Renewable Energy 215 (2023) 119013

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Energetic valorization of biogas. A comparison between centralized and decentralized approach

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ARTICLE INFO

Keywords:
Energy efficiency
Manure co-digestion
Combined heat and power system
Economic feasibility

ABSTRACT

In the present manuscript, the energy efficiency and economic feasibility of different digestion configurations were evaluated by considering a double turbocharged engine, Jenbacher type JGS 320 GS-BL. Scenarios considered a single farm producing the biogas needed to run the engine (Scenario 1). The second scenario assumed a centralized system treating manure from the surrounding farms (Scenario 2). The third scenario considered partial decentralization with farms treating locally produced wastes, and biogas being transported and valorized in a centralized engine (Scenario 3). Centralized valorization showed the best results. However, this scheme is inappropriate due to the size of the farm needed to support this configuration. The transport of wastes to a centralized treatment unit showed similar efficiency values but the economic feasibility was adversely affected. The worst performance was found for the decentralized configuration with efficiency in the range of 39–43%, much lower values than those obtained from previous cases (58%) with null economic feasibility due to the high costs associated with the transport of biogas either by truck or through a piping system.

1. Introduction

The digestion process consists of the degradation of organic substances in the absence of oxygen. A series of sequential biological reactions give rise to biogas containing mainly methane with a lower heating value of 35.8 MJ/m^3 and CO_2 in variable proportions, which are dependent on the fermenting conditions and the reactor operating regime. The high methane content of biogas (about 60%) makes it suitable for energetic valorization either directly for producing heat in a burner, or in more complex equipment for producing electricity using combined heat and power (CHP) engines, fuel cells, and microturbines [1,2]. Other valorization options consider gas cleaning and upgrading to reach a quality similar to that of natural gas [3]. The use of biogas for energy production or as a substitute for natural gas aids in reducing greenhouse gas (GHG) emissions on two fronts, by avoiding the uncontrolled release of methane and by reducing the use of fossil fuel for energy production, thus aiding in the decarbonization of different human activities [4]. Anaerobic digestion serves as a means for obtaining energy from wastes but also for cycling nutrients through the properly management of digestate. Although, there is broad evidence regarding the environmental benefits of anaerobic digestion, all these valorization alternatives involve installing additional equipment in the waste treatment facility, increasing capital investment, along with operating and maintenance costs. These high installation costs are the main disincentive requiring support from fiscal subsidies [5,6].

Several reports available in the literature deal with the required size of farms to guarantee the feasibility of the digestion for treating manures. Table 1 lists some results regarding the feasibility of the digestion process. It should be noted that the size required to guarantee feasibility is conditioned by the level of society development, site geographical and climatic conditions, and technological complexity of the facility.

The design of a small-scale digester raises issues regarding the energy demand associated with the pretreatment of substrates and temperature conditions. Other relevant factors are the devices needed for achieving good mixing in the digester and optimization of the feeding mixtures when different wastes are introduced into the process to enhance biogas production [15]. These factors may also explain why gas valorization for electricity production is not considered when analyzing small-scale digestion systems.

The proliferation of biogas plants for valorizing organic wastes and

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https://doi.org/10.1016/j.renene.2023.119013
Received 4 November 2022; Received in revised form 31 May 2023; Accepted 8 July 2023
Available online 8 July 2023

Table 1
List of studies available in the scientific literature regarding feasibility of anaerobic digestion.

Feed	Size	Other issues	Reference
Cattle manure	Large farm size (>4000 animals)	Minimum electrical power 740 kWe	[7]
Cattle manure, maize silage and grass silage	Large farm size (>4000 animals)	Minimum electrical power 1000 kWe	
Sheep manure and potato processing factory waste	Farm size (2000 animals)	Low profitability	[8]
Cattle manure and wheat straw	Farm size (250 animals)	Low profitability	[9]
Manure and agricultural crop residues	Household (Digester <6 m^3)	Only biofertilizer considered as a valuable product	[10]
Food wastes	Small scale prototipe (Digester 7 m^3)	Automated. High energy demand	[11]
Dairy manure, dairy by-products and food wastes	Household 50 animals (Digester 8 m^3)	Need to reduce costs	[12]
Pig slurry	Small farm size (Digester 30 m^3)	Feasible in rural areas of china	[13]
Swine manure	1300 heads	Feasible if biofertilizer is set a selling price	[14]

manures allows reducing greenhouse gas emissions by avoiding methane release into the atmosphere and by substituting fossil fuels use for energy production [16]. However, installation costs should decrease along with simplifying operating procedures and maintenance tasks to make this a reality. Ihara et al. [12] studied a small-scale digester (8 m^3) reporting on the acute need to reduce these costs. However, they also indicated that increasing hydraulic retention time and digester temperature are necessary, but these two factors raise capital investments. Ramaswamy and Vemareddy [17] evaluated a plug flow reactor for the digestion of cow manure and food wastes made of fiberglass with a volume of 30 L. These authors indicated that their design was compact without needing regular agitation, which is crucial to decreasing energy requirements.

Many livestock farms have a lower number of animals than those necessary to keep a large-scale digester running of the size required to achieve profitability. Therefore, wastes need to be available in farm surroundings, but this may not always be the case to sustain large-size digesters where electricity or gas upgrading is feasible. Therefore, small-scale digestion may be a convenient solution as long as the system provides significant benefits to farmers, laboring is highly simplified and the valorization costs of biogas are distributed between different actors.

The desire to integrate anaerobic digestion as a possible alternative for increasing the circularity of the economic model must consider that the current energy production scheme is associated with large-size farms to attain feasibility when a CHP unit or biogas upgrading is the valorization choice. However, other factors must be added to the difficulties already found when attempting the installation of large-scale anaerobic digesters. There is a widespread belief that increasing the size of farms results in environmental pollution and the deterioration of animal welfare. The application of different techniques for adequately treating organic wastes implies additional investments that may add economic pressure on small farms and only those with a larger size can reach feasibility. An increase in scale allows cost reductions and facilitates complying with environmental and sanitary regulations. Robbins et al. [18] reviewed the relationship between farm size and animal welfare indicators. These authors found no evidence of any adverse effect, with the increase in farm size. What is more striking, is the evidence that larger farms permit more specialized and professional animal health management, which is just opposite to the arguments used for avoiding their presence.

Centralized and decentralized configurations for waste treatments have both benefits and weaknesses, which can move the balance in any direction based on social context and economic conditions. He et al. [19] reported on the performance of both configurations in the china context, indicating that centralized systems have better environmental performance and social benefits in addition to higher energy efficiency. However, the benefits associated with small-scale systems should not be disregarded and may in some circumstances outcompete those of the centralized approach.

In the present manuscript, the valorization of biogas for electricity production was analyzed by considering a double turbocharger engine for producing heat and electricity and estimating the best farm size configuration capable of producing the needed amount of biogas to feed the engine. The system was evaluated under different scenarios. Technical and operational constraints of each scenario were considered, assessing their impact on energy recovery and operating costs. The manuscript analyzes the implications of small-scale systems regarding energy efficiency and profitability against large-scale systems. The aim was to estimate the feasibility of using high-efficiency CHP units coupled with decentralized digestion systems focusing on estimating costs and factors that adversely affect profitability.

2. Material and methods

2.1. Description of scenarios

The analysis is based on livestock farms dedicated to swine growth for the meat processing industry. The size of the farm was categorized as small, medium, and large. This classification is based on the Spanish Ministry of Agriculture using as a category a major livestock unit (MLU). This unit is equivalent to a cow with 500 kg of live weight, neither pregnant nor lactating, with an average body condition [20]. Three groups of farms are defined: Group 1 with up to 120 MLU, Group 2 within the range of 120–480 MLU, and Group 3 within 480–720 MLU range.

Different plant configurations were analyzed by considering the annual availability of manure and co-substrate. It was assumed that an animal of 1400 pounds (635 kg) would produce 54 kg/cow d of feces and urine at a solid content of 120 g TS/kg [21]. For pigs of 50–100 kg weight, the equivalence to MLU factor used was 0.14 [22] and the amount of manure estimated per MLU and day was 42.86 kg. Under previous assumptions, the amount of pig slurry expected was estimated per farm.

The estimated biogas production was based on published data reported in the literature. González-Arias et al. [23] reported a value of 308.5 ± 18.2 mL CH_4/g VS running a laboratory-scale digester at a hydraulic retention time (HRT) of 40 days under mesophilic conditions (temperature of 37 °C with total solid (TS) content of the feed of 55 g/L and volatile solid (VS) content of 37.5 g/L). Under batch conditions, higher methane yields are usually reported. Schommer et al. [24] obtained a yield of 480 mL CH_4/g VS, Baek et al. [25] reported a value of about 340 mL CH_4/g VS for swine manure, whereas Liu et al. [26] reported 305.3 mL CH_4/g VS. However, much lower values have been reported by Wang et al. [27], in this case 192 mL biogas/g VS, also when testing batch conditions. In this same line is the value reported by Riaño et al. [28], with a methane yield of 115 mL mL CH_4/g VS, differences explained by the different characteristics of manures.

Methane yields reported by Angelidaki and Ellegaard [29] from centralized biogas plants were about 290 mL CH_4/g VS. Hanum et al. [30] reported a value of 238 mL CH_4/g VS under mesophilic continuous conditions at 30 d HRT. Considering these previous values and taking into account that batch assays and continuous systems present enormous experimental differences regarding the dynamic conditions inside the reactor; it is expected that the different hydrodynamic behavior influence methane production at a given organic loading rate (OLR) and HRT. Thus, methane yields obtained from batch tests are higher than those derived from semi-continuous operating reactors [31]. González et al. [8] reported a 40% decrease in methane production derived from continuous conditions compared with batch test. Therefore, the value here assumed was 272 mL CH_4/g VS, which was derived as the average of those previously indicated, after reducing yields from batch assays.

The daily biogas production was estimated from the OLR applied (g VS/L d) and the size of the digester was calculated using an HRT of 40 days. Energy production was estimated by considering a double turbocharged engine. The biogas for operating this unit was the parameter used to calculate the number of farms and the mass of co-substrate needed. Three scenarios were studied. Scenario 1 considers a single large farm co-digesting pig manure and sugar beetroots. A schematization is shown in Fig. 1. Plant profitability was estimated by considering electricity and heat production.

Scenario 2 considers a centralized plant located on one of the farms. Manure transport from the others is performed either by truck (Scenario 2.1) or by a piping system (Scenario 2.2). Co-substrates are always transported by truck. The minimum distance between farms was 1 km based on Royal decree 306 [20]. The average distance from the farm to the centralized treatment plant was assumed as 17.3 km. This value was obtained from the swine population density in Castilla y León (17.1 swine/km^2). The circular area containing the required number of pigs was divided in three sectors, locating each farm in the middle of the sector.

Scenario 3 assumes that manure is co-digested on the same farm. Biogas collected is submitted to preliminary treatment for water removal and compressed before being transported and used in a CHP engine. Large-distance transport of biogas by truck (Scenario 3.1) or a piping gas system (Scenario 3.2) are the main characteristics of this Scenario. Upgrading biogas to natural gas quality was not studied because electricity production by gas engines does not require CO_2 removal [32]. Although the removal of CO_2 would reduce the volume of gas needing transport, the process has a high energy demand and high installation costs; therefore, the application of this technology is commonly associated with obtaining biomethane as vehicle fuel or injection into the natural gas grid [33,34]. Other upgrading processes involve the removal of siloxanes and halogenated compounds, but these trace contaminants are common in biogas derived from sewage sludge and landfill gas [35,36]; thus, their removal was neither considered in

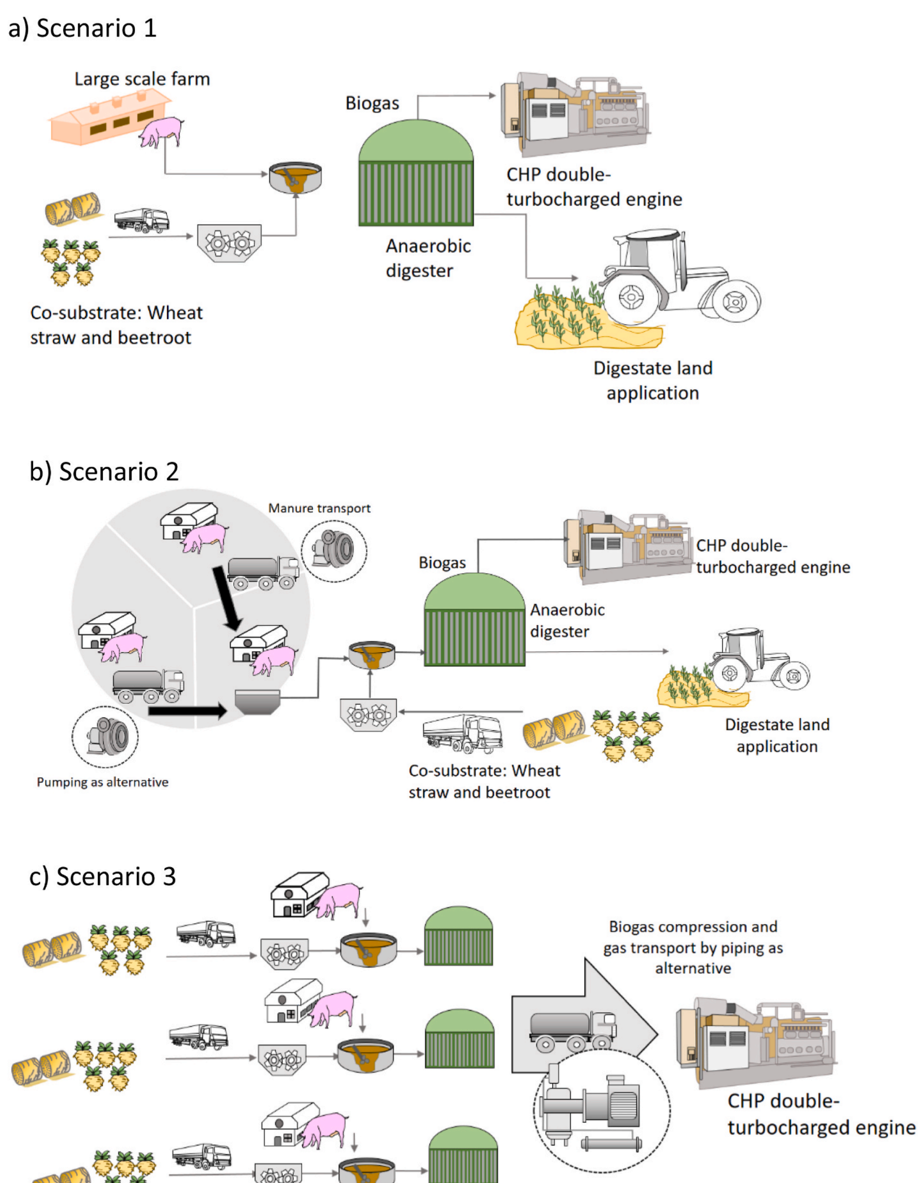

Fig. 1. Schematization of different scenarios considered. a) Scenario 1: large-scale farm treating manure and co-substrates. b) Scenario 2: Centralized manure treatment with the transport of manure c) Scenario 3: Decentralized manure treatment with the transport of biogas.

the present study.

2.2. Co-substrates

Agronomic wastes are also a suitable co-substrate. However, this material is a lignocellulosic type requiring longer digestion times when compared with carbohydrates, and some of the organic structure may not be available to the anaerobic microflora leading to low biogas yields unless pre-treatments are applied. Values in the range of 0.2–0.4 L CH_4/g VS were reported for sunflower, rapeseed wastes, wheat, and rice straw [37–42]. In the present manuscript, a value of 0.227 L CH_4/g VS was assumed for wheat straw considering a TS content of 652 g/kg and 91% VS [21]. The density of the straw was assumed as 200 kg/m^3.

Another substrate recently considered a suitable material for energy production is sugar beetroot. This crop is used for the sugar industry. However, it is experiencing severe difficulties due to the drop-down in prices after removing the European sugar quota system in 2017 [43], causing a decrease in surface area cultivated in southern European countries [44]. Sugar beet pulp is a by-product of the sugar industry often used for animal feeding, but its methane potential is high enough to be a suitable co-substrate (0.36 L CH_4/g TS [45]). An optimum value obtained from manure co-digestion was 0.347 L CH_4/g VS (mixture of poultry manure and cow dung) reported by Dima et al. [46]. Reports found in the literature dealing with continuous conditions are those of Gómez-Quiroga et al. [47], who studied the digestion of this material under thermophilic regimen. These authors indicated a fast degradation, reporting a value of 0.315 L CH_4/g VS. Other values reported by Aboudi et al. [48], also under continuous configuration, obtained average values of 0.260 L CH_4/g VS. In the present study an average value for the specific methane production (SMP) was 0.288 L CH_4/g VS (average of the previous ones).

The total solid content of beetroot (whole plant) was assumed as 162 g/kg with a VS content of 80.2% based on data reported by Fang et al. [49] and Odoh et al. [50]. The bulk plant density was assumed as 800 kg/m^3 to take into account void space during transport. The co-digesting mixture was estimated by maximizing the final SMP, considering as constraints a TS content of 14% for the mixture, with beetroot TS accounting for 25% as the maximum percentage in the mixture. This limitation is set to avoid foaming problems during digestion due to its high sugar and protein content [51,52].

2.3. Detailed plant description

The digester working volume (V_{dig}) was calculated using the amount of biogas needed for the CHP engine. A relationship was established between the solid content of the feed, the specific gas production and an HRT of the reactor for predicting the expected volume.

$$V_{dig} = \frac{B \bullet \%CH_4}{SMP \bullet \%VS \bullet [TS] \bullet \rho_{feed}} \bullet HRT \quad (1)$$

where B is the daily gas production (expressed in m^3 biogas/d), $\%CH_4$ is the methane composition in biogas, assumed here as 60%. %VS is the volatile solid percentage based on total solids. SMP is the specific methane production expected under continuous conditions, [TS] is the total solid concentration of the influent, and HRT is the hydraulic retention time applied to the biological process. ρ_{feed} is the density of the feeding mixture with a value of 1.12 kg/L. The volume of the digester was initially evaluated, considering an HRT in a range between 30 and 50 days. The concentration of total solids in the feed was between 60 and 140 g TS/L with a content of 75% VS. SMP was evaluated in the range of 200–400 mL CH_4/g VS.

The digestion plant for medium and large-scale farms consisted of storage deposits with a storage capacity of 15 days. For liquid slurry, a production rate of 0.71 m^3/MLU d with a TS content of 60 g/L (after washing operations) was assumed. The packing density of straw was 1 m^3/200 kg, and for beetroot, this value was 1 m^3/800 kg. A mixing tank is used for homogenizing the slurry and the finely ground co-substrate to attain a feed with 14% TS solid content as the maximum value. This material is fed daily into the digester, assuming an HRT of 40 days under mesophilic conditions. The biogas produced contains 60% methane. The inorganic content of the feed was to remain constant during degradation. Thus estimation of VS removal was based on biogas specific production. The mass of digestate was calculated as the difference between the incoming volatile solids with the feed and the mass of biogas produced daily. Composting of digestate was included as a way of comparison for estimating the effect on the final mass of material needing final disposal. It was assumed that a 40% reduction in VS is attained with a final product having 50% solid content. Composting was considered to be performed with the addition of yard trimmings as structuring material using a mass proportion of 1:1. Yard trimmings are to be recovered after composting with a recovery rate of 80%.

Digestate and supernatant application was based on crop nitrogen needs with a value of 130 kg N/ha for wheat and 250 kg N/ha for beetroot, assuming a nitrogen content of 3.8 kg N/t of digestate and 4.5 kg N/m^3 of supernatant [53,54]. The size of equipment was based on the CHP fuel demand. Scenarios studied shared as common parameter the mass of biogas supplied to the engine. Electricity, thermal energy, and digestate were the main products of the process.

2.4. Engine description

The biogas engine studied was a lean-burn, four-stroke Otto cycle, Jenbacher type JGS 320 GS-BL. The cogeneration system has two different cooling circuits, the main and the auxiliary. The biogas consumption of the engine is 2,607 kW, equivalent to a daily biogas mass flow of 10,486 kg/d. The electrical efficiency of this engine is 40.2%, with a thermal efficiency of 45.7%. Technical characteristics can be consulted in Ref. [55]. The energy balance was carried out using data from the manufacturer and energy contained in biogas.

2.5. Economic feasibility calculation

Economic analysis was performed considering the material annually treated by the plant, using capital cost investment data given by Naqi et al. [56], and the sixth-tenth rule. The AD plant bare module cost is projected to be $8.22 million, with a capacity to treat 90,000 t/year of wet biomass. The estimation of the engine cost and operating and maintenance (O&M) costs were based on the nominal electric power of the device (E_{nom} (kW)) and the electric power demanded (E (kW)) using the following equations [57,58], and applying an exchange rate of 1.07 USD to EUR.

$$Engine\ cost = -138.7 \cdot Ln(E_{nom}) + 1,727.1 \left(\frac{\$}{kW}\right) \quad (2)$$

$$O\&M\ costs = 0.1696 \cdot E_{nom}^{-0.2} \cdot \left(1 - 0.6875 \cdot \left(\frac{E}{E_{nom}}\right)\right)\left(\frac{\$}{kWh}\right) \quad (3)$$

Costs associated with biogas transport systems were estimated from data gave by Hengeveld et al. [59], updating costs with annual worldwide inflation values [60]. The cost of the pipeline for manure transport was estimated using data found in Bietresato et al. [61] and also updated with inflation values [60]. Transport distance of co-substrate was estimated by considering the percentage of cultivated area. In the case of cereal straw, a yield of 3.7 t/ha was assumed [62] and the amount of straw generated corresponds to 40% of cereal yield. To take into account that straw is also used for animal feeding, it was assumed that only 30% of straw was available for the digestion plant as a co-substrate. In the case of beetroot, a yield of 13.9 t/ha (dry basis) was assumed.

Economic profitability was estimated by the net present value (NPV). NPV was obtained as the sum of expected cash flows measured in today's currency and considering a discount rate (r) of 3%:

$$NPV = -IV + \sum_{t=1}^{n} \frac{CF_t}{(1+r)^t} \tag{4}$$

where IV is the initial investment of the digestion plant. CF is the cash flow expected at time t. CF was calculated from the difference between revenues and expenditures. A plant construction period of 2 years was assumed. The straight-line depreciation method was used for a 15-year period with a salvage value of 5%. The average lifespan of the plant was 30 years. Money disbursement was distributed in three years (20%/60%/20%). The working capital was assumed as 5% of IV.

Electricity trading price was set at 185.87 €/MWh, the average price of energy in Spain between June 2021 and May 2022 [63]. The selling-purchase price of thermal energy was set at 20.5 €/MWh, which would be the average price given by Zhang et al. [64]. Taxes were assumed as 0.65€/GJ of biogas.

Annual maintenance costs were assumed as 1.5% of the plant capital costs [65]. Transport costs were estimated for a truck capable of transporting 20 t or an equivalent volume for a material with a density of 1 t/m^3. Fuel consumption was 35 L diesel/100 km. Diesel fuel energy content was 10.44 kWh/L [66] (44.8 MJ/kg, diesel density of 0.8396 kg/L, [67]). The cost of transporting waste for loaded and empty vehicles was 1.7786 and 1.2450 €/km respectively [68]. The energy demand of a large-scale digestion plant was assumed as 110 MJ/t of thermal energy and 66 MJ/t of electricity and for farm size plants the thermal energy demand was set at 250 MJ/t keeping the same previous value for electricity demand [69]. Energy demand for biogas compression at 130 bar was 0.53 kWh/m^3 [59] and at 8 bar was 0.24 kWh/m^3 [70]. The cost of transporting biogas for loaded and empty vehicles was 2.9996 and 1.4998 €/km respectively [68]. Detailed description of economic estimations assumptions and data are available as supplementary material S1.

3. Results and discussion

3.1. Engine energy balance

The energy balance of the biogas engine is represented schematically in Fig. 2 at 100% loading. Fig. 2a represents the Sankey diagram and Fig. 2b shows relative values. The balance was carried out using data from the manufacturer and energy contained in biogas. The present case considers a biogas consumption of 2,607 kW. The electrical efficiency of this engine is 40.2%, with a thermal efficiency of 45.7%. The complex design of the engine having a double turbocharger gives as a result a better efficiency, which cannot be attained with smaller CHP engines. Electricity production would be 1,048 kW with thermal power of 1,214.2 kW, as represented in the Sankey diagram. This high efficiency is possible due to the large scale of the engine analyzed.

The useable thermal power of the engine is 1,467.7 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 1,214.2 kW and corresponds to the energy derived from previous devices with exception of intercooler 1. The energy of this intercooler is disregarded due to its low temperature (<55 °C) and thus low energy content, which makes its thermal recovery difficult. The exit temperature of exhaust gases was set as 142 °C to avoid condensation problems, so any energy recovery further this point was also disregarded. This accounts for 187.2 kW, which represents 7.2% of the total energy contained in biogas (See Fig. 2b).

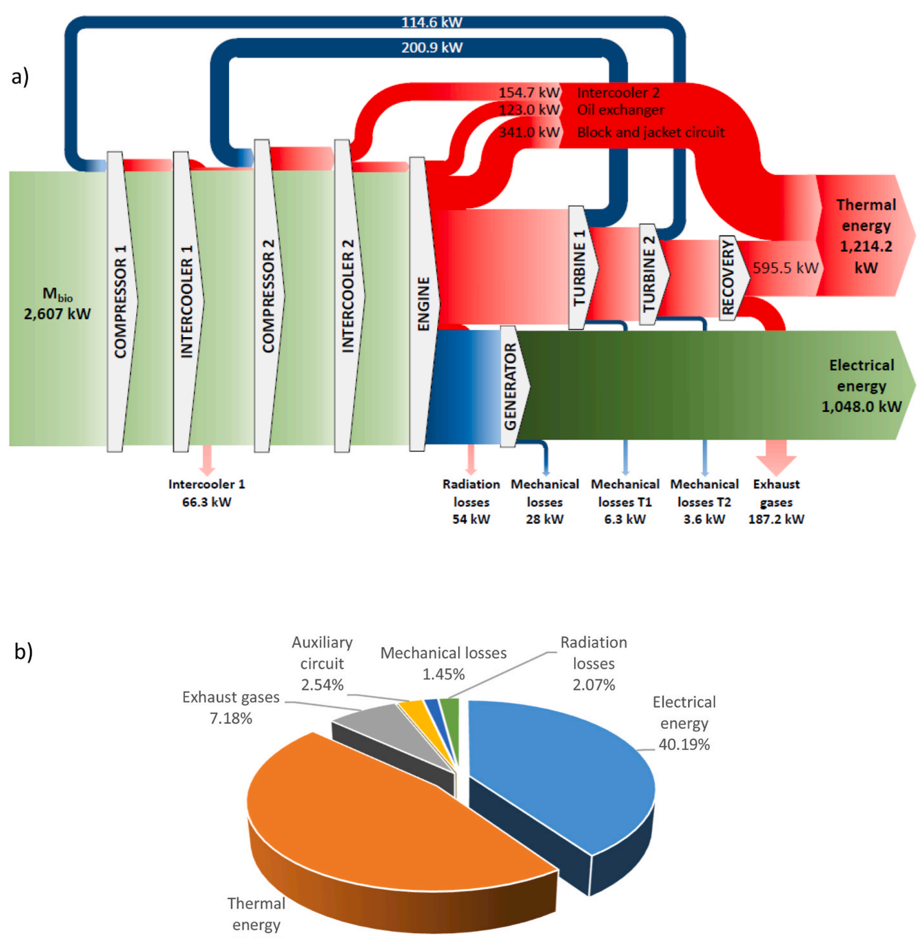

Fig. 2. Thermal balance of the engine a) Sankey diagram. b) Relative values of the energy balance.

3.2. Scenario 1

This scenario studies biogas production from a single farm along with methane valorization using a CHP engine. For a digestion system to be coupled to a double turbocharged engine (JGS 320 GS-BL), the productivity of the reactor must be kept at its maximum. Thus the reactor should be operating at high organic loading rates, which is attained either by increasing the solid content of the feed or working, if possible, at low residence times. However, a feed with higher solid content may bring as consequence, a decrease in specific methane production [71] and reaction rate due to diffusion restrictions and localized inhibitory conditions [72]. The TS content of the feed was limited to 14% to avoid excessive accumulation of inhibitory compounds and diffusion limitations.

The engine would need a daily volume of biogas of 10,490 m^3, supplied by the digester. The volume of the digester (under assumptions previously stated in the material and method section) to accomplish this requirement would be excessive. Digester volume is a function of HRT, methane yield and solid content of the feed. Fig. 3 shows the expected volume with varying values of these parameters (TS content, HRT and SMP), thus evidencing the need to attain maximum methane yields at the minimum possible retention time without causing biomass washout. If only swine manure is considered as substrate (with a TS content of 60 g/L), the digester working volume to supply the fuel for the engine would be 20,560 m^3 at an HRT of 40 days. The size of the farm would be equivalent to 6000 MLU, a value no contemplated in Spanish regulation.

If co-digestion is assumed, then a mixture containing a wet mass proportion of 68.6/9.8/21.6 of manure/straw/beetroot gives the maximum value of methane yield (0.253 L CH_4/g VS) under restrictions previously considered for the mass of beetroot added. Therefore, the volume of the digester needed would now be 7600 m^3 (working volume) to supply the same amount of fuel for the engine. However, the size of the farm is still excessive. The number of MLU to cover the substrate demand for the digester would be 1700 (equivalent to a farm growing 12,000 pigs). Thus, scenario 1 is unfeasible when considering single digestion of manure or a co-digestion case for a single farm.

The installation of new livestock farms of large size has been a cause of social discomfort in Spain and other European countries, where demonstrations of public disagreement became evident associated either with real or perceived negative effects by the community linked to this type of activity [73]. The installation of new digestion plants should be in consonance with the structure of agronomic activities and social context [74]. Therefore, centralized waste treatment may be suitable for locations where treatment plants are directly linked to a large industrial sector, but in the case of a group of several agronomic activities, deciding the final location of the plant may become a complex task, needing the involvement of the local population in the final decision.

3.3. Scenario 2

This scenario considers the amount of manure produced by a farm of the maximum Spanish category of 720 MLU as the top value and 480 MLU as the bottom value in group III. The number of farms needed to supply biogas to the engine would be between 3 and 4, based on the farm size here considered. In this scenario, three farms were assumed to be served by a centralized digestion plant located in one of these installations. Manure is transported from the remaining two farms by truck or piping. Table 2 shows the main parameters of the installation and data regarding the supply of co-substrates.

The centralized plant in scenario 1 and 2 has the same dimensions. Straw from cereals was considered as a complementary co-substrate, given the limitations associated with foam formation when digesting beetroot. The availability of straw was estimated by considering crop yield and the use of straw for other uses such as animal feeding; limiting to using just 30% of the total produced. Available straw was thus estimated as 0.44 t/ha (dry base). Straw transport costs were based on the truck loading capacity (20 t or 20 m^3 for a material with a density value of 1 m^3/t). However, straw-bales have much lower density (200 kg/m^3),

Table 2
Parameters characterizing digestion plant in Scenario 2. A centralized digestion plant located on one farms treats its own organic material along with dejections produced by the other two.

Parameter	Value
Digester size (working volume) (m^3)	7,600
HRT (days)	40
OLR (kg VS/m^3 d)	3.3
Capital investment centralized digestion plant (M€)	7.43
Engine cost (M€)	0.81
Biogas production (m^3/d), STP	10,486
% CH4	60
Biogas density (kg/m^3)	1.2
LHV methane (MJ/m^3)	35.8
Digestate (t/year), 30% TS	20,657
Anaerobic supernatant (m^3/year)	52,158
Swine manure mass stream (t/year)	53,144
TS Swine manure (g/L)	60
Co-substrate	
Cereal straw demand (t/year)	7,584
% crop area for cereal[a]	11.3
Crop yield (t/ha)	3.7
Straw yield (expressed as percentage of crop yield production)	40%
Straw available for the plant (expressed as percentage of straw produced)	30%
Straw transport distance (km/year)	62,159
Beetroot demand (t/year)	16,734
% crop area for beetroot[a]	5
Beetroot yield (t/ha), wet base	85.82
Beetroot yield (t/ha), dry base	13.9
Beetroot transporting distance (km/year)	6,808

[a] [75].

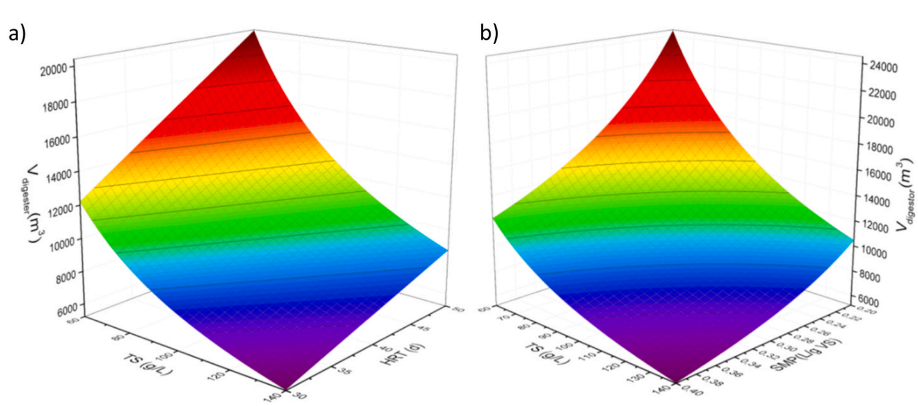

Fig. 3. Digester size estimated at varying values of TS, HRT and SMP. a) values represented at a SMP mean value of 0.3 L CH_4/g VS. b) HRT mean values of 40 days.

increasing the number of trips needed. The estimation for beetroot transport was performed similarly to that of straw. The use of the whole plant as substrate gives better results regarding transport costs. The loading factor of the truck was 0.8 to consider void spaces when loading the material. Therefore, the distance obtained for supplying beetroot to the centralized plant is 9 times lower.

Digestion of material was assumed, having the mixture a methane yield of 0.253 L CH_4/g VS. However, the silage of straw and beetroot would increase methane yield, favoring the energy balance because it reduces the total mass of co-substrate needed, and therefore the number of trips and distance for transport. Any increase in methane yield also affects the energy balance of the plant because the amount of remaining solids is reduced. Ensiling straw with sugar beet leaves increases BMP between 18 and 34% after 6 months' ensilage period [76]. If an average improvement in biogas production of 26% is considered, then the mass balance is affected by reducing the amount of digestate needing final disposal by 35% and reducing digester size by 20%.

The plant needs to manage digestate, which can be used as an organic amendment without any economic value. Thus a material with a water content of 70% is to be transported and serve as a fertilizing product for cereal and beetroot cropland application. This assumption was also used for the anaerobic supernatant. Based on the nitrogen demand for these crops, the application distance for supernatant irrigation and digestate spreading was calculated, resulting in a value of 33,903 km.

Composting not also improves quality of organics, but also allows reducing water content, increases stabilization degree thus reducing even more the mass of material needing final disposal and therefore transport requirements. If composting is carried out prior to cropland application the amount of material needing final disposal would decrease from 56.6 to 23.7 t/d (58% decrease), keeping the assumption of substrate ensilage.

Fig. 4 shows the net energy produced (electricity and thermal energy) expressed as a percentage of the energy contained in biogas. The best value of energy recovery was found for the centralized option with a single macro-farm, but this scenario was considered unfeasible due to the social rejection and legal constraints in many countries. Considering ensilage would benefit the balance due to the lower distance needed for raw material transport, and disposal of digestate and supernatant. However, this improvement leads to a 59% energy recovery, which is a slight increase compared with Scenario 1 (58.3%).

Centralizing manure treatment from several farms also showed promising results because their transport, either by truck (Scenario 2.1) or a piping system (Scenario 2.2), does not heavily penalize the energy balance. A slight improvement was obtained when a piping system is introduced. In the present case, the analysis was carried out considering three farms, but if this strategy is applied to the case where several small farms of 120 MLU (850 pigs) are assumed, then the centralized plant would serve 14 farms. The increase in the number of farms results in a manure transport distance of 89,488 km/year, which translates into 3,440 additional kilometers. However, the effect on the net energy balances is meaningless since the efficiency under this assumption is 56.9%.

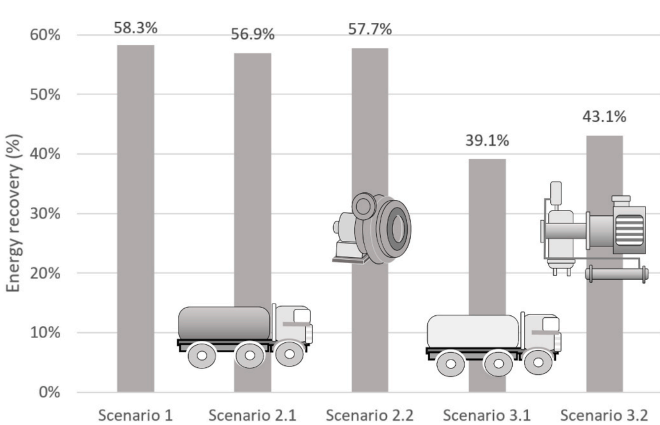

Fig. 4. Energy recovery from biogas expressed as percentage. Energy produced as electricity and thermal energy produced from a CHP unit are used to estimate the recovery using the energy contained in biogas as base. Scenario 1: centralized treatment, Scenario 2: Centralized manure treatment with the transport of manure by truck (2.1) or piping (2.2), Scenario 3: Decentralized manure treatment with the transport of biogas by truck (3.1) or piping (3.2).

3.4. Scenario 3

This scenario evaluates the installation of a digester for each livestock farm. Thus the amount of co-substrate needed is not affected. Farms are located outside the incidence area of the others. Therefore, activities of co-substrate collection and transport report no interference. The same assumptions used in the previous case were also used in the present scenario. The transport distance is reduced now by 42% because the distance covered by the truck on each trip is lower. Table 3 shows the main characteristics. Just as in Scenario 2, the engine is located at one of the plants. Therefore, biogas produced by the other two farms is transported either by truck (Scenario 3.1) or piping (Scenario 3.2). The maximum pressure for compressing raw biogas was 130 bar to avoid problems with CO_2 crystal formation at higher pressures when considering truck transport. Whereas an 8 bar pressure was assumed for the piping system. Fig. 5 also shows results obtained from Scenario 3. In this case, decentralization highly reduces the efficiency of the global process. An excessive amount of energy is needed for compressing biogas, resulting in 1,522 MWh/year when transported by truck and 612 MWh/year when assuming piping.

The localized treatment of manure does not affect the global amount of digestate produced. However, the distance traveled for digestate land disposal and supernatant application is modified in a similar way as it was the collection of co-substrates. Thus, the estimated distance was 19,576 Km/year Fig. 5 shows the energy demand disaggregated into categories. Engine losses are the same for all options, but other categories experienced a significant increase in Scenario 3. The transport distance of co-substrates and digestion by-products is reduced in this scenario. However, this fact does not compensate for the increase in energy demand by biogas transport either by truck or by using a piping system. The partial decentralization has much lower efficiency. Nevertheless, this alternative may be considered suitable for cases where a centralized digestion unit would not be socially accepted due to the inconvenience created by the high traffic of trucks dedicated to the transport of co-substrates and disposal of digestion by-products. Social acceptance is one of the main factors that can be deterministic in the

Table 3
Main parameters characterizing anaerobic digestion plant in Scenario 3. Here is assumed the installation of a digestion plant for each farm. Biogas is then transported to a centralized CHP engine located on one of the farms.

Parameter	Value
Digester size (working volume) (m^3)	2,540 x 3
HRT (days)	40
OLR (kg VS/m^3 d)	3.3
Capital investment digestion plant (3 plants) (M€)	11.8
Engine cost (M€)	0.81
Biogas production (m^3/d), STP	10,486
Biogas to be transported (m^3/d), STP	6,990
Straw transport distance (km/year)	36,083
Beetroot transport distance (km/year)	3,947
Reduction in co-substrate transport distance (%)	42
Volume of biogas transported by truck at 130 bar (m^3/year)	19,888
Biogas transport distance by truck (km)	47,671
Energy demand for biogas transport by truck (MWh/year)	1522
Volume of biogas transported by the piping system at 8 bar (m^3/year)	323,190
Energy demand for biogas transport by the piping system (MWh/year)	612

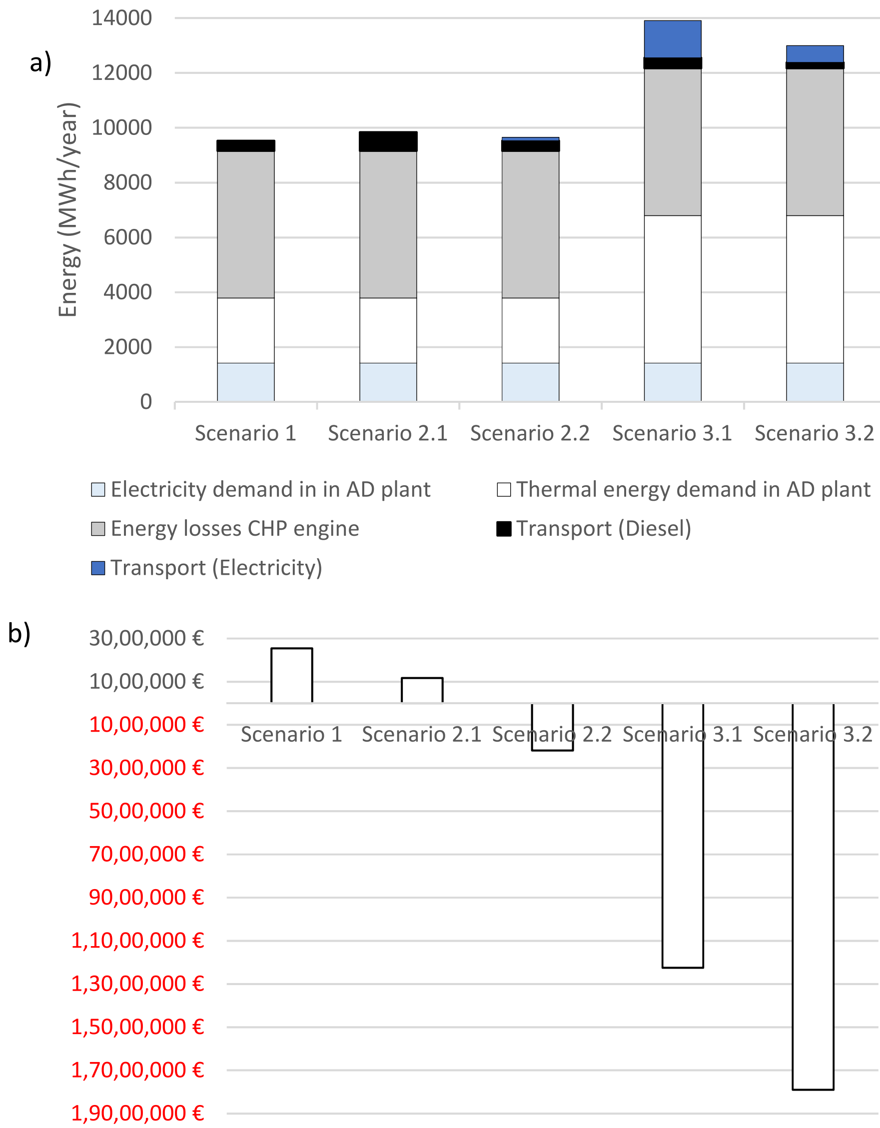

Fig. 5. a) Description of energy demand for different alternatives evaluated and b) NPV obtained from the economic analysis. Scale in red refers to negative values. Scenario 1: centralized treatment, Scenario 2: Centralized manure treatment with transport of manure by truck (2.1) or piping (2.2), Scenario 3: Decentralized manure treatment with transport of biogas by truck (3.1) or piping (3.2).

widespread of technology. Although other factors such as economics, availability of incentives, and technical complexities are also relevant, the approval of the local community for the project is fundamental [77]. Partial decentralization, either by transporting a fraction of the main substrate or by carrying out a joint valorization of biogas in a different centralized installation, may serve as measurements dedicated to alleviating social discomfort.

NPV graph is also represented in Fig. 5. Scenario 3 results unfeasible with the transport of biogas by piping as the worst economic option; although this scenario reported better energy balance than its homologous partner. Details of cost estimations are included in supplementary material S2. Centralized digestion (Scenario 1) is the best option with a positive NPV value having an internal rate of return (IRR) of 4.89%, but with a period of investment return of 24 years. Ensilage of co-substrates results in better profit, with an IRR of 9.88%, thus reducing the period for returning the investment to 15 years. The centralized option with the transport of swine manure by truck also gives positive results but with lower economic feasibility.

Decentralization and biogas networks are being recently proposed as suitable technological options for creating rural gas networks capable of supplying biogas that can be upgraded into a quality fuel suitable for injection into the natural gas grid [59,78]. However, this option demonstrated to have higher costs than the centralized one. The present study compared biogas valorization in a centralized CHP under different treatment configurations. Partial decentralization of the treatment system resulted economically unfeasible. On the contrary, partial decentralization is more convenient for the existing farm production scheme in many countries. Therefore, efforts should be focused on optimizing the use of resources and assessing the global impact on the local economy and social acceptance of rural biogas networks for in-situ valorization. Aspects regarding social acceptance for large-scale centralized technologies should be addressed and policy changes should be undertaken if energy efficiency is set as the main criteria for decision making.

Results may be greatly improved if costs regarding partial gas upgrading and transport by piping are externalized, avoiding the farmer assuming such high inversions. Then the implementation of this option would have better acceptance among farmers who are already experiencing excessive production costs due to the current energetic crisis and exacerbated inflation of raw materials. In addition, a network of low-quality gas may also be useful if other treatment technologies may benefit from it, as would be the case of in-situ gasification of forest wastes. The biogas network could be considered a national infrastructure, as is usually the case of other transport networks, such as natural gas and crop irrigation infrastructures. National governments manage these infrastructures due to the intangible benefits they bring to a given country or society in general since they may not be attractive enough when managed privately. Biogas networks could fit into this type of infrastructure if they become part of the energy transition toward decarbonization. The existence of this type of infrastructure would make it possible to use biogas from small livestock farms as an energy resource. This would also aid in maintaining small agro-livestock farms as a way of life for certain people, while also allowing the use of local energy resources in a sustainable manner, contributing to fight against depopulation of rural areas.

The availability of incentives, specially adapted to the agronomic context and social structure, is necessary if digestion plants are to become main actors in the bio-energy sector. Given the high installation costs of the different alternatives studied, a compensation scheme should be created for waste treatment facilities capable of producing bio-energy or upgrading biogas to serve as a natural gas substitute. The benefits of anaerobic digestion may be undeniable, but the costs and complexity of the technology are barriers that still need to be overcome. The mitigation of GHG emissions and capacity for substituting fossil fuels are factors that should be reflected in economic incentives, particularly when biogas is obtained from waste streams associated with agronomic sectors.

The decision of the final configuration adopted, in addition to economic aspects, must also take into account social and environmental benefits, respecting the structure of agronomic activities and the local economy. All these factors are not easily quantifiable, but efforts should be performed to include these variables in the selection of the best alternative. Future work will be dedicated to developing a multi-criteria model to aid in assessing different alternatives. However, current results allow identifying the main factors affecting the feasibility of the partial decentralization scheme and its associated costs.

4. Conclusions

The present manuscript assessed the concept of partial decentralization of waste treatment considering medium-scale farms. Swine manure was assumed to be co-digested with beetroot (as an energy crop) and wheat straw. Biogas produced was valorized in a unique CHP engine of high efficiency (double-turbocharger, Jenbacher type JGS 320 GS-BL), considering as revenues electricity and heat sales. The analysis showed centralization as the best option when considering energy efficiency and economic feasibility, with an efficiency value of 58.3% and an IRR of 9.88% if the ensilage of co-substrates is applied. However, this alternative requires farm sizes not contemplated in Spanish regulation. Therefore, partial decentralization may be a better option for the existing production scheme. Decentralized manure treatment, along with central valorization of biogas, allows attaining efficiencies close to that of the centralized option without disrupting traditional farming but keeps the inconvenience of co-substrate transport. Currently, the economic feasibility is null when considering manure transport by piping or biogas transport for attaining partial decentralization. In the latter case, the energy efficiency attained was 43.1%, but it avoids long-distance transport of raw materials which is usually a cause of discomfort to neighbors. The construction of a manure piping system or a rural biogas network by local governments may aid in externalizing costs and improving the economic balance of farmers for treating manures. Results indicate that a change in waste management is needed, either a regulatory modification to favor centralized systems integrated into large-scale farm production schemes or keep the traditional farm structure but, in this case, implementing suitable incentive to offset higher costs and lower efficiencies of the decentralized approach.

CRediT authorship contribution statement

Ruben González: Conceptualization, Methodology, Balance equation calculation, Graph preparation. **José García-Cascallana:** Investigation, Balance equation calculation, Validation. **Xiomar Gómez:** Data curation, Writing – original draft, preparation, Balance equation calculation. Graph preparation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Authors appreciate collaboration of EXPORINSA for making available information regarding the production scheme and facility design.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.renene.2023.119013.

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