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Decentralized Biogas Production in Urban Areas: Studying the Feasibility of Using High Efficiency Engines

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Abstract: The decentralized treatment of wastes is studied for an urban scenario considering a high-density population of 2500 inhab./km². Food and garden waste were assumed to be treated in a co-digestion configuration using several mid-size digesters. In contrast biogas and digestate valorization were carried out in a centralized manner. Electricity and thermal energy were produced from this configuration, accounting for 1.3% of residential electricity demand and 3.2% of thermal demand when using double-turbocharged engines. However, the location of the treatment plants is a factor that may raise social discomfort. Rejection of locating the plant in specific sites close to residential neighbors, nuisance due to possible odor and gaseous emissions, and house market distortions are just a few of a long list of problematic aspects that may threaten the decentralized alternative. These factors are of great relevance and must be given a practical solution if the circular economic model is to be implemented by considering the insertion of waste streams into the production system and generating local energy sources and raw materials.

Keywords: energy; combined heat and power engines; anaerobic digestion; digestate valorization; local waste treatment

1. Introduction

Anaerobic digestion is considered a technology capable of transforming organic wastes into energetic products and obtaining digestate as a by-product susceptible to valorization in agriculture. However, the implementation of this technology, although widely spread, still experiences high installation costs making its application unfeasible on small and medium-sized systems. In addition, the recent events regarding the war scenario in Ukraine are setting much pressure to obtain energy sources and gaseous fuels from local resources. Anaerobic digestion may be an excellent ally in the production of local gaseous fuels but also have several disadvantages regarding the complexity of the biological process and the need for qualified personnel to perform daily tasks and keep an adequate maintenance of industrial equipment.

Decentralized waste treatment has gained attention in recent years due to the lower impacts associated with collection and transport, along with the easiness of controlling process parameters when treating smaller waste quantities [1,2]. However, there are limits based on reasonableness to the distance wastes are to be transported from the collecting point to the centralized treatment center [3]. Therefore, treating wastes locally has been proposed as a suitable alternative for low-populated areas, small livestock farms or developing countries where treating organic wastes may serve as a local source of biogas for cooking. This strategy, although technically feasible in some regions, faces several constraints regarding climatic conditions and substrate characteristics. Wang [4] reported that several digesters installed in China and Nepal were not operating at optimal conditions, and up to 50% were not functional after a short period. Similar reports regarding the installation and operating

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conditions of small digesters in China and India expressed concerns regarding low biogas production and inefficient operation [5–7].

Other researchers assessing the performance of small digestion units in Egypt reported on the feasibility of these small plants [8]. These authors considered in their analysis only the biofertilizer derived from digestate as a valuable product, disregarding energy production. A different evaluation also dealt with small-scale digestion systems, but in this case, using a prototype. Authors reported higher energy demand per unit of biogas produced when compared with large-scale units [3], making the process non-competitive.

It is true that a further proliferation of small-scale digesters in developing countries may aid in significantly reducing global emissions of methane [9]. However, these digesters must keep operative during their whole life cycle. Luo et al. [10] studied different small-scale digestion units in China (30 – 200 m^3), stating that with some technical improvement and keeping operation at ambient conditions, small digesters with a simple configuration may attain biogas productivities of 0.47 $m^3/m^3_{reactor}$ d. In addition, these authors indicated that the farmer could perform the operating and maintenance tasks of small digesters after some basic training.

On the other side of the coin, centralized digestion does not face a clear horizon. Large-scale plants take advantage of economies of scale, but these plants may confront social rejection when integrated into mega-farm projects. The large number of animals held in large-scale farms allows for reducing costs and keeping better control of health risks. An increase in farm scale also makes it easier to comply with guidelines and guarantee animal welfare so that animals are raised and slaughtered humanely [11]. However, any attempt to increase the efficiency of meat production systems collides with the general trend of rejecting industrial animal production [12].

Anaerobic digestion is the best biological option for treating high organic strength effluents, but the methane potential of manures may not be high enough to assure plant feasibility. This fact, in addition to other factors such as high installation costs and the high price of co-substrates, may represent significant barriers to increasing the implementation of digestion technology in many countries [13,14]. Velásquez Piñas et al. [15] analyzed the Brazilian scenario of biogas plants using mono-substrates, such as cattle manure. These authors indicated that digestion was feasible if an electrical power higher than 740 kWe was installed. This value was increased to 1000 kWe when co-digestion was considered. In a different study, González et al. [16] evaluated the techno-economic feasibility of treating sheep manure considering a farm size of 2000 animals and electricity production from biogas. Even under the assumption of co-digestion, the system had low economic feasibility. Imeni et al. [17] reported results regarding the feasibility of a cattle farm with 250 adult animals. Profitability was only achieved if co-digestion with raw briquette straw was implemented.

There is wide experience applying digestion technology in the farm and agro-industrial sectors. In recent years, the interest has moved to extrapolating experience from anaerobic digestion gained in different waste treatment sectors into urban areas, thus allowing the local treatment of food waste. This approach benefits from lower distances for transporting wastes and obtaining a local source of biogas. However, the final disposal of digestate is still pending a clear solution since, if not properly solved; this factor may threaten the whole process implementation [18]. The decentralized approach considers the presence of several small units for digesting the material. It should also consider the use of low-emission vehicles for waste collection and pretreatments to reduce the mass of residues and minimize odors [19].

Even if the installation of several small digestion units is feasible, there are other factors needing optimization. The valorization of biogas by combined heat and power (CHP) units is heavily penalized since electricity conversion efficiency is higher for large-capacity engines. In contrast, smaller ones are limited by efficiencies of about 34% [20]. It should also be analyzed if it would be reasonable to change a currently centralized operating system for treating urban wastes for a decentralized treatment approach, which may be controversial. In previous work, authors evaluated the feasibility of producing biogas using small-scale digestion systems in urban and rural areas [21]. In their previous work, biogas derived from small digestion systems could scarcely cover 5.8% of a home's thermal demand. If electricity production is considered, then small-scale digestion and in-

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situ biogas valorization are not a good couple. It seems more reasonable to assume a hybrid approach where biogas is produced in a decentralized way and converted into electricity in high-efficiency engines.

The amount of electricity expected from food waste derived from urban areas could be about 2.4-4.1% of the total electrical demand of the population. This value was estimated by Nguyen et al. [22] for the Vietnam case, representing a motivating factor to search for an optimal configuration capable of integrating sustainability principles, energy production and circularity goals. However, the local treatment of waste needs to consider several aspects regarding reactor design, operating conditions, climatic factors and social aspects [1,23]. Win et al. [24] analyzed the decentralization scheme by considering waste treatment at high-producing centers. These authors indicated that subsidies and incentives are needed to attain economic feasibility. However, after so many years of experience in digestion technology development, the focus should be placed on attaining a profitable process, otherwise this technology may not become a real driver in the energy sector. Experience already gained in the digestion of manures and the treatment of agronomic waste may be useful in adapting technologies for the local treatment of wastes in urban areas.

In the present manuscript, a hybrid approach of waste treatment and biogas valorization was assessed, assuming decentralized anaerobic digestion and a centralized biogas valorization unit using CHP engines. Energy production potential was obtained by assuming food and yard wastes as feeding material. Estimations of electricity and thermal energy were carried out considering engine's efficiency and seasonal climatic conditions.

2. Materials and Methods

2.1. Engine description

The biogas engine studied was a lean-burn, four-stroke Otto cycle, Jenbacher type JGS 320 GS-BL. This engine consists of two inlet mixture compression stages and two intercooler stages with plate heat exchangers. Combustion takes place under lean-burn conditions, using spark ignition from spark plugs. The compressors are driven by the exhaust gases expanded in the turbines. Both components are mechanically coupled by means of a rotating shaft. The arrangement of the cylinders is based on two rows of ten units in a V-shape. Analysis of this engine was based on Cascallana et al. [25]. This engine is fueled by biogas and uses an electronic carburetor mixing the incoming gases before being compressed in the first compression stage. Each of the two rows of cylinders has a turbocharger consisting of a centrifugal compressor driven by a centripetal turbine, which uses exhaust gases for its operation. The intercoolers are air-to-water heat exchangers cooled by the main and auxiliary circuits.

Table 1 shows the geometric parameters of the engine.

Table 1. Geometric parameters of the JGS 320 GS-BL engine [26].

Parameters of Engine type J 320 GS-D121	Value
Engine strokes (strokes/cycle)	4
Total displacement (cm^3)	48,670
Number of cylinders (units)	20 in V
Number of cylinder lines (units)	2
Angle of the cylinders (°)	70
B, bore (mm)	135
S, stroke (mm)	170
S/B, stroke/bore ratio	1.26
r_C, engine compression ratio (dimensionless)	11.8
n, engine rotation speed (rpm)	1,500
Average piston speed (m/s)	8.5
Piston displacement (L)	2.43
Piston area (cm^2)	143

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Combustion chamber volume (cm^3)	225
Combustion chamber/displacement ratio(%)	6.8

Engine operating and performance parameters are shown in Table 2. Table 3 contains the characteristics and operating parameters of turbochargers. The tolerances are ±5% for biogas consumption (composition: CH_4 65% and CO_2 35%) and ± 8% for the other parameters. Loading degree is considered 100% for a methane flow rate corresponding to a biogas flow rate of 458 kg/h with a 65% methane content. The power is determined at operating conditions at standard reference conditions ISO/3046/1: altitude 100 m above sea level (a.s.l.), pressure 100 kPa, temperature 25 °C and humidity 30%. The volume is reported at standard conditions for biogas, combustion air and exhaust gases, pressure 101 kPa and temperature 0 °C [27].

Table 2. Performance characteristics of the JGS 320 GS-BL engine [27].

Performance parameters of engine type J 320 GS-D121	**Degree of loading (%)**		
	100	**75**	**50**
Minimum LHV[1] of biogas (kWh/m^3)	5		
[2]CH_4 number/Minimum CH_4 number	135/100		
P_{eng}, engine mechanical power (kW)	1,095	821	548
Electrical power (cos φ = 1) (kW)	1,067	798	529
MEP, mean effective pressure (kPa)	1,800	1,350	901
Radiation power losses (kW)	54		
Mechanical power losses (kW)	28	23	19
Power loss of exhaust gases (100 °C) (kW)	685		
Power loss of exhaust gases (180 °C) (kW)	550		
Power loss of exhaust gases (0 °C) (kW)	740		
Exhaust gas temperature (°C)	490		
M_{air}, air mass flow inlet (kg/h)	5,176		
M_{eg}, Exhaust gas mass flow (wet) (kg/h)	5,634		
M_{bio}, biogas mass flow (kg/h)	458		
η_{mec}, Mechanical efficiency (%)	41.2	40.1	38.2
Electrical efficiency (cos φ = 1) (%)	40.2	39	36.8
η_e, engine thermal efficiency (%)	41.3		
Energy efficiency (%)	82.5		
BC, biogas consumption (kW)	2,655	2,046	1,436
Min-Max biogas pressure range at the biogas inlet train (mbar)	80-200		
Main circuit thermal power (kW)	645	519	394
Block and jacket circuit power (kW)	341	336	296
P_{INT-2}, intercooler 2 power (kW)	181	78	5
Oil exchanger power (kW)	123	105	93
Auxiliary circuit thermal power (kW)	77	58	38
P_{INT-1}, intercooler 1 power (kW)	77	58	38
F, ratio fuel/air (%)	8.8		
Max. admissible exhaust back pressure after engine (kPa)	6		
Max. admissible pressure drop in front of intake-air filter (kPa)	1		

[1] LHV: Lower heating value. [2] Methane number: is a measure of resistance to detonation. Pure methane has assigned a value of 100 and hydrogen a value of 0.

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Table 3. Turbochargers characteristics and operating parameters.

Turbocharger parameters	Value	References
Maximum temperature of the mixture at second intercooler (°C)	83.9	[26]
Maximum temperature of mixture at first intercooler (°C)	55	[26]
η_{mec1}, η_{mec2}, Mechanical efficiency of turbocharger transmission	97	[28]
R, universal constant of ideal gas (J/kg K)	287.05	[29]
γ, adiabatic coefficient of air, mixture and gases (dimensionless)	1.4	[30]

The engine cooling system is shown schematically in Figure 1, representing the main and auxiliary circuits. The purpose of the three-way thermostatic valves is to regulate the thermal power exchanged by the use of recirculating water without flowing through the plate heat exchangers. This allows adapting the water mass flow to all circumstances based on the degree of loading and, therefore, the amount of thermal energy transferred. When the engine is at full load, the flow through the bypass is zero, and all the energy is transferred. However, a fraction of the water flow is bypassed at a lower loading, reducing the amount that finally reaches the heat exchanger.

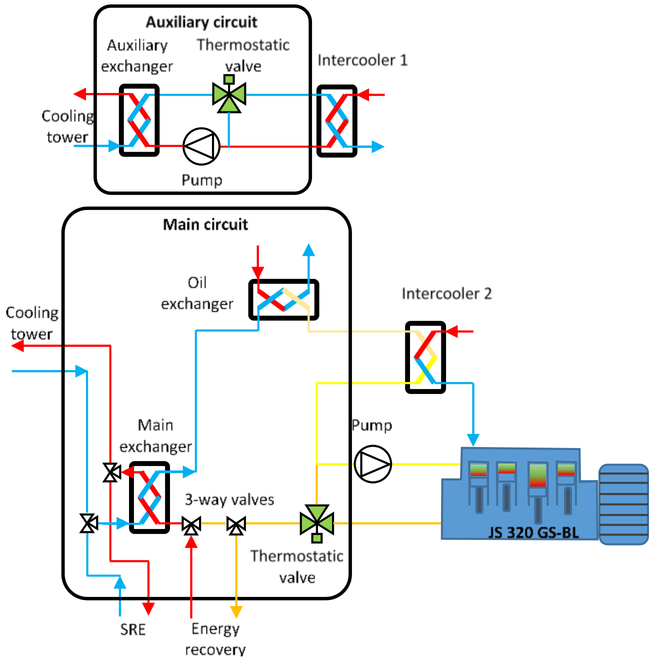

Figure 1. Engine cooling system. This system is composed by two separate lines: the main and auxiliary circuit.

2.2. Engine performance equations

Figure 2 shows the general operating scheme of the cogeneration system, considering the cooling circuit coupled to a heat recovery unit. The cogeneration system has two different cooling circuits, the main and the auxiliary. Each of these circuits has a plate heat exchanger that divides them into primary and secondary circuits. The primary section of the main circuit is responsible for cooling the engine block, the cylinder heads, the oil circuit inside the CHP unit, the intercooler 2 of the twin-turbo system [27] and the heat recovery system of the exhaust gas. The main circuit in its second section allows thermal energy to be transferred to other devices via a heat exchanger or dissipated in the cooling tower. The auxiliary circuit cools intercooler 1 via its primary circuit [27], while the

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secondary circuit dissipates the thermal energy in cooling towers. This thermal energy is disregarded due to its low temperature, which makes its use difficult, containing just a small share of the total energy contained in biogas. The primary section of both cooling circuits uses a 37% glycol solution in water as heat transfer fluid to prevent freezing when the engine is out of service.

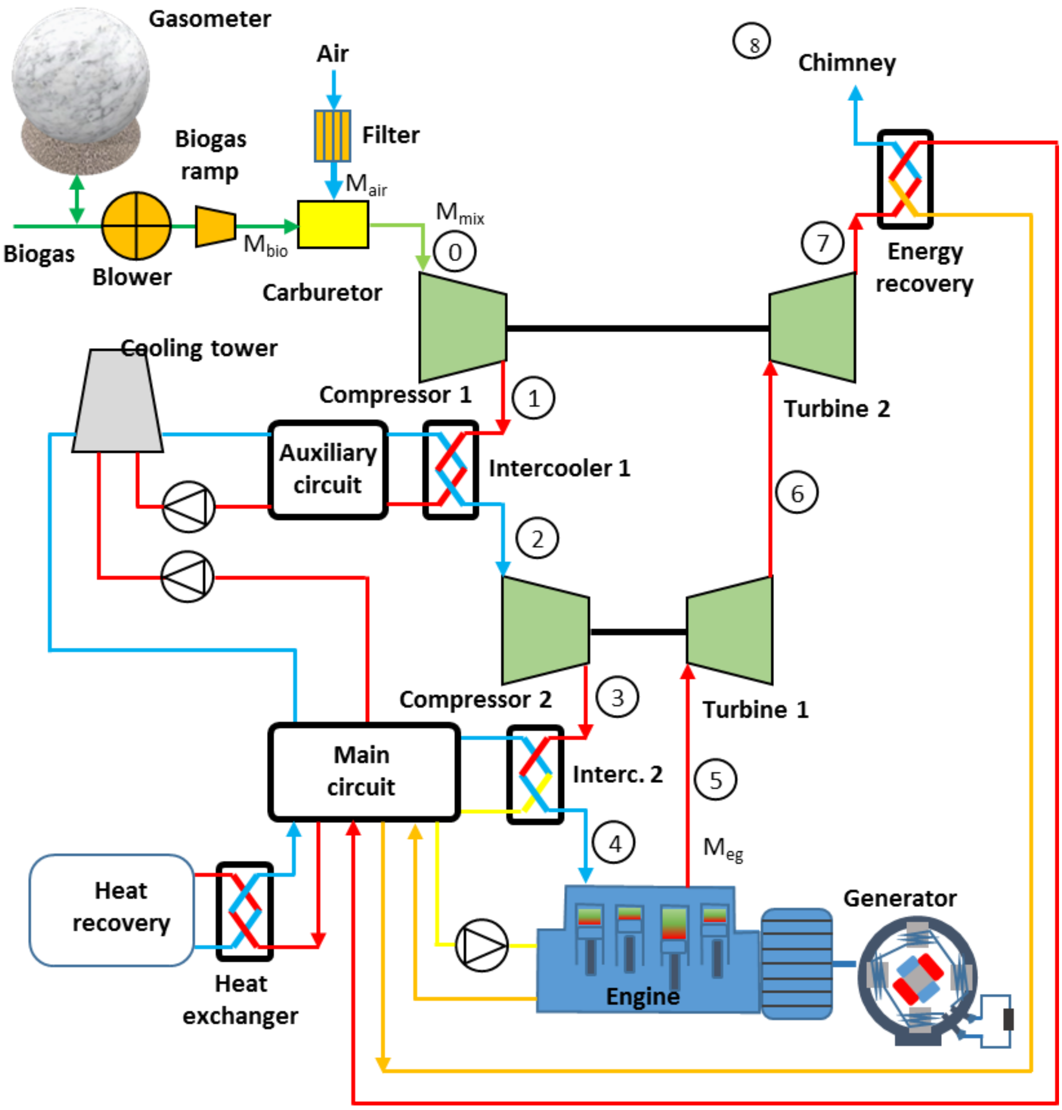

Figure 2. General operating diagram of the biogas engine.

Mass and energy balance were established for the double turbocharger. Numbers in Figure 2 were used to indicate the different calculation sections. Parameters obtained from compression were used to estimate those of the turbine. The power developed by the turbine was that necessary to drive the compressor after considering mechanical losses during power transmission by the common shaft.

The mass flow of the combustion mixture, M_{mix}, (biogas and air, M_{biogas} and M_{air}) is estimated by equation (1) and this value is conserved, thus being the same for the mass flow of exhaust gases (M_{eg}). The mass ratio of biogas to air is represented by parameter F in equation (2).

$$M_{mix} = M_{eg} = M_{air} \cdot (1 + F) \quad (1)$$

$$F = M_{biogas}/M_{air} \quad (2)$$

The twinning energy balance is the ratio of the mechanical power (P) between compressor and turbine as shown by equations (3) and (4).

$$P_{T1} = P_{C2}/\eta_{mec2-T1} \tag{3}$$

$$P_{T2} = P_{C1}/\eta_{mec1-T2} \tag{4}$$

where subscripts 1 and 2 represent the first and second stage, T and C also used as subscripts stand for turbine and compressor. Thus, P_{T1} represents turbine power in stage 1. The mechanical efficiency is here denoted by η_{mec}. $\eta_{mec1\ C2-T1}$ and $\eta_{mec1\ C2-T1}$ are assumed to be 97% at most. This is due to the intrinsic limits of the turbine-compressor system, which set restrictions to the full recovery of energy from exhaust gases when the nominal compression ratio is reached.

Compressor and turbine rotational speeds (n_C, n_T) are also twinned. The relationship between these speeds is shown in equation (5) and (6). The subscript 1 and 2 represents again the stage analyzed.

$$n_{C1} = n_{T2} \tag{5}$$

$$n_{C2} = n_{T1} \tag{6}$$

Equation (7) estimates the mechanical power developed by the engine (P_{eng}).

$$P_{eng} = V \cdot \frac{2 \cdot n}{N} \cdot \frac{1}{60} \cdot MEP \tag{7}$$

where V is the total displacement volume of the cylinder per cycle (0.04867 m^3/cycle), n is the engine rotation speed (1,500 rpm), N is the number of engine strokes (4 strokes/cycle). MEP (mean effective pressure) is a theoretical parameter representing the average pressure during a complete cycle and gives an idea of the effective work done (1,800 kPa).

Equation (8) gives the engine MEP, where ρ_{adm-a} and ρ_{bio} are the densities of air and biogas respectively at the entrance to the combustion chamber. LHV is the lower heating value of biogas, η_V and η_e are the volumetric and combustion efficiency of the engine. η_V and η_e depended on the loading degree and were calculated by least squares adjustment to keep consonance with the MEP value given by the manufacturer.

$$MEP = \rho_{adm-a} \cdot \eta_V \cdot F \cdot \frac{LHV}{\rho_{bio}} \cdot \eta_e \tag{8}$$

The specific heat of air (c_{p-air}), fuel-air mixture (c_{p-mix}) and exhaust gases (c_{p-eg}) were considered equivalent. The specific heat of air was obtained from equation (9) [31].

$$c_{p-air} = R \cdot (3.56839 - 6.788729 \cdot 10^{-4} \cdot T + 1.5537 \cdot 10^{-6} \cdot T^2 - 3.29937 \cdot 10^{-12} \cdot T^3 - 4.66395 \cdot 10^{-13} \cdot T^4) \tag{9}$$

The compression ratio (r_C) is estimated as the proportion between the inlet and outlet pressure. For the first stage compressor, subscript 0 were used to indicate inlet and 1 to represent the outlet stream. Compression was assumed isentropic thus, the equivalence in equation (10) when considering the isentropic ratio, where p_1 is substituted by p_{1s}.

$$r_{C1} = p_1/p_0 = p_{1s}/p_0 \tag{10}$$

The compression ratio used for the first and second stage of compression are 1.85 and 2.57, respectively [26]. Initial pressure is 101.3 kPa. The isentropic outlet temperature T_{1s} is calculated using equation (11).

$$T_{1s} = T_0 \cdot \left(\frac{1}{r_{C1}}\right)^{\frac{1-\gamma}{\gamma}} \tag{11}$$

The specific heat ratio (γ) is 1.4 for air and initial temperature (T_0) is 25 °C. The isentropic efficiency (η_{is-C1}) is the ratio of the temperature increase that takes place under real and ideal compression conditions according to equation (12). Subscript 1 and 2 were used for the first or second stage. Isentropic efficiency for the first and second stage were 75% [28].

$$\eta_{is-C1} = \frac{T_{1s} - T_0}{T_1 - T_0} \tag{12}$$

The compressor power (P_{C1}) is calculated from equation (13)

$$P_{C1} = \frac{M_{mix}}{3{,}600} \cdot c_{p-mix} \cdot (T_1 - T_0) \tag{13}$$

The power of the intercooler (P_{INT1}) is estimated from equation (14) using the difference in temperature conditions between the inlet point (T_1) and outlet point (T_2). Pressure after a cooling stage was estimated assuming the behavior of the gas mixture as ideal gas.

$$P_{INT1} = \frac{M_{mix}}{3{,}600} \cdot c_{p-mix} \cdot (T_1 - T_2) \tag{14}$$

Equations are equivalent for the second compressor and intercooler. In this case, the outlet condition for the compressor uses subscript 3, and the outlet condition for intercooler uses subscript 4. Equations (15-18) –for turbine 1– are used to estimate power (P_{T1}), isentropic efficiency (η_{is-T1}), inlet pressure (p_5) and the expansion ratio (r_{ex-T1}). The nomenclature used in these equations was set by considering subscript 5 to identify inlet condition, and 6 for outlet stream.

$$P_{T1} = \frac{P_{C1}}{\eta_{mec1}} = \frac{M_{eg}}{3{,}600} \cdot c_{p-eg} \cdot (T_6 - T_5) \tag{15}$$

$$\eta_{is-T1} = \frac{T_5 - T_6}{T_5 - T_{6s}} \tag{16}$$

$$p_5 = p_6 \cdot \left(\frac{T_5}{T_{6s}}\right)^{\frac{\gamma}{\gamma-1}} \tag{17}$$

$$r_{ex-T1} = p_5/p_6 = p_5/p_{6s} \tag{18}$$

The isentropic temperature and pressure are denoted by T_{6s} and p_{6s}. The expansion ratio, calculated as the ratio between inlet and outlet pressure, is considered here to be equivalent to that of the isentropic condition. The same equations are applied for turbine 2 using subscripts 6 and 7 to indicate inlet and outlet streams. The power associated with chimney energy recovery (P_{ER}) is calculated by equation (19). Inlet and outlet points are identified by subscripts 7 and 8.

$$P_{ER} = \frac{M_{eg}}{3{,}600} \cdot c_{p-eg} \cdot (T_7 - T_8) \tag{19}$$

2.3. Methodology for evaluating decentralized biogas production in mid-size communities

The efficiency of small-scale digesters is reduced with decreasing size because the energy demand of auxiliary equipment associated with reactor operation does not follow a linear relationship. Different digesters sizes were assumed by considering working conditions under different hydraulic retention times (HRT). The treatment of a mixture of food and garden waste was assumed by considering a population of 150,000 inhabitants with a mean population density of 2500 inhab./km^2. Assumptions for input materials are specified in Table 4. 60% methane content in biogas was assumed. The digestion process is to be run under mesophilic conditions at a total solid (TS) feed content of 11%. Biogas production from the waste mixture was estimated by disregarding synergies between co-substrates.

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Table 4. Assumptions for food and garden waste: Solid content and specific methane production (SMP). TS: Total solid, %VS: percentage of volatile solids.

Parameter	Food waste	Reference	Garden waste	References
Production (kg/year per capita)	77	[32]	110[1]	
TS content (g/kg)	150		610	[33]
%VS	90	[34,35]	77.5[2]	[33,36]
SMP (mL CH_4/g VS)	340	[37,38]	257	[39]

[1] Estimated as the difference between the mixture of food waste and garden waste production by subtracting the amount of food waste produced. Mixture of food waste and garden waste for Spain is 187 kg/person year [40]. [2] Estimated as average values of those reported in references.

Daily biogas production (DBP, expressed in m^3/d) was calculated based on equation (20)

$$DBP = \frac{WP \times Nº_{inhab} \times TS \times \%VS \times SMP}{365000 \times [CH_4]} \quad (20)$$

where WP is the waste production factor either for food waste or garden waste (expressed as kg waste/inhab. year. Nº inhab stand for the number of inhabitants considered, TS is the total solid content of the waste, %VS is the content of volatile solids of the waste expressed as percentage, SMP is the specific methane production and [CH_4] is the methane composition of biogas.

The digester volume was calculated by considering the working volume of the reactor and assuming a head space equivalent to 30% of the total digester volume. The working volume ($V_{working}$) was set as a variable parameter from 50 to 500 m^3, thus calculating the number of reactors needed to treat the volumetric flow of wastes (Q_{total}, m^3/d) at a TS content of 110 g/L.

$$Q_{total} = Nº_{digesters} \times Q_i \quad (21)$$

where $Nº_{digesters}$ is the number of digesters needed to treat the mass of waste produced daily. Q_i is the volumetric flow set as input for a single digester. This flow is estimated considering the working volume of the reactor and the HRT as expressed in equation (22).

$$Q_i = \frac{V_{working}}{HRT} \quad (22)$$

The total volumetric flow of wastes was obtained from the mass flow of TS daily produced (Fm_{TS}) and the concentration of TS of the feed [TS] expressed in terms of kg/m^3.

$$Q_{total} = \frac{Fm_{TS}}{[TS]} \quad (23)$$

Digester dimension was estimated considering a cylinder having equivalent magnitudes for diameter and height and a core formed by a spherical cap with a height equivalent to a sixth of the cylinder diameter. The estimation of the decentralized plant size was based on the reactor cylinder base dimension using a multiplying factor of 20. Electricity demand for the treatment plants was estimated as 15% of electricity produced at engine full load. The thermal demand of digesters was estimated considering the heat needed to increase the temperature of the feed from ambient temperature (5 °C in winter and 20 °C in summer) to digestion temperature (37 °C). The heat specific value (Cp) of the feeding slurry was assumed to be equivalent to that of water (4200 J/kg °C). The thermal demand of the digestion plant was estimated as shown in equation (24).

$$Q^{\circ}_{digestion} = F_{feed} \times Cp \times \Delta T \quad (24)$$

where $Q^{\circ}_{digestion}$ is the heat required to increase the temperature of the feed from ambient conditions to fermentation temperature. F_{feed} is the mass flow of feed daily introduced into the digester and ΔT is the thermal gradient. Thermal losses of the digester were estimated, assuming a value of 1.2 W/m^2 °C for the heat transfer coefficient of the digester wall and a value of 0.95 W/m^2 °C for the digester cap.

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$$Q^{\circ}_{loss} = U \times A \times \Delta T \quad (25)$$

where Q°_{loss} is the thermal loss of the digester. U is the heat transfer coefficient. A is the area available for heat transfer. The thermal loss of the digester is estimated by summing losses from the wall and the digester cap. The total heat demand is the heat demanded to treat the mixture of wastes produced daily.

$$Q^{\circ}_{total\ demand} = N^{o}_{digesters} \times (Q^{\circ}_{digestion} + Q^{\circ}_{loss}) \quad (26)$$

Electricity demand for Spain was 5259.3 kWh/year home [41] and thermal demand was 5233.21 kWh/year home [42] with a mean value of 2.5 person per home [43]. Digestate derived from decentralized units is dewatered using a multi-disc screw press sludge dehydrator. The digester location was assumed to be in the city extra-radius, assuming a multiplying factor of 4 to be applied to the distance marked by city urban limits. Land application of digestates considers the transport of dewatered material (25% TS content) to a linear distance of 30 km, assuming a tortuosity factor of 1.4. Truck transport capacity was 40 t with a fuel consumption of 30 L diesel/100 km. Energy demand for digestate drying was estimated considering a value of 2270 kJ/kg as water heat vaporization with a factor of 1.2 to consider difficulties in removing bound water. 70% efficiency was assumed for the drying equipment. The LHV of digestate was between 15 and 18 MJ/kg [44–46].

3. Results

3.1. Analysis of engine performance

Electricity production would be 1,084.8 kW with 1,056.6 kW of thermal power. This high efficiency is possible due to the large scale of the engine. Figure 3 shows the mass and energy balance of the engine and the double turbocharger at 100% load. The reference temperature adopted was ambient conditions (25 °C) to evaluate two rows of cylinders. It should be noted that there is a mismatch of 20.6 kW in excess, which is 0.8% of the amount of energy brought into play at the start point of energy calculations. The thermal efficiency given by the manufacturer is 41.3%, equivalent to 1,096.5 kW. This value differs from that obtained from the theoretical calculation, a difference of 39.8 kW (1.55% of the total energy contained in the biogas). This error may be explained by the fact that in the manufacturer's real tests, there are conditions that the theoretical calculations do not consider, such as the use of $c_{p\text{-}aire}$ instead of that for the mixture (air-fuel) or that the average temperature of the flow between the inlet and outlet was used as the temperature for each stage. In any case, the difference is small enough to allow predictions for electricity and thermal energy production.

Equations predicted a total efficiency for the engine of 80.4% (taking into account the 20.6 kW in excess), slightly higher than the value of 82.5% given by the manufacturer. The usable thermal power of the engine is 1,314.5 kW and corresponds to that derived from both intercoolers, the oil exchangers, the block engine and exhaust gases (with a temperature of 142 °C). The useful thermal power is 1,056.6 kW because the energy derived from intercooler 1 is disregarded due to its low temperature (< 55 °C). The temperature of exhaust gases was 142 °C. Any energy recovery further this point was disregarded to avoid condensation problems. Thus, energy recovery accounts for 423 kW. The energy flows of the main and auxiliary cooling circuits are shown in Figure 4. The adopted point of approximation between the exhaust air temperature and the inlet water is 5 °C for intercooler 1 and 10 °C for intercooler 2 [27].

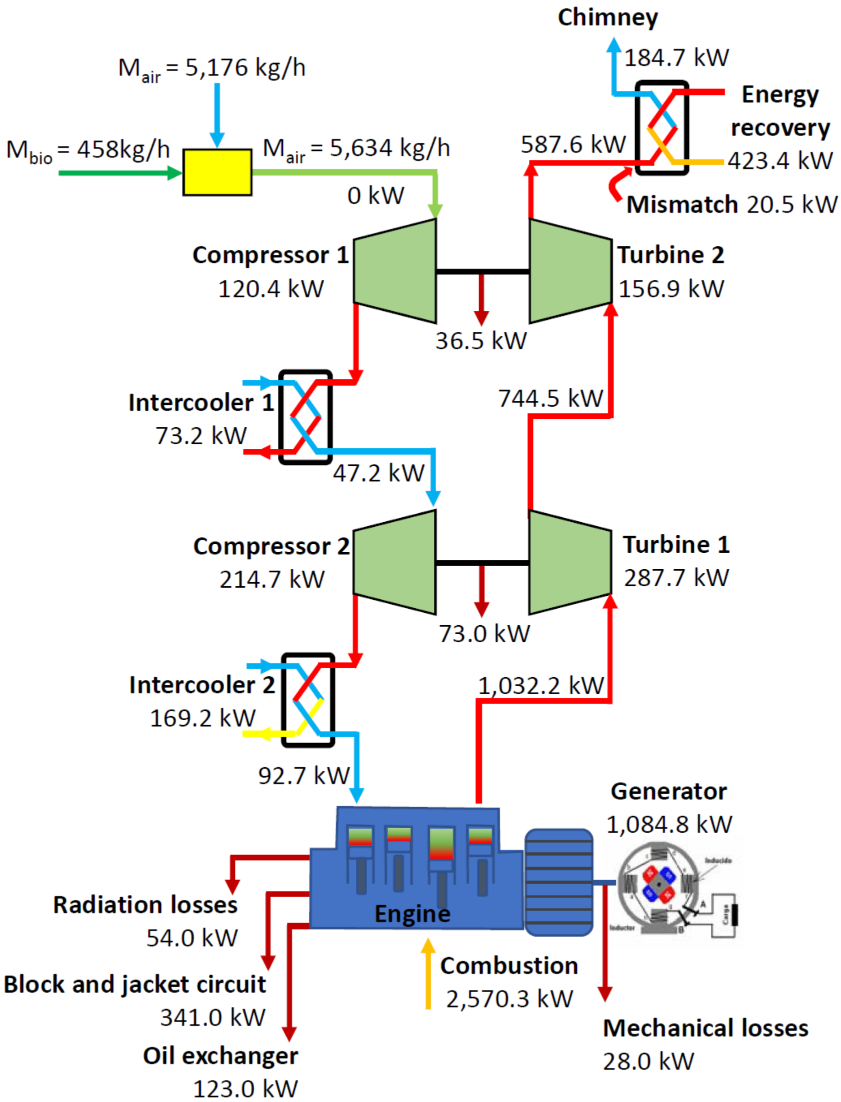

Figure 3. Mass and energy balance of engine and double turbocharging (total of two symmetrical lines).

The compression power of the first stage is 120.4 kW (35.9% of the total) because the inlet temperature of the mixture was 25 °C, the outlet temperature was 101.4 °C (+305.6%) and the compression ratio was 1.85. The compression power of the second stage is 214.7 kW (64.1%), more than 1.8 times that of the first one, as the inlet temperature of this second stage has increased from 55 to 190.4 °C (+246.2%), and the compression ratio increased from 1.85 to 2.57 (+38.9%). The thermal power of each turbine stage is slightly higher than that of the compressor due to the mechanical losses occurring in the drive shafts (+3% in each stage). The density of the inlet mixture has increased from 1.2 to 4.7 kg/m^3 at the inlet of the cylinders (+291.6%). Therefore, the mass flow induced into the cylinders is almost four times higher, translating into a significant increase in efficiency.

The mean specific mechanical power per unit mass and displacement was 0.168 kW/kg, equivalent to 18.7 kW/L for single compression. These values increase to 0.199 kW/kg and 23.0 kW/L for double compression. The engine JGS 320 GS-BL with 1,095 kW of mechanical power with 5,200 kg and 48.7 L would be equivalent to 6,183 kg and 60.0 L for single compression. The mechanical efficiency when applying double compression is increased by 3.7% compared to single compression. The compression ratio is 4.2% higher for double compression, and thus increasing the mechanical efficiency; the MEP is 23.3% higher for double compression. The double compression engine allows a better energy recovery, thus justifying the centralized configuration when producing electricity

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from biogas. In addition, this type of engine allows heat recovery, which is an important benefit for local population.

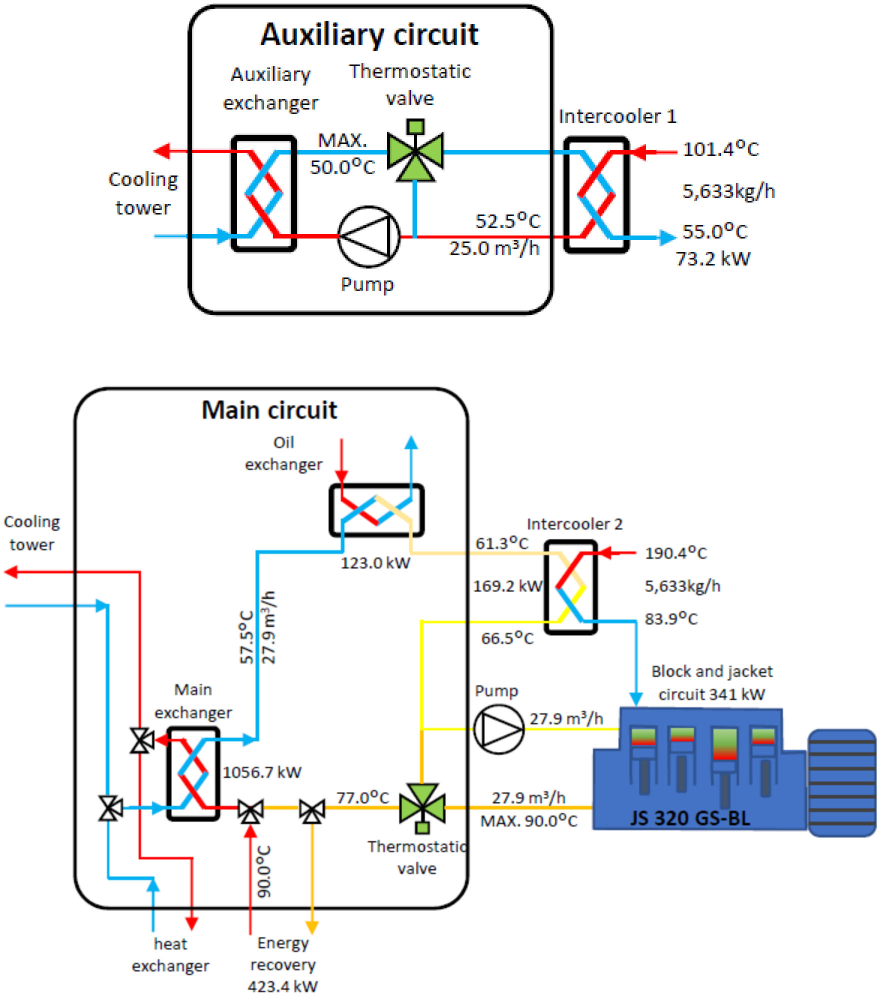

Figure 4. Schemes of engine auxiliary and main cooling circuit. Results obtained from mass and energy balance.

The location of the engine close to the city area facilitates that inhabitants benefit from the extra thermal energy produced. If bonuses are distributed in the form of heat to the local population, they may be more receptive to the strategy of treating waste in a decentralized manner. However, as inconvenient appears, supplying heat to several small digester units, requiring a new heat source to provide them with the thermal energy necessary to reach operating temperatures.

3.2. Technical feasibility of decentralized configuration

Considering the assumptions associated with waste production, the expected volumetric flow of material susceptible to co-digestion accounts for 294 m^3/d. Decentralized treatment of this material can be carried out in several digesters homogenously distributed in the city area. The HRT applied to the digestion process greatly influences the size and number of digesters needed. Figure 5 shows the number of digestion units needed for treating this mixture. The minimum value of HRT evaluated was 15 days. Although this value may be feasible for treating food waste as a single substrate, their treatment with garden waste may cause an incomplete degradation due to the high lignocellulosic character of this latter material, needing longer retention times [47].

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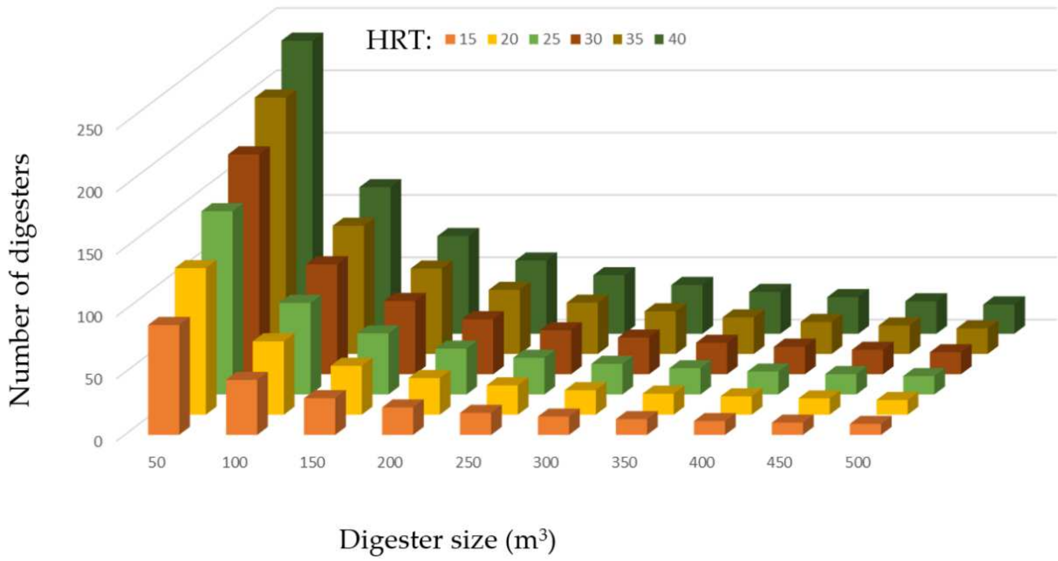

Figure 5. Number of digesters needed for treating daily food and garden waste production for a hypothetical city of 150,000 inhabitants.

Tian et al. [48] studied the decentralized digestion of wastes, reporting better results regarding global warming potential when evaluating the life cycle assessment of different treatment configurations. However, the treatment of this type of waste in a distributed form, when implemented in cities, implies having enough area susceptible to locating digesters and the auxiliary equipment associated with grinding and mixing procedures for preparing digester feed and subsequently, when digestion ends, the auxiliary equipment necessary for digestate dewatering and storing this material until finding final disposal. It should be added the lower efficiency attained when comparing centralized and decentralized waste treatment systems, as demonstrated by González et al. [49] when evaluating decentralized treatment of swine manure. Considering the minimum digester size at the lower HRT of 15 days, the use of the smallest digesters translates into an area of 2.65 hectares needed for locating the 88 small treatment plants, whereas this value increases to 7.06 hectares if the highest HRT is selected for the same working volume of reactors.

The location of these units would not be free of controversy. Locating a great number of digestion plants may not be free of generating odors and nuisance, although efforts made for covering equipment and avoid adverse visual effects. Reducing offensive gaseous emissions and eliminating involuntary spills of fresh material would probably become an impossible task. These activities, when carried out close to residential areas, may cause rejection by neighbors. The attempt to install such type of units will probably cause the revival of the "not in my backyard" syndrome, which transforms into "not in anybody's backyard", no matter how useful the idea of locally treating waste may seem [50]. Locating such units in urban areas would also translate into a decrease in green areas. For the case examined here, if a value of 25 m^2/inhab. is considered as the average value of available green area [51], then the decrease of these areas would be 0.7% in the best case, but it rises to 1.9% when the highest HRT is considered. The question is how many neighbors will be willing to accept reducing their green areas for locating a permanent waste treatment facility in their vicinity, particularly considering that this decrease would not be evenly distributed and therefore, some specific areas would suffer the main reduction.

There are several reports in the literature regarding the social rejection caused when planners try to locate different treatment centers that are needed in terms of the public interest but find a ferrous opposition when the specific location of the installation is to be set [52–55]. However, if the proximity of the location is not close enough, so adverse effects are not experienced by residents, but economic benefits could be obtained in terms of jobs or energy bonuses, then a greater willingness to accept may be possible [56]. Locating these installations in the extra radius may be feasible since

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population density in these areas is much lower. The most suitable option when taking any kind of decision regarding energy production or waste treatment must be based on different aspects such as technical, economic, environmental and social criteria so to compile with sustainable engineering principles [57].

The number of digesters needs to be set based on efficiency considerations. Thus, the volume and number of digestion units were estimated by considering the amount of thermal energy available. The volumetric flow of biogas expected is 482 m³/h, a value estimated from SMP data. Considering the use of two engines, the gas loading would be 55.7%, thus reducing the efficiency of electricity conversion and the thermal energy available. Figure 6a represents the thermal energy available for the two extreme values of digester configuration (under maximum and minimum retention time). The greater the hydraulic retention time, less thermal energy is available for other uses because of the increase in digester size and thermal losses associated with the reactor surface. The blue band in this graph represents the range of available thermal energy under different thermal gradients at an HRT of 40 days. Similarly, the gray band represents the case for the HRT of 15 days. Obviously, the thermal energy available in this latter case is much greater, with a narrower band due to lower thermal losses experienced in the winter period because of the lower size of digesters.

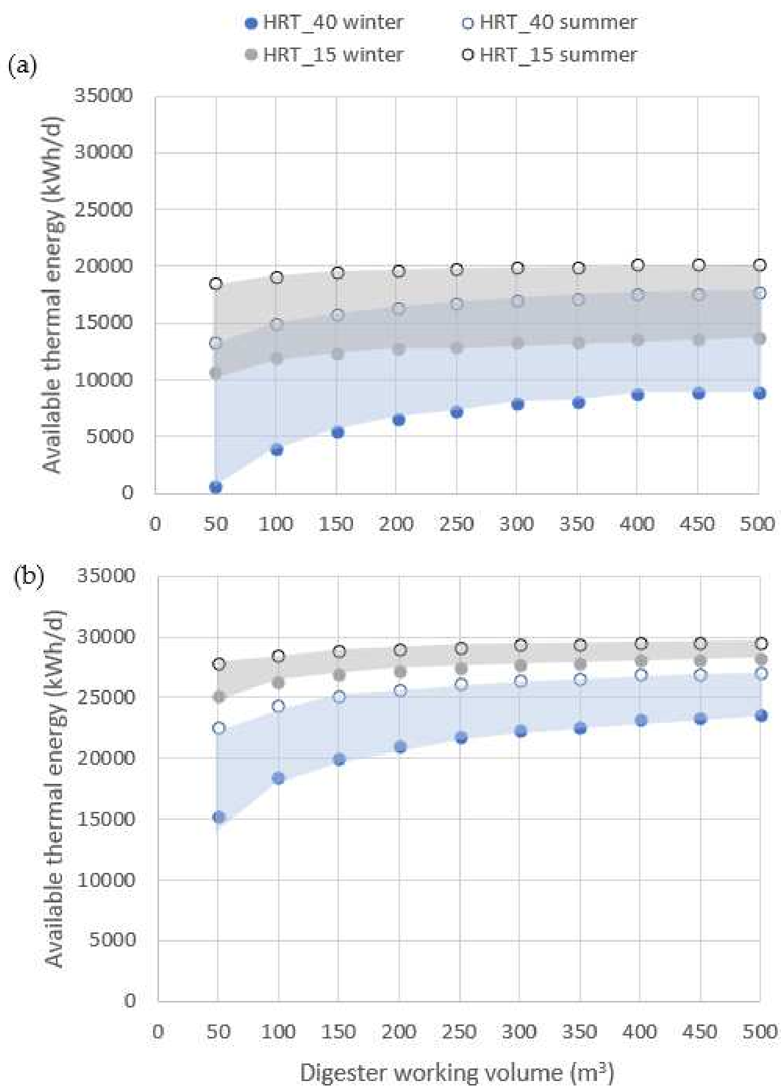

Figure 6. a) Available thermal energy obtained for digestion units of different sizes. b) Estimation of available thermal energy if pretreatment of yard waste is assumed, attaining an SMP improvement of 40%.

The distribution presented in Figure 6a considers the number of digesters needed for each reactor size studied, which is represented in the x-axis. The amount of gas obtained penalizes engine performance since the efficiency is adversely affected by the lower loading of engines. Thus, electrical efficiency reduces to 37.8%. The electricity available for daily activities would be scarcely enough to cover less than 1% (0.98%) of the daily energy needs of a city of 150,000 inhab. In the case of thermal needs, the system could cover 2.5% of the city requirements in the summer period, when thermal losses are at a minimum if assuming the implementation of the lowest HRT. However, in the winter period, almost all thermal energy available is necessary to keep system operating temperature when considering the lowest digester size.

The previous values may be improved if the SMP of garden waste could be increased by the application of pretreatments. However, thermal and mechanical pretreatments increase the energy demand of the global process [58,59]. Chemical pretreatments by adding alkali or acid solutions are usually accompanied by high temperatures to become more effective, but costs and corrosive effects are disadvantages to be added [60,61]. Other pretreatments may be more beneficial in terms of energy demand and auxiliary equipment, as it is micro-aerobic pretreatment or pre-acidification with digestate [62,63]. Small air additions into anaerobic systems have demonstrated to increase methane production by up to 19% [64], whereas other authors have reported an increase of up to three times [65]. If a modest 10% increase in methane production is assumed for yard wastes, then the benefits would translate into the coverage of 2.4% of thermal needs of the city requirements in summer periods, a value also estimated by assuming the lowest retention time. A further increase up to 40% allows to load engines close to 73.4% of their maximum capacity, which translates into higher values of efficiency in electricity production and thermal recovery. Thus, 1.3% of electricity demand could be covered by CHP engines, whereas a value of 3.2% is obtained for covering thermal needs, also under the same assumptions. Figure 6b shows the thermal energy range available under the latest assumption.

The energy provided by CHP engines, either electricity or thermal energy, may seem low. However, this type of energy production system may be integrated into other renewable energy systems in a hybrid scheme, thus reducing the demand for fossil energy sources. By investing in this type of energy, jobs can be created for the local population and sustainable development can be promoted [66], favoring the decarbonization of the economy. The size of single digesters needed for treating the daily mass of waste produced was 350 m^3.

This size was selected because it is the value obtained after minimizing available thermal energy changes with digester size. Thus, the number of digesters needed would be 13 units. The location of digesters in the community extra radius will be such that the zone selected falls outside the city borders. For a population density of 2500 inhab./km^2, the urban area will account for 60 km^2. Increasing this area by a factor of 4, the diameter of the circumference will be 17.5 km. Therefore, the digester will be located at a distance one from each other of 4.2 km following the circumference perimeter. One factor that was not considered in the present estimation was the price of land. Some city surrounding areas may have a higher land price due to specific landscape attributes, making them the living preference of high-income residents, thus adding constraints to the availability of suitable locations. The localization of a waste treatment plant will affect the price of land, probably reducing the value of land surroundings, adversely affecting house pricing.

Previous estimations were carried out considering a solid content of the feed of 110 g/L. The increase in the solid content of the feed may increase productivity thanks to better use of digester volume [67]. Nevertheless, there is a limit to increasing solid content in digestion systems, which is dictated by mass transfer restrictions and inhibitory compounds, significantly affecting methane yields [68,69]. Considering as a limit, a value of 14% solid content prior to experiencing process adverse effects [70], the number of digesters will be reduced to 10 units, thus decreasing the impact caused by the presence of decentralized plants in city surroundings.

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3.3. A practical solution is necessary to digestate final disposal

Anaerobic digestion is a friendly technology because of its low energy demand. However, producing digestate as a by-product impairs restrictions that may not be easy to overcome. In the present case, the slurry produced daily is 60 t/d (TS content of 25%). Land application of this material is not feasible within city borders. Transport towards city surrounding is necessary where agronomic application is feasible. The energy needed to transport digestate if land spreading is the final disposal option accounts for 0.5 TJ/year, which is the least energy-intensive option. Composting digestate in a centralized facility may be a way to reduce the total amount of material requiring land spreading. Composting has been evaluated as a suitable way for valorizing digestate and increasing the quality of the organic material [71,72]. Mineralization attained during aerobic conversion reduces volatile solid content and modifies the chemical characteristics of the organic matter [73,74]. However, land requirements for a composting treatment plant are high, and the search for a market is necessary to attain the commercialization of the end product.

Thermal valorization of this material translates into an excessive energy demand because a previous drying operation is necessary prior to implementing an incineration or pyrolysis/gasification stage. The estimated amount of energy demanded if digestate is to be dried up to a 90% TS content is 61.4 TJ/year. However, the amount of energy contained in digestate is in a range between 82 and 98.3 TJ/year, based on previous assumptions regarding LHVs. This implies that about 62 – 75% of the energy in digestate is required for drying. Energetic valorization of this material does not seem suitable unless other benefits are obtained, as it is the recycling of nutrients from combustion ashes. Thermal processes have high installation costs, so they are better suited to a large-scale scenario where centralization of biomass treatment is the main aim [75–77].

Although there are several advantages to implementing waste treatment decentralization, the valorization of biogas and digested material have better performance with a centralized configuration. The concept of decentralizing the treatment of organic wastes in high-density populated urban areas may seem irrational given all difficulties that can be encountered regarding location and the nuisance caused to neighbors. The centralized treatment of digestate through thermal processes may show a better balance with increasing scale if digestate valorization is carried out in conjunction with other lignocellulosic biomass and waste sources. Alternatives for valorization may consider its transformation into fuels and activated carbon [78,79]. However, these are highly energy-intensive processes more suited to a large-scale centralized configuration. Other alternatives, such as microalgae cultivation and media for bacterial growth, are promising options but still at an infancy stage [80–82].

4. Conclusions

The decentralized treatment of wastes presents several advantages regarding the local processing of organics and reduction in transport distance. However, implementing this type of configuration requires analyzing technical details associated with the number of digestion units needed and the location of small treatment plants in city areas. Production of electricity from biogas and valorization of digestates are activities better suited to large-scale centralized configurations given the higher efficiency of these installations and high costs. An essential factor to be considered when analyzing the decentralized treatment of wastes is the perception of the local population to this alternative and possible nuisance, which may appear as a consequence of treating organic materials susceptible to producing odors and offensive emissions close to residential areas.

In the present document, digestion of food and garden wastes were assumed to be locally treated in city surroundings, needing 10 digesters for the best scenario, capable of producing electricity to cover 1.3% of the demand and 3.2% of thermal needs (summer period) when using high-efficiency engines (double turbocharged). However, the location of these small plants would not be free of controversy, probably making the whole treatment proposal unfeasible unless the local population enjoys tangible benefits, such as energy bonuses or economic compensations. Decentralization is highly penalized by lower efficiencies due to the smaller scale of treatment units. Thus a compensation mechanism should be available if this alternative is to be seriously considered as a

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feasible option for producing local resources from waste and integrating waste streams into the circular economy concept.

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