–	–
P. Hidalgo	–	1.7

While there are several ways to reduce these emissions, for the Canary Islands an increased use of renewable energy sources (RES) is a feasible and very attractive option. The islands are excellently suited for the exploitation of RES, with an average 4.68 kWh/m^2/d of solar irradiation,

Table 11
Total quantified emissions

Tm_{eq} CO_2	Sureste	Jinámar	Tazacorte	P. Hidalgo
Indirect emissions	2,720	1,262	138	172
Direct emissions	12,336	9,642	22	138.7
Total	17,879	10,904	160	310.7

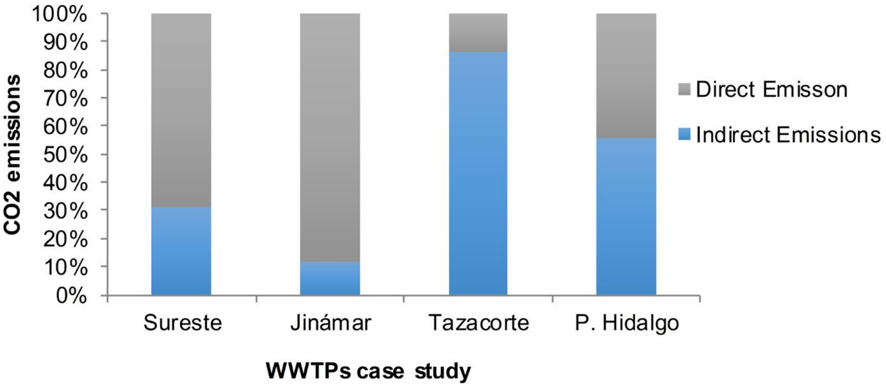

Fig. 7. Percentage of direct and indirect emissions of the analyzed WWTPs.

a 5.5–8 m/s wind speed range in many suitable areas [59] and an average 19–20 kW/m wave energy potential. The integration of these clean technologies, (internal and external to the plant) will be explained and simulated in later publications.

The direct methane emissions are the most difficult to reduce due to the impossibility of changing the ambient temperature. With respect to sludge removal, and given the increasingly more restrictive waste discharge legislation [60], a new approach is required for its treatment (either centralized or in each plant) through the implementation of technologies such as anaerobic digestion to reduce emissions, to generate energy as a by-product (possibly for consumption by the plant itself) and to contribute to enhancing the circular economy in the islands.

A new economic approach is required in the islands, one that interrelates with sustainability and aims to increase the value of the endogenous products, materials, and resources of the application area, enabling them to remain in the economy for the longest possible time. In this regard, European policies are committed to the transition of the linear economy towards a circular model, in which waste generation is minimized. In the particular situation with which this study is concerned, restructuring the management model of WWTPs could be used to facilitate second-generation products.

Until about a year ago, 98.5% of the sludge from the Canary Islands was dumped into landfills [61]. However, in Gran Canaria (responsible for 26% of the sludge in the archipelago), a biomethanation plant has recently been installed to treat the sludge and generate biogas that subsequently generates energy through a combustion process covering 60% of the energy demand of the Ecopark where the plant is located. The next step is to exceed 100% of the energy demand and inject the energy surplus into the insular power grid [62]. The approach that has been taken in Gran Canaria, a highly populated island, took into account the large amount of sludge on the island and its optimized road network. However, specific solutions need to be analyzed for each region on an individual basis, depending on the type of sludge to be treated and whether the objective (nutrient recovery, obtaining compost, obtaining energy, mass reduction, and stabilization, etc.) or technique is economically and technically feasible.

Finally, the selection of the technology used for managing wastewater sludge should have as one of its main criteria evaluation of the environmental footprint. Teoh and Li [63] published a study in 2020 using life cycle assessments of each process. Their conclusions confirm that anaerobic digestion, pyrolysis, and supercritical water oxidation are not only more effective in reducing sludge volume and pollutants but also have lower global warming and toxicity potential.

4. Conclusions

The aim of this study was to quantify and evaluate GHG emissions in WWTPs. The proliferation of this kind of plant has generated a new climate change focus within the islands and other regions characterized by its dependence on external water and energy resources.

For the purposes of GHG emissions quantification in this study, the absence of local/regional guidelines or a comprehensive methodology to calculate the carbon footprint left by WWTPs resulted in the need to use IPCC protocols to obtain many of the results.

According to the results obtained, a typical large capacity plant (>10,000 m^3/d) in the Canary Islands would emit 446,975 Tn_{eq} CO_2 per plant over its estimated 25 y of useful life. After taking into account the number and capacities of all the WWTPs in the islands, the contribution of the archipelago amounts to 228,436 Tn_{eq} CO_2/y.

In terms of indirect emissions, energy consumption is the most intensive emitter in the vast majority of the plants under study, with aerobic processes as the main consumers. Likewise, the robust equipment necessary for the operation of the smaller-sized WWTPs increases their specific energy consumption and consequently their emissions, with percentages of 0.06% compared to 2.42% Tn_{eq} CO_2/m^3 in the largest and smallest size plants, respectively. With respect to the development of improved climate change mitigation, the introduction of the use of RES in WWTPs is a feasible and highly attractive option.

Regarding the transport of sludge, the relative GHG emissions value increases as the size of the plant decreases. This is because the very small plants are located in small municipalities, generally far from landfills. Consequently, the replacement of this type of sludge management model and the incorporation of technologies that facilitate a circular economy must be specifically analyzed to assess whether on-site management outweighs the advantages of centralized management as well as causing a lower environmental impact as a whole.

The direct emissions of the WWTP plants are particularly significant, due not only to the amounts involved but more importantly to their much higher warming potential than CO_2. Of the chemical compounds analyzed, the CH_4 values are more constant than those for N_2O due to the installation of de-nitrification processes in some plants. In this regard, reducing the amount of emissions entails a high degree of difficulty, as the conventional processes of the plants themselves generate it.

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References

[1] IPCC, Working Group I Technical Support Unit, An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty, Intergovernmental Panel on Climate Change, Geneva, Switzerland, 2018.
[2] J.C. Doelman, E. Stehfest, A. Tabeau, H. van Meijl, Making the Paris agreement climate targets consistent with food security objectives, Global Food Secur., 23 (2019) 93–103.
[3] G.M. Locosselli, E.P. de Camargo, T.C.L. Moreira, E. Todesco, M. de Fátima Andrade, C.D.S. de André, P.A. de André, J.M. Singer, L.S. Ferreira, P.H.N. Saldiva, M.S. Buckeridge, The role of air pollution and climate on the growth of urban trees, Sci. Total Environ., 666 (2019) 652–661.
[4] L. Onofri, F. Bianchin, V. Boatto, How to assess future agricultural performance under climate change? A case-study on the Veneto region, Agric. Food Econ., 7 (2019) 16.
[5] J.F.T. de Souza, S.A Pacca, How far can low-carbon energy scenarios reach based on proven technologies?, Mitigation Adapt. Strategies Global Change, 24 (2019) 687–705.
[6] C. de Guttry, D. Süsser, M. Döring, Situating climate change: psychological distances as tool to understand the multifaceted dimensions of climate change meanings, Geoforum, 104 (2019) 92–100.
[7] M. Wang, C. Feng, Impacts of oriented technologies and economic factors on China's industrial climate mitigation, J. Cleaner Prod., 233 (2019) 1016–1028.
[8] G. Bachner, J. Mayer, K.W. Steininger, Costs or benefits? Assessing the economy-wide effects of the electricity sector's low carbon transition – the role of capital costs, divergent risk perceptions and premiums, Energy Strategy Rev., 26 (2019) 100373.
[9] IEA, World Energy Outlook 2016, International Energy Agency, Paris.
[10] E.S. Spang, W.R. Moomaw, K.S. Gallagher, P.H. Kirshen, D.H. Marks, The water consumption of energy production: an international comparison, Environ. Res. Lett., 9 (2014) 105002.
[11] C.P. Tan, Q. Zhi, The energy-water nexus: a literature review of the dependence of energy on water, Energy Procedia, 88 (2016) 277–284.
[12] J.L. Peña, R. Rodríguez, Are EU's climate and energy package 20-20-20 targets achievable and compatible? Evidence from the impact of renewables on electricity prices, Energy, 183 (2019) 477–486.
[13] P. Tsafack, D. Ngwashi, B. Ducharne, E. Tanyi, Greenness percentage of the said green renewable energy: a case study, Energy Rep., 5 (2019) 979–986.
[14] A. Rahil, R. Gammon, N. Brown, J. Udie, M.U. Mazhar, Potential economic benefits of carbon dioxide (CO_2) reduction due to renewable energy and electrolytic hydrogen fuel deployment under current and long term forecasting of the social carbon cost (SCC), Energy Rep., 5 (2019) 602–618.
[15] Y.L. Liu, M. Hejazi, P. Kyle, S.H. Kim, E. Davies, D.G. Miralles, A.J. Teuling, Y.J. He, D. Niyogi, Global and regional evaluation of energy for water, Environ. Sci. Technol., 50 (2016) 9736–9745.
[16] P.T. Vo, H.H. Ngo, W. Guo, J.L. Zhou, P.D. Nguyen, A. Listowski, X.C. Wang, A mini-review on the impacts of climate change on wastewater reclamation and reuse, Sci. Total Environ., 494 (2014) 9–17.
[17] J. Bosque-Maurel, J. Vilá-Valentí, Geography of Spain, Planeta Publishing House, Barcelona, 1990.
[18] M. de Terán, L.S. Sabaris, Regional Geography of Spain, Ariel Publishing House, Barcelona, 1987.
[19] G. Morales-Matos, The Canary Islands, an isolated region?, Assoc. Spanish Geogr. Bull., 32 (2001) 155–175.
[20] Articles 349 and 355 of the Treaty on the Functioning of the European Union (TFEU), The Outermost Regions, Technical Sheets on the European Union, Estrasburgo, France, 2016.
[21] Great Virtual Encyclopedia of the Canary Islands: Nature and Culture, GEVIC Project, Rincon Association for the Study of Social Creativity, Canary Islands, Spain, Available at: http://www.gevic.net/, access date: 02/02/2015.
[22] Canary Islands Institute of Statistics, Indicators for Years on Water Supply and Treatment in Canary Islands, Total Volume of Water Controlled and Distributed to Users, Las Palmas, 2013.
[23] J.J. Braojos, I. Farrujia, J.D. Fernandez, Tenerife Water Resources to Climate Change, Island Council of Aguas de Tenerife, Canary Islands, Spain, 2006.
[24] United Nations, Water for a Sustainable World. Report on Water Resources in the World, Italy, 2015.
[25] J.M. Veza, Desalination in the Canary Islands: an update, Desalination, 133 (2001) 259–270.
[26] Government of the Canary Islands, Canary Islands Energy Plan, Ministry of Industry, Commerce and New Technologies, Canary Islands, Spain, 2007.
[27] J.R. Stokes, A. Horvath, Energy and air emission effects of water supply, Environ. Sci. Technol., 43 (2009) 2680–2687.
[28] Y.F. Gu, Y.-N. Dong, H.T. Wang, A. Keller, J. Xu, T. Chiramba, F.T. Li, Quantification of the water, energy and carbon footprints of wastewater treatment plants in China considering a water–energy nexus perspective, Ecol. Indic., 60 (2016) 402–409.

[29] N. Sununta, R. Kongboon, S. Sampattagul, GHG evaluation and mitigation planning for low carbon city case study: Dan Sai Municipality, J. Cleaner Prod., 228 (2019) 1345–1353.

[30] Directive 91/271/EC of the European Economic Community Council, May 21, 1991.

[31] Spanish Association of Supply and Sanitation Public Operators, Wastewater Treatment Report in Spain, South Blue Tide, Spain, 2013.

[32] K. Aikens, M. McKenzie, P. Vaughter, Environmental and sustainability education policy research: a systematic review of methodological and thematic trends, Environ. Educ. Res., 22 (2016) 333–359.

[33] Ministry of Agriculture, Food and Environment of the Government of Spain, Roadmap of Fuzzy Sectors A-2020, Executive Summary, 2014.

[34] European Commission, Europe 2020: A Strategy for Smart, Sustainable and Inclusive Growth, Working Paper, Brussels, 2010.

[35] Intergovernmental Panel on Climate Change, Working Group III, Contribution to the Fifth Assessment Report, Mitigation of Climate Change, New York, 2014.

[36] J. Bylka, T. Mroz, A review of energy assessment methodology for water supply systems, Energies, 12 (2019) 4599.

[37] California Air Resource Board, Local Government Operations Protocol: For the Quantification and Reporting of Greenhouse Gas Emissions Inventories, United States, 2010.

[38] U.S. Environmental Protection Agency, Greenhouse Gas Emissions Estimation Methodologies for Biogenic Emissions from Selected Source Categories: Solid Waste Disposal Wastewater Treatment Ethanol Fermentation, United States, 2010.

[39] O.K. Nielsen, M.S. Plejdrup, M. Winther, M. Nielsen, S. Gyldenkærne, M.H. Mikkelsen, R. Albrektsen, M. Thomsen, K.H. Hjelgaard, H. Katja, P. Fauser, H.G. Bruun, V.K. Johannsen, T. Nord-Larsen, L. Vesterdal, I. Callesen, O.H. Caspersen, N.S. Bentsen, E. Rasmussen, S.B. Petersen, T.M. Olsen, M.G. Hansen, Denmark's National Inventory Report 2019: Emission Inventories 1990–2017-Submitted Under the United Nations Framework Convention on Climate Change and the Kyoto Protocol, Denmark, 2019.

[40] S. Eggleston, L. Buendia, K. Miwa, T. Ngara, K. Tanabe, IPCC Guidelines for National Greenhouse Gas Inventories, Japan, 2006.

[41] K. Pagilla, A Systematic Approach to Establishing Carbon Footprints for Wastewater Treatment Plants, Water Environment Federation, Alexandria, Washington DC, U.S., 2009.

[42] C. Hill, Discussion Paper for a Wastewater Treatment Plant Sector Greenhouse Gas Emissions Reporting Protocol, Prepared for the California Wastewater Climate Change Group and the Bay Area Clean Water Agencies, Oakland, 2007.

[43] G. Mannina, G. Ekama, D. Caniani, A. Cosenza, G. Esposito, R. Gori, M. Garrido-Baserba, D. Rosso, G. Olsson, Greenhouse gases from wastewater treatment — a review of modelling tools, Sci. Total Environ., 551–552 (2016) 254–270.

[44] M. Molinos-Senante, F. Hernández-Sancho, R. Sala-Garrido, G. Cirelli, Economic feasibility study for intensive and extensive wastewater treatment considering greenhouse gases emissions, J. Environ. Manage., 123 (2013) 98–104.

[45] Ministry of Industry, Energy and Tourism of Spain, Royal Decree 738/2015, of 31 July, by Which the Activity of Electricity Production and Clearance Process in Electrical Systems of Non-peninsular Territories is Regulated, Spain, 2015.

[46] T. Janse, P. Wiers, The climate footprint: a practical tool to address climate change, Water Sci. Technol., 56 (2007) 157–163.

[47] Spanish Institute for the Diversification and Energy Saving, CO_2 Emission Factors and Coefficients Step by Primary Energy from Different Sources Final Energy, Spain, 2014.

[48] C. Remy, B. Lesjean, J. Waschnewski, Identifying energy and carbon footprint optimization potentials of a sludge treatment line with life cycle assessment, Water Sci. Technol., 67 (2013) 63–73.

[49] Catalonia Generalitat Office, Interdepartmental Commission on Climate Change, Practical Guide for the Calculation of Greenhouse Gas (GHG) Emissions, Spain, 2015.

[50] Metropolitan Water Supply and Sanitation Company of Seville, Inventory of Greenhouse Gas Emissions in the Urban Water Cycle, Spain, 2014.

[51] Intergovernmental Panel on Climate Change, Guidelines for National Greenhouse Gas Inventories, Vol. 5 – Waste, Chapter 6 – Wastewater Treatment and Discharge, Switzerland, 2006.

[52] Canary Islands Government, Ministry of Infrastructure, Transport and Housing General Water Directorate, Ground-water Control Program, Water Framework Directive, Canary Islands, Spain, 2006.

[53] Intergovernmental Panel on Climate Change, Guidelines for National Greenhouse Gas Inventories, Vol. 5 – Waste, Chapter 2 – Waste Generation, Composition and Management Data, Switzerland, 2006.

[54] Intergovernmental Panel on Climate Change, Guidelines for National Greenhouse Gas Inventories, Volume 4: Agriculture, forestry and other land use. Chapter 11. N_2O emissions from managed soils, and CO_2 emissions from lime and urea application, 2006.

[55] J.R.M Rodríguez, M.A.S. Turégano, Competitiveness and quality in the sun and beach tourist destinations. The case of the Canary Islands, Cuadernos de turismo, 22 (2008) 123–143.

[56] Ministry of Public Works, Housing and Water of the Island Council of La Palma, Decree 166/2001, of July 30, Which Approves the Insular Hydrological Plan of La Palma., 2001.

[57] Ministry of Public Works, Housing and Water of the Island Council of La Gomera, Decree 101/2002, of July 26, Which Approves the Insular Hydrological Plan of La Gomera, 2002.

[58] G.-J. Gerbrandy, The EP Calls for the Gradual Elimination of Landfills and the Incineration of Recyclable Materials, Initiative Report of the European Parliament, European Commission, Brussels, Belgium. Available at: http://www.europarl.europa.eu/, access date: 04/10/15.

[59] R. Calero, J.A. Carta, Action plan for wind energy development in the Canary Islands, Energy Policy, 32 (2004) 1185–1197.

[60] M. Hu, L. Gao, Z.H. Chen, C.F. Ma, Y. Zhou, J. Chen, S. Ma, M. Laghari, B. Xiao, B.P. Zhang, D. Guo, Syngas production by catalytic in-situ steam co-gasification of wet sewage sludge and pine sawdust, Energy Convers. Manage., 111 (2016) 409–416.

[61] J.J. Sadhwani, B. Del Río-Gamero, Valorization of Sewage Sludge as Second Generation Products, Towards a Circular Economy, 7th International Congress on Energy and Environment Engineering and Management (CIIEM7), Canary Islands, Spain, 2017.

[62] J. Quesada, La autosuficiencia energética de los ecoparques empieza la cuenta atrás, Canarias7 Press Journal, Canarias 7 Press Journal, Canary Islands, Spain, Available at: https://www.canarias7.es/, Access date: 11/05/2019.

[63] S.K. Teoh, L.Y. Li, Feasibility of alternative sewage sludge treatment methods from a lifecycle assessment (LCA) perspective, J. Cleaner Prod., 247 (2020) 119495.