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Environmental and techno-economic analysis of a biomethane energy community in southern Spain

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ABSTRACT

The increasing focus on renewable energy has spotlighted bioenergy from waste materials, emphasizing waste-based biorefinery processes for waste management and renewable energy production. Anaerobic co-digestion has emerged as a viable alternative, producing higher energy–density biogas. This study conducts a comparative environmental life cycle analysis of current waste management practices, fertilizer consumption, and domestic heat consumption with the incorporation of a biomethane plant in a small municipality in South-Spain. It evaluates the combination of more than two substrates while conducting a comprehensive analysis of the full range of available waste to optimize biomethane production and minimize the carbon footprint.

Additionally, a novel business model is introduced, involving energy communities comprising municipal stakeholders, small businesses, and households engaged in gas self-consumption. This model aims to benefit the municipality economically and environmentally, ensuring local energy supply security and potentially offering affordable renewable fuel prices through European funding subsidies. Currently, while gas-based community energy models exist, the injection of biomethane into the grid for community consumption is yet to be realized. However, the European Union's goals of promoting a circular economy and empowering rural sectors indicate progress towards this objective. From 2027, a new EU Emissions Trading System 2 scheme will impose emissions payments on buildings and small industries, highlighting the need for cost-effective decarbonization strategies where biomethane could play a crucial role.

The environmental impact assessment reveals that implementing a biomethane injection system significantly mitigates all environmental impact categories. A well-balanced co-digestion mixture enhances biomethane production and emission abatement, achieving an 89% reduction in CO_2-eq emissions in domestic heating. Establishing a cooperative model with municipal collaboration proves viable, with a 17% internal rate of return and a possibility to decrease the price paid by the energy community below 40€/MWh. Potential revenue from biogenic CO_2-eq, compost, and gas sales through Guarantees of Origin and Proof of Sustainability further enhances profitability, underscoring the environmental and economic potential of anaerobic co-digestion within energy communities.

Introduction

In recent years, there has been a surge in interest surrounding the generation and application of renewable energy, reflecting a global shift away from fossil fuel-based sources towards more sustainable production and consumption practices. Of note within the realm of renewable energy is the attention drawn by governmental bodies to bioenergy derived from waste materials. This perspective highlights the potential

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Abbreviations: AD, Anaerobic Digestion; ACoD, Anaerobic Co-Digestion; ALCA, Attributional Life Cycle Assessment; CBA, Cost-Benefit Analysis; C/N, Carbon-to-Nitrogen ratio; GWP, Global Warming Potential; OFMSW, Organic Fraction of Municipal Solid Waste; WWTP, Wastewater Treatment Plant; IRR, Internal Rate of Return; GO, Guarantee of Origin; PoS, Proof of Sustainability; LHV, Lower Heating Value; HHV, Higher Heating Value; ETS, Emissions Trading Scheme; DSCR, Debt Service Coverage Ratio; PS, Pig Slurry; SS, Sewage Sludge; MR, Meat Residues; FVW, Fruit and Vegetable Wastes.

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of waste-based biorefinery processes to tackle waste management issues while simultaneously contributing to the production of renewable energy [1].

In line with this viewpoint, the European Union has set ambitious targets to significantly reduce waste landfilling by 2030, as outlined in Directive 2018/85. This directive stipulates that all recyclable or recoverable waste, especially in municipal waste, should be diverted from landfills unless it provides the most environmentally beneficial solution. Additionally, by 2035, the EU aims to restrict the proportion of municipal waste sent to landfills to just 10 %.

Within this framework, anaerobic digestion (AD) emerges as a promising technology for biogas production, offering dual benefits in waste management and renewable energy generation. Anaerobic digestion is recognized as one of the most efficient biological treatments for organic waste, aligning with the objectives of a circular economy. This approach seeks to minimize waste generation and maximize resource utilization, thereby addressing environmental pollution stemming from inefficient waste management practices. Furthermore, these efforts are in line with the EU's targets for renewable energy consumption, aiming for a 42.5 % share of renewable energy in gross final energy consumption by 2030, as per the latest update of the Renewable Energy Directive (RED III), with a specific focus on advanced biofuels, where biogas and biomethane play pivotal roles.

Anaerobic digestion of waste yields biogas, primarily consisting of methane (CH_4) in the range of 50–70 %, accompanied by carbon dioxide (CO_2) at 30–45 %, and minute quantities of hydrogen, nitrogen, oxygen, and hydrogen sulfide, each constituting less than 5 % of the composition [14]. While biogas offers versatile pathways for energy conversion into electricity, heat, and mechanical energy for transportation, its valorization through an upgrading process is advisable. This process involves the removal of CO_2 and impurities to produce biomethane, which boasts competitive energy efficiency compared to biogas. Moreover, biomethane holds the advantage of enhanced transportability and compatibility with injection into natural gas grids, enabling its utilization across a diverse array of applications [7].

Furthermore, anaerobic digestion yields a by-product known as digestate, characterized by its nutrient-rich organic composition. This material serves as a sustainable alternative to mineral fertilizers in agricultural fields, thereby mitigating the depletion of critical resources such as phosphorus and potassium. Additionally, digestate contributes to carbon capture efforts by incorporating non-digestible organic matter into agricultural soils.

The application of AD is predominantly observed in treating single substrates, also referred to as mono-digestion. However, anaerobic mono-digestion encounters significant hurdles. Various studies highlight its susceptibility to inadequate organic loading and an imbalanced carbon-to-nitrogen (C/N) ratio [12]. These factors contribute to the formation of inhibitory compounds like NH_3 and H_2S, resulting in diminished biogas or methane yield [26]. Moreover, nutrient imbalances during mono-digestion can destabilize the process, impacting the quality of the resulting digestate. For instance, a low C/N ratio in the feed increases the presence of free ammoniacal nitrogen in the digestate, thus reducing its value as a fertilizer [12].

In response to these challenges, anaerobic co-digestion (ACoD) has emerged as an optimal alternative, offering synergistic benefits in producing higher energy density biogas. This is attributed to factors such as a balanced C/N ratio and optimal organic loading of mixed feedstocks [28]. From an energetic valorization perspective, anaerobic co-digestion may outperform mono-digestion (Hossain et al., 2023). However, a comprehensive understanding of the environmental implications of co-digestion compared to mono-digestion is imperative before implementing it as a sustainable alternative.

Research efforts have explored the environmental benefits of co-digestion such as the combination of sewage sludge with organic fraction of municipal solid waste (OFMWS) [13], as well as pig manure with agri-food residues [11]. These studies evaluate the environmental impact arising from managing these waste streams using ACoD technology. Additionally, these publications conduct comparisons with baseline scenarios, crucial for assessing the net impact achieved with biorefinery implementation. This assessment is pivotal, particularly in scenarios involving biogas transactions, as the combined price of Guarantees of Origin (GO) and Proof of Sustainability (PoS) for decarbonizing industrial and residential sectors is contingent upon the level of carbon footprint abatement achieved [24].

However, gaps remain, particularly regarding the combination of more than two substrates while conducting a comprehensive analysis of the full range of available waste in the community to determine the best-practise combination for maximizing both biomethane production and its richness in biogas, while minimizing the carbon footprint. Moreover, unlike other studies that complement their findings with economic analyses [23], this study introduces a novel approach by incorporating a new business model through energy communities formed by all municipal stakeholders engaged in gas self-consumption, including the municipality itself, small businesses, and residential households. This initiative aims to benefit the entire municipality both economically and environmentally. Furthermore, not only does it ensure local energy supply security, but it could also lead to highly affordable prices for renewable fuels through European funding subsidies (European [5].

In this context, energy communities play a crucial role in facilitating active citizen participation in the energy system. These communities bring together individuals and businesses to collaborate on collective energy projects, primarily focused on generating renewable energy to meet members' needs. The establishment, operation, and growth of energy communities are facilitated by factors such as the energy market structure, legal frameworks, administrative support, and social infrastructure [2]. Participants in energy communities enjoy both direct and indirect benefits, including lower energy costs, incentives, favorable supply tariffs, improved energy efficiency, and reduced consumption [9].

Currently, the possibility of a gas-based community energy model exists, either through on-site biogas/biomethane consumption or district heating and cooling networks. However, the injection of biomethane into the grid for community consumption remains unrealized. Nonetheless, with the objectives of promoting a circular economy and empowering rural sectors, the European Union is moving towards this goal [22]. Starting from 2027, buildings and small industries not covered by the EU Emissions Trading System (ETS) will fall under a new ETS 2 scheme, emphasizing the need for economically viable decarbonization strategies (European [3]. In this context, biomethane could play a pivotal role, offering a cost-effective decarbonization solution compared to electrification alternatives like heat pumps [27], both economically and in terms of household occupancy [21].

In light of the above, this study aims to assess the environmental and economic feasibility of implementing a biomethane-based energy community in a rural municipality in southern Spain. The main research questions are: (i) what is the optimal combination of locally available organic residues to maximize biomethane production while minimizing the carbon footprint? and (ii) can such a system be economically viable under a cooperative community model? This work addresses current research gaps by analyzing a complex co-digestion system involving more than two substrates, a combination not commonly studied in the literature. Furthermore, it integrates a detailed life cycle assessment (LCA) with a techno-economic evaluation within the framework of an energy community, an approach that remains scarce in rural contexts. The results contribute to the scientific understanding of sustainable biogas valorization strategies and support decision-making for rural decarbonization under the upcoming EU ETS2 scheme.

Material and methods

An environmental assessment was conducted using SimaPro 8, the most widely used professional software for evaluating the life cycle environmental impact of processes, with the Ecoinvent database version 3. The methodology evaluates the environmental performance of two residue management strategies from a cradle-to-gate perspective. The environmental assessment comprises the following phases: (1) goal and scope definition; (2) inventory analysis; (3) impact assessment; (4) interpretation. Specific methodological aspects, main hypotheses, and key assumptions are detailed in the following subsections.

Goal and scope definition

This study follows an attributional life cycle assessment (ALCA) approach, as defined by the ISO 14040 framework. The attributional approach focuses on describing the environmental burdens associated with the current and prospective systems based on direct relationships between inputs and outputs. The inventory modeling was performed using Ecoinvent v3.0, with the “Allocation, cut-off by classification” system model, which is consistent with the attributional methodology. This approach allows for a comparative evaluation between baseline and anaerobic digestion scenarios without modeling market-mediated consequences.

This phase defines the study goals, system boundaries, cut-off rules, and functional unit, which form the basis for reporting the environmental assessment results. The primary objective of the study was to evaluate the environmental impacts of AD as an alternative waste management technique compared to conventional practices such as direct fertilization, composting, or landfilling. The assessment aims to quantitatively measure the environmental footprint of each scenario from cradle-to-gate.

Scenario description

This study examines two waste management scenarios with equal mass fraction and composition ratio of waste inputs. The initial scenario embodies traditional waste management approaches, encompassing the customary utilization of synthetic fertilizers with nutritional properties comparable to those found in resulting compost. Additionally, it considers the prevailing environmental consequences stemming from the domestic consumption of natural gas in boilers.

The second scenario considers the existence of a biorefinery. The biorefinery scenario entails a biogas plant located in the Murcia region, specifically in the town of study, with a population of approximately 21,700 inhabitants. The plant utilizes various waste resources from the region and nearby industries, including the Organic Fraction of Municipal Solid Waste (OFMWS), weekly market residues of fruits and vegetables (FVW), sewage sludge (SS) from the Wastewater Treatment Plant (WWTP), pig slurry (PS), and meat residues (MR).

In the current scenario can be distinguished:

a) PS Treatment: this process entails on-site waste storage on farms for approximately 8 days, followed by stabilization in an open storage tank for 120 days. Subsequently, the treated waste is transported to the field and applied to the soil as a fertilizer source, rich in nitrogen, phosphorus, and potassium, is considered.
b) SS Treatment: SS from the El Pozo factory undergoes composting treatment. Regarding SS management, it is presumed that 61.1 % of the WWTP residues are dehydrated and are subsequently utilized as fertilizer in agricultural fields, with the remaining 38.9 % collected and subjected to composting procedures and its application in agricultural practises. These percentages are consistent with observed averages within the Spanish region during the year 2022.
c) Municipal Solid Waste (MSW): MSW is managed in accordance with prevailing practices in Spain, where the separation and valorization of such residues remain limited. It is assumed that in the case of study, residues from selective collection follow the waste disposal pattern outlined in Ecoinvent for Spain. As observed in the preceding scenario, most of these residues are directed to landfill facilities, with the remaining portion incinerated.
d) FVW Treatment: 85 % of the FVW are subsequently directed to landfill or incineration, aligning with the waste management practices outlined in the Spanish dataset within Ecoinvent. Conversely, the remaining 15 % undergo composting.
e) Avoided Outputs Production: It is assumed that the natural gas is utilized for boilers employed in residential heating systems. Consequently, the environmental footprint linked to boiler operation, utilizing an energy-equivalent amount of natural gas to that of the biogas produced at the facility, is duly accounted for, inclusive of the environmental impacts spanning the entire natural gas value chain. With regard to the compost generated for utilization as fertilizer, a conventional agricultural product such as Urea is regarded as the avoided product. In this context, an equivalent quantity of 0.21 tons of compost is considered analogous to 9 kg of Urea, as indicated by [25].

In the AD scenario can be distinguished:

To evaluate the environmental impact throughout the waste value chain, a holistic approach is adopted, requiring an understanding of the process stages in the biorefinery.

a) Pretreatment: the initial phase of the biogas plant’s operation involves a physical pretreatment process aimed at reducing particle size, augmenting the available surface area for enzyme adsorption, and fostering enhanced contact between the inoculum and the substrate. This process entails the sorting and compaction of municipal solid waste, followed by the fragmentation of OFMSW. The segregated waste fraction has been estimated at 73.2 %, which will be recycled by waste type (aluminum, steel, glass, paper and cardboard, HDPE plastics, PET, and other plastics), with 57.3 % of the segregated fraction being OFMWS [17].

Furthermore, solid–liquid separation of PS is conducted through screening and settling, as this enhances the biogas/methane yield by optimizing the utilization of the highly biodegradable liquid fraction, while the solid fraction is directed towards composting. The amalgamation of OFMSW with the liquid fraction of PS, along with MR, crushed FV, and SS, undergoes homogenization in a tank before entering the digester.

b) Digester: the digestion process is facilitated by a single-stage digester, operating under continuous digestion conditions, with a total retention time of 21 days and a working temperature of 35 °C. The temperature of the biogas exiting the digester is maintained at 35 °C under atmospheric pressure. It is assumed that the waste input flow remains constant throughout the year, disregarding seasonal variations. Therefore, a baseline biogas production load is established, and the annual operating time is fixed at 7,000 h.

During instances of excess biogas production at the biomethanation plant, and before purification, when storage systems reach their maximum capacity, a flare is installed on-site. The flare is responsible for controlled combustion of the excess biogas, thereby reducing its environmental impact. Then, prior to injection into the local gas network for domestic self-consumption by the energy community, the produced biogas undergoes purification.

c) Purification: purification of the biogas to achieve 95–98 % methane purity has been proposed. Biogas purification to biomethane involves several processes, including hydrogen sulfide removal. Amino acid scrubbing, using a solution such as monoethanolamine, selectively absorbs H2S from the biogas. Gas conditioning is then conducted to optimize the biogas for further purification, adjusting its temperature, pressure, and moisture content. Cooling or heating is applied to bring the biogas to the desired temperature range, while excess moisture is removed through techniques like condensation or drying. The final step involves methane enrichment, aiming to increase the methane content in the biogas, utilizing pressure swing adsorption techniques.

d) Digestate Treatment: following digestion, the digestate undergoes a dewatering process, where the liquid fraction is directed to a nearby wastewater treatment plant, while the solid fraction (digested matter) undergoes a decomposition phase utilizing forced aeration and irrigation systems for 28 days. Subsequently, the decomposed material is transferred to piles for a curing phase lasting 62 days. These piles are regularly turned to facilitate natural aeration. Finally, the processed material undergoes screening to separate mature compost from incompletely decomposed portions. The composting facility is equipped with biofilters for exhaust gas treatment. The compost is ultimately utilized as a fertilizer absorbed by agricultural soil, with no associated environmental impact assumed.

A simplified mass and energy balance of the AD outputs was estimated in Fig. 1 to better clarify the avoided impacts associated with replacements. This assessment is based on the input flow of each substrate, normalized per functional unit (1 MWh biomethane, LHV). The resulting information supports the inventory development for the LCA:

- Biomethane, produced through anaerobic digestion and biogas purification (Process A), serves as a substitute for natural gas, thereby avoiding emissions from its combustion in the boiler (Process B) as well as the environmental impacts of natural gas extraction and distribution (Process C).
- Compost production from dehydrated digestate and the solid fraction of PS (Process D) replaces the use of chemical fertilizers, thereby reducing demand. The current industrial fertilizer production process (Process E) involves significant natural gas consumption due to the high-temperature requirements, along with substantial water and electricity use for pumps, compressors, and other equipment.

Municipality waste production

The initial phase of this project entails evaluating the potential for biogas and biomethane production in the locality of the study, while concurrently evaluating the community's level of biomethane self-sufficiency. The composition ratio was determined based on several criteria, which include i) maximizing waste utilization to mitigate the environmental impact associated with current waste treatment practices, ii) achieving a carbon-to-nitrogen ratio in the substrate close to the optimal range of 20–30, and iii) maximizing biomethane production in the correct proportion (approximately 70 % richness).

The methodology employed to assess the quantities of biogas produced from mono-substrate and the richness of biomethane is proprietary to the university research group and therefore falls outside the scope of this paper.

System boundary definition

Fig. 2 illustrates the boundaries of the evaluated system. Within these boundaries, further detail is provided below regarding what is included and excluded in the project:

1) The waste is considered as the input to the system without tracing its upstream origins. This implies that the preceding process, encompassing waste generation, its prior storage, and transportation to the plant, which are contingent upon the logistics and management plan for generated waste, are considered beyond the scope of this project. This facilitates its extrapolation to other ad-hoc projects.
2) The study does not account for the environmental impact associated with the construction of the digester or pre- and post-treatment facilities, as it is deemed insignificant, as indicated in other environmental studies [23].
3) Concerning the process of separating the residual fraction, the collection transport of each separated and non-separated fraction has been included, along with appropriate end-of-life treatment for each through recycling (plastics, metals, etc.) and for the non-recoverable fraction, which includes sanitary landfilling and incineration according to the mix of unrecoverable waste.
4) It is assumed that the impact during the crushing of FVW, MR, and their agitation with OFMWS, SS, and PS in the homogenization tank is negligible. This is because the classification stage of the residual fraction consumes more energy and generates higher emissions. Moreover, energy consumption data obtained from other studies are not disaggregated according to the classification, crushing, or agitation phases.
5) Regarding the composting stage, the transport phase of the generated compost has not been considered, and the emissions associated with the spreading of compost on land have been deemed negligible, as observed in other referenced studies.
6) Concerning the liquid fraction of the digestate, it is assumed to be sent for WWTP outside the plant.

Functional unit

In Eco auditory, the functional unit is the definition of the functional outputs of the product system. The main purpose of the functional unit is to provide a reference to which the inputs and outputs can be related.

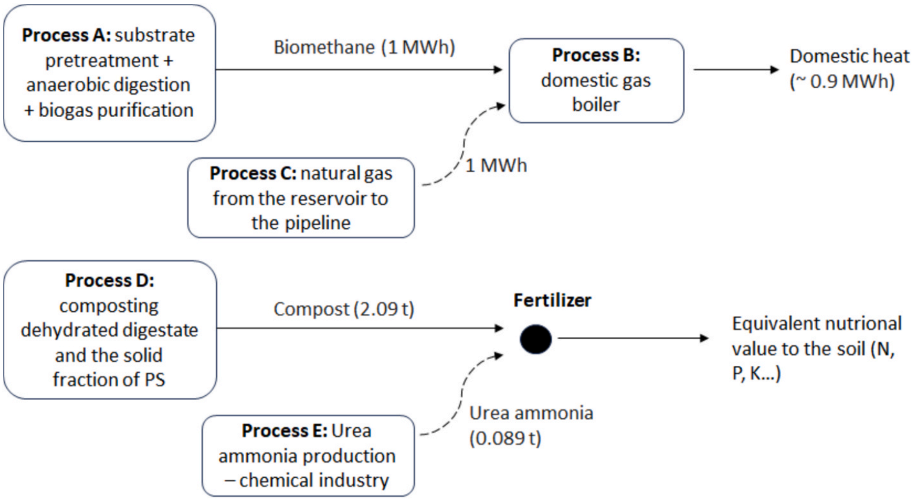

Fig. 1. Mass/energy balance of AD outputs processes and their impact on replacements. Values are normalized per functional unit: 1 MWh of biomethane (LHV basis).

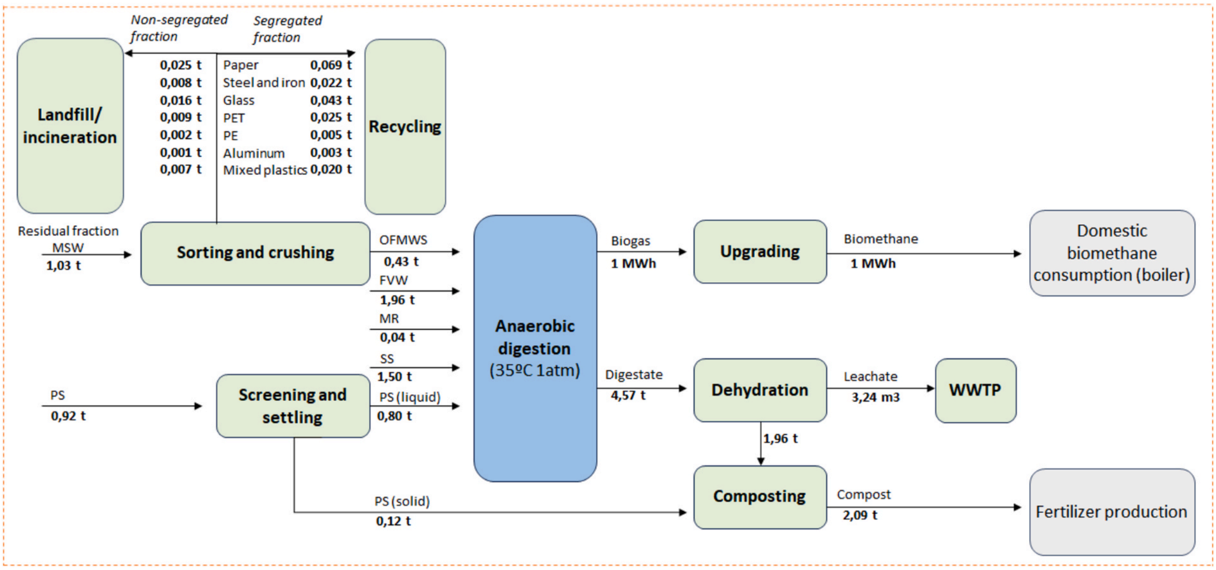

Fig. 2. Mass/energy flow and life cycle assessment system boundary of the biomethane energy community.

The functional unit of the study is 1 MWh of biomethane, which refers to the Lower Heating Value (LHV) produced in the biorefinery. It is crucial to refer to the environmental impact per unit of energy to understand the environmental impact reduction that biomethane consumption offers to the consumer, particularly in the context of decarbonization.

Inventory analysis

Current Scenario:

The inventory of the baseline scenario is depicted in Table 1. The inventory for PS treatment encompasses emissions to air, water, and soil during storage and stabilization periods, as well as the positive effect of avoiding synthetic fertilizer application in the field. These data have been sourced from [8]. The total fraction considered (both solids and liquids) corresponds to a mass proportion of 86.5 % liquid and the remaining solid, maintaining the same ratio as presented in the aforementioned reference.

For SS treatment, the inventory of the fraction that is dehydrated and sent for agricultural use includes the necessary energy and flocculant consumption, emissions associated with spreading on agricultural soil, and the positive effect of fertilization. These data have been obtained from [15]. On the other hand, the fraction sent for composting has been derived from [25]. During the composting process, considerations include energy, water, and flocculant consumption, emissions not captured during composting, and treatment of the residual liquid fraction in the WWTP. This inventory has also been used to model the estimated FVW fractions destined for composting, as well as for the composting stage in the AD plant.

Furthermore, both the OFMWS and the fraction of FVW directed to landfill and incineration are consistent with the municipal waste mix in Ecoinvent for Spain. Regarding avoided outputs, the environmental impact of Urea consumption and heat production in domestic boilers from Ecoinvent has been considered. The equivalent Urea to the compost produced has been considered from [25].

AD Scenario:

In this phase, the consumption of raw materials, energy, and emissions to the atmosphere, water, and soil are quantified for each scenario. The inventory has been compiled partly from literature and partly through predefined processes in Ecoinvent and it is shown in Table 2.

a) Pretreatment: The consumption of electricity and diesel for the separation and pressing process of the residual fraction, and its crushing, is considered. Additionally, water is consumed in the homogenization tank of the mixture. These data have been obtained from [20]. On the other hand, electricity is consumed for the PS pretreatment line for the agitation process during settling and for the pumping system. Moreover, emissions associated with the 3-day pre-storage of the PS are accounted for. Regarding the separation of solid waste, the final recycling treatment for each of the separated fractions is included, while for the mixed components not separated, the usual treatment process in Spain by product type is introduced, namely, landfilling and incineration.
b) Digester: Electrical consumption for heating the digester by electric boiler and water consumption for the homogenization tank, is considered in this process. Emissions associated with the burning of biogas in the flare are also accounted for.
c) Dehydration and composting: Inventory data have been obtained from [25] and weighted for the specific quantity of digestate produced by performing a mass balance between the input mass flow and the output biogas, and the quantity of separated solid PS during settling. During the process, considerations include energy, water, and flocculant consumption, emissions not captured during the composting process, and treatment of the residual liquid fraction in the WWTP.
d) Upgrading: This biogas process has been taken from Ecoinvent and modified to remove the subprocess of biogas and its considered life cycle impact. Similarly, the process of heat production in a biogas boiler has been taken from Ecoinvent, removing the biogas's life cycle impact considered in the process. Additionally, for the purification process, the volume of biomethane needs to be modified to the output conditions of 5 atm in accordance to Ecoinvent-defined process.

Environmental impact assessment

The purpose of the third phase of the eco auditory is to evaluate the inventory to gain deeper insights into its environmental implications. To accomplish this, the impact assessment models select environmental issues, called impact categories, and use category indicators to summarize and explain the inventory results. In this study, a widely recognized midpoint methodology was utilized, specifically the CML-IA implemented in the SimaPro 8.0 software.

Table 1
Life cycle inventory for the current waste management scenario. Values are normalized per functional unit: 1 MWh of biomethane (LHV basis). Emissions and resource consumptions are expressed per flow and categorized by treatment type. Avoided impacts refer to substitution of synthetic fertilizer and natural gas.

Waste treatment current scenario	Flow	Quantity	Unit	Reference
PS storage and field spreading				[8]
Air emissions	Carbon dioxide	6.48	kg	
	Ammonia	4.86	kg	
	Methane	0.46	kg	
	Dinitrogen monoxide	1.99E-2	kg	
	Nitrogen, total	5.92E-2	kg	
	Nitrogen oxides	0.14	kg	
Water emissions	Nitrogen compounds	0.57	kg	
	Phosphorus	0.24	kg	
Soil emissions	Copper	6.48	kg	
	Zinc	50.27	kg	
Avoided products	Inorganic nitrogen fertiliser	−3.2	kg	
SS dehydration and field spreading				[15]
Polyelectrolyte	Aluminium chloride	0.49	kg	
Energy consumption	Electricity	4.86	kWh	
	Diesel	2.01E-2	kg	
Avoided products	Ammonium nitrite	−0.29	kg	
	Single superphosphate	−8.24E-2	kg	
	Potassium chloride	2.66E-2	kg	
Liquid fraction output	Treatment of wastewater	0.79	m3	
Air emissions	Ammonia	0.12	kg	
	Dinitrogen monoxide	5.50E-3	kg	
Water emissions	Cadmium	5.50E-6	kg	
	Chromium	5.50E-4	kg	
	Copper	2.20E-3	kg	
	Mercury	5.50E-6	kg	
	Nickel	1.38E-4	kg	
	Lead	5.50E-4	kg	
	Zinc	2.74E-3	kg	
	Phosphorus	2.74E-2	kg	
Soil emissions	Cadmium	2.74E-5	kg	
	Copper	8.24E-3	kg	
	Mercury	2.74E-5	kg	
	Nickel	5.50E-4	kg	
	Lead	1.93E-3	kg	
	Zinc	1.40E-2	kg	
SS composting				[25]
Water consumption	Fresh water	0.14	m3	
Energy consumption	Electricity	107.03	kWh	
	Diesel	11.35	kg	
Avoided products	Urea	−11.35	kg	
Liquid fraction digestate	Treatment of wastewater	0.34	m3	
Air emissions	Methane	6E-2	kg	
	Ammonia	4.75E-2	kg	
	Particles > 10 µm	0.13	kg	
Water emissions	COD	0.17	kg	
	TOC	5.48E-2	kg	
	Total nitrogen	1.31E-2	kg	
FVW landfilling and incineration	Market for MSW	1.96	ton	Ecoinvent
MSW landfilling and incineration	Market for MSW	1.03	ton	Ecoinvent
Outputs. Avoided products				
Fertilizer	Urea	89.57	kg	
Heat	Natural gas, boiler condensing modulating	1	MWh	

Energy community model

Once the environmental benefits have been analyzed, it is interesting to complement them with an assessment of the economic impact on the energy community. However, first, the structure of the energy community must be understood.

The development of an initiative such as creating an energy community requires a legal entity capable of achieving the proposed objectives. Among the available options, establishing a cooperative is one of the most suitable and successful. Cooperatives have demonstrated their success over time, as their primary objective is not to obtain economic profits, but to benefit the community as a whole. For this reason, many implemented energy community projects have been carried out through REScoops (cooperatives of renewable energy sources) (Alonso Saavedra and Giovannini, 2021).

Collaboration with local authorities is particularly relevant, as they can provide institutional support, facilitate the necessary administrative procedures, and help ensure the stability and viability of the project [9]. Local authorities can promote the hiring of the local energy community to supply energy to public facilities, generating stable income. Additionally, they can be instrumental in obtaining guarantees from financial institutions. Furthermore, local authorities can provide community spaces for the installation of the necessary technology.

Moreover, the project financing approach offers a suitable option for financing given the scarcity of resources in local energy community models, where financing is based on the cash flows generated by the project itself. This financing method may involve the participation of private investors, financial institutions, and development agencies interested in supporting renewable energy projects and obtaining returns from them.

Cost-benefit analysis

To evaluate economic feasibility, a cost-benefit analysis (CBA) was applied in this study, starting with an assessment of the project's cash flow and understanding the profitability margin of the project. Specifically, the Internal Rate of Return (IRR) has been calculated to assess the profitability of an investment. The IRR is defined as the discount rate at which the present value of all future cash flows equals the initial investment, i.e., the rate at which an investment breaks even. The IRR is calculated as the rate of return (r*) for which the following expression holds in equation (1):

$$NPV(r^{*}) = -INV + \sum_{n=0}^{n} \frac{S_n}{(1+r^{*})^{n}} = 0 \tag{1}$$

where Sn is the cash flow balance at year n, r* is the financial discount factor chosen for the discounting at time n, and INV is the investment of the project.

The IRR must be compared with the project's cost of capital (WACC), which is the cost of financing the project through equity and debt. If the WACC is lower than the project's IRR, it means that the investment is generating a return that exceeds the average cost of financing for the company, and therefore the project is creating value for the shareholders.

Furthermore, it is also advisable to ensure that equity contributors, i.e., the energy community, are obtaining a sufficient return to

Table 2
Life cycle inventory for the anaerobic digestion (AD) scenario. All quantities are normalized per functional unit: 1 MWh of biomethane (LHV basis). The table includes resource consumption, emissions to air, water, and soil, and output flows from pretreatment, digestion, composting, and upgrading stages.

	Waste treatment AD scenario	Flow	Quantity	Unit	Reference
	Pretreatment (sorting)				[20]
	Air emissions	Ammonia	3.31E-2	kg	
		Methane	3.24	kg	
	Energy consumption	Diesel	0.90	kg	
		Electricity	22.70	kWh	
	Water consumption	Fresh water	3.31E-2	m3	
	Pretreatment (screening and settling)				[8]
	Air emissions	Carbon dioxide	0.10	kg	
		Methane	0.12	kg	
		Ammonia	6.10E-2	kg	
	Energy consumption	Electricity	0.24	kWh	
Digester	Digester				
	Energy consumption	Electricity	90.81	kWh	
	Water consumption	Fresh water	0.31	m3	
	Outputs. Residual fraction MSW (sorting)				Ecoinvent
	Landfilling/ incineration	Waste paperboard	87.57	kg	
		Waste packing glass, unsorted	29.19	kg	
		Scrap steel	16.22	kg	
		Waste polyethylene terephthalate	29.19	kg	
		Waste polyethylene	6.49	kg	
		Waste aluminum	1.62	kg	
		Waste plastic, mixture	1.62	kg	
	Recycling	Paper	118.39	kg	
		Packing glass	74.59	kg	
		Steel and iron	37.30	kg	
		PET	43.78	kg	
		Mixed plastics	34.05	kg	
		PE	8.11	kg	
		Aluminum	4.86	kg	
	Dehydration and composting				[25]
	Water consumption	Fresh water	1.15	m3	
	Energy consumption	Electricity	132.97	kWh	
		Diesel	4.86	kg	
	Polyelectrolyte	Aluminium chloride	6.49	kg	
	Air emissions	Methane	0.48	kg	
		Ammonia	0.38	kg	
		Particles > 10 µm	1.06	kg	
		MVOC	9.6E-2	kg	
	Water emissions	COD	1.34	kg	
		TOC	0.44	kg	
		Total nitrogen	0.11	kg	
	Liquid fraction digestate	Treatment of wastewater	3.24	m3	
	Upgrading, injection and final consumption				Ecoinvent
	Purification	High pressure, amino washing	1	MWh	
	Heat	Biomethane, boiler condensing modulating	1	MWh	

compensate for the associated risk with their investment. The way to guarantee viability for the energy community is to ensure that the cost of equity is lower than the IRR associated with the cash flows of the investment received by the energy community. These cash flows are the project's cash flows to which the long-term debt loans and the advance of the grant granted by the bank (in the case of the project's start year) are added, and the debt service payments (principal and interest) during all 10 years until the debt service maturity are subtracted.

On the other hand, the providers of financing through debt, i.e., the bank, also assess the risk and interest in getting involved in financing by evaluating the Debt Service Coverage Ratio (DSCR), which assesses the energy community's ability to meet its debt obligations. This ratio is calculated for each year, so it is of interest to evaluate the minimum and average ratios for all years. Ratios greater than 1 are of interest because they indicate that with the project's cash flows, the energy community can meet its financial obligations.

$$DSCR_n = \frac{Availablecashflowfordebtservice(yearn)}{DebtService(yearn)} \tag{2}$$

where the debt service entails the repayment of principal and interest on the long-term bank debt of the unsubsidized investment, along with the payment of interest on the subsidized portion not paid in advance, and the principal once the remaining subsidy is received in the second year. The long-term debt repayment of the unsubsidized investment follows a French amortization method, meaning that the community's instalment payment remains constant each year.

Inputs for the cash flow:

a) 82.4 % of the generated biomethane is allocated for the community's self-sufficiency, while the remainder is sold in a long-term contract in the gas market. To assess the demand that the biomethane plant can meet, a decreasing monotonic curve of gas consumption has been constructed with data related to demand under a regulated tariff in the Spanish Spot market [16] and scaled to an average of 1,808 kWh annually per household [10], assuming an average of 3 persons per household.
b) The CAPEX is set at €2,500/kWh and the OPEX at 4 % of the CAPEX [6]. The plant is amortized over its 30-year assumed lifespan.
c) For the selling price to the gas network, a financial contract for 10 years at a fixed price of €38.6/MWh has been established. This price has been estimated as the average of monthly closing prices of TTF negotiated from the next year 2025 onwards. The selling price will also encompass GO and PoS certificates. The market's willingness to pay for these certificates will vary depending on the sector with which the bilateral contract is established and on the level of carbon footprint reduction achieved. This is particularly relevant for sectors with mandated consumption requirements, such as transportation under the Renewable Energy Directive III (RED III), or those with incentives for consumption through the ETS market.

Moreover, due to the project's funding status, the selling price of the GO certificates will be subject to limitations. The state may conduct regulated auctions to allocate these certificates, akin to the planned European Energy Exchange auctions in France.

d) The sale of captured biogenic CO_2 has not been considered.
e) The selling price of biomethane for self-consumption has been set at €50/MWh.
f) The selling price of compost is assumed to be zero, meaning it will be provided free of charge as fertilizer for the municipality's agricultural lands.
g) It is assumed that the EU approves the granting of economic aid from Next Gen funds, which subsidizes around 60 % of the investment (European [4].
h) Given the financial constraints often faced by energy communities, it is common to request an advance of up to 80 % of the granted subsidy by providing a guarantee as collateral. This measure helps communities to have the necessary resources to carry out their energy projects without compromising their financial capacity in the short term. A grace period of 1 year is established, meaning that during the first year, while the plant is being constructed, there are no cash flows, only interest is paid during this first year, and no principal.
i) It is considered that the loan for the remaining subsidy (not advanced) is received two years after the start of the project.
j) The contribution from the community as equity is considered to be 15 % of the CAPEX.
k) The cost of equity is assumed to be 8 %, suitable for biogas projects [6].
l) A loan with an interest based on the 10-year EURIBOR, plus a margin of 200 bps, is assumed. With current EURIBOR values around 4 %, the interest results in 6 %.

m) Due to the financial limitations faced by energy communities, banks offer advances on subsidies with a term of 2 years, which coincides with the time it takes to deliver the remaining portion of the subsidy. The interest on the advanced subsidy is set at 4.5 %, lower than the usual interest on bank loans, because loans for advance subsidy present less risk of default.

Sensitivity analysis

To assess the robustness of the environmental results and address uncertainty in key model parameters, a One-At-a-Time (OAT) sensitivity analysis was performed. This analysis is consistent with ISO 14040/14044 guidelines, which recommend uncertainty evaluation in comparative life cycle assessments.

Three critical parameters were selected based on their influence on biogas production and environmental impacts:

(i) the carbon-to-nitrogen (C/N) ratio of the feedstock mixture,
(ii) the methane content (% CH_4) in the produced biogas, and
(iii) the proportion of each organic waste stream (e.g., OFMSW, pig slurry, meat residues).

Each parameter was individually varied by ± 10 % and ± 20 % while holding all other parameters constant. The resulting changes in key environmental indicators, particularly the Global Warming Potential (GWP), were evaluated to determine the sensitivity of the model outcomes.

This approach allows identifying the most influential parameters in the anaerobic digestion system and provides insights into the robustness of the proposed energy community model.

Results and discussion

Waste mixture assessment

Based on the available data on total waste, the resulting C/N ratio is calculated to be 21.72 (refer to the Table 3, Scenario: "Total available residue"). While this C/N ratio falls within the previously considered optimal range, the methane richness is only 34 % [19]. To achieve a balance in the C/N ratio and a methane richness exceeding 70 % with the available waste quantity, it would be necessary to substantially reduce the consumption of MR [18]. Despite contributing to a favourable C/N ratio, meat waste provides a methane richness of less than 20 % in proportion to the waste mass. Additionally, minimizing the consumption of PS is advisable since both methane richness and the C/N ratio have values well below the suitable range.

To address this issue without significantly reducing the consumption of these wastes – ultimately aiming to eliminate their baseline impact and maximize biomethane production – it would be necessary to increase the quantity of OFMSW substantially. The table illustrates that to achieve a methane richness of at least 70 % and a C/N ratio equal to 20, nearly 100 times more OFMSW would be required (refer to the table, Scenario: "OFMSW from other municipalities").

Furthermore, the municipality of study is not part of any consortium with other municipalities, meaning there is no formal agreement or association for jointly managing urban waste with other localities. Due to this situation, it is not feasible to obtain urban waste from other consortiums, as each municipality has its own regulations and waste management systems. Additionally, the logistics and transportation of waste can be complex and costly.

Two different scenarios were considered for the project. In scenario 1, a C/N ratio of 20 was prioritized, while in scenario 2, a high methane concentration (≥70 % CH4) was sought. In both cases, the objective was to maximize the utilization of waste, with minimal restrictions on the consumption of meat waste and the liquid fraction of slurries, with set quantities of 0.50 and 10.00 ktons, respectively.

Scenario 2 has been chosen, prioritizing a high concentration of methane (70 % biomethane), as this scenario yields a greater amount of biomethane while utilizing less than a third of the waste compared to scenario 1. Additionally, a C/N ratio of 16 is achieved in this scenario.

Environmental impact analysis

In Fig. 3, each impact category has been normalized with SimaPro to equivalent energy terms to assess the most affected impact categories. Among these, five highly pertinent impact categories were selected for detailed analysis: Four highly pertinent impact categories were selected for detailed analysis: global warming potential (GWP) in ton CO_2-eq Acidification (AC) in ton SO_2, Eutrophization (EF) ton PO_4-, Marine water Ecotoxicity (MWE) in ton 1,4-DB and Fresh Water Ecotoxicity (FWE) in ton 1,4-DB.

The environmental impacts for the aforementioned categories are disaggregated by the main subprocesses of the two scenarios and are

Table 3
Residues inputs, C/N ratio and mono-substrate biomethane production. *In bold the values which have been fixed.

Scenarios	WWTP sludge (kton)	OFMWS (kton)	PS liquid fraction (m^3)	FVW waste (kton)	Meat, offal (kton)	C/N	% CH_4 richness	Biomethane (m^3)
Total available residues	**18.75**	**5.41**	**1.33** $\cdot 10^5$	**24.54**	**7.10**	21.7	34	0.82 $\cdot 10^6$
OFMWS from other municipalities	**18.75**	483	**1.33** $\cdot 10^5$	**24.54**	**7.10**	24.1	**70**	104 $\cdot 10^6$
Scenario 1: C/N 20	**18.75**	**5.41**	1.57$\cdot 10^5$	**24.54**	7.00	**20**	34	0.84 $\cdot 10^6$
Scenario 2: 70 % CH4	**18.75**	**5.41**	**10.00**$\cdot 10^5$	**24.5**	**0.50**	16.0	70	1.41 $\cdot 10^6$

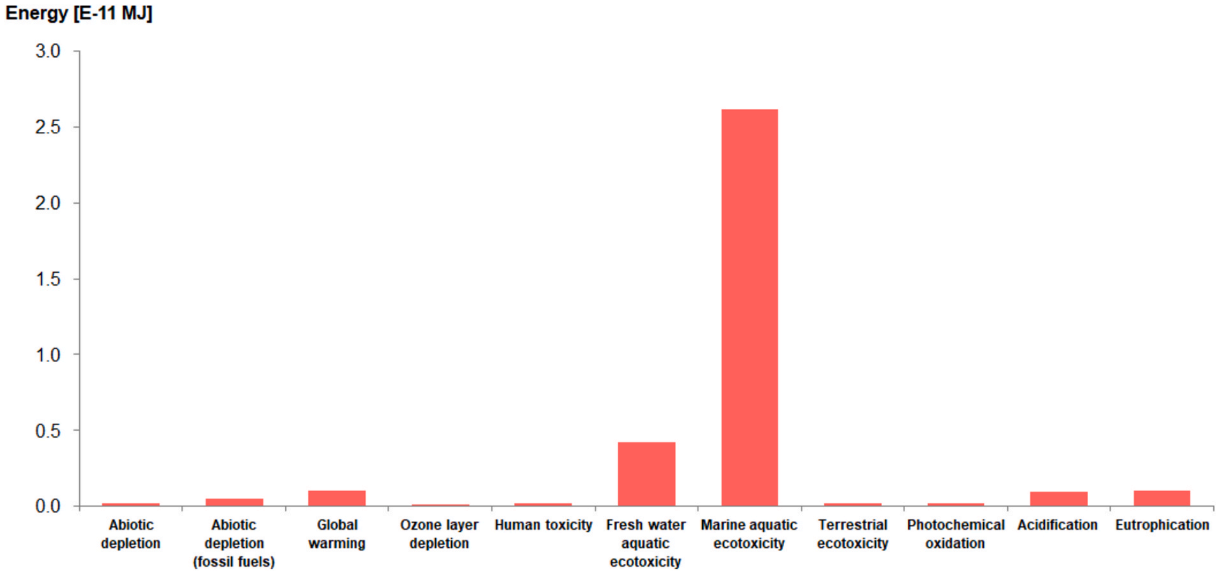

Fig. 3. Environmental impact categories normalized to energy terms.

shown in Table 4 and also illustrated in Fig. 4. These figures depict the contributions (positive or negative) of each process to the total environmental impact of the scenario. According to the results, it is evident that the scenario involving the biorefinery project, which combines the digester, pre-treatments, and composting, demonstrates the best outcomes in each evaluated impact category.

Global warming

The phase involving the separation, pressing, grinding, and homogenization of the OFMWS accounts for the most significant impact in the biorefinery scenario, primarily due to high electricity consumption and emissions during the process, amounting to 0.25 ton CO_2-eq. This is followed by the dehydration and composting stage due to the energy consumption it requires, the lifecycle of aluminium chloride flocculant, and uncollected emissions to air and water. Next is the digester stage due to its high electrical consumption, followed by the purification stage due to electricity consumption and emissions related to raw gas compression, H_2S removal, gas conditioning, and methane enrichment of biogas. Notable impacts in the base cases include the significant avoided impact of 0.29 ton CO_2-eq from not generating heat in domestic gas boilers, primarily due to direct emissions produced during combustion, though also affected by the lifecycle of the natural gas obtained, the mix of which in Spain originates from imports from various countries (in 2021, 75.1 % from Algeria, 20.8 % from Norway, and 4.1 % from Russia). The significant impact of pre-treatment of slurries is noteworthy, amounting to 0.16 ton CO_2-eq, due to considerable emissions to air during long periods of storage for stabilization and during spreading on land, as well as emissions to water and soil. Additionally, noteworthy is the avoided production of urea, derived from ammonia, considered one of the most energy-intensive and emissions-intensive industries. The primary source of emissions in its manufacturing process is the hydrogen production stage through steam methane reforming, which accounts for over 70 % of the process's energy consumption and emits carbon dioxide and carbon monoxide in the process. Finally, there is the impact produced during the pre-treatment of SS and FVW, due to emissions during dehydration and spreading on land, and composting.

From the results obtained, a domestic consumer of biomethane avoids a carbon footprint of 0.25 tons CO_2-eq /MWh, which represents the difference in carbon footprint between the Sc DA and Sc Base scenarios. For a municipal domestic heating consumer, which generates 0.285 tons CO_2-eq /MWh in his natural gas boiler, this represents an 89.0 % carbon abatement.

Table 4
Environmental impact assessment of AD Scenario (Sc AD) and current Scenario (Sc Base). All quantities are normalized per functional unit: 1 MWh of biomethane (LHV basis).

		GWP (ton CO_2-eq)	EP (ton PO_4-eq)	MWE (ton 1,4-DB-eq)	AC (ton SO_2-eq)	FEW (ton 1,4-DB-eq)
Sc AD						
	Pretreatment (sorting)	0.004	6.876E-04	244.825	4.856E-04	0.190
	Pretreatment (screening and settling)	0.250	1.345E-07	0.147	5.884E-07	8.066E-05
	Digester	0.029	4.696E-05	46.032	2.093E-04	0.013
	Dehydration and composting	0.097	3.757E-04	171.653	0.001	0.049
	Upgrading, injection and final consumption	0.015	3.035E-05	21.730	8.624E-05	0.014
Sc Base						
	SS dehydration, field spreading (61.1 % mass) + composting (38.9 % mass)	0.061	2,594E-04	84.163	6.646E-04	0.039
	PS storage and field spreading	0.164	9.774E-04	1,246.579	9.017E-04	6.705
	FVW composting (15 % mass) + landfilling and incineration (85 % mass)	0.028	5,994E-05	112.709	2.191E-04	0.028
	MSW landfilling and incineration	0.001	3.237E-06	47.975	5.303E-07	0.011
	Urea- fertilizer (avoided product)	0.109	1.357E-04	106.579	4.799E-04	0.074
	Domestic heat- natural gas (avoided product)	0.285	4.530E-05	42.716	2.676E-04	0.022

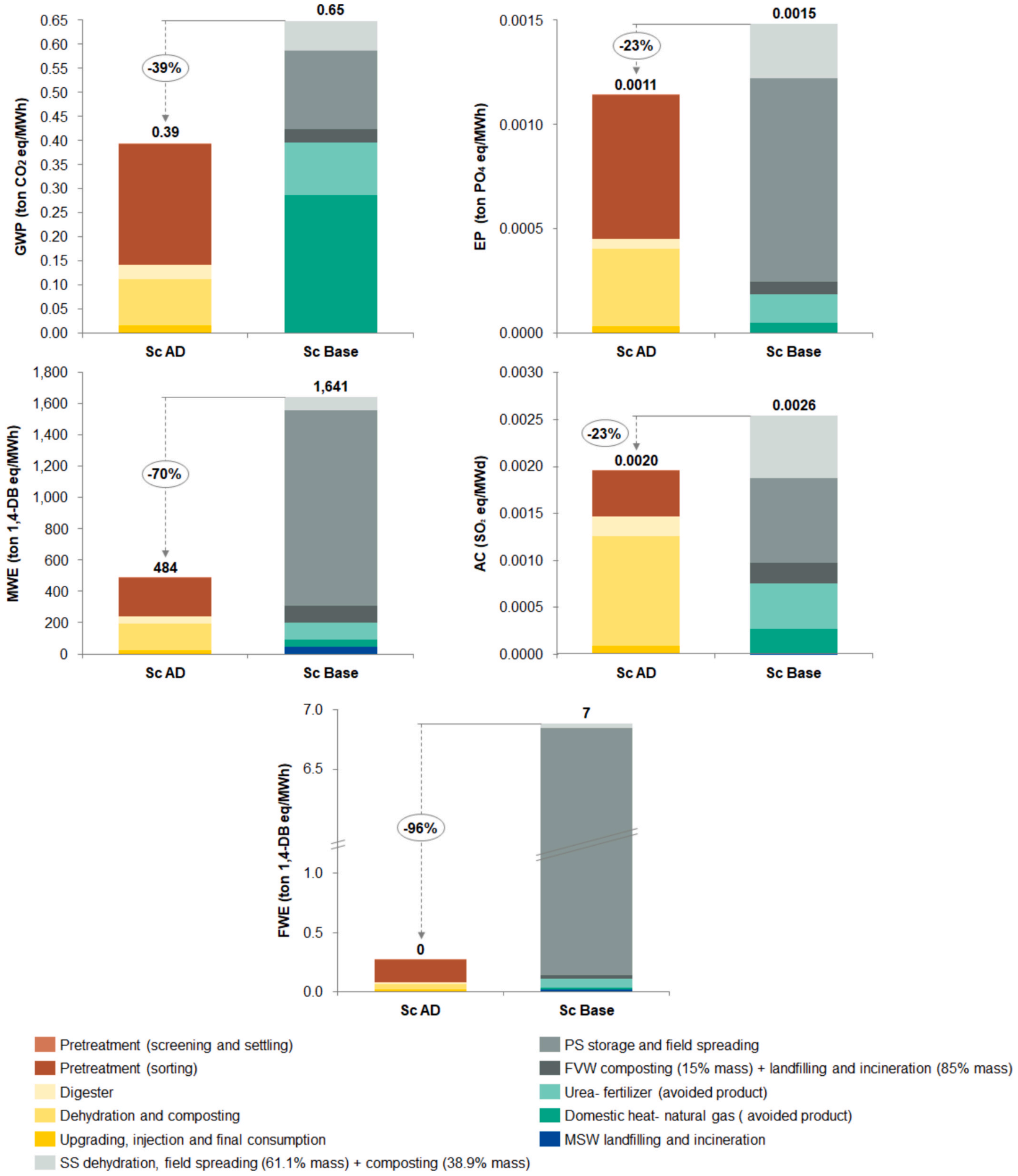

Fig. 4. Comparative environmental impact assessment of AD Scenario (Sc AD) vs current Scenario (Sc Base).

Eutrophization

This category refers to the emission of substances contributing to the formation of nutrients such as nitrogen and phosphorus, which promote abnormal algae growth, affecting the life of aquatic species. In the base case, spreading PS and dehydrated sludge on land are the main sources of emissions (nearly 85 % in eutrophication), affecting air, water, and soil. Phosphorus, ammonia, nitrate, copper, and zinc are the primary factors responsible for eutrophication. Next is the impact produced during the production of synthetic fertilizer (urea) in the chemical industry, originating from ammonia production and having the highest characterization factor in this impact category, thus contributing more to eutrophication. The impact associated with injection into the network is somewhat lower than in the base case; however, emissions related to the disposal and incineration of non-separated residues from the residual fraction, followed by emissions during composting, especially ammonia and its derivatives, make it notable.

Marine water Ecotoxicity

Marine water ecotoxicity refers to the emissions of toxic substances in marine water ecosystems harmful to their species. Earth's natural cycles transport most waste to the sea, through movement generated by wind, rivers, groundwater, and runoff. For this reason, many materials reach the end of their useful life in the sea, negatively affecting this ecosystem. As shown in Fig. 4, the phase of separation of the residual fraction causes the greatest impact, mainly due to the management of non-recyclable waste separated from the residual fraction through landfills or incineration. Leachate infiltration in landfills and emissions to the air from incineration and landfilling, driven by factors such as wind, cause these wastes to be carried away and end up contaminating seas or oceans. Similarly, the composting stage also contributes to marine toxicity generation, due to emissions of substances considered during stabilization. In comparison to the base cases, the impact is reduced to less than a third. The primary cause of impact in the base cases comes from emissions during the four months of PS stabilization and spreading on land, accounting for 77 % of this impact category.

Acidification

This category refers to the emission of acidic gases that, upon contact with cloud water, could cause acid rain precipitation. The gases that most affect are ammonia, nitrogen oxides (NOx), and sulfur oxides (SOx). The main source of impact on acidification is emissions during the composting and pre-treatment phases of the residual fraction, in addition to the electricity consumption for both mentioned process stages and for the digester. Improvement is observed in this category compared to the initial scenario, where the most notable impact during PS treatment should be highlighted, followed by sludge treatment and urea production.

Fresh water aquatic ecotoxicity

This category refers to the emissions of toxic substances in freshwater ecosystems, including rivers, lakes, and streams, and their harmful effects on aquatic life. Freshwater ecosystems are particularly sensitive to pollutants due to their low dilution capacity and high biodiversity, which relies on stable water quality. As shown in Fig. 4, the greatest impact comes from the separation of the residual fraction, mainly due to the management of non-recyclable waste via landfills or incineration. Leachate infiltration and air emissions from these processes contribute to freshwater contamination. Additionally, the composting stage generates freshwater toxicity through the emission of substances during stabilization. Compared to the base cases, the impact is reduced by 96 %. In the base cases, the dominant source of impact stems from emissions during stabilization of PS and subsequent spreading on land, which accounts for 97.5 % of the total impact in this category.

Economic performance

It is observed in Fig. 5 that the initial year yields losses due to the project being in the construction phase, thus yielding no income. During this period, the sole cash inflow is attributed to the advance subsidy. Subsequent years exhibit positive cash flows, resulting in IRR of 17 %, surpassing the WACC of 6.7 %. Moreover, a notable IRR of 29 % is attained, significantly exceeding the equity cost of 8 %. This signifies substantial revenue for the energy community, facilitating potential reductions in gas acquisition costs for community members.

Lastly, it is noteworthy that both the minimum and average DSCR, standing at 1.25 and 1.96 respectively, exceed 1. Consequently, there exists no risk of default or monetary loss for the bank, thereby enhancing the likelihood of loan approval for the entity.

Sensitivity analysis results

The One-At-a-Time (OAT) sensitivity analysis revealed that the methane content in the produced biogas is the most influential parameter on the environmental performance of the system. A ± 20 % variation in methane concentration resulted in an average variation of ± 15 % in the Global Warming Potential (GWP) results.

Changes in the carbon-to-nitrogen (C/N) ratio had a moderate influence: a ± 20 % shift in this parameter led to variations of approximately ± 8 % in GWP, primarily due to its impact on digestion efficiency and digestate quality.

Lastly, varying the contribution of each substrate, particularly the organic fraction of municipal solid waste (OFMSW), also impacted the results. A ± 20 % change in OFMSW input led to GWP changes in the range of ± 6–8 %, highlighting the importance of substrate availability and mixture optimization in rural biogas systems.

These findings indicate that while the model is generally robust, future applications should carefully consider substrate quality and methane yield when replicating or scaling the proposed biomethane energy community.

A summary of the parameters tested, their variations, and corresponding effects on GWP is presented in Table 5, which also indicates the relative sensitivity level of each variable.

Conclusions

This study assessed the environmental and economic feasibility of

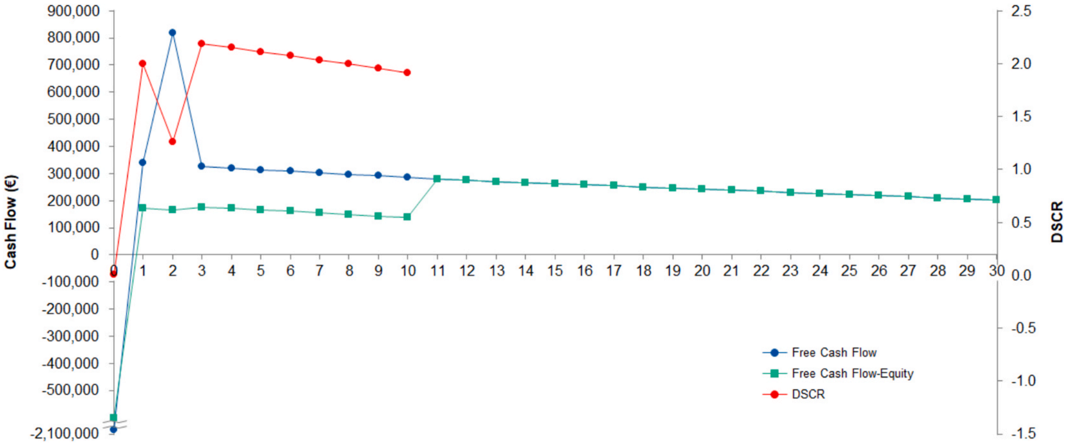

Fig. 5. Economic performance indicators.

Table 5
Summary of tested parameters (methane content, C/N ratio, and OFMWS proportion), their variations, and sensitivity analysis on GWP.

Parameter Modified	Variation Tested	Impact on GWP	Sensitivity Level
Methane content in biogas	±20 %	±15 %	High
Carbon-to-nitrogen (C/N) ratio	±20 %	±8%	Moderate
Proportion of OFMSW in mixture	±20 %	±6-8 %	Moderate

implementing a biomethane-based energy community in a rural municipality in southern Spain, based on the co-digestion of multiple organic waste streams. The results indicate that anaerobic digestion with biomethane injection offers significant environmental benefits compared to the current waste management scenario, particularly in terms of climate change mitigation. Specifically, a reduction of up to 89 % in CO_2-equivalent emissions was achieved, mainly due to the substitution of fossil fuels for domestic heating and synthetic fertilizers in agriculture.

The co-digestion system combined organic fraction of municipal solid waste, sewage sludge, pig slurry, and meat industry residues. This resulted in a balanced carbon-to-nitrogen (C/N) ratio and high methane yield (70 %), supporting stable digestion and efficient upgrading. The proposed system also demonstrated economic viability under a cooperative energy community model, with an internal rate of return (IRR) of 17 % and local energy costs below 40 €/MWh.

A sensitivity analysis was conducted to evaluate the robustness of the environmental results. Methane content in the biogas emerged as the most influential parameter, followed by C/N ratio and the proportion of OFMSW in the mixture. Despite these sensitivities, the overall environmental performance remained positive across the tested ranges.

However, the study presents some limitations. It relies on Ecoinvent 3.0, which may not reflect current background data, and does not include a probabilistic uncertainty analysis. Additionally, the analysis focuses on a single case study, and further work is needed to assess scalability and variability in substrate availability, governance, and energy demand.

Future research should address these limitations by incorporating updated life cycle inventory databases, applying dynamic modeling approaches, and exploring CO_2 capture or valorization strategies to enhance environmental performance. The integration of seasonal fluctuations, behavioral aspects of community participation, and grid injection constraints could also improve the realism and replicability of similar systems.

Overall, the proposed model represents a promising pathway for rural decarbonization under the EU ETS2 framework, providing a replicable framework that supports circular economy principles and community-driven energy transition.

CRediT authorship contribution statement

Pablo Gómez-Sánchez de Rojas: Writing – original draft, Software, Visualization, Investigation. **Javier Victoria-Rodríguez:** Writing – original draft, Supervision, Data curation, Investigation, Visualization. **Carlos Morales-Polo:** Resources, Validation, Project administration, Writing – original draft, Supervision, Conceptualization, Investigation. **María del Mar Cledera-Castro:** Project administration, Supervision, Conceptualization, Writing – original draft, Resources, Investigation, Validation.

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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.

Data availability

Data will be made available on request.

References

[1] Awasthi MK, Sindhu R, Sirohi R, Kumar V, Ahluwalia V, Binod P, et al. Agricultural waste biorefinery development towards circular bioeconomy. Renew Sustain Energy Rev 2022;158:112122. https://doi.org/10.1016/j.rser.2022.112122.

[2] Biresselioglu ME, Limoncuoglu SA, Demir MH, Reichl J, Burgstaller K, Sciullo A, et al. Legal provisions and market conditions for energy communities in Austria, Germany, Greece, Italy, Spain, and Turkey: a comparative assessment. Sustainability 2021;13:11212. https://doi.org/10.3390/su132011212.

[3] European Commision, 2023a. ETS2 : buildings, road transport and additional sectors - European Commission [WWW Document]. URL https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/ets2-buildings-road-transport-and-additional-sectors_en (accessed 4.1.24).

[4] European Commision, 2023b. What is the Innovation Fund? - European Commission [WWW Document]. URL https://climate.ec.europa.eu/eu-action/eu-funding-climate-action/innovation-fund/what-innovation-fund_en (accessed 4.1.24).

[5] European Commision, 2022. Energy communities [WWW Document]. URL https://energy.ec.europa.eu/topics/markets-and-consumers/energy-communities_en (accessed 4.1.24).

[6] Fraunhofer ISE, 2018. Levelized cost of electricity renewable energy technologies.

[7] Hakawati R, Smyth BM, McCullough G, De Rosa F, Rooney D. What is the most energy efficient route for biogas utilization: Heat, electricity or transport? Appl Energy 2017;206:1076–87. https://doi.org/10.1016/j.apenergy.2017.08.068.

[8] Hollas CE, Bolsan AC, Chini A, Venturin B, Bonassa G, Cândido D, et al. Effects of swine manure storage time on solid-liquid separation and biogas production: a life-cycle assessment approach. Renew Sustain Energy Rev 2021;150:111472. https://doi.org/10.1016/j.rser.2021.111472.

[9] Iazzolino G, Sorrentino N, Menniti D, Pinnarelli A, De Carolis M, Mendicino L. Energy communities and key features emerged from business models review. Energy Policy 2022;165:112929. https://doi.org/10.1016/j.enpol.2022.112929.

[10] IDAE, 2022. Consumos del Sector Residencial en España [WWW Document]. URL https://www.idae.es/uploads/documentos/documentos_Documentacion_Basica_Residencial_Unido_c93da537.pdf.

[11] Jiang Y, Zhang Y, Wang S, Wang Z, Liu Y, Hu Z, et al. Improved environmental sustainability and bioenergy recovery through pig manure and food waste on-farm co-digestion in Ireland. J Clean Prod 2021;280:125034. https://doi.org/10.1016/j.jclepro.2020.125034.

[12] Karki R, Chuenchart W, Surendra KC, Shrestha S, Raskin L, Sung S, et al. Anaerobic co-digestion: current status and perspectives. Bioresour Technol 2021;330:125001. https://doi.org/10.1016/j.biortech.2021.125001.

[13] Karolinczak B, Walczak J, Bogacka M, Zubrowska-Sudol M. Life Cycle Assessment of sewage sludge mono-digestion and co-digestion with the organic fraction of municipal solid waste at a wastewater treatment plant. Sci Total Environ 2024;907:167801. https://doi.org/10.1016/j.scitotenv.2023.167801.

[14] Ladan HM, Ijah UJJ, Baba J. Conversion of Biogas from Municipal Solid Waste of Kaduna State to Bio-methane. UMYU J Microbiol Res (UJMR) 2023;8:90–100.

[15] Lombardi L, Nocita C, Bettazzi E, Fibbi D, Carnevale E. Environmental comparison of alternative treatments for sewage sludge: an Italian case study. Waste Manag 2017;69:365–76. https://doi.org/10.1016/j.wasman.2017.08.040.

[16] MIBGAS, 2022. Ficheros anuales consumo gas natural. 2022 [WWW Document]. URL https://www.mibgas.es/es/file-access?path=AGNO_2022/XLS.

[17] Montejo C, Tonini D, del C. Márquez M, Fruergaard Astrup T. Mechanical–biological treatment: performance and potentials. An LCA of 8 MBT plants including waste characterization. J Environ Manage 2013;128:661–73. https://doi.org/10.1016/j.jenvman.2013.05.063.

[18] Morales-Polo C, del M. Cledera-Castro M, Hueso-Kortekaas K, Revuelta-Aramburu M. Anaerobic digestion in wastewater reactors of separated organic fractions from wholesale markets waste. Compositional and batch characterization. Energy environmental feasibility. Sci. Total Environ. 2020;726:138567.. https://doi.org/10.1016/j.scitotenv.2020.138567.

[19] Morales-Polo C, del M. Cledera-Castro M, Revuelta-Aramburu M, Hueso-Kortekaas K. Anaerobic digestion of organic fraction combinations from food waste, for an optimal dynamic release of biogas, using H2 as an indicator. Sci Total Environ 2023;857:159727. https://doi.org/10.1016/j.scitotenv.2022.159727.

[20] Morero B, Vicentin R, Campanella EA. Assessment of biogas production in Argentina from co-digestion of sludge and municipal solid waste. Waste Manag 2017;61:195–205. https://doi.org/10.1016/j.wasman.2016.11.033.

[21] Noussan M, Negro V, Prussi M, Chiaramonti D. The potential role of biomethane for the decarbonization of transport: an analysis of 2030 scenarios in Italy. Appl Energy 2024;355:122322. https://doi.org/10.1016/j.apenergy.2023.122322.

[22] Otamendi-Irizar I, Grijalba O, Arias A, Pennese C, Hernández R. How can local energy communities promote sustainable development in European cities? Energy Res Soc Sci 2022;84:102363. https://doi.org/10.1016/j.erss.2021.102363.

[23] Pasciucco F, Francini G, Pecorini I, Baccioli A, Lombardi L, Ferrari L. Valorization of biogas from the anaerobic co-treatment of sewage sludge and organic waste: Life cycle assessment and life cycle costing of different recovery strategies. J Clean Prod 2023;401:136762. https://doi.org/10.1016/j.jclepro.2023.136762.

[24] Pototschnig A, Conti I. Renewable support schemes and Guarantees of Origin applied to renewable energy regulation. In: Law in the EU's Circular Energy System. Edward Elgar Publishing; 2023. p. 239–60.

[25] Righi S, Oliviero L, Pedrini M, Buscaroli A, Della Casa C. Life Cycle Assessment of management systems for sewage sludge and food waste: centralized and decentralized approaches. J Clean Prod 2013;44:8–17. https://doi.org/10.1016/j.jclepro.2012.12.004.

[26] Yellezuome D, Zhu X, Wang Z, Liu R. Mitigation of ammonia inhibition in anaerobic digestion of nitrogen-rich substrates for biogas production by ammonia stripping: a review. Renew Sustain Energy Rev 2022;157:112043. https://doi.org/10.1016/j.rser.2021.112043.

[27] Yue X, Deane JP, O'Gallachoir B, Rogan F. Identifying decarbonisation opportunities using marginal abatement cost curves and energy system scenario ensembles. Appl Energy 2020;276:115456. https://doi.org/10.1016/j.apenergy.2020.115456.

[28] Zhou L, Guo F, Pan S, Lu B, Du L, Wei Y. Synergistic digestion of banana pseudo-stems with chicken manure to improve methane production: Semi-continuous manipulation and microbial community analysis. Bioresour Technol 2021;328:124851. https://doi.org/10.1016/j.biortech.2021.124851.