Master Thesis

Fugitive methane emissions in Spain. Calculation, comparison and impact

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Abstract: The purpose of this article is to present a guide of methane (CH4) emissions from different treatment centers within Spain. To carry out this study, estimation calculation methods modelled with IPCC parameters have been used. The methane emissions that have been estimated come from biogas plants, landfills and wastewater treatment stations, all of which treat waste as raw materials. For estimation, knowledge of the type and amount of input residues as well as locational context parameters has been required. The estimated values obtained have been compared with the registered data declared for each installation, with the aim of making a numerical comparison that allows understanding the estimation error and the reliability of the calculation methods. The ultimate goal of this study is to improve the understanding of the environmental impact of methane emissions into the atmosphere through these facilities and thus be able to take future correction and prevention measures, such as the case of methane burning torches to reduce it to carbon dioxide, potentially less polluting.

Keywords: Methane; fugitive emissions; landfills; residues; wastewater plants; biogas plants.

1. Introduction

Greenhouse gases (GHG) are currently one of the biggest environmental concerns due to their involvement with the global warming that threatens the earth. Among the gases that make up that list, carbon dioxide (CO2) and methane (CH4) are among the most common. CO2 is the most abundant since it is the most oxidized form of carbon that can be found and is generated from oxidation reactions. For its part, CH4 has a potential 28 times greater than CO2, which is why the study of its emissions, and their prevention is essential [1].

Anaerobic digestion or decomposition (AD) is a waste management process for biodegradable materials which a stabilized digestate residue and a gas product consisting mainly of CO2 and CH4. Methane from the waste sector accounts for around 3% of global anthropogenic GHG emissions [2].

The CH4 emissions that correspond to those generated by landfills add up to a total of 8% of the anthropogenic totals, most of them due to fugitive emissions [3]. Besides, it is expected to increase by 25% in the next 15 years, increasing from 30 MtCH4 to 43 MtCH4 [4]. In Europe, landfills are the second largest anthropogenic CH4 emission source [5].

In order to reduce environmental impacts and evaluate the efficiency of gas recovery systems, managing fugitive emissions from landfills is one of the priorities for the waste industry. It would be necessary to carry out direct measurements on the emissions since the models carry some errors. Nevertheless, the analysis of fugitive emissions from landfills is strongly complex due to the large surfaces they occupy and the spatial and temporal variability, the flow data are punctual and often cannot be transported to other areas or sectors of the same landfill [6].

Anaerobic digestion is also found in wastewater treatment plants (WWTP) for sewage sludge stabilisation, where the organic matter of sewage sludge is converted into biogas, which in some cases, is used for heat and electric production (co-generation). CH4 emission sources can be found in both water and sludge. Up to 26% of the carbon footprint of the whole WWTP (36 kg CO2e/(PE · y)) can be attributed to methane emissions from wastewater treatment and mainly from sludge treatment [7]. A study affirms that 75% (27 kg CO2e/(PE y)) of climate-relevant emissions from WWTP come from methane emissions from sludge treatment, in which 6% comes from raw sludge and 94% from the digested one [8]

Regarding biogas plants, recent studies have determined that methane leaks can be the source of significant fugitive methane emissions from various locations [9]. Nevertheless, the surged growth of the biogas industry creates new challenges about emissions monitoring, quantification and reduction.

2. State of the Art

Landfills

The measurement of methane emissions in landfills is highly complex and imprecise, since it involves large areas with a large spatial and temporal variability. CH4 measurements are made from the surface of the landfill to several kilometers away and over different time scales, from minutes to months.

Measuring at the surface has the advantage that there is no interference with other CH4 sources around, but it has the disadvantage of extrapolating emissions homogeneously over a very large area. The most used methods to measure CH4 emissions from landfills are presented in the following table 1 [10]:

Table 1. The most common methods used to identify and quantify CH4 emissions from landfills.

Distance	Method
Surface	Screening
1 m^2	Surface camera
100 m^2	Eddy Covariance
10.000 m^2	Radial Plume Mapping
Entire landfill	Trace gas dispersión / Aerial mass balance

Measurements of methane emissions in a landfill can be carried out using qualitative or quantitative techniques. Qualitative techniques seek to locate landfill "hotspots" or determine surface emission patterns with potentially high CH4 emissions. These techniques should be used in combination with the quantitative techniques; however, they can be useful for establishing field experimental designs, verifying the integrity of cover materials and planning site maintenance. Among them stand out:

- Portable CH4 analyser
- Field infrared survey
- UAV survey
- Visual inspection

Each of them has its advantages, disadvantages, and limitations. This article will not go into detail about the properties of each one, but it is worth mentioning that the main advantage of these techniques is that they are fast and simple. Below is a series of quantitative techniques that have been developed and are currently used in different countries [A]:

- Vertical soil gas concentration profiles
- Closed surface flux chambers
- Open surface flux chambers

- Eddy covariance
- Stationary mass balance
- Radial plume mapping
- Mass balance using aerial measurements
- Stationary tracer gas dispersion
- Dynamic tracer gas dispersion
- Differential absorption LiDAR (DIAL)
- Inverse modelling – stationary
- Inverse modelling – dynamic
- Inverse modelling – aerial

Initially, methane (CH4) emission measurements from landfills were made for research purposes, to obtain specific emissions over a place and time, or to monitor variability. At the present time, CH4 emissions reported for regulatory purposes are usually based on models, but they are estimated using waste data, these emissions are commonly overestimated due to a conservative approach and a lack of actual knowledge relating to deposited waste and CH4 oxidation.

The main challenges about quantifying landfill CH4 emissions are high spatial and temporal emission variations. A mass emission method is required to quantify CH4 emission from an entire landfill rather than a surface emission factor method. DIAL and tracer gas dispersion are mass emission methods. Applying the, accordingly, total CH4 emissions from the landfill are measured and thus the challenge of spatial variability of emissions is avoided. Both the DIAL technique and the tracer gas dispersion method have been demonstrated successfully in several landfill studies. However, the DIAL method uses very complicated and expensive equipment, which is a barrier to routine measurements. On the other hand, the tracer gas dispersion method takes an easier approach and uses more affordable equipment. Radial plume mapping, eddy covariance and the stationary mass balance method are affected by the complex topography of the landfill and only cover a fraction of the landfill, therefore, extrapolation to the entire landfill area is needed, which adds more uncertainty to the measurements.

Calculation of methane captured in landfills can be easily done if flow meters are used in the landfill gas collection system and its composition is analyzed. However, field conditions can make it difficult to calculate diffuse emissions. Therefore, to date, the most common is to model landfill gas production to estimate diffuse emissions.

The chosen model must take into account the composition of the waste. The amount of gas produced by a landfill (and therefore the amount of greenhouse gases) and its composition depend on several factors:

- The amount of waste dumped.
- The age of the dumped waste.
- The composition of the waste dumped.
- The environmental physical-chemical conditions (humidity, temperature, pH, etc.).
- The efficiency of the gas collection system from the landfill.

- The type of cover.

Below, in image 1, a map of Spain is shown with the different points that correspond to landfills..

Image 1. Representation of the different landfills that are distributed throughout Spain [11].

Biogas Plants

In the last decade, more waste has been directed to alternative treatments such as biogas plants in order to reduce landfills [12]. The biogas sector in Europe has grown tremendously in the past. In all likelihood, the biomethane market (upgrading of biogas to natural gas quality) will strengthen against the general trend. At the end of 2018, more than 18,000 biogas plants were in operation [13]. The most used technology in this type of installation is anaerobic digestion (AD) in the agricultural sector with concrete tanks with integrated membrane domes with generally two layers as a biogas storage system. The International Energy Agency bioenergy report that most are associated with municipal wastewater treatment plants and landfill gas power units, approximately 52 and 129 plants respectively. In Spain, the raw material with which the biogas plants operate come from agricultural and industrial waste. The main use for biogas is for electricity production, heat and combined heat and power (CHP). Excess biogas is pretended to be flared to reduce the potential methane emissions. Future opportunities exist for intensive livestock and food processing industries in, driven by readily available feedstock from process waste, higher electricity prices and demand for on-site electricity, heat or steam [14].

Main objective using AD technology in the agricultural and energy sector is the reduction of GHG emissions compared to conventional systems. In particular in the energy sector, the GHG reduction efficiency of the AD technology is usually evaluated by means of a life cycle assessment. The measurement sequence that is usually carried out for detected methane fugitives is as follows [15]:

1- On-site approach: It consists of a site survey for identification of unknown emission sources and a quantification step. The leakage and hot spot detection was performed on-site with a slightly different approach for the biogas plants and the landfill. Afterwards a static chamber method was used for emission quantification of selected emission sources.

2- Leakage detection on biogas plants: The survey measurements were initially made by means of an infrared camera in the digesters (Image 1). The instrument uses a range of wavelength. Methane has an absorption and emission maximum in this range. The camera visualizes biogas leaks as a grey cloud using a special image overlay technique which allows remote detection of potentially dangerous leaks. However, the chamber does not provide concentration values and has a relatively small detection limit [16]. Methane concentrations were analyzed by a gas analyzer at the point of emission if accessible.

3- Emission quantification of methane leakages: Methane emission rates from the identified leaks are quantified using a static chamber. Although dynamic chambers are generally more suitable for leak quantification of biogas plant, the flat area of covered anaerobic lagoons allows a simple application of a static chamber to encapsulate the leak.

Once the chamber has enclosed the emission point, the methane concentration increases within the chamber volume. A biogas analyzer is then used to measure the methane concentration.

4- Emission quantification of area sources: The chamber was put on several locations of the surface from the open lagoons and encapsulated small sections thereof. Samples were taken at time different intervals. The surface specific emission mass flow rate is calculated according to an equation that relates the volume and area of the chamber.

The mass flow rates of surface specific emissions from individual measurements were averaged for each measurement. Then, the overall emission rate from the area source is calculated by extrapolation with the surface area.

In this article, it will be used a simpler model that is used for the case of water treatment plants.

Image 2. Infrared image of a biogas leakage from the membrane fixation of the digester of biogas plant [16].

Image 3 shows a map of the Iberian Peninsula with the biogas plants that are in operation. Those under construction and those in the project process have been excluded.

Image 3. Biogas plants currently operating in the Iberian Peninsula [17].

Wastewater Treatment Stations

In treatment plants, the phenomenon of anaerobic digestion also occurs, where the organic matter of the sludge is converted into biogas. As has been commented previously, this gas can be used for the production of heat and electricity. Unfortunately, part of the biogas generated is lost during the process due to leaks, entrainment of gas bubbles and residual gas potential in the digested sludge [18]. Although studies on direct methane emissions from anaerobic digestion reactors are lacking, there are numerous references on methane emission sources from WWTP components in the literature. Among the components of the plant, the following stand out: the thickener, the intermediate storage tank, the previous sludge dehydration, the combined heat and power plant (CHP) and the torch [19].

A reliable method for the continuous measurement of gas emissions at the digester sludge outlet is the Flux-Chamber Method: a gas-tight membrane is used to collect gas emissions from the sludge shaft at the digester's head [20].

The flow chamber spills with a known scavenging flow air by using a compressor, a measurement gas is pumped in, filtered and dried. Methane and carbon dioxide concentrations are measured online using two infrared photometers Image 2. This method is applied for 28 days to continuously quantify digester methane emissions at different organic loading rates.

Figure 1 shows the Flux-Chamber method scheme:

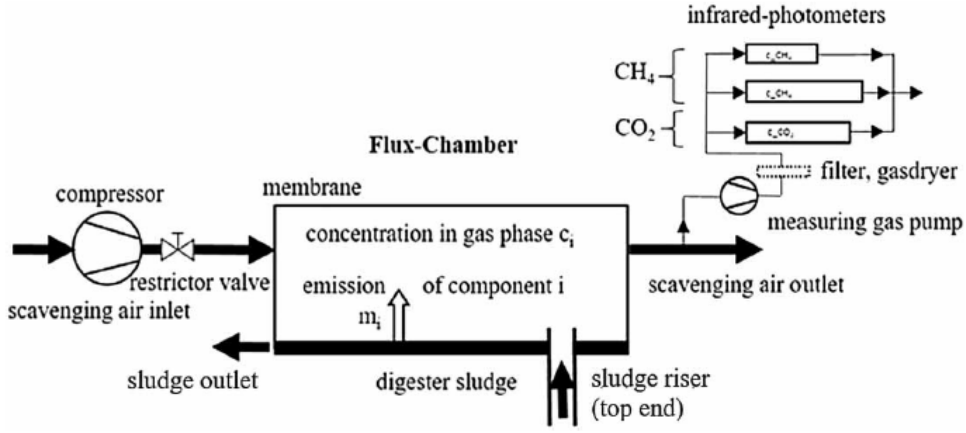
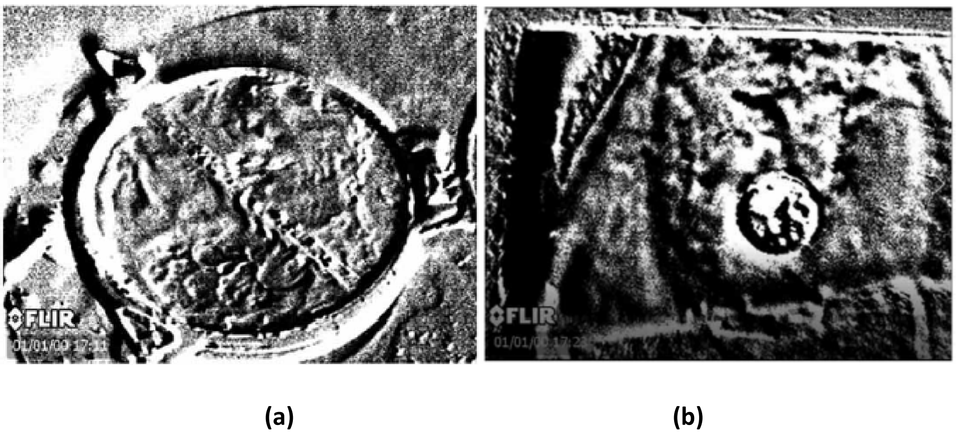


Figure 1. Flow chart of the applied Flux-Chamber method [20].

The balance quality (BQ) is calculated according to equation (1) presented below, where Fj_{out} and Fi_{in} are the in- and outflow COD-mass flows.

$$\boldsymbol{BQ} = \frac{\sum_{j=1}^{n} \boldsymbol{Fjout}}{\sum_{j=1}^{m} \boldsymbol{Fjin}} * \boldsymbol{100}[\%] \qquad (1)$$

This method is commonly used and can be found in many studies carried out for various WWTP around the world. However, to carry out the calculation it is necessary to know all the flows that affect the digester, data that is sometimes tedious to find. Since in this article it has worked with general data on inlet flows, it has been decided to resort to the equation 2 where it is only necessary to know the flow that is treated in WWTP.



(a) **(b)**

Image 4. Images examples of investigated methane point sources leaking manhole sealing and (a) sludge riser's top end at the digester's head (b) [20].

In image 5, the different WWTPs found in the Spanish geography have been represented.

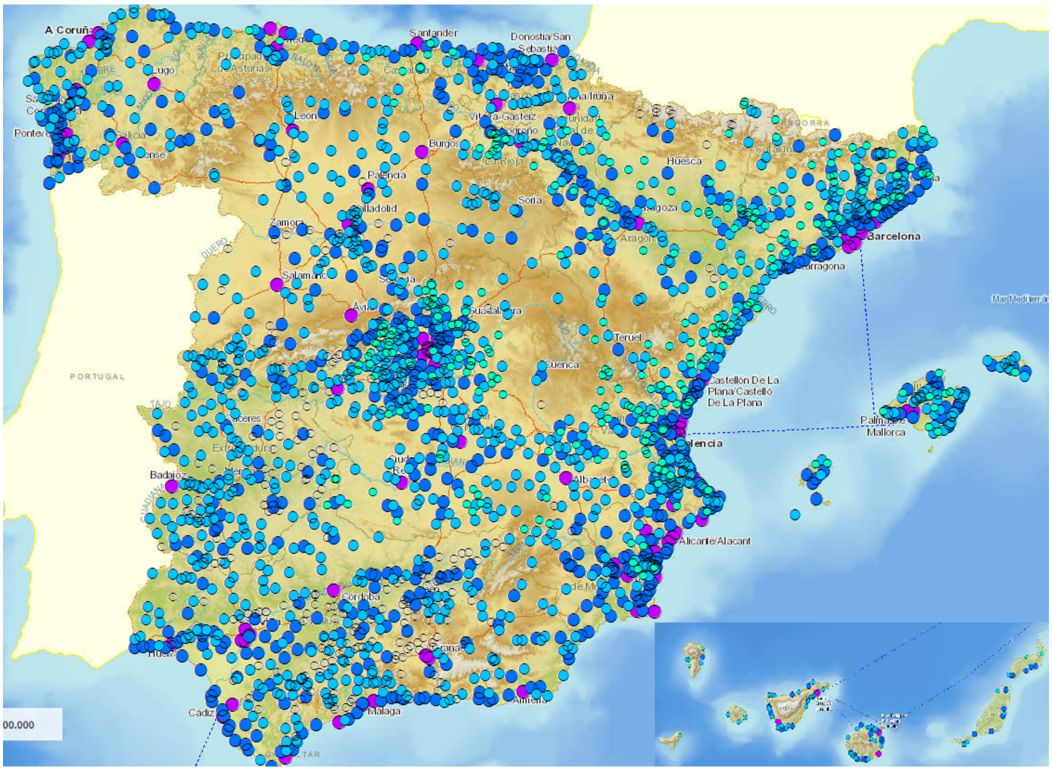


Image 5. Mapping of WWTPs in Spain [21].

3. Objectives

The objective of this project is to determine the impact of different Spanish facilities that use urban waste as a raw material: biogas plants, landfills and WWTP. For this purpose, different calculation methods will be discussed to select the one that best fit a precise estimate and the appropriate parameters will be selected based on the context of each installation. In order to calculate these methane emissions, it will first be necessary to make a list with all the input data for all the selected installations and describe their main characteristics.

The results obtained will be used to compare the registered values of methane emissions and thus be able to analyze the precision of the chosen method.

4. Materials and Methods (Methodology)

Wastewater Treatment Plant

For the estimation of methane emissions in wastewater treatment plants, the equation (1) will be used as recommended by some authors [23]. This formula is the 6.1 equation of the IPCC guidelines:

$$\mathrm{CH4\ emissions} = \mathrm{Bo} * \mathrm{MCF}\,(\mathrm{TOW} - \mathrm{S}) - \mathrm{R} \qquad (2)$$

where Bo is the maximum CH4 producing capacity (kg CH4/kg BOD) (default value: 0.6); MCF is the CH4 correction factor (recommended default value); TOW is the total organics in wastewater entering the treatment facility per year (kg BOD/yr); S is the organic component removed as sludge per year (kg BOD/yr); R is the amount of CH4 recovery (or flared) per year (kg CH4/yr).

The guidelines recognize that only few countries may have data on sludge removal (S) and CH4 recovery (R); in case of no data is, the default values should be zero, resulting in an inaccurate estimation for aerobic treatment facilities with anaerobic digesters for sludge stabilization.

This article collects information on inlet flows of numerous wastewater treatment plants. Given that obtaining specific data on sludge outlet flows is very complicated and, in some cases, there are no accessible data, it has been decided to establish the S value with 25% and the TOW with 30%. This assumption will generate a certain error since each water treatment plant has its own data and they do not always correspond to those that have been established.

Some authors have shown that the use of equation (2) with the IPCC default parameters results in higher emission values than those measured in treatment plants [22-23]. This has led to a study to adjust the value of MCF [24]. The proposed modifications to the IPCC Guidelines are listed in Table 2, corresponding to three new treatment systems entries with their MCF:

Table 2. Summary of the proposed new entries and default MCF values for domestic wastewater treatment, based on Table 6.3 of the IPCC Guidelines [25].

Type of treatment and discharge pathway or system	Comments	Proposed MCF	IPCC's MCF
Centralized, aerobic treatment plant	Must be well managed. Some CH4 can be emitted from settling basins and other pockets.	0.06	0.0
Centralized, aerobic treatment plant with anaerobic sludge digesters	Must be well managed. Some CH4 can be emitted from settling basins and other pockets. Fugitive emissions from digesters are considered.	0.32	This is a new entry in Table 3
Centralized, anaerobic (or anoxic) aerobic treatment plant	Must be well managed. Some CH4 can be emitted from settling basins and other pockets	0.08	This is a new entry in Table 3
Centralized, anaerobic (or anoxic) aerobic treatment plant with anaerobic sludge digesters	Must be well managed. Some CH4 can be emitted from settling basins and other pockets. Fugitive emissions from digesters are considered	0.34	This is a new entry in Table 3

The Figure 2 shows an illustrated scheme of the different MCF:

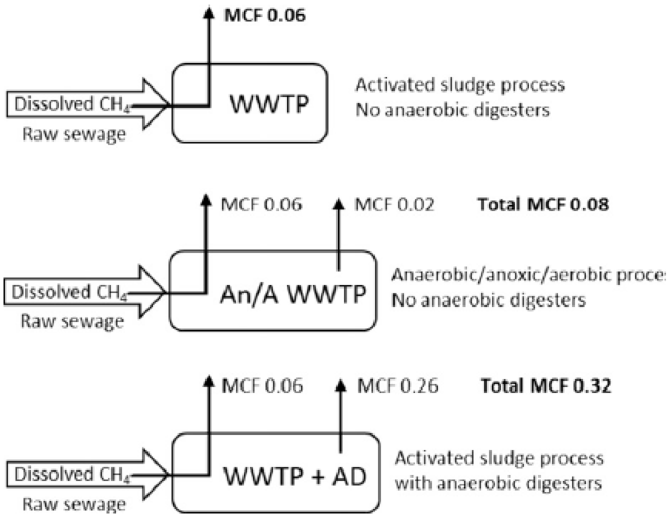


Figure 2. Methane Correction Factors (MCF) [24].

Table3. Default values for wastewater according to IPCC guidelines.

Type of treatment and discharge pathway or system	Comments	MCF	Range
Untreated system			
Sea, river and lake discharge	Rivers with high organics loadings can turn anaerobic.	0,1	0 – 0,2
Stagnant sewer	Open and warm	0,5	0,4 – 0,8
Flowing sewer (open or closed)	Fast moving, clean. (Insignificant amounts of CH4 from pump stations, etc.)	0	0
Treated system			
Centralized, aerobic treatment plant	Must be well managed. Some CH4 can be emitted from settling basins and other pockets.	0	0 – 0,1
Centralized, aerobic treatment plant	Not well managed. Overloaded.	0,3	0,2 – 0,4
Anaerobic digester for sludge	CH4 recovery is not considered here.	0,8	0,8 – 1,0
Anaerobic reactor	CH4 recovery is not considered here.	0,8	0,8 – 1,0
Anaerobic shallow lagoon	Depth less than 2 meters, use expert judgment.	0,2	0 – 0,3
Anaerobic deep lagoon	Depth more than 2 meters.	0,8	0,8 – 1,0
Septic system	Half of BOD settles in anaerobic tank.	0,5	0,5
Latrine	Dry climate, ground water table lower than latrine, small family (3-5persons)	0,1	0,05 – 0,15
Latrine	Dry climate, ground water table lower than latrine, communal (many users)	0,5	0,4 – 0,6
Latrine	Wet climate/flush water use, ground water table higher than latrine	0,7	0,7 – 1,0
Latrine	Regular sediment removal for fertilizer	0,1	0,1

Biogas Plants

The method for calculating methane emissions for biogas plants will be similar to that used for wastewater treatment plants, that is, the same equation (2) will be used. This assumption is due to the fact that the raw material that enters the biogas plants is similar to the WWTP and its digester has the same operation.

Landfills

By contrast, in the case of landfills, the calculation method is somewhat more complex and detailed. The equation used takes into account that methane is generated but part of it is oxidized and a large part is recovered or eliminated [26]:

$$\text{CH4 emitted} = \text{CH4 generated} - \text{CH4 collected} - \text{CH4 oxidised} \qquad (3)$$

To do this, it is necessary to obtain the value of CH4 generated. To calculate this value, it has been obtained by avoiding zero-order models (or standard emission factors) since they generate very imprecise results. This is because they only take into account the tons dumped in the year of the calculation. They do not take into account the complexity of the specific conditions of the landfill. his model takes into account the filling history of the landfill or the average annual inflows and its useful life. They are based on kinetic equations of the first degree. The most used: Landgem model, GasSim, Level II (IPCC) and ADEME.

They all start from this first-order kinetic equation (4):

$$Q_{CH4} = L_0 * M * k * e^{-k(t-x)} \qquad (4)$$

where QCH4: Amount of methane produced per year (m3/year), LO: methane generation potential (m3CH4/t of waste), M: tons of waste dumped (t), X: year in which the waste is deposited and t: year of the emissions inventory (t greater than or equal to x).

The following figure shows a scheme by way of comparison between the model of order zero and order one for the IPCC method.

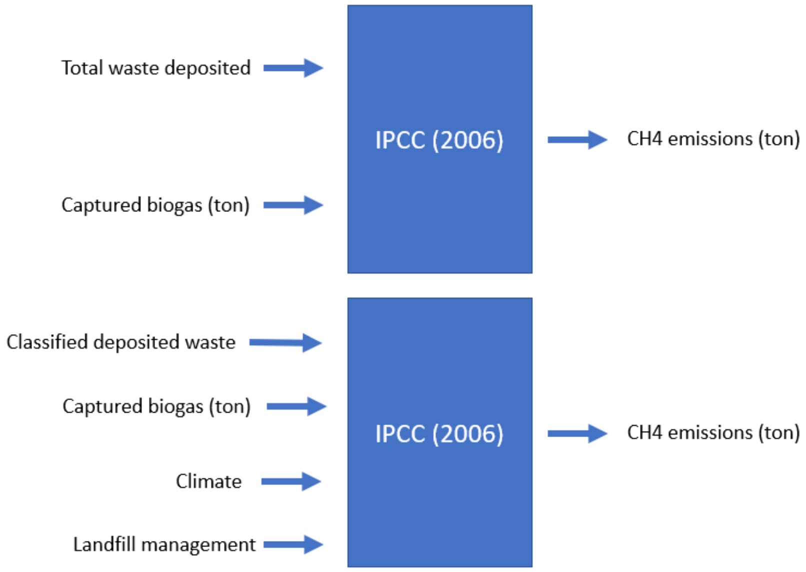


Figure 3. Scheme of the zero order model (top) and first order model (bottom).

In order to choose one of the methods mentioned above, a table has been prepared with some of the possible advantages and disadvantages to analyze which method best covers some important features.

Table 4. Some advantages and disadvantages of the different first-order models.

	IPPC (Level 2)	**ADEME**	**GasSIM**
Is the fact that part of the biogenic carbon fraction is not degraded taken into account?	Yes	Yes	Yes
Is sequestered carbon calculated and a value presented?	Yes	No	No
Can the value be calculated accurately (fraction-by-fraction degradability parameters available)?	Yes	No	Yes
Can the value be calculated globally for the entire waste mass (for example, is the mean degradability parameter provided for MSW)?	Yes	No	Yes

In view of the results obtained in Table 4, it has been decided to use the IPCC model. It is also the one used to calculate methane emissions in landfills in Spain. In order to perform the calculation correctly, a generic waste composition based on the literature had to be selected. Each landfill will have a different composition depending on the climatic zone and the type of population to which it supplies the service. The following table shows the genetic composition of the residue that has been used for the calculations of methane emissions [27].

Table 5. Composition of the waste that reaches the landfill [27].

Residue	Composition (%)
Textiles	0
Paper	6
Parks and gardens	5
Non-food organic	35
Food	40
Wood	1
Compost rejection	13
Sewage sludge	0

The calculation sequence to use is shown below:

The first thing is to calculate the amount of degradable organic carbon (DDOCmdT) that can be decomposed from a waste for the year T (Gg):

$$DDOCmd_T = W_T * DOC * DOCf * MCF \quad (5)$$

WT is the amount of residues deposited in tons. DOC is degradable organic carbon during the year of deposit (fraction), in other words, it is the content of organic matter that each type of waste contains. It can be estimated following the table 6:

Table 6. DOC values for the different classes of waste [28].

IPPC 2006 model classification		New classification	
Residue	**DOC**	**Residue**	**DOC**
Textiles	0,24	Textiles	0,24
Paper	0,4	Paper	0,4
Parks and gardens	0,2	Parks and gardens	0,2
non-food organic		non-food organic	
Food	0,15	Food	0,15
Wood	0,43	Wood	0,43
Compost rejection	-	Compost rejection	0,12
Sewage sludge	0,05	sewage sludge	0,05

DOCf is fraction of DOC that can be decomposed under anaerobic conditions (fraction). In turn, a table with values for the estimation of its parameter is also followed:

Table 7. DOCf estimate for waste components (paper, wood, food, and yard trimmings) [28].

Residue	DOCf
Textiles	0,4
Paper	0,44
Parks and gardens	0,45
Non-food organic	
Food	0,58
Wood	0,61
Compost rejection	
Sewage sludge	

Finally, the thermal MCF refers to the methane correction factor (fraction). This value varies depending on the type of landfill. Table 8 reflects different MCF values for each type of landfill.

Table 8. Value of the MCF parameter depending on the type of landfill [28].

Landfill type	MCF
Managed anaerobic	1
Managed semi-anaerobic	0,5
Unmanaged (>5m depth)	0,8
Unmanaged (<5m depth)	0,4

With all these parameters, DDOCmdT values can be obtained for each type of waste. The next step is to calculate DDOCmaT: cumulative DDOCm at the end of year T (Gg).

$$DDOCma_T = DDOCmd_T + DDOCma_{T-1} * e^{-k} \quad (6)$$

To calculate this parameter, it is only necessary to use the DDOcm of the year T and previous ones plus a new parameter: k.

K is reaction rate constant (year -1). It will be necessary to go to table 9, which shows different values of the contrast depending on the type of waste and climatic zone.

Table 9. Values of the rate constant of methane generation (k). [28]

	Climatic zone			
Residue	**Warm wet**	**Warm dry**	**Tropical wet**	**Dry tropical**
Textiles	0,06	0,04	0,07	0,045
Paper	0,06	0,04	0,07	0,045
Parks and gardens	0,1	0,05	0,17	0,065
non-food organic	0,1	0,05	0,17	0,065
Food	0,185	0,06	0,4	0,085
Wood	0,03	0,02	0,035	0,025
Compost rejection	0,185	0,06	0,4	0,085
Sewage sludge	0,185	0,06	0,4	0,085

The next step is to calculate the parameter DDOCm decompT, which is DDOCm decomposed during the year T (Gg).

$$DDOCm\ decomp_T = DDOCma_{T-1} * (1 - e^{-k}) \quad (7)$$

Finally, the methane generated can be calculated with equation 8:

$$CH4\ generated_T = DDOCm\ decomp_T * F * \frac{16}{12} \quad (8)$$

Where F is volumetric fraction of methane in generated landfill gas (fraction) and according to the literature a value of 50% is assumed.

To generate the value of methane emitted into the atmosphere, it is necessary to return to equation 2, which considers the recovered and oxidized methane. If the recovered value is not available, it will be considered zero. For its part, the value of oxidized methane is considered to be 10% generically.

In order to understand the aforementioned calculation sequence, a block diagram has been prepared that explains the steps followed with all the parameters involved.

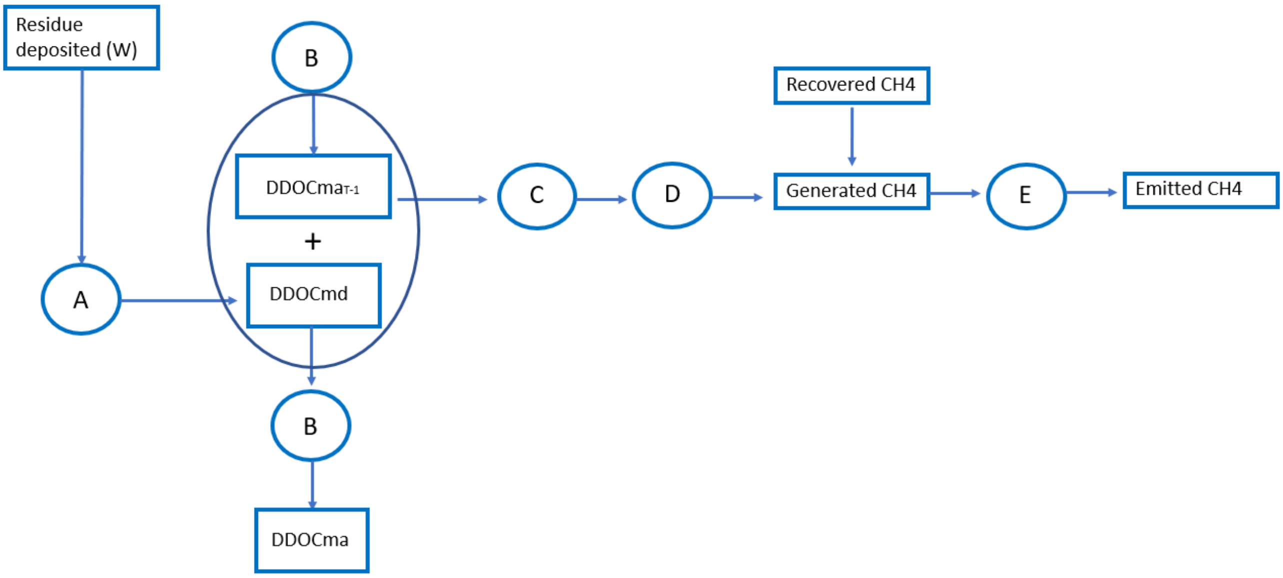


Figure 3. Calculation scheme using block diagram [28].

5. Results and Discussion

33 biogas plants, 87 WWTPs and 119 landfills have been studied. Those facilities that present data or have an appreciable capacity have been chosen, thus ignoring those that are small in size.

The results obtained for fugitive methane emissions can be found in annexes A, B and C for biogas plants, treatment plants and landfills, respectively. They also reflect the officially registered published emissions data. In this way it has been possible to make a comparison that allows us to see the magnitude of error with the calculation estimate.

This comparison is reflected in figure 5 where the data obtained has been compared with the calculations and the recorded data of emissions of each installation. As can be seen, the difference is very significant, especially in the case of the WWTP, where it reaches almost 100%.

The data obtained is represented in the following figures and tables. Figure 4 has qualitatively represented the emissions generated by each type of waste within the landfill, in such a way that it is possible to get an idea of how each type contributes to the total emissions.

Finally, table 10 shows the total annual data on methane emissions for each facility.

Figure 4. Graphic representation of the contribution of each residue to the methane emissions of the landfill.

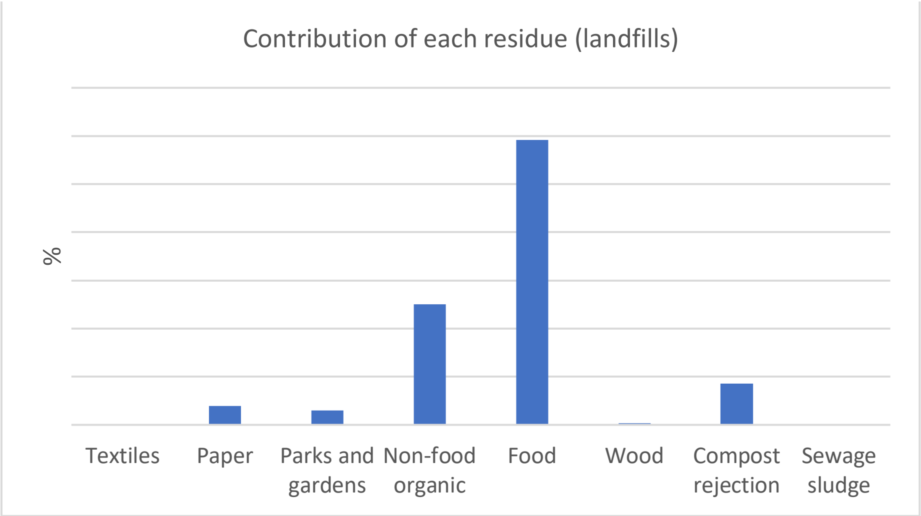
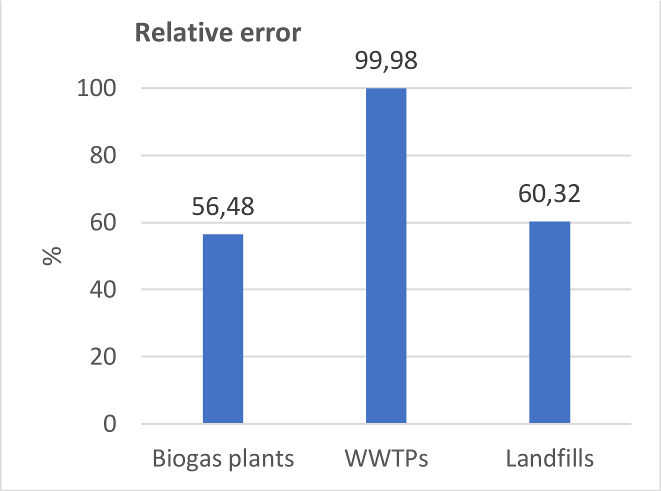


Table 10. Annual methane emissions.

	m³/year
Biogas plants	30.412
WWTPs	20.304.369
Landfills	15.009.302

Although these data are based on many assumptions and estimates, they can be used as a reference for studies of environmental impacts and how each facility contributes to greenhouse gases.

Figure 5. Relative error between the estimated value with calculations and the officially registered value.



The main reasons that lead to such a large error are as follows:

- In all the facilities it has been decided to set the value of recovered methane (R) as zero, since no value has been available. Obviously, this value sufficiently outlines the result, since, as previously mentioned, almost all the facilities have a methane recovery system, either in a flare or as electricity production.
- The officially recorded values are also the result of an estimated calculation, not of values taken in situ with special devices. In addition to this, several installations do not have this data, so they have not entered the comparison.
- The oxidation factor has been set generically at 10%, according to the literature.
- Regarding biogas plants, the initial data is scarce and there are not many values of inlet flows for certain installations. This condition further increases the uncertainty and the error produced. This lack of information is due to the small number of biogas plants and the lack of regulation that currently exists.
- In the case of WWTPs and biogas plants, the values of S and R have been set as 25% of the input organic material and 0, respectively. This assumption is due to lack of information. This, of course, alters the result.
- For its part, in the case of landfills, it is vitally important to understand the large area they occupy and how complicated and imprecise it is to obtain a reliable value. Even with in situ measurements, the data is highly distorted due to spatial and temporal variability. The calculations are a reflection of several parameters that try to estimate the conditions of each landfill as much as possible. Firstly, it was decided to set an average waste bag composition, which is a very broad estimate since each landfill community could have different values. However, the lack of information

forces us to use this estimate. Additionally, the parameter k and MCF could change in some landfills if the specific information of said facilities is known.

- The calculation of landfills has greater precision when emissions are calculated year by year. In this article only the emissions for a specific year are calculated without taking into account the emissions of previous years, therefore a small error is made.

6. Conclusions

Below are some of the conclusions that have been obtained throughout the project. Some of these deductions have already been mentioned in previous sections of the article and can be repeated in this section.

- Waste treatment facilities pose a problem for the environment due to their large generation of methane. A methane recovery or storage system is of great importance to prevent large amounts of methane from being emitted into the atmosphere. However, leaks can always occur in lines, digesters, etc. For this reason, it is of fundamental importance to have measurement and monitoring techniques for possible leaks in order to correct them as soon as possible.
- The ways of calculating methane emissions are extremely inaccurate, since it works with a multitude of parameters that depend on unknown factors. It is therefore essential to have all the data regarding the installation in order to be very precise.
- Of the three types of facilities that have been studied in this article, it is undoubtedly the WWTP that emits the most methane into the atmosphere. Regardless of the inaccuracy of the data and the unreliability of the values obtained from the landfills, it is concluded that this is due to the fact that the WWTPs work with organic raw material, while the landfills have organic and non-organic material that does not generate methane.
- As for the method of calculation, for WWTPs and biogas plants, an improvement to the formula used should be sought, since it does not cover all the parameters that really affect the facilities. On the other hand, for landfills, the calculation used (IPCC level 3) is clearly more precise than the rest of the calculations mentioned. That is why, although it is not very precise, it is still the most reliable method for estimating methane emissions in a landfill.

Appendix A

Name	**Location**	**Input waste (ton/year)**	**Number of digesters**	**Digester volume (m^3)**	**Emitted CH4 (ton/year)**	**Reported CH4 emissions (ton/year)**
Bens	A Coruña					
A Laracha - Aratel	A Laracha	60.000	1		2880	
SOLOGAS	As Somozas	40.000	2		1920	
LIFE NIMBUS	El Prat de Llobregat					
Vilanant	Figueres	11.000	1	2.078	528	
Vilademuls	Vilademuls	12.230	2		587,04	39
Consorci Per A la Gestió de Residusdel Valles Oriental	Granollers	52.000	1	3.000	2496	223
Planta Elena	Cerdanyola del Vallès					248
Torre Santamaría	Balaguer	16.750	3	1.200	804	42
Alcarràs	Alcarràs				0	1
Seròs	Seròs				0	60
La Galera	Montsiá	32.850	2		1576,8	
Godall 2	Montsiá				0	49
Enagas Huesca	Llares	140.000			6720	7

La Almunia de Doña Godina	La Almunia de Doña Godin	200			9,6	3
Peñarroya	Teruel		2	3.000	0	
Ólvega	Ólvega	60.000			2880	3
Villalonquéjar	Burgos	32.850			1576,8	
Olmedo	Olmedo		1	1.300	0	
Villacastín	Villacastin				0	
CESPA Madrid	Madrid				0	461
Valdemingómez	Pinto	218.000	9	3.600	10464	7
Luchente	Llutxent	86.500			4152	
Vall de Uxó	Vall de Uxó	40.000			1920	
Villanueva de la Serena	Villanueva de la Serena	11.000	1	1.204	528	
Los Santos de Maimon	Los Santos de Maimon				0	
Zurgena	Zurgena	31.000			1488	
Almería-Aqualia	Almeria		3	4.078	0	
Medina-Sidonia	Huelvacar				0	7150
La Calahorra	La Calahorra				0	0
Antequera	Antequera	60.000			2880	3560
Campillos	Campillos	60.000			2880	
Alcalá de Guadaíra	Alcalá de Guadaíra					
Galivi Solar	Lorca		2	1.500		

Appendix B

Name	Location	Water flow (m^3/day)	Number of digesters	Emitted CH4 (ton/year)	Reported CH4 emissions (kg/year)
Sur	Getafe	561.086	10	2.183.511,8	3.643
La China	Madrid	321.855	7	12.525.24,9	288.292
Butarque	Madrid	306.541	3	1192.929,2	271.527
Viveros de La Villa	Madrid	190.080	3	739.711,8	
La Gabia	Madrid	172.800	4	672.465,2	
Arroyo Culebro Cuenta Baja	Getafe	172.800	6	672.465,2	
Rejas	Madrid	146.448	4	569.914,3	
Alcalá de Henares Oeste	Alcalá de Henares	74.818	2	291.160,3	24.597
Arroyo de La Vega	San Sebastián de los Reyes	60.000	4	233.494,9	6.047
Casaquemada	San Fernando de Henares	86.700	0	33.740,0	
La Reguera	Móstoles	80.353	2	312.700,2	7.210
Valdebebas	Madrid	52.000	2	202.362,2	114
Arroyo del Soto	Móstoles	113.680	2	442.394,9	1.570
Torrejon de Ardoz	Torrejon de Ardoz	75.000	2	291.868,6	384
Sur Oriental	Rivas-Vaciamadrid	69.120	2	268.986,1	154.344
Soto Gutierrez	Ciempozuelos	26.000	1	101.181,1	

Aranjuez	Aranjuez	21.000	3	81.723,2	
Arroyo El Plantío	Majadahonda	15.000	1	58.373,7	
La Poveda	Arganda del Rey	13.000	0	5.059,1	3.483
Alcalá de Henares Este	Alcalá de Henares	31.000	0	12.063,9	
Guadarrama Medio	Villanueva de la Cañada	17.500	0	6.810,3	
Arroyo Valenoso	Boadilla del Monte	20.000	1	77.831,6	
El Endrinal	Collado Villalba	36.388	1	14.1606,9	6.358
Velilla	Velilla de San Antonio	20.000	0	7.783,2	
Navalcarnero	Navalcarnero	35.000	2	136205,3	1.473
Monte Boyal	Casarrubios del Monte	6.432	0	2.503,1	
Tres Cantos	Tres Cantos	13.200	0	5.136,9	
La Almozara	Zaragoza	34.560	2	13.4493,1	
Teruel	Teruel	20.600	1	80.166,6	
Jaca	Jaca	14.633	0	5.694,6	
Huesca	Huesca	24.000	1	93.397,9	
San Mateo del Gallego	Zaragoza	12.000	1	46.698,9	16.920
Calatayud	Calatayud	8.500	0	3.307,8	
La Cartuja	Cartuja Baja	260.000	0	10.1181,1	
Miranda del Ebro	Miranda de Ebro	11.850	0	4.611,5	
Valladolid	Valladolid	101.000	3	393.049,7	8
Burgos	Villalonquéjar	156.000	4	607.086,7	
Bejar	Bejar	42.000	0	16.344,6	3.150
Salamanca	Salamanca	117.500	3	457.260,8	
León	Trobajo del Cerecedo	8.928	0	3.474,4	
Ávila	Ávila	33.000	1	128.422,1	
Palencia	Palencia	45.000	2	175.121,1	85
Bierzo Bajo	Carracedelo	82.191	0	31.985,3	
Segovia	Segovia	41.280	1	160.644,5	
Zamora	Zamora	2.600	1	10.118,1	
Soria	Soria	48.000	1	186.795,9	
Aranda de Duero	Aranda de Duero	20.640	1	80.322,2	
Guijuelo	Guijuelo	5.000	2	19.457,9	
Ricao	Cangas de Onís	41.299	0	16.071,8	
Baiña	Mieres	138.240	0	53.797,2	
Fieres	Langreo	1.620	0	630,4	
Maqua	Maqua	130.702	1	508.637,5	
Villaperez	Oviedo	421.200	0	163.913,4	
Gijon Este	Guijon	45.000	0	17.512,1	
Gijon Oeste	Guijon	137.376	2	534.609,9	
Guadalajara	Guadalajara	45.000	2	175.121,1	28.010
Azuqueca de Henares	Azuqueca de Henares	31.000	0	12.063,9	
Alcazar de San Juan	Alcazar de San Juan	24.000	1	93.397,9	4.007
Villarobledo	Villarobledo	8.500	0	3.307,8	
Hellín	Hellín	12.000	0	4.669,9	
Tarancón	Tarancón	5.280	0	2.054,7	
Manzanares-Membrilla	Manzanares	8.791	0	3.421,1	
Albacete	Albacete	49.500	2	192.633,3	9.592
Talavera de la Reina	Talavera de la Reina	34.500	0	13.425,9	
Santa Maria de Benquerencia	Toledo	14.000		5.448,2	10.496

Estiviel	Toledo	36.000	3	140.096,9	11.616
Sagra Centro	Cobeja	12.000	0	4.669,9	
Puertollano	Puertollano	30.000	0	11.674,7	
Valdepeñas	Valdepeñas	12.000	1	46.698,9	
Ciudad Real-Miguelturra	Miguelturra	41.000	2	15.955,5	
Almansa	Almansa	6.900	0	2.685,2	
Logroño	Logroño	103.680	3	403.479,2	
Calahorra	Calahorra	23.000	2	89.506,4	
Vuleta Ostrera	Suances	109.382	1	425.668,9	
San Pantaleón	San Pantaleón	113.616	2	442.145,9	
Castro Urdiales	Castro-Urdiales	28.000	0	10.896,4	
Guillarei	Tui	35.000	2	136.205,3	
Lagares	Vigo	691.200	2	2.689.861,0	
Bens	Bens	135.000	2	525..363,4	44.500
Placeres	Pontevedra	77.760	1	302609,4	
Lugo	Lugo	76.500	2	297.705,9	
Silvouta	Santiago de Compostela	51.600	0	20.080,6	
Reza	Orense	51.840	2	201.739,6	
Cambados-Vilanoba de Arousa	Cambados	1.200	0	466,9	3.643

Appendix C

Name	**Location**	**Input waste (ton/year)**	**Emitted CH4 (ton/year)**	**Reported CH4 emissions (kg/year)**
Centro de Tratamiento de Albox	Andalucía	73.605	50.515,4	619.482,5
Centro de Tratamiento de RSU de Almeria	Andalucía	91.858	63.042,5	2.465.753,4
Planta de clasificación de RCD, de RNP de la agricultura y vertedero de cola	Andalucía	862	591,6	6.484,0
Centro de tratamiento de Gádor	Andalucía	167.682	115.080,8	1.567.732,1
Complejo Medioambiental Sur de Europa	Andalucía	200.236	137.422,7	4.414.003,0
Complejo Medioambiental de Bolaños	Andalucía	200.000	137.260,7	706.240,5
Complejo Medioambiental de Miramundo	Andalucía	311.000	213.440,4	10.882.800,6
Complejo Ambiental de Montalbán	Andalucía	199.791	137.117,3	2.009.132,4
Complejo Ambiental de Córdoba	Andalucía	159.884	109.729,0	631.659,1
Ecocental de Granada	Andalucía	476.251	326.852,8	3.409.436,8
Complejo Medioambiental Vélez de Benaudalla	Andalucía	162.918	111.811,2	2.161.339,4
Centro de Tratamiento de RSU de Villarrasa	Andalucía	250.813	172.133,9	2.541.856,9
PLnata de compostaje de RSU de Jaén	Andalucía	58.867	40.400,6	2.298.325,7
Complejo Medioambiental de Guadiel	Andalucía	140.192	96.214,3	1.628.614,9
Complejo Medioambiental Sierra Sur	Andalucía	93,048	63,9	1.582.952,8
Complejo Medioambiental de la Costa del Sol Occidental	Andalucía	362.944	249.089,8	6.803.653,0
Complejo Ambiental Los Ruices	Andalucía	294.960	202.432,1	4.170.471,8
Complejo Ambiental de Valesquillo	Andalucía	207.013	142.073,8	5.418.569,3
Complejo Mediaambiental Montemarta-Cónica	Andalucía	459.489	315.348,9	70.319.634,7
Complejo Ambiental La Vega	Andalucía	128.202	87.985,5	1.780.821,9
Complejo Medioambiental Mata Grande	Andalucía	32.860	22.551,9	1.582.952,8
Complejo Medioambiental Campiña 2000	Andalucía	57.161	39.229,8	1.674.277,0
Vertedero de RSU de Huesca	Aragón	35.941	24.809,5	64.321,2

Vertedero de RSU de Barbastro	Aragón	29.904	20.642,3	#¡VALOR!
Vertedero de RSU de Fraga	Aragón	13.870	9.574,2	470.319,6
Vertedero de RSU de Alcañiz	Aragón	24.275	16.756,6	2.155.251,1
Vertedero de RSU de Teruel	Aragón	29.011	20.025,8	0,0
Vertedero RDU Ejea de los caballeros	Aragón	30.077	20.761,7	772.013,7
Vertedero de RSU de Calatayud	Aragón	31.097	21.465,8	299.477,9
Vertedero de RSU de Illueca	Aragón	262.196	180.989,7	#¡VALOR!
COGRESA - Centro de tratamiento de residuos	Asturias	425.810	701.744,9	2.515.873,7
Complejo Medioambiental de Meruelo	Cantabria	259.349	430.982,0	11.111.111,1
CTRU Albacete	Castilla La Mancha	183.513	126.676,1	1.032.248,1
CTRU Alcázar de San Juan	Castilla La Mancha	74.190	51.212,2	124.089,8
CTRU Almagro	Castilla La Mancha	159.638	110.195,5	#¡VALOR!
CTRU Cuenca	Castilla La Mancha	71.291	49.211,0	194.780,8
CTRU Torrija	Castilla La Mancha	96.923	66.904,4	533.240,5
Ecoparque de Toledo	Castilla La Mancha	230.000	158.765,3	1.309.401,8
CTRU de Urraca Miguel	Castilla Y León	68.022	46.954,5	2.000,0
CTR Arenas de San Pedro	Castilla Y León	12.849	8.869,5	768.287,7
CTR Aranda de Duero	Castilla Y León	29.384	20.283,3	95.397,3
Vertedero de Abajas	Castilla Y León	49.127	33.911,6	2.167.427,7
CTR San Román de la Vega	Castilla Y León	178.973	123.542,2	929.094,4
CTR Palencia	Castilla Y León	65.569	45.261,2	826.484,0
CTR Salamanca	Castilla Y León	132.265	91.300,4	1.372.675,8
CTR Los Huertos	Castilla Y León	56.685	39.128,7	
CTR Los Huertos	Castilla Y León	42.000	28.991,9	
CTR Soria	Castilla Y León	31.038	21.425,0	1.257.229,8
CTR Valladolid	Castilla Y León	189.950	131.119,4	762.576,9
CTR Zamora	Castilla Y León	68.022	46.954,5	1.774.579,9
CTR de Manresa	Cataluña	46.000	76.442,1	131.864,5
Depósito controlado de Can Mata	Cataluña	200.000	332.356,8	18.360,7
CTR de Orís	Cataluña	58.173	96.670,9	
Depósito controlado de Berga	Cataluña	13.242	22.005,3	280.575,3
Depósito controlado de Garraf	Cataluña	0	0,0	
CTR de Lloret de Mar	Cataluña	103.169	171.444,6	2.008.649,9
CTR de Pedret i Marzà	Cataluña	45.000	74.780,3	817.541,9
Depósito controlado de Banyoles	Cataluña	50.000	83.089,2	3.584.474,9
CTR de Llagostera (Solius)	Cataluña	100.000	166.178,4	108.709,3
CTR L'Espluga de Francoli	Cataluña	6.428	10.681,9	54.758,0
CTR de Mas de Barberans	Cataluña	22.498	37.386,8	66.231,4
Complejo de valorización y deposición de residuos de Tivissa	Cataluña	15.000	24.926,8	8.567,7
CTR de Montoliu de Lleida	Cataluña	85.814	142.604,3	1.467.917,8
CTR de Clariana	Cataluña	5.946	9.881,0	55.522,1
CTR de Tremp	Cataluña	4.339	7.210,5	100.091,3
Depósito controlado de Balaguer	Cataluña	12.535	20.830,5	34.627,1
Depósito controlado de Castellnou	Cataluña	12.053	20.029,5	379.593,6
Depósito controlado de Cervera	Cataluña	0	0,0	
Depósito controlado de Granadella	Cataluña	9.000	14.956,1	62.846,3
Depósito de Les Borges Blanques	Cataluña	50.000	83.089,2	197.974,1
Depósito Controlado de Bellver de Cerdanya	Cataluña	8.517	14.153,4	6.220,7
Depósito controlado de Montferrer i Castellbò	Cataluña	6.107	10.148,5	287.709,3
Vertedero nuevo de RSU de Alicante	C. Valenciana	128.045	212.783,1	28.863,0

Planta de tratamiento de RU y clasificación de envases del Baix Vinalopó-Elche	C. Valenciana	116.220	193.132,5	77.109,6
Planta de Tratamiento de Residuos Urbanos del Campello	C. Valenciana	254.987	423.733,3	1.847.392,7
Planta de tratamiento de RSU Piedra Negra	C. Valenciana	81.354	135.192,8	2.433.835,6
Planta RSU de Villena	C. Valenciana	73.606	122.317,3	28.863,0
Planta de RSU Cervera del Maestre	C. Valenciana	80.000	132.942,7	1.019.330,3
Vertedero de Reciplasa en Onda	C. Valenciana	141.401	234.977,9	877.254,2
Planta de tratamiento de RU Algimia de Alfara	C. Valenciana	81.354	135.192,8	2.584.474,9
Vertedero de Caudete de las Fuentes	C. Valenciana	112.346	186.694,8	2.333.745,8
Vertedero de dos aguas	C. Valenciana	324.803	539.752,3	11.293,8
Ecoparque de RSU de Badajoz	Extremadura	101.736	69.624,2	71.092,8
Ecoparque de RSU de Mérida	Extremadura	66.664	45.622,3	38.385,1
Ecoparque de RSU de Villanueva de la Serena	Extremadura	727.222	497.682,8	51.274,0
Ecoparque de RSU de Talarrubias	Extremadura	15.072	10.314,7	3.977,2
Ecoparque de RSU de Navalmoral	Extremadura	42.465	29.061,4	21.940,6
Ecoparque de RSU de Cáceres	Extremadura	50.431	34.513,0	9.400,3
Complejo Medioambiental de Cerceda	Galicia	780.426	1.278.352,7	2.252,7
Planta de tratamiento de residuos de la Coruña	Galicia	138.040	226.112,2	750.380,5
Complejo medioambiental de tratamiento de RU y asimilables de Barbanza	Galicia	29.334	48.697,7	706.240,5
Vertedero de Ca Na Putxa	Islas Baleares	135.740	225.343,7	3.187.627,1
Planta de compostaje de Cavià	Islas Baleares	14.000	23.241,6	
Área de Gestión Integral de Residuos "Es Millà" - Mahón	Islas Baleares	63.297	105.080,1	2.080.974,1
Complejo Medioambiental de Zurita	Islas Canarias	59.568	55.014,8	4.687.975,6
Complejo Ambietnal de Salto del Negro	Islas Canarias	290.574	268.363,5	3.378.995,4
Complejo ambiental de Juan Grande	Islas Canarias	163.582	151.078,3	919.330,3
Complejo ambiental de Zonzamas	Islas Canarias	100.078	92.428,4	5.662.100,5
Complejo medioambiental de La Dehesa	Islas Canarias	5.758	5.317,9	
Complejo ambiental El Revolcadero	Islas Canarias	11.300	10.436,3	354.642,3
Complejo Ambiental de los Morenos	Islas Canarias	43.774	40.428,1	54.490,1
Complejo Ambiental de Arico	Islas Canarias	466,556	430,9	2.146.118,7
Vertedero de Nájera	La Rioja	40.000	66.471,4	704.286,1
Ecoparque La Rioja	La Rioja	107.054	177.900,6	
Planra de tratamietno Las Dehesas	C. de Madrid	927.600	634.813,8	8.464,2
Centro de tratamietno Pinto	C. de Madrid	718.701	491.851,3	19.634,7
Centro de tratamiento Colmenar Viejo	C. de Madrid	247.360	169.283,7	423.333,3
Depósito controlado Alcalá de Henares	C. de Madrid	200.980	137.543,0	1.923.709,3
Planta de tratamiento de RSU de El Gorguel	Murcia	89.298	63.465,9	388.333,3
Centro de tratamiento RSU de Fuente Álamo	Murcia	60.000	42.643,2	14.975.799,1
Centro de tratamiento de RSU de Jumilla	Murcia	10.996	7.815,1	72.001,5
Planta de tratamiento de Cañada Hermosa	Murcia	206.740	146.934,4	4.871.902,6
Centro de gestión de residuos de Lorca	Murcia	72.213	51.323,3	2.369.421,6
Planta de reciclaje y compostaje de Cárcar	Navarra	20.320	32.704,4	27.820,4
Centro de tratamiento El Culebrete	Navarra	41.108	60.946,2	318.377,5
CTRU de la Mancomunidad de Pamplona	Navarra	163.690	242.684,7	1.378.394,2
Vertedero de Gardelegi	Pais Vasco	35.000	51.890,6	11.292,2
Planta de compostale y Vertedero de Artigas	Pais Vasco	15.000	22.238,8	1.534.581,4
Vertedero de Jata	Pais Vasco	160.000	237.214,0	2.731.958,9

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-Posibilidad de poner una columna con los habitantes equivalentes de las EDAR
-Referencias de páginas webs