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

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Abstract: The study examines decentralized waste treatment in an urban setting with a high-density population of 2500 inhab./km^2. The co-digestion of food and garden waste was assumed by using several mid-size digesters, while centralized biogas and digestate valorization was considered. The studied configuration generates electricity and thermal energy, covering 1.3% of the residential electricity demand and 3.2% of thermal demand. The use of double-turbocharged engines under the most favorable scenario aids cities in reaching sustainability goals. However, the location of treatment plants is a factor that may raise social discomfort and cause a nuisance to citizens. Locating waste plants near residential areas causes discomfort due to possible odors, gaseous emissions, and housing market distortions. Such problematic aspects must be addressed for the decentralized alternative to work. 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

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1. Introduction

Anaerobic digestion is considered a technology capable of transforming organic wastes into energetic products and obtaining digestate as a by-product that is susceptible to valorization in agriculture. Although widely spread, the implementation of this technology 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 putting much pressure on obtaining energy sources and gaseous fuels from local resources. Anaerobic digestion may be an excellent ally in the production of local gaseous fuels but may 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, transport, and the ease of controlling the process parameters when treating smaller waste quantities [1,2]. However, there are limits based on reasonableness in terms of 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 conditions of small digesters in China and India expressed concerns regarding low biogas production and inefficient operation [5–7].

Other researchers assessed the performance of small digestion units in Egypt and reported on the feasibility of these small plants [8]. These authors considered in their analysis only biofertilizers 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. The authors reported a higher energy demand per unit of biogas produced when compared with large-scale units [3], making the process non-competitive.

Further proliferation of small-scale digesters in developing countries may aid in significantly reducing global emissions of methane [9]. However, these digesters must remain 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 maintaining operation at ambient conditions, these small units with a simple configuration may attain biogas productivities of 0.47 $m^3/m^3_{reactor}$ d. In addition, these authors indicated that farmers 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.

Digestion technology has been successfully applied in the farm and agro-industrial sectors. However, the focus has shifted to extrapolating this experience from anaerobic digestion gained in different waste treatment sectors into urban areas as a means of locally treating 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 implementation of the process [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].

Despite the feasibility of installing small digestion units, there are other factors needing optimization. The valorization of biogas by combined heat and power (CHP) units is heavily penalized since the electricity conversion efficiency is higher for large-capacity engines. In contrast, smaller ones are limited by efficiencies of about 34% [20]. It should be assessed whether a decentralized waste treatment system would be more practical than the current centralized system. In previous work, the authors of this paper 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 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.

Decentralization may aid in increasing social consciousness regarding materials reuse and cycling, thus making citizens aware of the impact caused by their daily activities on the environment. Treating waste as close as possible to the generation point increases social responsibility regarding consumption habits and reduces the discarding rate. The decentralized approach is yet full of challenges due to its intrinsic lower efficiency and higher installation costs. It is important, therefore, to find an equilibrium between the expected theoretical benefits and the discomfort that may be created due to the proximity of waste treatment centers. The present manuscript assessed a hybrid approach of waste treatment and biogas valorization, assuming decentralized anaerobic digestion and a centralized biogas valorization unit using CHP engines. The present study considered practical aspects regarding the location of decentralized plants in current existing cities and the space availability for implementing decentralized proposals. The energy production potential was obtained by assuming food and yard wastes as feeding material. Estimations of electricity and thermal energy were carried out considering the engine's efficiency and seasonal climatic conditions.

2. Materials and Methods

2.1. Engine Description

The engine studied was a double turbocharged engine with a high efficiency. The biogas engine was a lean-burn, four-stroke Otto cycle, Jenbacher type JGS 320 GS-BL. This engine consisted of two inlet mixture compression stages and two intercooler stages with plate heat exchangers. Combustion took place under lean-burn conditions using spark ignition from spark plugs. The compressors were driven by the exhaust gases expanded in the turbines. Both components were mechanically coupled by means of a rotating shaft. The arrangement of the cylinders was based on two rows of ten units in a V-shape. Analysis of this engine was based on Cascallana et al. [25]. This engine was fueled by biogas and used an electronic carburetor to mix the incoming gases before compressing them in the first compression stage. Each of the two rows of cylinders had a turbocharger consisting of a centrifugal compressor driven by a centripetal turbine, which used exhaust gases for its operation. The intercoolers were 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)	1500
Average piston speed (m/s)	8.5
Piston displacement (L)	2.43
Piston area (cm^2)	143
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 the turbochargers. The tolerances were ±5% for biogas consumption (biogas composition was assumed as CH_4 65% and CO_2 35%) and ±8% for the other parameters. The loading degree was considered to be 100% for a methane flow rate corresponding to a biogas flow rate of 458 kg/h with a 65% methane content. The power was determined at operating conditions at standard reference conditions as per ISO/3046/1 [27]: altitude 100 m above sea level (a.s.l.), pressure 100 kPa, temperature 25 °C, and humidity 30%. The volume was reported at standard conditions for biogas, combustion air and exhaust gases, pressure 101 kPa, and temperature 0 °C [28].

Table 2. Performance characteristics of the JGS 320 GS-BL engine [28].

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)	1095	821	548
Electrical power (cos φ = 1) (kW)	1067	798	529
MEP, mean effective pressure (kPa)	1800	1350	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)	5176		
M_{eg}, exhaust gas mass flow (wet) (kg/h)	5634		
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)	2655	2046	1436
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
$P_{INT\text{-}2}$, intercooler 2 power (kW)	181	78	5
Oil exchanger power (kW)	123	105	93
Auxiliary circuit thermal power (kW)	77	58	38
$P_{INT\text{-}1}$, intercooler 1 power (kW)	77	58	38

Table 2. *Cont.*

Performance Parameters of Engine Type J 320 GS-D121	**Degree of Loading (%)**		
	100	**75**	**50**
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 had an assigned value of 100, and hydrogen had a value of 0.

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	[29]
R, universal constant of ideal gas (J/kg K)	287.05	[30]
γ, adiabatic coefficient of air, mixture and gases (dimensionless)	1.4	[31]

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

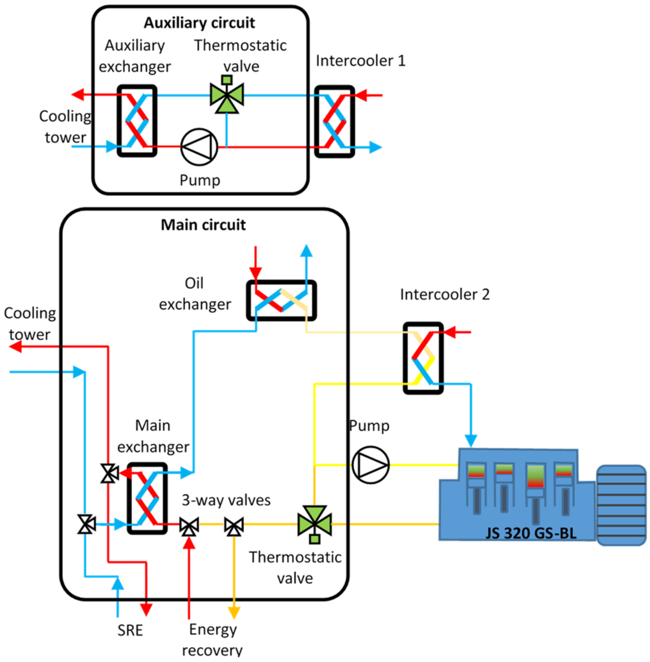

Figure 1. Engine cooling system. This system was composed of two separate lines: the main and auxiliary circuit.

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 had two different cooling circuits, the main and the auxiliary. Each of these circuits had a plate heat exchanger that divided them into primary and secondary circuits. The primary section of the main circuit was responsible for cooling the engine block, the cylinder heads, the oil circuit inside the CHP unit, intercooler 2 of the twin-turbo system [28], and the heat recovery system of the exhaust gas. The main circuit in its second section allowed for thermal energy to be transferred to other devices via a heat exchanger or dissipated in the cooling tower. The auxiliary circuit cooled intercooler 1 via its primary circuit [28], while the secondary circuit dissipated the thermal energy in cooling towers. This thermal energy was disregarded due to its low temperature, which made its use difficult, containing just a small share of the total energy contained in the biogas. The primary section of both cooling circuits used a 37% glycol solution in water as the heat transfer fluid to prevent freezing when the engine was out of service.

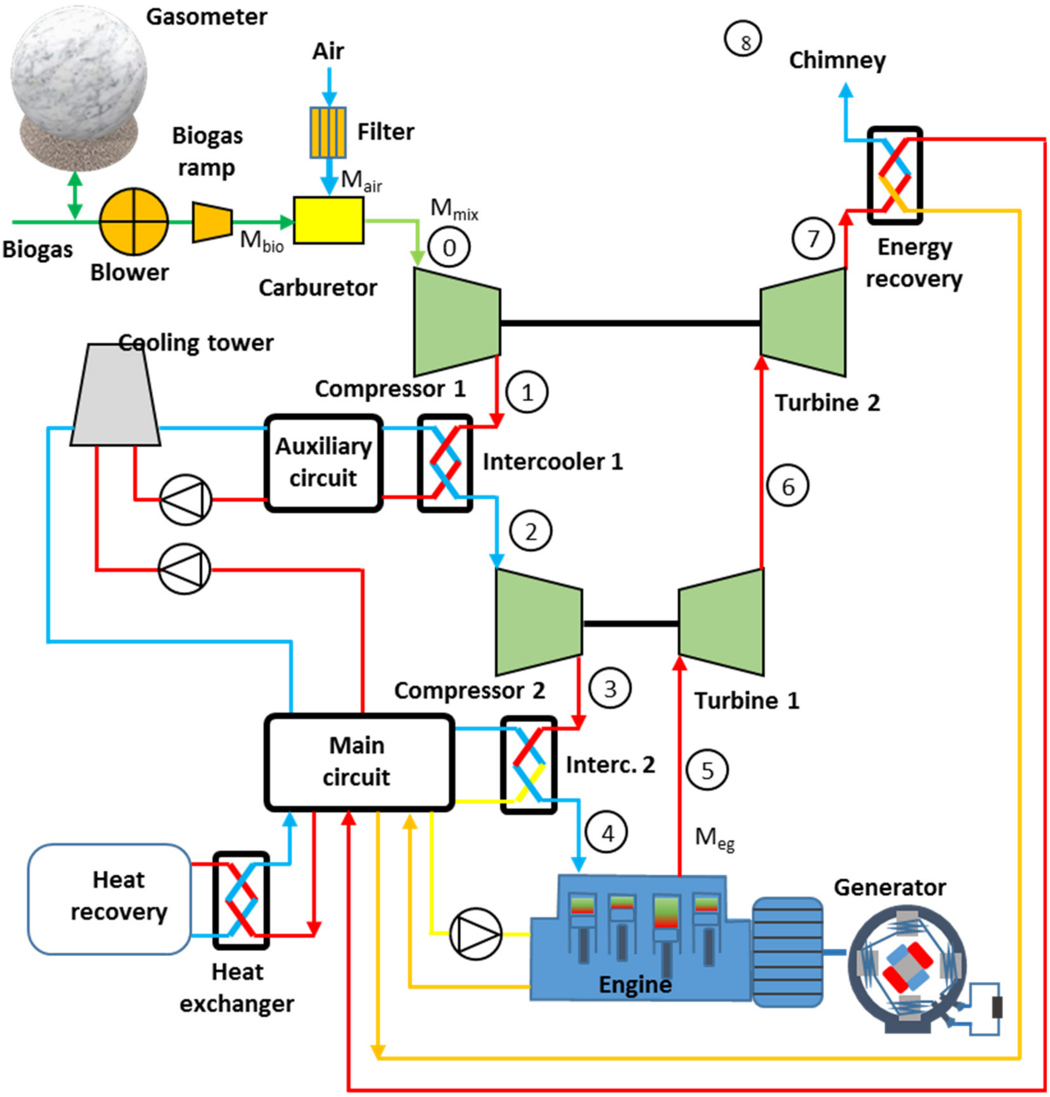

Figure 2. General operating diagram of the biogas engine.

Mass and energy balances were established for the double turbocharger. The numbers in Figure 2 were used to indicate the different calculation sections. The 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}) was 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).

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

$$F = M_{biogas} / M_{air} \tag{2}$$

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

The compressor and turbine rotational speeds (n_C, n_T) were also twinned. The relationship between these speeds is shown in Equations (5) and (6). The subscripts 1 and 2 again represent 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 (1500 rpm), and 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 achieved (1800 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, and η_V and η_e are the volumetric and combustion efficiencies of the engine, respectively. 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}), the 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) [32].

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

The compression ratio (r_C) is estimated as the proportion between the inlet and outlet pressure. For the first-stage compressor, subscript 0 was used to indicate the inlet and 1 to represent the outlet stream. Compression was assumed isentropic; thus, it was equivalent pin 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 ratios used for the first and second stages of compression were 1.85 and 2.57, respectively [26]. The initial pressure was 101.3 kPa. The isentropic outlet temperature T_{1s} was 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) was 1.4 for air, and the initial temperature (T_0) was 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). Subscripts 1 and 2 were used for the first or second stages, respectively. The isentropic efficiencies for the first and second stages were 75% [29].

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

The compressor power (P_{C1}) was calculated from Equation (13)

$$P_{C1} = \frac{M_{mix}}{3600} \cdot c_{p-mix} \cdot (T_1 - T_0) \tag{13}$$

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

$$P_{INT1} = \frac{M_{mix}}{3600} \cdot c_{p-mix} \cdot (T_1 - T_2) \tag{14}$$

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

$$P_{T1} = \frac{P_{C1}}{\eta_{mec1}} = \frac{M_{eg}}{3600} \cdot c_{p-eg} \cdot (T_6 - T_5) \tag{15}$$

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

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

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

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

$$P_{ER} = \frac{M_{eg}}{3600} \cdot c_{p-eg} \cdot (T_7 - T_8) \quad (19)$$

2.3. Methodology for Evaluating Decentralized Biogas Production in Mid-Size Communities

The efficiency of small-scale digesters is reduced with decreasing their size because the energy demand of the auxiliary equipment associated with the reactor operation does not follow a linear relationship. Different digester 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 the input materials are specified in Table 4. A 60% methane content in the biogas was assumed. The digestion process was assumed 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.

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

Parameter	Food Waste	Reference	Garden Waste	References
Production (kg/year per capita)	77	[33]	110 [1]	
TS content (g/kg)	150		610	[34]
%VS	90	[35,36]	77.5 [2]	[34,37]
SMP (mL CH_4/g VS)	340	[38,39]	257	[40]

[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 was 187 kg/person year [41]. [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)

$$DBP = \frac{WP \times N^{\circ}{}_{inhab} \times TS \times \%VS \times SMP}{365,000 \times [CH_4]} \quad (20)$$

where *WP* is the waste production factor either for food waste or garden waste (expressed as kg waste/inhab. year). N° inhab. stands 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 a percentage, *SMP* is the specific methane production, and [CH_4] is the methane composition of biogas. A range of 5% variation was assumed for the *SMP*, *TS*, and *VS* content of the feed. A Monte Carlo simulation was carried out using the Excel®MSO 2016 (16.0.4266.1001) software.

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 ranging 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.

$$Q_{total} = N^{\circ}{}_{digesters} \times Q_i \quad (21)$$

where $N^{\circ}{}_{digesters}$ 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 was 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 produced daily (Fm_{TS}) and the concentration of TS of the feed $[TS]$ expressed in terms of kg/m^3.

$$Q_{total} = \frac{Fm_{TS}}{[TS]} \tag{23}$$

The digester dimension was estimated considering a cylinder with equivalent magnitudes for the 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. The electricity demand for the treatment plants was estimated as 15% of the electricity produced at full engine load. The thermal demand of the 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 the digestion temperature (37 °C). The specific heat 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).

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

where $Q^{\circ}{}_{digestion}$ is the heat required to increase the temperature of the feed from ambient conditions to the fermentation temperature. F_{feed} is the mass flow of feed introduced into the digester daily, and ΔT is the thermal gradient. The 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.

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

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

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

The electricity demand for Spain was 5259.3 kWh/year home [42], and the thermal demand was 5233.21 kWh/year home [43] with a mean value of 2.5 persons per home [44]. The digestate derived from decentralized units was 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 the city's urban limits. The land application of digestates considered the transport of dewatered material (25% TS content) to a linear distance of 30 km, assuming a tortuosity factor of 1.4. The truck transport capacity was 40 t with a fuel consumption of 30 L diesel/100 km. The energy demand for digestate drying was estimated considering a value of 2270 kJ/kg as the heat of vaporization of water with a factor of 1.2 being used to consider difficulties in removing bound water. A 70% efficiency was assumed for the drying equipment. The LHV of digestate was between 15 and 18 MJ/kg [45–47].

3. Results

3.1. Analysis of Engine Performance

The electricity production was determined to be 1084.8 kW with 1056.6 kW of thermal power. This high efficiency was 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 a 100% load. The reference temperature adopted was ambient conditions (25 °C) to evaluate two rows of cylinders. It should be noted that there was a mismatch of 20.6 kW in excess, which was 0.8% of the amount of energy brought into play at the starting point of the energy calculations. The thermal efficiency given by the manufacturer was 41.3%, which was equivalent to 1096.5 kW. This value differed from that obtained from the theoretical calculation with 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′ real tests, there were conditions that the theoretical calculations did not consider, such as the use of c_{p-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 was small enough to allow for predictions for electricity and thermal energy production.

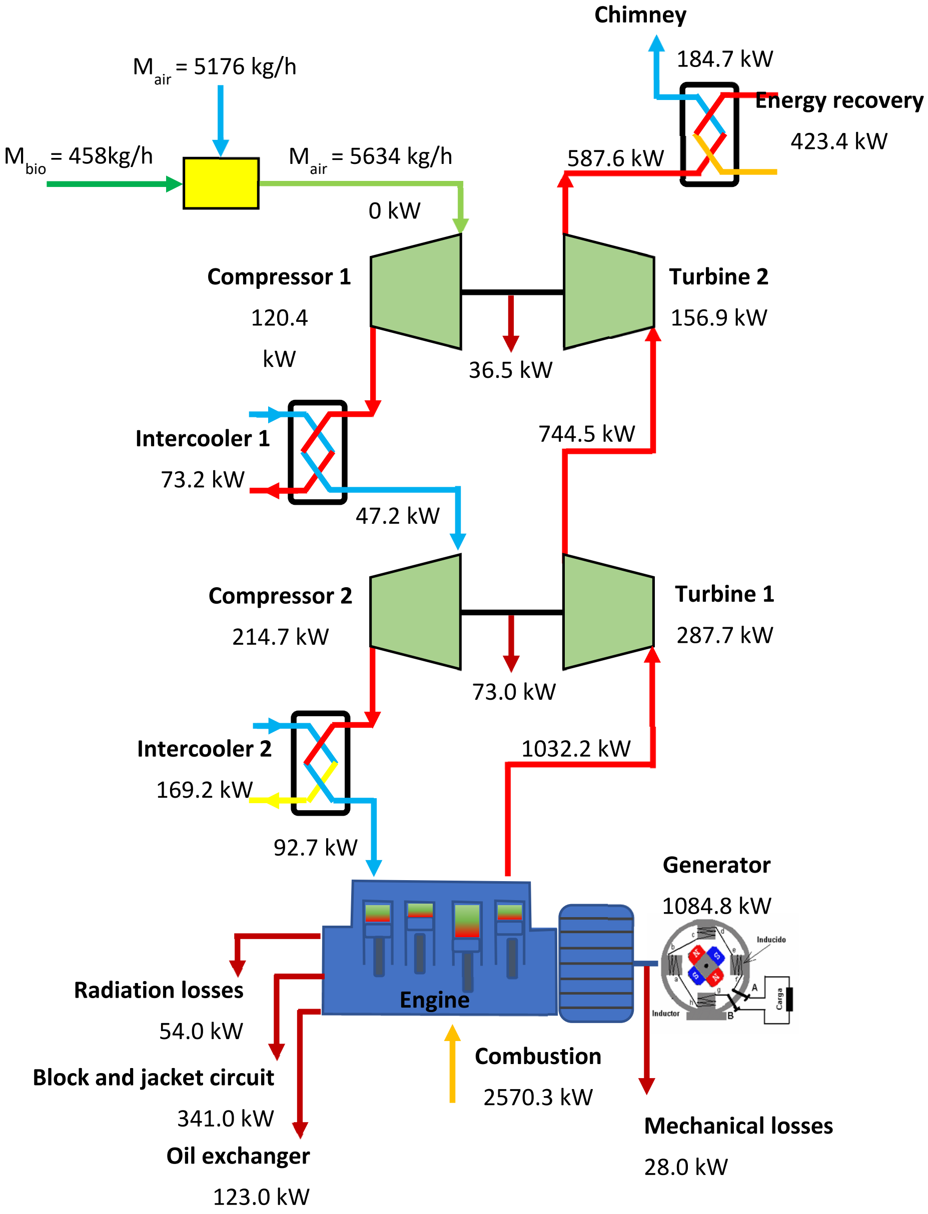

Figure 3. Mass and energy balance of engine and double turbocharging (total of two symmetrical lines).

The equations predicted a total efficiency for the engine of 80.4% (taking into account the 20.6 kW in excess), which was slightly higher than the value of 82.5% given by the manufacturer. The usable thermal power of the engine was 1314.5 kW and corresponded to that derived from both intercoolers, the oil exchangers, the block engine, and the exhaust gases (with a temperature of 142 °C). The useful thermal power was 1056.6 kW because the energy derived from intercooler 1 was disregarded due to its low temperature (<55 °C). The temperature of the exhaust gases was 142 °C. Any further energy recovery from this point was disregarded to avoid condensation problems. Thus, the energy recovery accounted 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 was 5 °C for intercooler 1 and 10 °C for intercooler 2 [28].

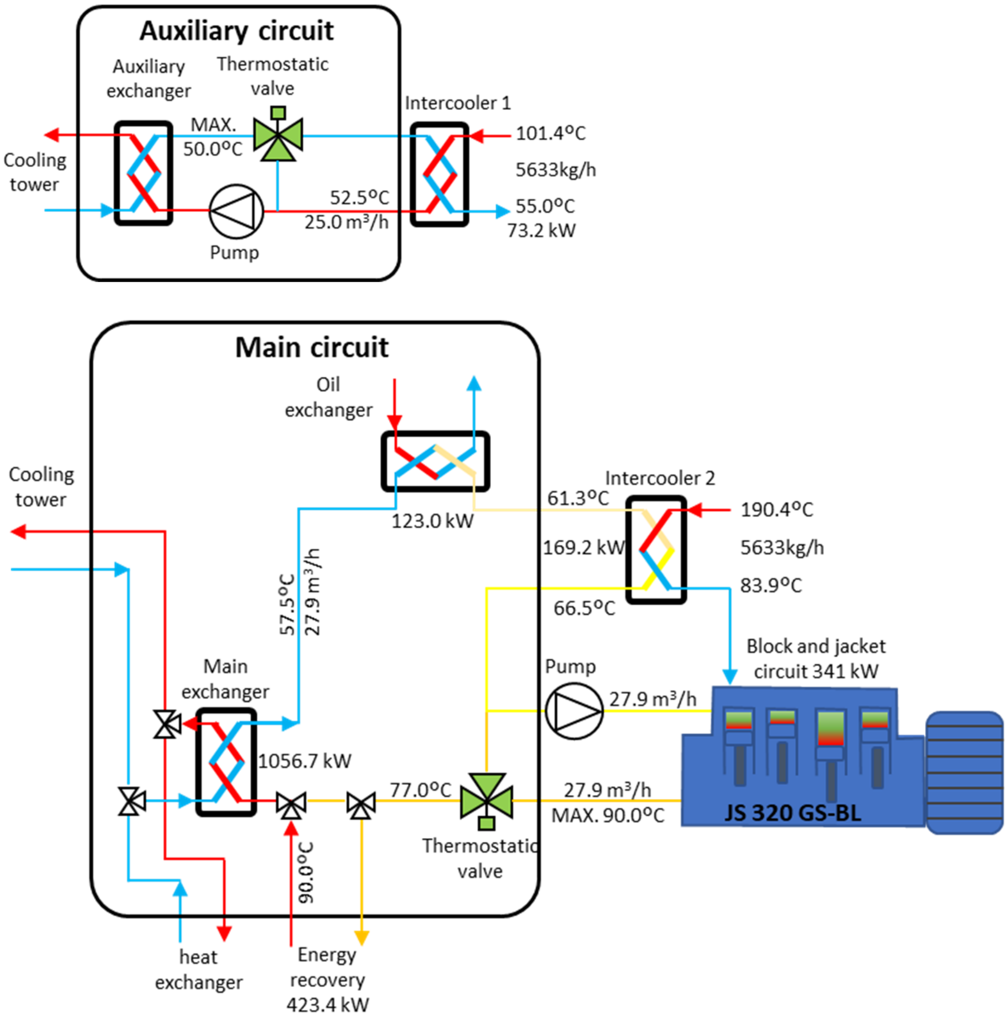

Figure 4. Schemes of engine auxiliary and main cooling circuit. Results obtained from mass and energy balance.

The compression power of the first stage was 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 was 214.7 kW (64.1%), which was more than 1.8 times that of the first one, as the inlet temperature of this second stage 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 was 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 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 was 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 increased to 0.199 kW/kg and 23.0 kW/L for double compression. The JGS 320 GS-BL engine with 1095 kW of mechanical power with dimensions of 5200 kg and 48.7 L would be equivalent to 6183 kg and 60.0 L for single compression. The mechanical efficiency when applying double compression was increased by 3.7% compared to that when applying single compression. The compression ratio was 4.2% higher for double compression, thus increasing the mechanical efficiency; the MEP was 23.3% higher for double compression. The double-compression engine allowed for a better energy recovery, thus justifying the centralized configuration when producing electricity from biogas. In addition, this type of engine allows for heat recovery, which is an important benefit for local populations.

The location of the engine close to the city area would facilitate the inhabitants benefitting from the extra thermal energy produced. If bonuses were 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, an inconvenience appears in the form of supplying heat to several small digester units, requiring a new heat source to provide them with the thermal energy necessary to reach the operating temperatures.

Other technical alternatives that may be considered for valorizing biogas include upgrading biogas to reach the quality of natural gas, the use of fuel cells for electricity production, or the use of micro-turbines. In the first case, the technology has matured, and its feasibility should be carefully analyzed since profitability is very case-specific and is based on the availability of governmental subsidies [48]. The use of fuel cells and micro-turbines are promising options, but these technologies still face several challenges regarding biogas cleaning and installation costs [49–51]. There are currently several applications of high-efficiency CHP engines in wastewater treatment plants, landfills, and industry [52–54]. Biogas contains several contaminants that need to be removed, such as sulfur compounds, ammonia, small amounts of oxygen, and moisture [55,56]. CHP engines present lower cleaning requirements when compared with other valorization alternatives, thus making them the preferred gas valorization option.

3.2. Technical Feasibility of Decentralized Configuration

Considering the assumptions associated with waste production, the expected volumetric flow of material susceptible to co-digestion accounted for 294 ± 1 m^3/d. The decentralized treatment of this material could be carried out in several homogenously distributed digesters in the city area. The HRT applied to the digestion process greatly influenced 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, its treatment with garden waste may cause an incomplete degradation due to the high lignocellulosic character of this latter material, which needs longer retention times [57].

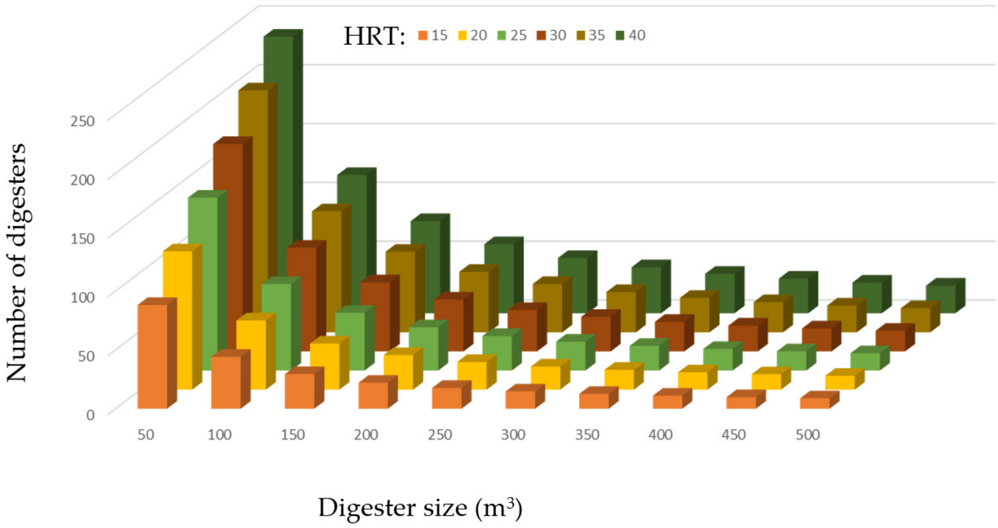

Figure 5. Number of digesters needed for treating daily food and garden waste production for a hypothetical city of 150,000 inhabitants.

Tian et al. [58] 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 the grinding and mixing procedures for preparing the digester feed and, subsequently, when digestion ends, the auxiliary equipment necessary for digestate dewatering and storing this material until finding a final disposal option. The lower efficiency attained when comparing centralized and decentralized waste treatment systems should be noted, as demonstrated by González et al. [59] when evaluating the decentralized treatment of swine manure. Considering the minimum digester size at a 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 could be made for covering equipment and avoiding 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. An attempt to install such types of units would 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 [60]. 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 [61], then the decrease in these areas would be 0.7% in the best case, but it would rise to 1.9% when the highest HRT is considered. The question is how many neighbors would 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 [62–65]. However, if the proximity of the location is not close enough so as to cause adverse effects to be experienced by residents but economic benefits could still be obtained in terms of jobs or energy bonuses, then a greater willingness to accept may be possible [66]. Locating these installations in the extra radius may be feasible since the 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 as to comply with sustainable engineering principles [67].

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 was 482 ± 18 m^3/h, a value estimated from SMP data. Considering the use of two engines, the gas loading would be 55.7 ± 2.1%, 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 configurations (under maximum and minimum retention times). The larger the hydraulic retention time, the less thermal energy is available for other uses because of the increased digester size and the 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 an HRT of 15 days. Clearly, the thermal energy available in this latter case is much greater, with a narrower band due to lower thermal losses experienced in winter because of the lower digester size.

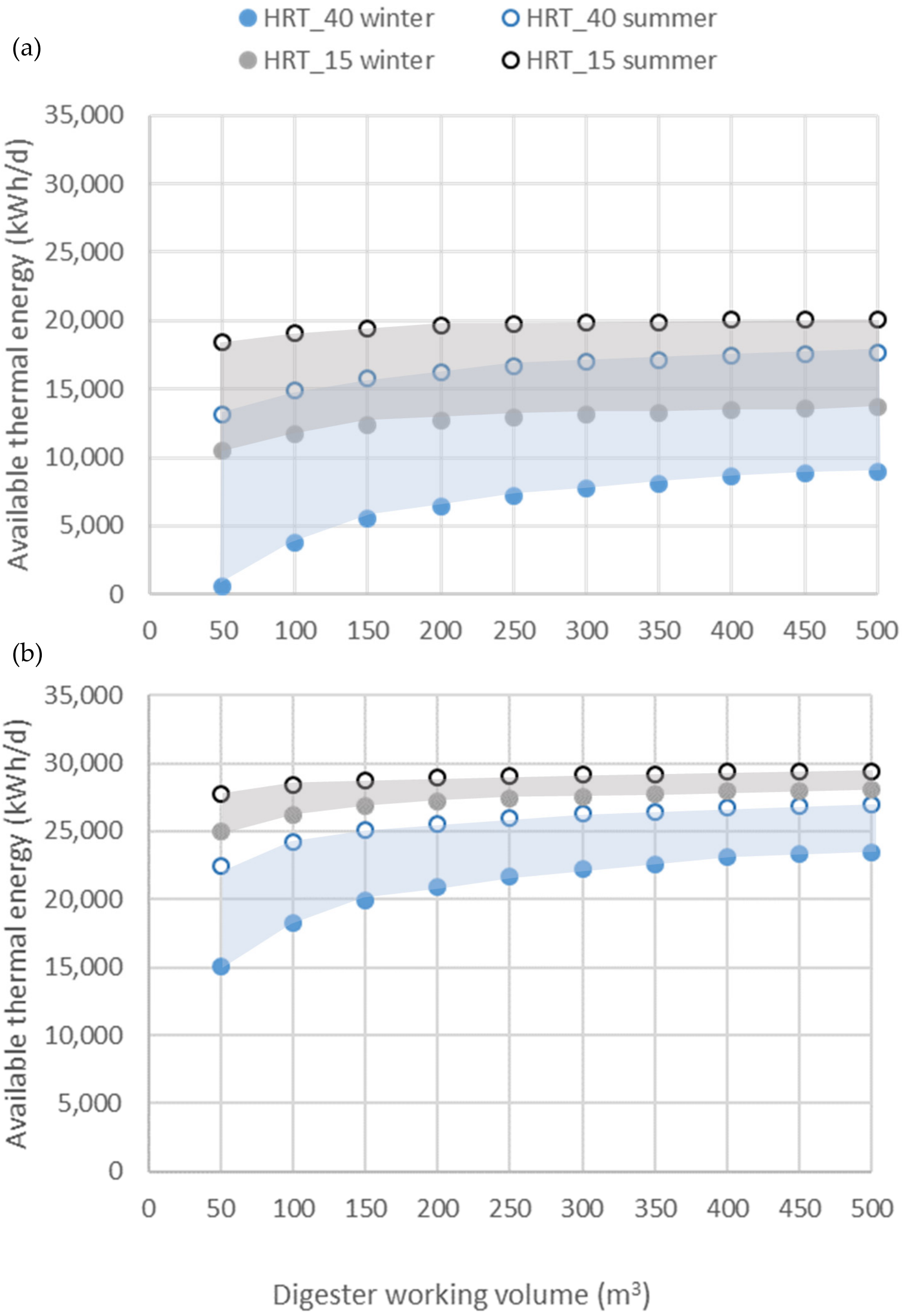

Figure 6. (**a**) Available thermal energy obtained for digestion units of different sizes. (**b**) Estimation of available thermal energy if pretreatment of yard waste is assumed, attaining an SMP improvement of 40%.

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 penalized the engine performance since the efficiency was adversely affected by the lower loading of the engines. Thus, the electrical efficiency was reduced to 37.8%. The electricity available for daily activities would be scarcely enough to cover less than 1% (0.96 ± 0.05%) 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's 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 the thermal energy available would be necessary to maintain the system operating temperature when considering the lowest digester size.

The previous values may be improved by applying pretreatments that could increase the garden waste's SMP. However, thermal and mechanical pretreatments increase the energy demand of the global process [68,69]. High temperatures usually accompany chemical pretreatments, such as using alkali or acid solutions, to become more effective, but costs and corrosive effects are disadvantages to be added [70,71]. Other pretreatments may be more beneficial in terms of energy demand and auxiliary equipment, such as microaerobic pretreatment or pre-acidification with digestate [72,73]. Adding small amounts of air to anaerobic systems can increase the methane production by up to 19% [74], while other studies have reported increases of up to three times [75]. If a modest 10% increase in methane production is assumed for yard wastes, then the benefits would translate into a coverage of 2.6% of the thermal needs of the city's requirements in summer periods, a value also estimated by assuming the lowest retention time. A further increase of up to 40% would allow for loading the engines close to 73.4% of their maximum capacity, which would translate into higher values of efficiency in terms of electricity production and thermal recovery. Thus, 1.3% of the electricity demand could be covered by CHP engines, whereas a value of 3.2% could be obtained for covering the thermal needs, also under the same assumptions. Figure 6b shows the thermal energy range available under the latest assumption, and Figure 7 shows the results obtained from the Monte Carlo simulation.

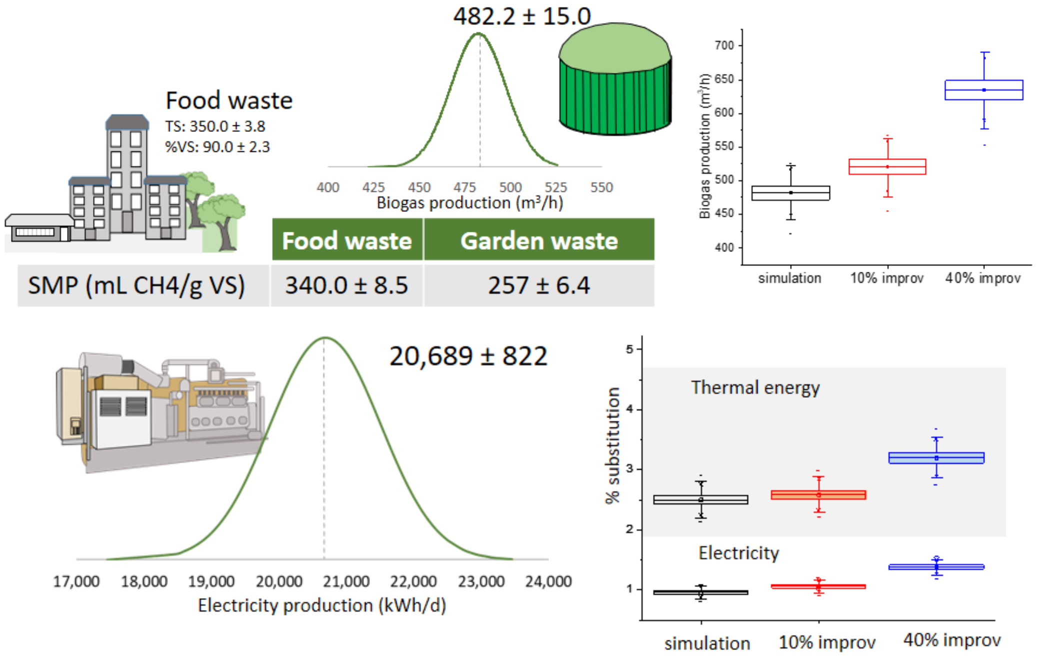

Figure 7. Results obtained from the Monte Carlo simulation, assuming normal distribution for data input.

The energy produced by CHP engines, whether in the form of electricity or thermal energy, may seem insufficient. However, these systems can be integrated into other renewable energy production systems in a hybrid scheme, thus reducing the dependence on fossil fuels. Investing in this type of energy can create jobs for local populations and promote sustainable development [76], favoring the decarbonization of the economy. The size of the single digesters needed for treating the daily mass of waste produced was 350 m^3.

This size was selected because it was the value obtained after minimizing the available thermal energy changes with the digester size. Thus, the number of digesters needed would be 13 units. The location of the digesters in the community extra radius would be such that the zone selected would fall outside the city borders. For a population density of 2500 inhab./km^2, the urban area would account for 60 km^2. By increasing this area by a factor of four, the diameter of the circumference would be 17.5 km. Therefore, the digester would be located at a distance of 4.2 km from one another following the circumference perimeter. One factor that was not considered in the present estimation was the price of land. Some areas surrounding a city 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 the surrounding land, 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 a better use of the digester volume [77]. Nevertheless, there is a limit to increasing the solid content in digestion systems, which is dictated by mass transfer restrictions and inhibitory compounds, significantly affecting methane yields [78,79]. Considering a value of 14% solid content prior to experiencing process adverse effects as a limit [80], the number of digesters would be reduced to 10 units, thus decreasing the impact caused by the presence of decentralized plants in the city surroundings.

The centralized valorization of biogas derived from several digesters also implies the development of a low-quality gas network for the transport of biogas to the high-efficiency engine location. Implementing this approach would translate into higher installation costs since compression units would be needed along with constructing a specific gas grid design for the underground transport of low-pressure gas. The carbon dioxide content in biogas sets limits to the pressure of the network. Therefore, a further analysis is necessary to evaluate the technical feasibility of this approach by considering additional auxiliary equipment linked to biogas compression and transport. Given the power input associated with the engine, the proposal is limited to a high flux of wastes or to a scenario of biogas co-valorization with other gases, such as natural gas or syngas derived from municipal solid wastes.

3.3. A Practical Solution Is Necessary to Finally Dispose of the Digestate

Anaerobic digestion is an eco-friendly technology with a low energy demand. However, the production of digestate as a by-product creates challenges that may not be easy to overcome. In the present case, the slurry produced daily was 60 t/d (TS content of 25%). The land application of this material is not feasible within city's borders. Transport to the city's outskirts is necessary for feasible agronomic application. Land spreading requires 0.5 TJ/year for digestate transport, which is the least energy-intensive option. The centralized composting of digestate reduces the material available for land spreading. Composting has been evaluated as a suitable way for valorizing digestate and increasing the quality of the organic material [81,82]. Mineralization attained during aerobic conversion reduces the volatile solid content and modifies the chemical characteristics of the organic matter [83,84]. However, the 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.

The thermal valorization of this material translates into an excessive energy demand because a drying operation is necessary prior to implementing an incineration or pyrolysis/gasification stage. The estimated amount of energy demanded if the digestate is to be dried up to a 90% TS content is 61.4 TJ/year. However, the amount of energy contained in the digestate ranges between 82 and 98.3 TJ/year, based on previous assumptions regarding LHVs. This implies that about 62–75% of the energy in the digestate is required for drying. The energetic valorization of this material does not seem suitable unless other benefits are obtained, such as the recycling of nutrients from combustion ashes. Thermal processes have high installation costs, so they are better suited to a large-scale scenario where the centralization of biomass treatment is the main aim [85–87].

Although there are several advantages to implementing waste treatment decentralization, the valorization of biogas and digested material performs better with a centralized configuration. The concept of decentralizing the treatment of organic wastes in high-density populated urban areas may seem irrational given all the difficulties that can be encountered regarding the location and the nuisance caused to neighbors. The centralized thermal treatment of digestate may show a better balance by combining it with other biomass and waste sources. Alternatives for valorization may consider its transformation into fuels and activated carbon [88,89]. 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 they are still at an infancy stage [90–92].

4. Conclusions

The advantages of decentralized waste treatment cannot be ignored. It offers the local processing of organics and reduces transport distances. However, for this configuration to work, technical details such as the number of digestion units required and the location of small treatment plants in city areas must be analyzed thoroughly. The production of electricity from biogas and the valorization of digestates are activities better suited to large-scale centralized configurations given the higher efficiency of these installations and the 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 the possible nuisance caused, 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, the digestion of food and garden wastes was assumed to be locally treated in the city surroundings, needing 10 digesters for the best scenario and capable of producing enough electricity to cover 1.3% of the demand and 3.2% of the thermal needs (summer period) when using high-efficiency engines (double turbocharged). These results are a first approximation towards achieving sustainable cities, where resources and energy may be obtained from their own urban ecosystem.

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

Future work will consider aspects regarding biogas upgrading and transport along with the feasibility of using a shared gas network for biogas and syngas derived from waste or biomass gasification.

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