Achieving energy self-sufficiency in wastewater treatment plants by integrating municipal solid waste treatment: A process design study in Spain

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Abstract

Water-energy nexus is a highlighted topic nowadays, particularly, the energy consumption in wastewater treatment plants (WWTPs) is becoming an important issue. WWTPs typically consume more energy than the one that can be obtained from the biogas produced from sludge anaerobic digestion. In this work, a process-level analysis is presented to study the feasibility of integrating wastewater and municipal solid waste (MSW) treatment to achieve the energetically self-sustainable operation of a WWTP. The influence of the climate of different regions across the Iberian Peninsula on the energy requirements has also been evaluated. Mesophilic and thermophilic digestion is compared in Salamanca as a case base, and the optimal digestion temperature is also evaluated, finding a value of 30ºC. Moreover, in all cities considered, it is necessary for MSW to provide between 37-40% of the facility energy consumption corresponding to around 0.19 kg of MSW per kg of sludge, with a small difference between cities. From an economic point of view, an investment between 0.09-0.16 €/kg of sewage sludge is required for the integrated process. Therefore, this techno-economic assessment demonstrates the feasibility of integrating these two treatments for a fully self-sufficient and sustainable process.

Keywords: Wastewater treatment plant, sewage sludge, municipal solid waste, energy

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1. Introduction

Pollution control and energy consumption are attracting attention because environmental pollution and resource depletion are indisputable facts that our society has to

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face on its path towards sustainability. Wastewater treatment plants (WWTPs) are key facilities for limiting the potential environmental impact of wastewater discharges into receiving water bodies. However, they are not exempt from creating environmental impacts because they consume a certain amount of energy, which implies the emission of greenhouse gases (GHG) when generated from conventional (non-renewable) energy sources [1, 2]. Energy is not only used on-site, for aeration or pumping, for example, but also off-site for transportation and production of different chemicals used in the treatment processes [3].

Until recently, energy was relatively affordable internationally, and most wastewater treatment facilities were not designed and operated with the goal of limiting energy consumption [4, 5], but only to satisfy certain effluent quality requirements defined by national regulations [6]. However, this has been changing in recent years, mainly due to the general framework to achieve the 2030-2050 goals defined for Climate and Energy by the European Union [7]. Nowadays, rapid population growth and urbanization have led to an increase in wastewater production, so the number of WWTPs has also increased, and effluent quality requirements have also become more demanding. This fact has resulted in large energy consumption due to the operation of WWTPs, with the corresponding increase in their indirect GHG emissions [8].

As a result, the water-energy nexus has begun to attract increasing attention from both environmental and economic points of view [9]. On the one hand, WWTPs can account for 15–20% of the total energy consumption of municipal public structures and facilities, representing, in addition, around 25-40% of the total operating costs of a conventional WWTP [5, 9]. On the other hand, the operation of WWTPs involves greenhouse gas emissions since the production of electricity with non-renewable energy sources generates them [6]. Moreover, these emissions have grown in recent years due to the increase in the volume of waste treated and the implementation of new processes aimed at achieving higher effluent quality [1]. This water-energy nexus is promoting a series of studies on the relationship between energy and water for sustainable development; in fact, the potential of energy self-sufficient WWTPs has become an area of increasing research and innovation.

Energy self-sufficient WWTPs are those that generate 100% or more of their operating energy requirements only from the energy embedded in the water and waste they treat, with no external energy supply [5, 10]. All major processes associated with wastewater treatment and sludge disposal technologies require energy, mainly in the form of electricity, for pumping, mixing, separation, and the treatment of wastewater and sludge [5]. Sewage sludge, the second product of the wastewater treatment process, requires treatment prior to the final disposal. Anaerobic digestion is a common technology for sludge treatment at WWTPs, but it is a very energy-intensive process itself [11] (about 14% of the total energy consumption of a WWTP [12]). However, anaerobic digestion produces biogas, which is the main energy source in a WWTP. The use of biogas for digester heating and electricity generation is a sustainable way to recover energy from WWTPs, as it could replace fossil fuels, with consequent sludge volume reduction [7]. However, not all WWTP have this option, because it is CAPEX intensive, and, in most cases, it does not cover the total energy requirements of the plant and is flared and wasted [11, 5], so natural gas and other fuels are used to produce electricity.

Even in developed countries, there is still a gap in the energy self-sufficiency of WWTPs, so it is necessary to investigate and apply new trends in circular economy and energy integration, and new technologies to achieve it [4]. Several works have studied the feasibility of integrating new technologies to improve biogas production in order to increase the amount of energy that can be obtained from WWTPs [13]. There are various ways to enhance the rate of biogas production, and among them, the pretreatment of sewage sludge before anaerobic digestion and co-digestion processes with other organic wastes have been widely studied. For example, on the one hand, Ferrer et al. [14] investigated the effect of a low-temperature pretreatment (70ºC) on the efficiency of thermophilic anaerobic digestion of primary and secondary waste sludge and they obtained an increase of up to 30% in biogas production. Ruffino et al. [15] evaluated the performance of mechanical and low-temperature (<100ºC) pretreatment of waste activated sludge in the largest Italian WWTP and they achieved that the specific production increased by 21% and 31% for waste activated sludge sample treated for 3 hours at 70 and 90ºC, respectively. Moreover, Jenicek et al. [16] showed that sludge thickening previous to anaerobic digestion can also improve biogas production. On the other hand, Maragkaki et al. [17] attempted to optimize biogas production from sewage sludge by co-digestion with a dry mixture of food waste, cheese whey, and olive mill wastewater and obtained that, if the mixture exceeds 3% (v/v) concentration in the feed, it can boost biogas yields. Wang et al. [18] evaluated the effects of the mixing ratio of excess sludge with chicken manure on methane yield and digestate dewaterability at thermophilic and mesophilic temperatures, and their results at an appropriate mixing ratio indicated that this process could obtain a high methane yield and an adequate dehydratability of the digestate.

In addition, one of the ways of generating clean energy that has gained importance in recent years is its production from waste, known as waste-to-energy (WTE). The collection and disposal of municipal solid waste (MSW) is one of the biggest challenges facing many countries today [19]. The increase in the world population, together with economic development, has led to rapid urbanization and industrialization, which has changed the pattern of consumption, causing MSW to proliferate at an alarming rate [20]. Worldwide, approximately 33% of MSW generated is inadequately managed, resulting in a number of consequences such as environmental pollution and climate change [21]. The rapid depletion of fossil fuel reserves and the associated greenhouse gas emissions have sparked worldwide interest in exploring the use of these waste streams as renewable energy sources [22]. Waste-to-energy conversion not only protects human health and the environment but also contributes considerably to the efficient saving of fossil primary energy, promoting the transformation of the energy structure [23]. Several waste-to-energy technologies, both conventional and non-conventional, have been described in recent literature. Conventional waste treatment or disposal techniques include composting, anaerobic digestion, and landfilling, while incineration, pyrolysis, gasification, and hydrothermal processing are considered non-conventional waste-to-energy technologies [21]. These nonconventional processes are thermochemical conversion processes and have become the focus of attention over the past few decades due to their benefits, such as higher conversion efficiency, zero waste concept and compatibility with a variety of feedstocks [22]. Among all of them, incineration is regarded as the most mature WTE technology used in the world. This process involves thermal decomposition by taking advantage of the heating value of the waste and the combustion heat generated can be converted into hot water, steam, or electricity [19]. For example, González-Núñez et al. [24] presented a multiscale approach for the valorization of MSW and sludge via co-incineration to produce power over 65 major cities of Spain. In their work, at process scale, the systematic techno-economic evaluation of the facility showed that 1.336 MW/kg of mixed waste could be produced.

As it can be seen in the literature, most of the works that study the treatment of sludge are focused on the increase of biogas production yield to achieve the self-sufficient operation of WWTPs. Another way to achieve the self-sufficient operation is the use of an external source of energy. Several works have considered the use of external sources, mainly renewable energy, but they have to deal with the inherent variability of these sources, and only a few works have considered the use of MSW as an external source of energy. For example, Odabaş Baş and Aydınalp Köksal [25] analyzed the environmental and economic benefits of integrating renewable energy sources, biogas, and solar energy in urban WWTPs. Nakatsuka et al. [26] conducted a life cycle assessment of the integration of wastewater treatment and incineration plants for energy-efficient urban biomass utilization. They focused their attention on clarifying the conditions necessary for the sustainable integration of WWTPs and MSW incineration plants, but they did not perform a process-level analysis to study the energy requirements in detail. In this work, a process design has been proposed in order to evaluate the integration of wastewater treatment and MSW incineration to achieve a self-sufficient operation in a WWTP. MSW is used within an integrated facility to produce steam to provide the thermal energy requirements in the anaerobic digestion process of the sewage sludge that cannot be covered by the biogas generated, and, also, to produce the total electricity requirements of the WWTP. However, the location of the facilities has an effect on the water temperature and, as a result, on the energy needs. A process system approach is used to integrate the use of MSW within WWTPs across different climates to evaluate the feasibility of such integration, the amount of MSW required across the territory as well as the cost of the integrated facility.

2. Process description

In this work, the integration of wastewater and MSW treatment combines two sections: sewage sludge treatment, because is the main thermal energy consumer of wastewater treatment, and the incineration of MSW, that is the provider of additional thermal energy to the previous section and supplies power to all the wastewater treatment to achieve an energetically self-sufficient operation. Note that it could be possible to reduce a certain amount of water before the digestion implementing thickening processes and, consequently, reduce the heating needs. However, the estimation of the power required to achieve that required further experimental results that are out of the scope of this work. Certainly, can be a matter of study for future work.

The sewage sludge treatment process is divided into four sections: biogas production, biogas purification, digestate conditioning, and energy production (biogas combustion). Firstly, the sewage sludge is fed into a bioreactor where it is anaerobically digested to produce biogas, which contains methane, carbon dioxide, nitrogen, hydrogen sulfide, ammonia, and moisture, and a decomposed substrate (digestate). The two main types of anaerobic digestion are considered, mesophilic and thermophilic, which operate between 30-37ºC and 50-55ºC, respectively [27]. Then, the produced digestate is conditioned in a reboiler, removing the excess of water and ammonia. This step is included so that the digestate can be used as a fertilizer later. The third step consists of the biogas purification by removing the CO_2 (and traces of NH_3) and the H_2S in a Pressure Swing Adsorption (PSA) system and a fixed-bed reactor, respectively. Once the biogas is mainly methane, it is burned with air in a furnace to provide the thermal energy requirements of the process. The combustion heat is used to heat the combustion air and the sludge feed and, in addition, to produce steam to heat the bioreactor and the heat exchanger of the sludge conditioning step.

The incineration of MSW is used to produce the additional thermal energy needed in the anaerobic digestion and the digestate conditioning and to supply the power requirements of the WWTP. MSW is burned in a furnace to produce the steam to heat the bioreactor and the heat exchanger of sludge conditioning when biogas is not sufficient, and the steam to feed a Rankine cycle to generate power. In the Rankine cycle, three different sections of the steam turbine are considered in this work with various operating pressures (high, medium, and low pressure). The treatment of the combustion gases generated in the incineration is not considered in this work. The evaluation of the incineration flue gas treatment has already been considered in a previous work [24], consisting of a selective catalytic reduction system, to remove NO_x, dioxins and furans by atomizing ammonia, an electrostatic precipitator to remove particles, followed by a Lime Dry Spray process to remove SO_2. Next, a filter is located before the adsorption tower devoted to remove heavy metals. An schematic diagram of the integrated process of sewage sludge and MSW treatment is shown in Figure 1.

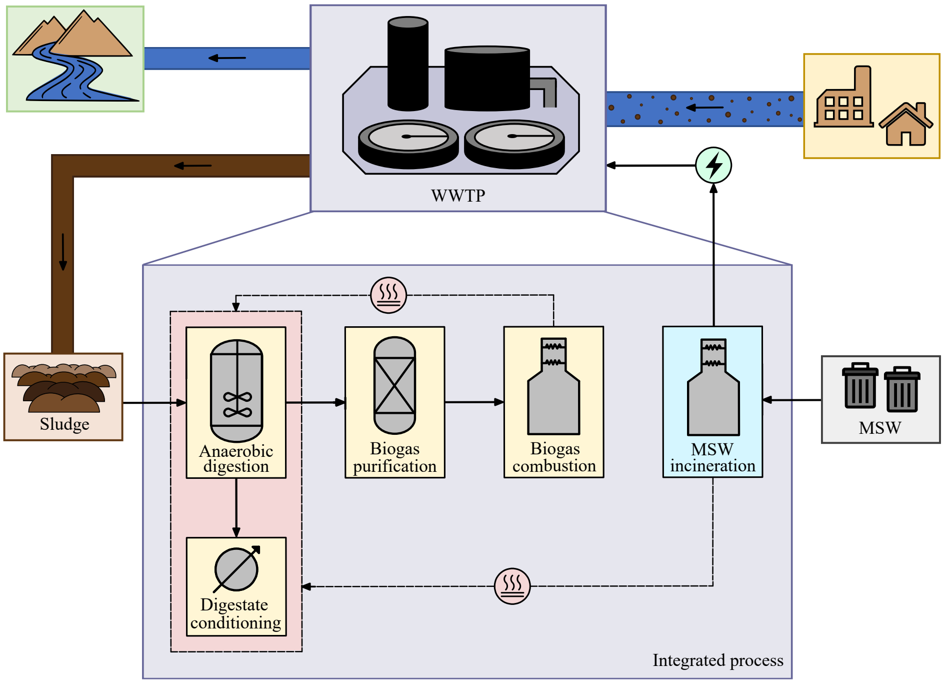

Figure 1: Schematic diagram of the integrated process of sludge and MSW treatment.

3. Modeling approach and cases of study

3.1. Modeling approach

This section presents a brief description of the different approaches to model the units involved in the process. Both processes, stand-alone digestion in Salamanca and the integrated process in all cities, have been modeled using an equation-based approach. These models are formulated using mass and energy balances, thermodynamics, chemical, and vapor-liquid equilibria, etc., to evaluate their performance and are based on the work of León and Martín [28]. The entire superstructure is formulated as a non-linear programming problem and is implemented in GAMS using CONOPT 3.0 [29] as preferred solver in a multistart optimization approach. The objective function is the minimization of the external energy requirements, given by Eq. 1. The aim of the work was to make the WWTPs as self-sufficient as possible. Based on that the optimization targeted reducing the external energy requirement. It is possible to use other objective functions that include the investment. In that case a multiobjective formulation can be presented to minimize also the infrastructure. However, this was out of the scope of the work.

$$Z = (E_{diges} - E_{biogas}) - E_{MSW} \tag{1}$$

Where E_{diges} is the total thermal energy required in the digestion process, E_{biogas} is the thermal energy supply by the generated biogas, and E_{MSW} is the external thermal energy that needs to be provided by MSW. The size of the problem is approximately 850-950 equations, depending on if stand-alone digestion or integrated process is modeled, and variables for each of the cases.

3.2. *Biogas production*

The anaerobic digestion of biomass is a decomposition process in the absence of oxygen that produces a gas, composed mainly of methane and carbon dioxide (biogas), and a decomposed substrate (digestate) and occurs at a bioreactor (shown in Fig. 2). This process is carried out by several reactions, such as hydrolysis, acidogenesis, and methanogenesis, and can take place at mainly two different ranges of operating temperatures: mesophilic (30 to 37ºC), and thermophilic (50 to 55ºC) [27].

In this study, the biomass considered is the sewage sludge produced at the WWTPs included in the evaluation (see Section 3.7). Apart from methane and carbon dioxide, biogas also contains nitrogen, hydrogen sulfide, oxygen, and ammonia, and is assumed to be saturated with water. In addition, it is considered that the volume of biogas produced in the digestion process depends on the operating temperature following the experimental data of Guo et al. [30] and Zupancic and Ros [31]. The other stream leaving the bioreactor is the digestate which is composed of the rest of the biomass, whose composition is calculated from the composition of the sludge by a mass balance and is bounded considering the work of Hernández et al. [32].

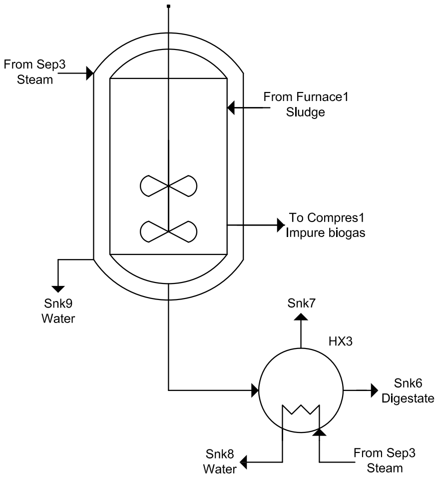

Figure 2: Flow diagram of the biogas production and digestate conditioning sections of the process.

Before entering the bioreactor, the sludge is preheated to the digestion temperature in the biogas furnace, thus, the energy balance to the digester only considers the reaction heat, which is computed considering the heat of combustion of each of the components. These energy requirements are covered by steam, which is produced via biogas combustion and MSW incineration when needed. Further details on sludge and biogas composition, the correlation of biogas production with temperature, and different mass and energy balances are shown in the Supplementary Material.

3.3. *Digestate conditioning*

The aim of conditioning the digestate is to remove the remaining H_2O and NH_3 via evaporation (Snk7 shown in Fig. 2). Both equilibrium systems, water, and ammonia are solved to obtain the outlet temperature, whose maximum value is 150ºC. Considering that water is partially removed and ammonia is totally eliminated, the outlet digestate is comprised of the water that is not evaporated, C, N_{Org}, K, P, and the mixture of elements defined as ”Rest”, and the mass flow rates of the different compounds leaving the evaporator are computed by mass balances. Finally, three parameters defined as K, N, and P indexes are computed that need to be met for the digestate to be used as fertilizer and to obtain some additional value from the biomass waste. Once computed mass balances, the energy balance is also computed to obtain the thermal energy requirements of this equipment considering the evaporation of water and ammonia. Further details can be found in the Supplementary Material.

3.4. Biogas purification

The biogas purification takes place in two stages: the H_2S removal and the CO_2, NH_3, and H_2O removal. A flow diagram of this section is shown in Figure 3.

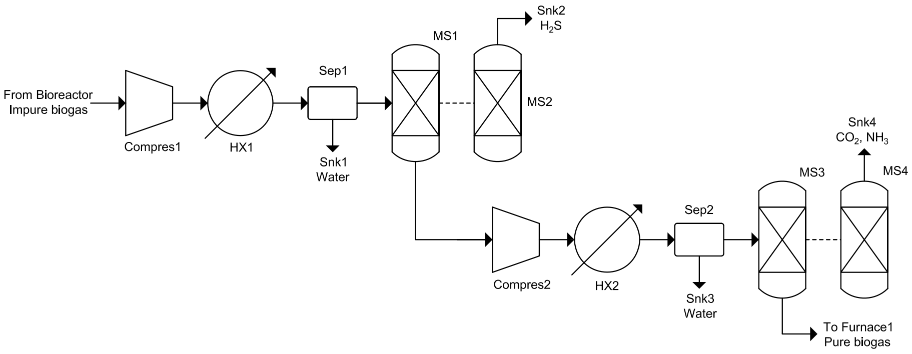

Figure 3: Flow diagram of the biogas purification section of the process.

3.4.1. H_2S removal

The remaining H_2S in the biogas is removed using a bed of Fe_2O_3 operating at 25-50ºC, where the following reaction takes place [33]:

$$H_2S \; + \; ZnO \; \rightarrow \; H_2O \; + \; ZnS \tag{2}$$

and, that can be regenerated using oxygen, following this reaction [33]:

$$Fe_2O_3 \; + \; 3 \; H_2S \; \rightarrow \; Fe_2S_3 \; + \; 3 \; H_2O \tag{3}$$

Considering that the H_2S is completely removed and the factor that the solid remains in the bed and water is generated, the mass balance model is computed based on the stoichiometry of the first reaction.

3.4.2. CO_2, NH_3, and H_2O removal (PSA)

A PSA system, which consists of a packed bed of zeolite 5A, is used to remove the CO_2. This system, typically, operates at low temperatures (25ºC) and moderate pressures (4.5 atm). In order for the plant to work in continuous operation, the system is modeled as two beds in parallel and, while the first is in operation, the other is regenerated. In addition, it is assumed that, in the PSA system, any other gas in the mixture is recovered, except NH_3, which is fully recovered, and the CO_2, which is recovered up to 95% [34].

3.5. Biogas combustion

After being conditioned, the biogas produced in the anaerobic digestion is burned with air in a furnace. The energy produced in the combustion of biogas is used for three purposes: to heat up the sludge fed to the digester, to pre heat up the air used in the biogas combustion and to produce utilities, steam, later used to provide the thermal energy requirements of the process in the bioreactor and the heat exchanger that conditions the digestate. A flow diagram of this section is shown in Figure 4.

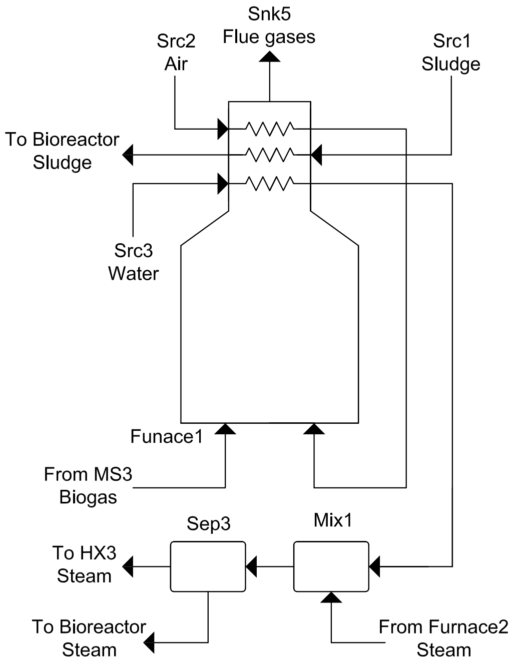

Figure 4: Flow diagram of the biogas combustion section of the process.

It is considered that the methane of the biogas totally reacts to carbon dioxide, following the next reaction:

$$CH_4 + 2\,O_2 \rightarrow CO_2 + 2\,H_2O \tag{4}$$

In addition, it is considered that the air has a composition of 21% oxygen and 79% nitrogen and it is introduced with an excess between 20-50% with respect to the stoichiometric and at the atmosphere temperature, taking into account the month of the year.

The total thermal energy that can be generated in the furnace ($Q_{Furnace1}$) can be obtained by the energy balance, considering that the upper limit of the adiabatic combustion temperature at the furnace is 1627ºC [35]. Further details are shown in the Supplementary Material.

Firstly, the inlet sludge is introduced into the furnace to be heated up to the operating temperature of the bioreactor, depending on the type of digestion that is taking place. Considering that the specific heat capacity of the sludge has the same value that the water one, the necessary heat (Q_{sludge}) is computed taking into account the inlet water temperature depending on the month considered.

Then, the combustion air is also introduced to the furnace to be heated up to 25ºC before reacting. The necessary heat (Q_{air}) in this case is computed taking into account the atmosphere temperature depending on the month considered.

After heating these two streams, saturated steam at 10.2 atm [36] is produced using the combustion gases in order to use it to maintain the temperature conditions in the bioreactor and to dehydrate the digestate in the heat exchanger. This pressure is chosen to always maintain the gradient temperature in the heat exchanges, because the maximum outlet temperature of the conditioned digestate is fixed to 150ºC in the heat exchanger, and, also, because they are common conditions on commercial steam. The energy needed to produce this steam (Q_{steam}) as well as the energy to heat up the sludge and the combustion air are computed in the Supplementary Material.

The maximum amount of steam that can be produced by the combustion of biogas is obtained by an energy balance (Eq. 5) combining the different energy requirements.

$$Q_{Furnace1} = Q_{sludge} + Q_{Air} + Q_{steam} \tag{5}$$

The outlet temperature of the flue gases is computed by another energy balance taking into account that there must be a minimum temperature rise of 10ºC between this temperature and the hottest inlet stream (see Supplementary Material).

Comparing the energy provided by the steam with the energy requirements of the bioreactor ($Q_{Bioreactor}$) and the heat exchanger (Q_{HX3}), it can be seen that the energy provided by the biogas combustion is not sufficient to produce the necessary steam to cover the total energy requirements. This energy is devoted to the bioreactor ($Q_{steam_{Bioreactor}}$) and to the heat exchanger that conditions the digestate ($Q_{steam_{HX3}}$), so the Equation 6 must be satisfied.

$$Q_{steam} = Q_{steam_{HX3}} + Q_{steam_{Bioreactor}} \tag{6}$$

To compute the additional energy that has to be supplied to the equipment by the steam produced through MSW incineration, two more terms are added to the energy balances: $Q_{extra_{Bioreactor}}$ for the additional energy in the bioreactor, and $Q_{extra_{HX3}}$ for the additional energy in the heat exchanger. Therefore, the Equations 7 and 8 must be satisfied.

$$Q_{HX3} = Q_{steam_{HX3}} + Q_{extra_{HX3}} \tag{7}$$

$$Q_{Bioreactor} = Q_{steam_{Bioreactor}} + Q_{extra_{Bioreactor}} \tag{8}$$

The amount of condensing steam that has to be produced in the furnace in which the MSW is incinerated to provide these energy requirements can be obtained by doing the energy balance (See Supplementary Material).

3.6. *MSW incineration*

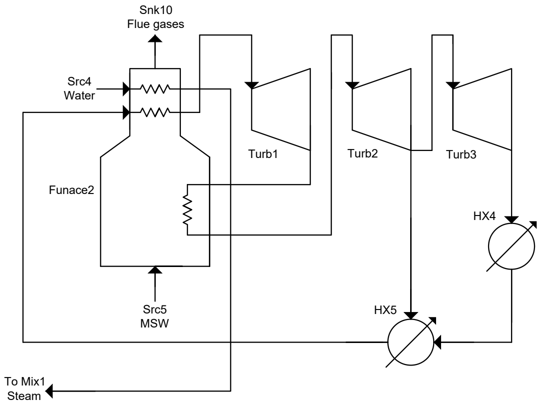

Figure 5: Flow diagram of the MSW incineration section of the process.

The section concerning MSW incineration is divided into two stages: MSW combustion and the Rankine cycle. MSW combustion takes place in a furnace and the energy that can be obtained depends on the composition (shown in Table 1) and is related to the lower heating value (LHV_{MSW}), which is computed by the equation of Dulong modified for the MSW.

$$LHV_{MSW}\left(\frac{kcal}{kg}\right) = 80.56\ C(\%) + 338.89\left(H(\%) - \frac{1}{8}\ O(\%)\right) + 22.22\ S(\%) + 5.56\ N(\%) \tag{9}$$

Table 1: MSW composition.

Component	Ultimate Analysis
C	57.62
H	8.45
O	31.50
N	0.24
S	0.47
Cl	1.72
Total moisture (%)	50

Part of this energy is devoted to the production of steam that provides additional energy in the digestion process. This steam is considered to be saturated at 10.2 atm as well as the produced with flue gases obtained by biogas combustion. The amount of MSW that is needed for thermal requirements ($fc_{(MSW_{thermal})}$) is computed taking into account the amount of condensing steam needed considering the value of the additional thermal energy in the bioreactor and the heat exchanger (see Supplementary Material).

So, in the end, the global energy balance on Eq. 10 must be satisfied.

$$Q_{extra_{HX3}} + Q_{extra_{Bioreactor}} = \left(fc_{(H_2O,Furnace1,Mix1)} + fc_{(H_2O,Furnace2,Mix1)}\right) \cdot H_{steam} \tag{10}$$

where H_{steam} is the specific enthalpy of the steam computed in the Supplementary Material.

The rest of the energy generated in the incineration of MSW goes for the production of steam that feeds the Rankine cycle to provide electrical energy. In this case, the energy contained in the flue gases is used in the different heat exchangers of the Rankine cycle to produce steam at different conditions. High, medium, and low pressure steam turbines are introduced to represent the multistage expansion in a real steam turbine. Common ranges in the operation of a Rankine cycle are considered: between 95-125 bar in the inlet stream of the high-pressure unit, between 11-35 bar for the medium pressure unit, and a range of 5-9.5 bar for the low pressure unit. The enthalpies and entropies of the different streams involved in the Rankine cycle are computed by the correlations proposed by León and Martín [28] as a function of pressure and temperature. In each of the turbines, the isoentropic efficiency is fixed at 0.9. The sum of the power produced in the turbines has the same value as the electrical consumption, so, modeling the Rankine cycle, the amount of steam and the energy requirements can be obtained. Once obtained these energy requirements the amount of MSW needed for power purposes ($fc_{MSW_{electrical}}$) can be determined by an energy balance. Further details are shown in the Supplementary Material.

Finally, by doing a mass balance, the total amount of MSW that is needed to provide the additional thermal energy requirements in the digestion process and the electrical requirements in the WWTP is determined (Eq. 11).

$$fc_{(MSW,Src6,Furnace2)} = fc_{MSW_{thermal}} + fc_{MSW_{electrical}} \tag{11}$$

3.7. Cases of study

The aim is to obtain the thermal energy requirements in sewage sludge digestion to evaluate the self-sufficient performance of the process. It is necessary to study how much of this energy can be produced using the generated biogas and how much energy has to be provided by MSW. This study is divided into two stages:

1) The evaluation of the operating conditions and optimization of the operating temperature of the anaerobic digestion, minimizing in both cases the external supply of thermal energy. Firstly, the evaluation and comparison of the operating conditions are made to the two main types of anaerobic digestion which operate at a different temperature: mesophilic (35ºC), and thermophilic (55ºC). This study has been developed considering the variation of the water and air temperature that exists along the year in the city of Salamanca, as a case base, because the thermal energy requirements depend on these temperatures. And, secondly, the operating temperature of the sludge digestion has been optimized considering the different water temperatures over the year, due to its effect on the amount of biogas produced and the energy consumption to heat up the sludge and dewatering step.

2) The study of the influence of the location on the thermal energy requirements. For the optimized process, different regions of the Iberian Peninsula have been studied considering the different climates that influence the air and water temperature each month which are shown in the Supplementary Material. In addition, the process of the incineration of MSW is modeled and integrated with the sludge anaerobic digestion to obtain the amount needed to provide the additional thermal energy and the power to operate the WWTP in these cities. Particularly, the climates that are chosen are:

- Oceanic climate in A Coruña, with temperatures between 10-13ºC and 10-11ºC in winter, and 16-19ºC and 14-16ºC in summer for air and water, respectively.
- Coastal Mediterranean climate in Barcelona, with temperatures between 9-13ºC and 9-10ºC in winter, and 20-23ºC and 17-19ºC in summer, for air and water, respectively.
- Continental Mediterranean climate in Salamanca and Madrid. In Salamanca, with temperatures between 4-6ºC and 6-7ºC in winter, and 18-21ºC and 15-17ºC in summer, for air and water, respectively; and, in Madrid, with 6-8ºC and 8ºC in winter, and 21-25ºC and 17-20ºC in summer.
- Oceanic Mediterranean climate in Sevilla, with temperatures between 11-12ºC and 11ºC in winter, and 23-27ºC and 19-21ºC in summer, for air and water, respectively.

These cities have been chosen to study most of the climates within the Iberian Peninsula, but also to cover a wide range of WWTPs sizes in order to evaluate their influence on the results.

The population of the different cities that are considered and the size of their WWTP is shown in Table 2. The size of each WWTP is related to the amount of organic matter that is treated, also shown in Table 2, considering that a person in Spain produces 26.9 kg of dry matter per year [37]. Also, it conditions its electricity consumption, shown in Table 2 too, considering that the average consumption of a WWTP in Spain is 5.6 kW/hab.eq. [38]. In the case of Madrid, it is shown that the size of the WWTP is lower than the population, and, also, that the size is lower than the size of the WWTP of Barcelona, despite the fact that the population of the latter is smaller. There is not one WWTP that covers the total population of Madrid, because of its high population, so there are several WWTPs distributed throughout the city and one of the largest is chosen in this work.

Table 2: Population of the city (hab.), size of the WWTP (hab.eq.), processed sludge in the WWTP (kg/s), total electricity consumption in the WWTP (kW) in Salamanca, La Coruña, Sevilla, Madrid, and Barcelona. a: Huerta Otea WWTP [39], b: Bens WWTP [40], c: Copero WWTP [41], d: La China WWTP [42], e: Baix Llobregat WWTP [43].

City	Salamanca	La Coruña	Sevilla	Madrid	Barcelona
Population (hab.)	144000^a	244850^b	689000^c	3266000^d	1637000^e
WWTP size (hab.eq.)	260040	600000	950000	1335000	1706250
Processed sludge (kg/s)	1.34	3.10	4.91	6.90	8.82
Electricity consumption (kW)	1.46	3.36	5.32	7.48	9.56

4. Results

In this section, the process analysis and economic results are presented for the case base of the WWTP in Salamanca and the integrated processes in the different WWTPs considered.

4.1. Case base analysis

4.1.1. Process analysis

As a case base, the operating conditions of the two operating modes of anaerobic digestion have been studied in the city of Salamanca. In both cases, mesophilic and thermophilic digestion, the most intensive sections of the process are the digestion itself and the digestate dewatering. The thermal energy needed in the process is provided by biogas combustion. The amount of biogas generated depends on the digestion temperature, obtaining 0.47 m^3/kg in the mesophilic condition and 0.58 m^3/kg in the thermophilic condition. The thermal energy that is needed in the digester has the same value in both cases, 914.5 kW, because it is considered an isothermal process, so it only depends on the enthalpy of the reaction. Nevertheless, the digestate dewatering consumes more energy in the mesophilic case, 467 kW vs. 358 kW, because the outlet temperature of the heat exchanger has always the maximum value (150ºC), so the gradient temperature of the thermophilic case is lower, and the average temperatures have the same value in both cases. These two thermal energy requirements do not change over the months. However, there are two more energy requirements in the process, which are the sludge heating before digestion and the air heating before combustion, and these values do change with the different water and air temperatures over the months. These values are shown in Figure 6. For the mesophilic case, the sludge and air heating consume from 163 kW and 13 kW, respectively, in January, the coldest month, to 101 kW and 2 kW in July, the warmest month. For the thermophilic case, the energy consumption changes from 275 kW to 213 kW in sludge heating, and, the energy consumption for air heating is the same as in the mesophilic case (from 13 kW to 2 kW), because the amount of air and the temperature gradients are the same in both cases. Figure 6 shows the additional thermal energy that is necessary for both digestion processes. The analysis shows that the energy provided by biogas combustion is not enough to comply with the total energy requirements. Although the digestion temperature is lower in the mesophilic case, it can be seen that the amount of additional energy is higher than in the thermophilic case, from 40% to 38% in mesophilic and from 38% to 36% in thermophilic, and, in both cases, is lower as the month gets warmer. As expected, this fact is due to the significant contribution of digestate dewatering to the total thermal energy requirements of the process, which is higher in mesophilic digestion (approximately 30% vs.

23%). In fact, the additional thermal energy without considering digestate conditioning is higher in the thermophilic case (16-20% vs. 9-14%) (Figure 6). Although it is shown that digestate dewatering consumes a large amount of energy this section of the process is included due to its advantages. The digestate can be used as fertilizer because it is rich in nutrients such as nitrogen, phosphates, and minerals, so it can reduce the need for artificial or synthetic fertilizers which are known to be harmful to the environment, and, also, more expensive. The removal of water reduces handling, transport, and storage costs and results in a drier compost that is easier to spread on the soil, and nutrients are not compromised during the dewatering process [44].

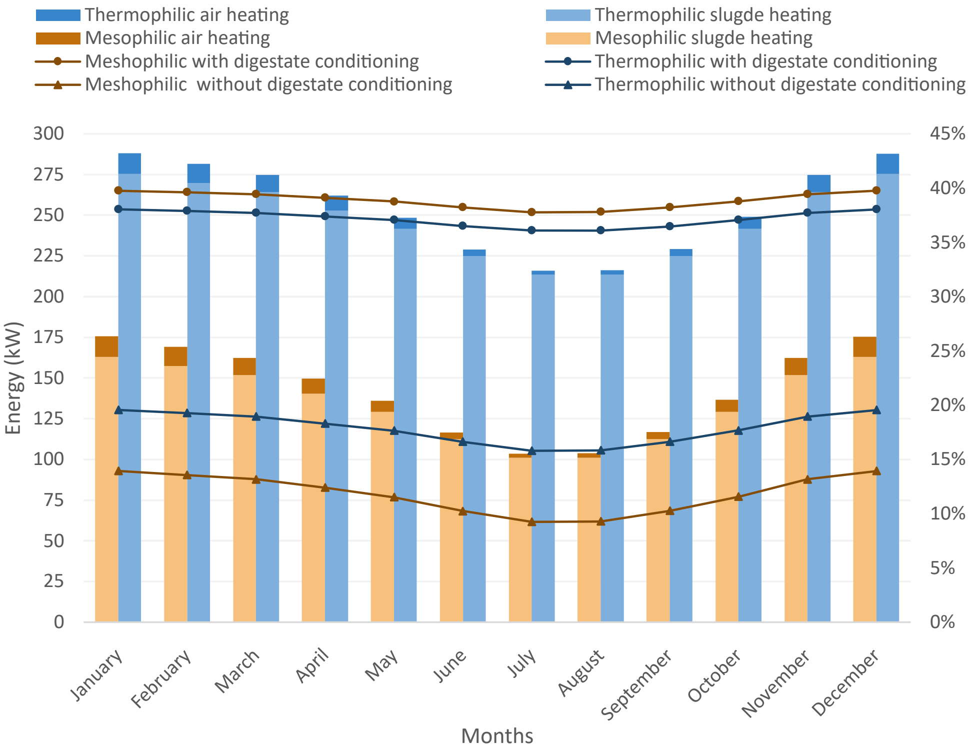

Figure 6: Energy contribution of sludge and air heating to mesophilic and thermophilic digestion in Salamanca and percentage of additional energy needed.

Then, once the process operation has been presented, the optimal digestion temperature is to be determined within the 30-55ºC range. It turned out to be 30ºC for all months, regardless of the water temperature. The optimization selects the lowest digestion temperature of the range in order to reduce the thermal energy involved in the process. Considering the previous part, the total energy requirements are slightly lower in the mesophilic case, because there is a net energy difference in its favor considering sludge heating up and digestate conditioning. However, while the additional thermal energy requirements are reduced with increasing digestion temperature, the increase in biogas production does not compensate. Therefore, the value of the total energy is crucial to obtain the optimal temperature. This optimal temperature is the value used to study the influence of the climate because it determines the value of the energy that heats up the sludge before digestion and the air before combustion. In this case, approximately, an additional energy between 38-40% is needed, a higher value than in the case of mesophilic digestion at 35ºC because the digestion temperature is lower. The change over the months and the different contributions to the total energy are shown in Section 4.2, where they are compared to other climates.

4.1.2. Economic analysis

An economic analysis of the digestion process for both operating conditions, mesophilic and thermophilic, in Salamanca, is presented in this section. Investment and operating cost are estimated. The investment does not present a variation over the months, so the total operating cost neither changes, because the amount of sludge that is treated is considered the same over the year and the design of the WWTP does not change over the months. The equipment cost was obtained for each month, and the maximum value has been considered to obtain the capital cost, i.e., the equipment is the same each month and only changes the utilization factor of some of them. The utilization factor is defined as the ratio between the capacity in each month of the equipment and its maximum capacity. In both digestion processes, only the utilization factor of the furnace changes. Taking into account the heat duty over the months shown in Figure 6 and the maximum capacity corresponding to January in both cases, the utilization factor of the furnace is reduced to 83.6% in the case of mesophilic and to 85.4% in the case of thermophilic. Regarding annualized investment, considering an annual capital charge ratio of 0.3 [45], similar costs are obtained: 0.079 €/kg of sludge for mesophilic digestion and 0.080 €/kg of sludge for thermophilic. These values are close because the main contributor to the investment is the equipment cost, particularly, the cost of the digester which is the same for both digestion processes. The cost of the digester contributes 84.6% to the total equipment cost in the case of mesophilic and 83.6% in the case of thermophilic. This gap is caused by the difference in the heat exchangers and furnace cost because the cost of the rest of the equipment has the same value in both cases. In Figure 7, the value and the breakdown of the equipment cost for both mesophilic and thermophilic processes in Salamanca are presented. The cost of the furnace in mesophilic digestion is lower because the thermal energy requirements are also lower, so the size of the equipment is reduced. The price of the furnace contributes to the equipment cost with a percentage of 7.97% in the case of mesophilic and 8.24% for thermophilic. For the heat exchangers, the cost is higher in the case of thermophilic, although the cost of the heat exchanger that dehydrates the digestate is lower, because the gradient temperature is lower, however, the cost of the heat exchanger after the digester is higher, for the same reason, and makes the total heat exchangers cost increases. Its contribution to the total equipment cost is 2.82% for mesophilic and 3.57% for thermophilic. The contribution for the rest of the equipment in both cases is 3.70% for compressors and 0.87% for the PSA system. In the case of operating cost, it is also similar in both digestion processes, because of the similarity in the investment cost, only deferring the items that directly depend on it. The operating cost has a value of 0.072 €/kg for mesophilic 0.073 €/kg for thermophilic. The operating cost and its breakdown are also shown in Figure 7 for mesophilic and thermophilic conditions in Salamanca.

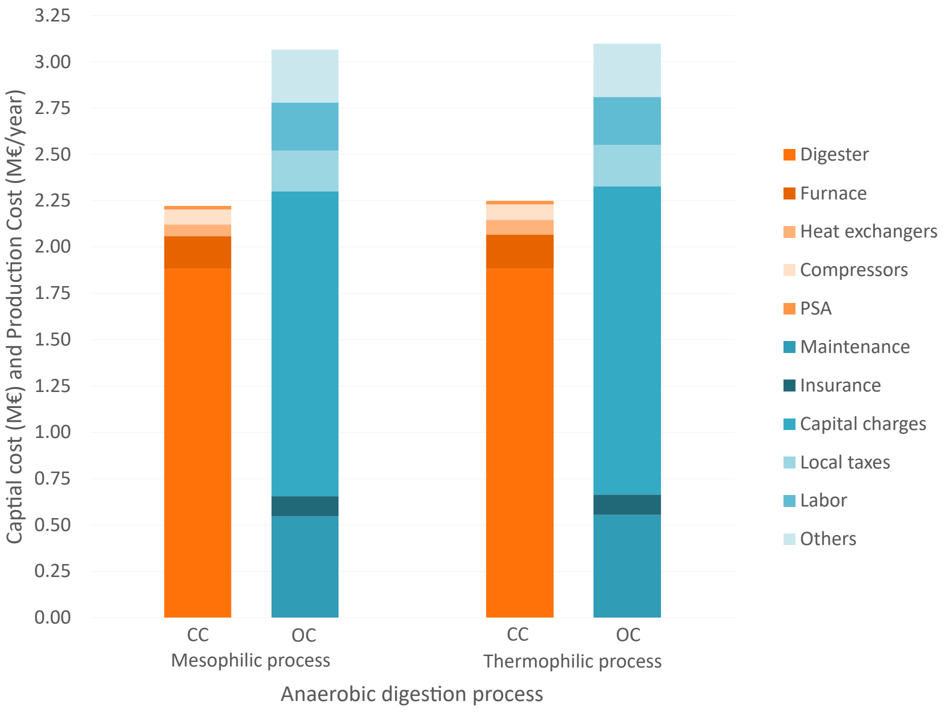

Figure 7: Value and breakdown of the capital cost (CC) and operating cost (OC) for mesophilic and thermophilic anaerobic digestion in Salamanca.

4.2. *Integrated process*

An integrated process that processes sewage sludge and municipal solid waste has been developed to provide for the energy required by the plant over the year, aiming at energy self-sufficient operation. Once the integrated process has been modeled, the influence of the climate on the energy requirements has been studied for different cities (Salamanca, Madrid, Barcelona, La Coruña, and Sevilla) taking into account that the optimal temperature for the digestion process is 30ºC. In all cases, the highest energy consumption corresponds to the digestion itself and to the digestate conditioning, it increases with the sewage sludge treated in the facility and it does not change over months. The value of energy required in the digester per kilogram of sludge is the same in all cities, 680 kJ/kg, because the digestion is considered an isothermic process and it occurs at the same temperature. The energy required to dehydrate the digestate per kilogram of digested sludge is around 364 kJ/kg in all cases because the model always chose the same value for the outlet temperature of the heat exchanger, 150ºC, assuming that the composition of the sewage sludge is the same in all cases. In Figure 8, it can be seen the total energy requirements per kilogram of sewage sludge treated for each city over the months. In all cases, the energy requirements are lower in the warmest months; however, the comparison between the highest and lowest value is different depending on the month. Most of the months, the energy requirements of Salamanca are the highest, because this city has the lowest temperature values, except June, July, and August. In these months, La Coruña has the highest energy consumption because the Oceanic climate tends to present mild summers, so water and air temperatures are lower. In Madrid, although it has the same climate as Salamanca, the energy requirements are lower, because the water temperature is, approximately, 2ºC higher and the air temperature is 3ºC higher each month, due to the lower altitude of the city. They are also slightly higher than in the case of Barcelona, except in summer when the trend changes. From January to April, between Madrid, Barcelona, and La Coruña, the first one is the major energy consumer per kilogram of sludge treated, and the same occurs from October to December; however, this trend changes between April and October, when the energy requirements of La Coruña increase, becoming even higher than those of Salamanca, which are the highest in most months. In all months, Sevilla presents the lowest energy requirements because the Continental Mediterranean climate presents the warmest temperatures, both air, and water.

As it has been discussed above, the energy required per kilogram of sludge for heating the sludge and the combustion air changes depending on the water and air temperature of the month, and in Figure 9 these energy requirements are shown for all cities. For all cases, June, July, and August present the lowest values because are the warmest months. Salamanca presents the maximum values, around 110 kJ/kg, because the winter in the Continental Mediterranean climate is the coldest one; nevertheless, in the warmest months, La Coruña exceeds the energy requirements of Salamanca, because it

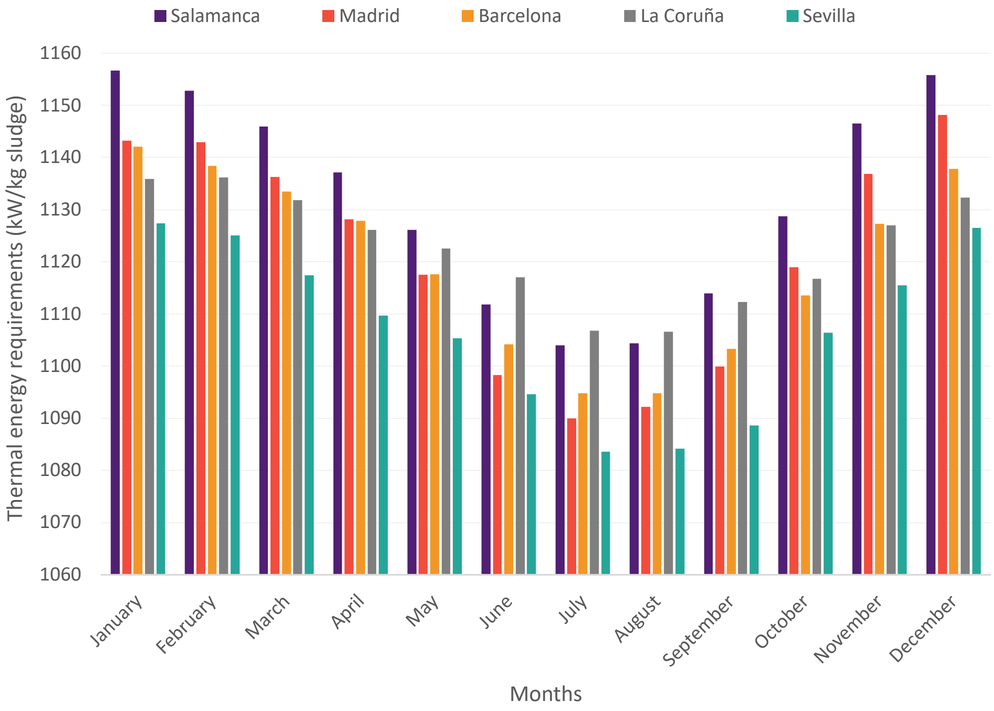

Figure 8: Total energy requirements per month in Salamanca, La Coruña, Sevilla, Madrid and Barcelona.

presents colder temperatures, around 61-70 kJ/kg vs. 56-66 kJ/kg. The minimum values are obtained in Sevilla, from 37 kJ/kg to 86 kJ/kg, because it is the city located in the most southern part of the Iberian Peninsula, so it presents higher temperatures every month. The highest difference between the maximum and minimum value is shown in Madrid, 58%, because it presents the largest gradient temperature over the months, and the minimum is found in La Coruña, 32%, where the thermal amplitude is lower due to the proximity of the Atlantic Ocean, which makes the climate milder; while, in Salamanca, this difference is 49%, in Sevilla, 56%, and, in Barcelona, 50%. This difference can also be seen in the shape of the curve presenting the data for the additional energy, which is more pronounced in the case of Madrid. The amount of additional energy to be provided by the MSW slightly varies between the different cities and is between 37% and 40% of the total energy required for the digestion process for all of them. This percentage is similar because the main contributor to the total energy required in the process is the energy for digestion and digestate conditioning, which represent around 91% of the total thermal energy. Its value increases as thermal energy requirements increase, so the same trend is observed as in the case of the energy needs throughout the year between cities. Therefore, the extremes are Seville, with the lowest percentage of additional energy, and Salamanca, with the highest, except in summer, when it is surpassed by La Coruña. In Madrid, Barcelona, and La Coruña occurs the same as in the previous case, the difference between the values of the additional energy is different depending on the month.

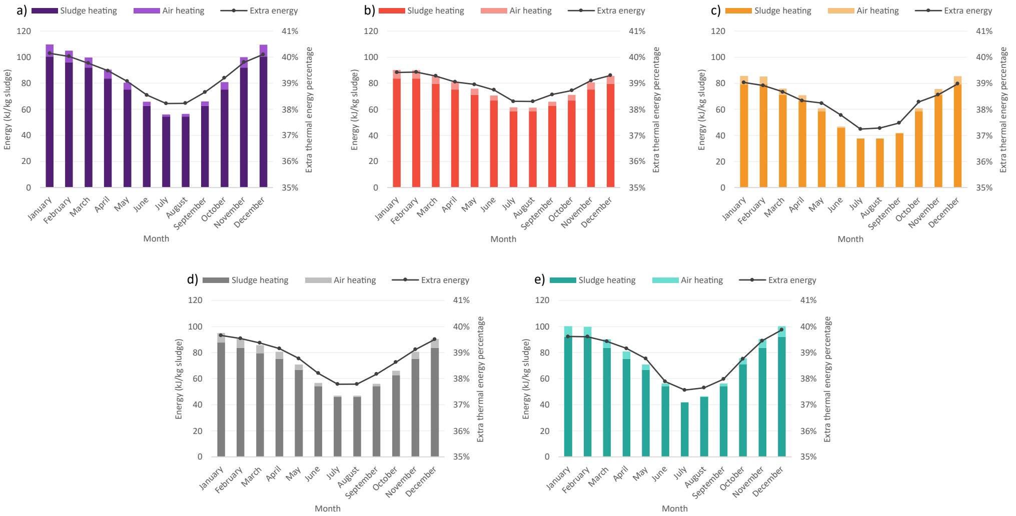

Figure 9: Energy contribution of sludge and air heating to digestion and percentage of additional energy needed in the different WWTPs per month: a) Salamanca, b) La Coruña, c) Sevilla, d) Madrid and e) Barcelona.

The average of the total amount of MSW fed to the incineration system is shown in Table 3. A fraction of this MSW is devoted to the production of steam to provide the additional thermal energy in the digestion process and the rest to produce electricity. The amount of MSW that is needed to provide the additional thermal energy is shown in Figure 10 for each city and changes over the months because of the variability in thermal energy requirements. As the size of the WWTP increases, the amount of MSW needed also increases. The variability of the amount of MSW in the smaller WWTP, as Salamanca and La Coruña, is almost negligible because it is a low value, around 0.03 kg/s and 0.08 kg/s, respectively; however it can be seen in the case of Barcelona, Madrid, and Sevilla, with an average of 0.21 kg/s, 0.17 kg/s, and 0.11 kg/s, respectively. The rest of the MSW is used in the Rankine cycle and this amount of MSW does not change over the months because the power consumption does not do it either. The high contribution of the electricity generation in the total amount of MSW fed, 87-88%, makes it to be almost constant over the year. This amount can be defined considering the amount of treated sludge and has a value of around 0.19 kg MSW/kg sludge in all cities.

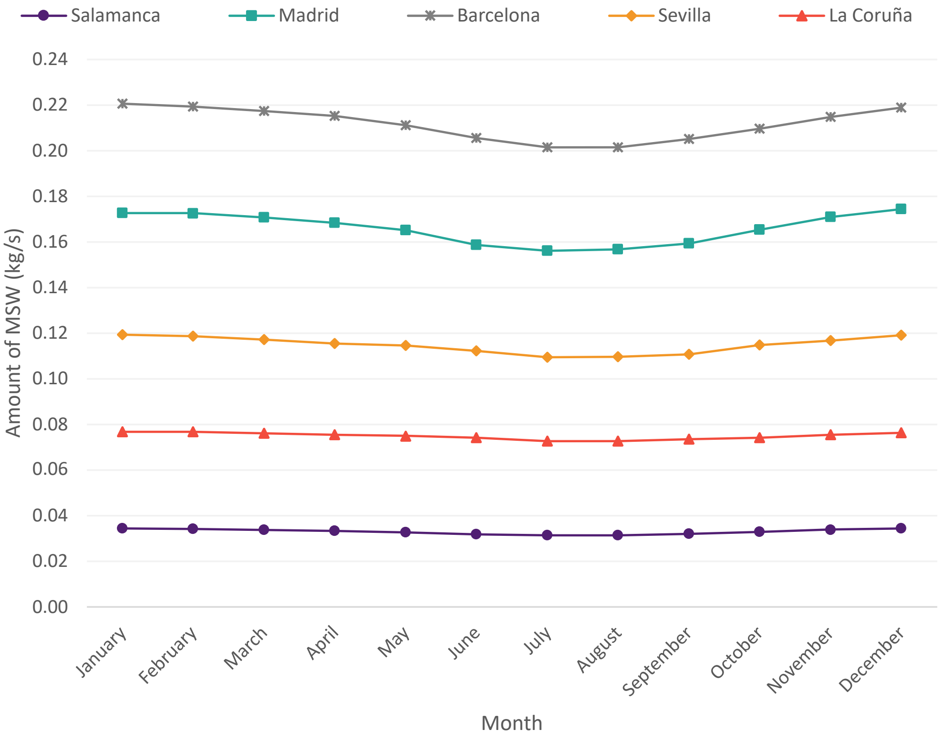

Figure 10: Amount of MSW to provide extra thermal energy requirements per month in Salamanca, La Coruña, Sevilla, Madrid, and Barcelona.

Regarding the electricity consumption, the amount of MSW needed to provide the electrical requirements is shown in Table 3, and it depends on the size of the WWTP. The highest consumption is found for Barcelona, 1.46 kg/s, which shows also the highest energy consumption (shown in Table 2). This amount can also be defined in terms of energy consumption, and, in all cities, it has a value of 0.55 kg/kWh in all months, as it was considered to vary only with respect to the size of the WWTP and invariable throughout the year. Also, in Table 3, the average percentage of the amount of total MSW generated in each city that is consumed, considering that, a person produces 455 kg of MSW per year [46], is shown. This percentage slightly changes over the months, because, as it was said, most of the fed MSW is devoted to electricity production and this amount does not change over the year. It can be seen that the percentage of the total MSW is not directly related to the size of the WWTP. This percentage is higher as the relationship between the population and the equivalent population (hab.eq.) of each city increases. Furthermore, in all cases, there is enough MSW to supply the plant, a fact that could be relatively predicted previously according to the work of González-Núñez et al. [24], where the energy that can be produced from MSW of different cities studied in this work is shown.

Table 3: Average of total MSW consumption (kg/s) in the integrated process, amount of MSW (kg/s) devoted to electricity and average percentage of the total amount of MSW produced in each city for each WWTP.

City	Salamanca	La Coruña	Sevilla	Madrid	Barcelona
Total MSW consumption (kg/s)	0.26	0.59	0.93	1.31	1.67
MSW for electricity (kg/s)	0.22	0.51	0.81	1.14	1.47
Percentage of total MSW (%)	11.19	16.64	9.33	2.77	7.07

4.2.1. Economic analysis

An economic analysis of the integrated process for the different cities is presented in this section. Investment and operating cost are estimated. As explained in the previous economic analysis, neither the investment nor the operating cost change over the months. As in the previous case, the utilization factor of the furnaces, the biogas furnace and the MSW one is the only one that changes. Taking into account the energy requirements shown in Figure 9, the utilization factor of the biogas furnace can be obtained. Its minimum values for the different cities are: 83.3% in Salamanca, 90.2% in La Coruña, 83.8% in Sevilla, 80.9% in Madrid, and 84.1% in Barcelona. The maximum reduction is obtained in the case of Madrid which shows the biggest difference in the energy requirements comparing cold and warm months and the minimum in La Coruña, whose difference is the smallest. In the case of the MSW furnace, the reduction in the utilization factor is almost insignificant, because the majority of the MSW is devoted to the production of electricity, whose consumption does not change over the months. The minimum value is around 98.9% for all cities. However, if only the production of steam to provide the thermal energy requirements in the digestion process is considered in the furnace, a big reduction in the value of its utilization factor can be seen. Its value is: 90.9% in Salamanca, 94.7% in La Coruña, 91.7% in Sevilla, 89.4% in Madrid, and 91.4% in Barcelona. The difference between the maximum and the minimum value of these values is due to the same reason as the biogas furnace. In Table 4, the total investment cost for the integrated process per kilogram of sewage sludge that is treated and per kilogram of MSW that is needed is shown. The total investment cost per kg of sludge goes from 0.09 €/kg to 0.16 €/kg and per kg of MSW, from 0.46 €/kg to 0.86 €/kg, in Barcelona and Salamanca, respectively. It can be seen that, as the size of the WWTP increases, the investment cost per kg of sludge and per kg of MSW decreases. Therefore, although, both capital costs are higher in the larger WWTP, they benefit from economies of scale. Figure 11 shows the breakdown of the equipment and the operating cost for

Table 4: Total investment cost of the integrated process per kg of sludge and per kg of MSW for the different cities.

City	Salamanca	La Coruña	Sevilla	Madrid	Barcelona
Investment (€/kg sludge)	0.163	0.116	0.099	0.093	0.086
Investment (€/kg MSW)	0.859	0.610	0.525	0.491	0.456

the different cities. The digester is the main item in the distribution of the capital cost in all cities, with around 51% of the total inversion, followed by the steam turbines, with a 25%. The digester percentage changes with the size of the WWTP, i.e., the amount of sewage sludge processed, it goes from 43% in Salamanca, which is the smallest WWTP, to 57% in Barcelona, which is the largest WWTP. The percentage corresponding to the steam turbines follows the opposite trend, it is lower as the size of the WWTP increases, ranging from 33% in Salamanca, to 20% in Barcelona, although their cost is higher in the last one because of the electricity consumption. The capital cost of the rest of the equipment slightly changes between cities. An average of 5.3% for the heat exchangers, 3.3% for the biogas furnace, and 13.1% for the MSW furnace, and the rest goes for the compressors and the PSA system. Regarding operating cost, all items that constitute this cost, increase with size, however, their contribution to the total value is different. The main contributor to the total value is the capital charges item with an average percentage of 60% of the total operating cost, but with a small increase with the size of the WWTP. It ranges from 58.2% to 61.1% in Salamanca and Barcelona, respectively. The percentage of the three other items which are represented that barely increase with the size and are almost constant are maintenance, insurance, and local taxes, with an average value of 20%, 4%, and 8%, respectively. As there are items whose percentage increases, the labor and the item which is called others decrease with the size. The relationship between the labor cost and the size of the WWTP is nonlinear, so, although the value increases with the size, its contribution to the total operating cost decreases; so, they benefit from economies of scale in this case. In the case of the item others, it is constituted by four contributors: miscellaneous materials, utilities, laboratory, and supervision. The miscellaneous materials and utilities cost are almost constant with the size; however, the laboratory and supervision costs are obtained as a percentage of the labor cost, so they decrease with the size and make the item other also decrease. Furthermore, it must be noted that the cost of the raw materials, sludge, and MSW, has not been considered, because as they are residues, they have been considered free. Considering only the section concerning the incineration of MSW, a price can be obtained for the electricity and put into perspective with other generation sources. This price is lower as the higher electricity consumption, so the biggest WWTPs take advantage of economies of scale. The highest price is obtained in Salamanca, 0.23 €/kWh, followed by La Coruña and Sevilla, with a price of 0.14 €/kWh and 0.12€/kWh, respectively, and, finally, the lowest electricity prices are obtained in Madrid and Barcelona, 0.10 €/kWh and 0.08 €/kWh, respectively. These prices are nearly constant throughout the months, as they minimally change because the operating cost also changes. This cost changes because the furnace is also used to produce the steam that provides the thermal energy requirements to the WWTP, which are different over the year, so the amount of MSW also changes changing the items of the cost depending on it. However, this price will increase if the gas treatment section, which is not considered, is included in the process. These prices are not far from the prices that present the two main renewable sources, 0.05-0.1 €/kWh for solar PV panels and 0.1-0.15 €/kWh for wind turbines, especially in the largest WWTP. If compared to the traditional energy sources, in most cases, they are lower that the prices of natural gas-based facilities that have an average value of 0.22 €/kWh and near to the prices of the coal-based plants, in the largest WWTP, which are around 0.1 €/kWh [47].

5. Conclusions

In this work, the energy requirements of different WWTP have been studied, particularly, the attention is focused on sewage sludge treatment. The thermal energy requirements of sewage sludge treatment are a difficult problem because the anaerobic digestion of sludge does not produce enough biogas to cover them. Because of that, an integrated process of sludge treatment and municipal solid waste treatment has been evaluated in order to make the WWTP self-sufficient in terms of energy. MSW is employed to supply the thermal energy that is necessary to cover the total process and can not be supplied by biogas, apart from generating the power requirements of the entire WWTP. Moreover, the influence of the climate in different regions of the Iberian Peninsula has been studied. The results show that it is feasible to integrate the treatment processes because there is enough MSW to provide energy to the WWTP in all cities. The amount of MSW required per kilogram of sludge is around 0.19 kg/kg, with a very small difference between cities, being lower as the average of additional thermal energy decreases. The investment cost ranges from 0.09 €/kg to 0.16 €/kg of sewage sludge, depending on the size of the WWTP due to economies of scale. Additionally, prices ranging 0.08-0.23 €/kWh are obtained for the electricity produced by the incineration of MSW. Comparing these prices to other renewable or traditional sources, there is a

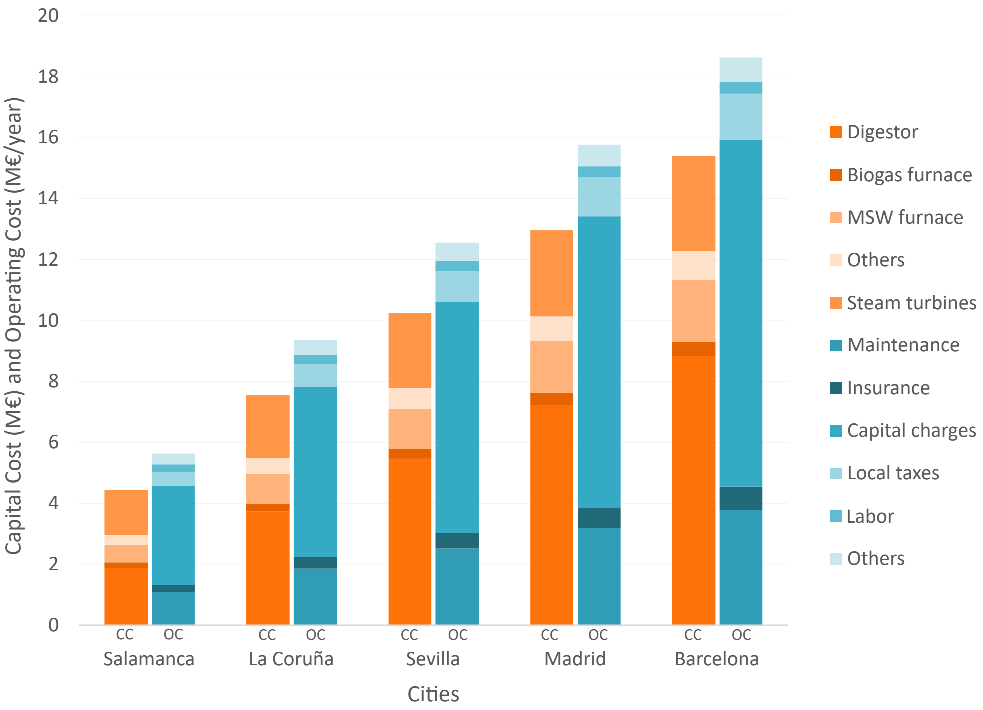

Figure 11: Value and breakdown of the capital cost (CC) and operating cost (OC) of the different WWTPs.

proximity in prices that makes feasible the use of MSW as an energy source in order to reduce the use of fossil fuels. This analysis allows for a successful integration of these treatment processes with the objective of a fully self-sufficient and sustainable system.

Nomenclature

Indices / sets/ subsets

b {Bioreactor, HX3}
m {Steam, Air, Sludge}

Variables/ parameters

E_{biogas}	Thermal energy provided by biogas (kW)
E_{diges}	Thermal energy requirements in digestion process (kW)
E_{MSW}	Thermal energy provided by MSW (kW)
$F_{(unit,unit1)}$	Mass flow rate of stream from unit to unit1 (kg s^{-1})

$fc_{(k,unit,unit1)}$	Mass flow rate of component k from unit to unit1 (kg s^{-1})
$fc_{MSW_{electrical}}$	Mass flow of MSW to provide electrical energy (kg s^{-1})
$fc_{MSW_{thermal}}$	Mass flow of MSW to provide thermal energy (kg s^{-1})
H_{steam}	Specific entalphy of saturated steam (kJ kg^{-1})
LHV_{MSW}	Lower heating value of MSW (kcal kg^{-1})
Q_{extra_b}	Additional energy requirements in unit b (kW)
Q_m	Energy requirements of stream m (kW)
Q_{steam_b}	Thermal energy provided by steam in unit b (kW)
Q_{unit}	Heat exchanged in unit (kW)
Z	Objective function

Equipments and others

$Bioreactor$	Digester
$Compresi$	Gas compressor i
$Furnacei$	Furnace i
HXi	Heat exchanger i
$Mixi$	Mixer i
MSi	Molecular sieve i
$Sepi$	Separator i
$Snki$	Sink of stream i
$Srci$	Inlet source i
$Turbi$	Gas expander i

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