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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

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ABSTRACT

Nowadays, biogas produced from the anaerobic digestion of biowaste is considered a valuable renewable energy source to implement the transition to a climate-neutral society. Recently, biogas upgrading to biomethane, instead of the usual co-generation of heat and electricity (CHP), has been an attractive option, as biomethane can be used for different purposes. This study performed the life cycle assessment (LCA) and life cycle costing (LCC) of different scenarios for the valorization of the biogas produced from the anaerobic co-digestion (AcoD) of secondary sewage sludge (SS) and organic fraction of municipal solid waste (OFMSW), pre-treated by an anaerobic dark co-fermentation (DF) process. Four configurations were compared, exploring the recovery of one or more of the following: heat, electricity and biomethane. Furthermore, two sensitivity analyses were performed on LCA analysis, considering the use of the produced biomethane as a fuel for transport and the European electricity mix expected by 2050, respectively. The use of biogas for CHP was the most environmentally friendly solutions in 8 out of 11 impact categories provided by the CML-IA baseline method; however, biogas upgrading-based scenarios showed less impacts in relevant categories, such as global warming potential (up to −1.14E+05 kg CO_2 eq. y^{-1}) and ozone layer depletion potential (up to −4.73E-01 kg CFC-11 eq. y^{-1}). Sensitivity analyses confirmed that the biogas upgrading processes should have generally a lower impact on climate change than CHP systems. Furthermore, the use of biomethane to replace petrol resulted to be the best option in terms of global warming potential (up to −5.67E+05 kg CO_2 eq. y^{-1}). All the proposed configurations represented economically sustainable projects, as they reported positive net present values (NPV) in 20 years (up to 10,518,291 €). Biogas upgrading-based scenarios showed the highest NPVs; nevertheless, the combined production of heat, electricity and biomethane was the most cost-effective option, thanks to biomethane revenues and electricity sales, despite the latter being modest. In conclusion, contrary to most of the previous studies in the literature, we found that CHP should not be neglected, as the optimal configuration may lie in the combined recovery of biomethane, electricity and heat.

1. Introduction

Nowadays, decarbonization is at the heart of sustainable development strategies worldwide (Herc et al., 2022). In particular, the European Union has strongly encouraged the use of renewable energy sources, and has set important goals to be achieved progressively. The first step is to reduce net GHG emissions by at least 55% by 2030, compared to the levels detected in 1990 (European Commission, 2019).

In this context, wastewater treatment plants (WWTPs) represent a way forward to circular economy (Pasciucco et al., 2022), due to the current paradigm shift towards systems that promote resource recovery, and bioenergy production from biowaste could play a key role towards system sustainability (Jain et al., 2022).

Compared to other biological and thermochemical conversion

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treatments, anaerobic digestion technology shows the most efficient energy input/output ratio (Wang et al., 2021). It is commonly used to perform biomass stabilization and co-generation of heat and electricity (CHP) from the combustion of the biogas produced during the process (Bhatia et al., 2018). Biogas is a mixture composed mainly of methane (55–65%), which make it a valuable energy source, and carbon dioxide (Khawer et al., 2022). Carbon content of biogas comes from organic waste, which in turn can derive from the CO_2 already present in the atmosphere; therefore, biogas can be defined as a carbon-neutral and renewable source of energy (Awe et al., 2017). The use of biogas as a fuel for CHP is a well-known strategy, and is the subject of continuous development by researchers (Baccioli et al., 2018).

Recently, biomethane production thorough biogas upgrading processes has gained a lot of interest. The main issues for biomethane production concern the removal of impurities (e.g., H_2S and siloxanes) and CO_2 from biogas. Because of that, there are many technologies for biogas upgrading to biomethane, showing pro and cons (Lombardi and Francini, 2020). Anyway, many European countries have provided government incentives to promote biogas upgrading (Baena-Moreno et al., 2020), as biomethane can be used for various purposes (Khan et al., 2021). For instance, Ferreira et al. (2019) compared the life cycle environmental impacts of the end-use of biomethane in ovens for cooking, light-duty vehicles for transportation and heavy-duty vehicles for work.

Many studies compared the processes of biomethane production and power generation from the anaerobic digestion of biowaste. In this regard, life cycle assessment (LCA) (Ding et al., 2021) and life cycle costing (LCC) (Ilyas et al., 2021) have widely applied, in order to evaluate the environmental and economic impacts, respectively, occurring during the entire life cycle of the process (Visentin et al., 2020). Venkatesh and Elmi (2013) proposed a systematic economic and environmental analysis to assess various options for the use of the biogas produced from the thermophilic anaerobic digestion of sewage sludge in a large-scale WWTP. According to the authors, the preferred solutions were those that converted over 75% of the biogas to transportation fuel. Ardolino et al. (2018) used LCA to compare biomethane production and CHP from the anaerobic digestion of organic waste, stating that the production of biomethane for road transport was always cleaner than the production of energy. Alengebawy et al. (2022) carried out a comparative LCA to evaluate three biogas utilization scenarios, finding that emission savings were achieved by the upgrading scenario in 8 out of 10 analyzed impact categories. Colzi Lopes et al. (2018) conducted an energy balance and LCA focusing on two alternative uses of the biogas produced from the anaerobic co-digestion of pre-treated microalgal biomass and primary sludge in a medium-scale WWTP. Contrary to the above cited studies, the authors declared that the preference for a specific scenario depended on the impact categories prioritized by decision-makers.

Nevertheless, biowaste management includes several treatment options; therefore, recovery strategies from biowaste require further investigation. This study performed the LCA and LCC of different scenarios for the valorization of the biogas produced from the anaerobic co-digestion (AcoD) of secondary sewage sludge (SS) and organic fraction of municipal solid waste (OFMSW), pre-treated by an anaerobic dark co-fermentation (DF) process. In particular, four configurations were compared, exploring the recovery of one or more of the following: heat, electricity and biomethane.

SS is often characterized by low organic loads, leading to poor biogas production (Cavinato et al., 2013). AcoD of SS with food waste is a popular solution to supply higher biodegradable organic loads (Pecorini et al., 2012). In recent years, the techniques of sludge pretreatment have been widely tested, as they generally improve biosolid disintegration (Uthirakrishnan et al., 2022). In turn, DF can be considered as a pre-treatment (Ghimire et al., 2015). The process of anaerobic dark fermentation favors the conversion of organic molecules into easily assimilable compounds, in particular volatile fatty acids (VFA), (Perez-Esteban et al., 2022), enhancing substrate degradation (Fang et al., 2020); however, the efficiency of the process depends on several parameters, especially the pH (Baldi et al., 2019).

In authors' knowledge, no previous studies conducted an LCA and LCC analysis on different management options of the biogas produced from the anaerobic co-treatment of SS and organic waste.

2. Materials and methods

An LCA was performed for this study, according to the LCA steps standardized by ISO 14040 (International Standard Organisation 2006a; 2006) and 14,044 (International Standard Organisation, 2006, 2006b, 2006): goal and scope definition, life cycle inventory analysis, life cycle impact assessment and interpretation. Specifically, an attributional LCA was conducted, focusing on the environmentally relevant flows to/from the investigated systems (Ardolino et al., 2018).

A financial analysis was carried out by a conventional LCC. Compared to a techno-economic analysis (TEA), LCC generally does not provide technological assessments, and was chosen for an integrated environmental and economic life cycle evaluation (Mahmud et al., 2021). The first two LCA steps represented the basis of the LCC study, while the third step was replaced by the economic analysis, computing the net present value (NPV) and the internal rate of return (IRR) of the projects.

2.1. Goal and scope definition

The goal of this study was to evaluate, from an environmental and economic point of view, the best strategy for the valorization of the biogas produced from the anaerobic co-treatment of SS, generated by the nearby WWTP (primary sedimentation is not planned), and source sorted OFMSW, which arises from the door-to-door collection carried out in the municipality served by the study case facility.

The reference plant is located in central Italy (Tuscany), and consists of the following treatment sections: i) pretreatment of SS and OFMSW, ii) mesophilic DF of the substrates followed by the iii) mesophilic AcoD of the DF residues, iv) biomethane/energy recovery from the biofuels produced by the processes of DF and AcoD (i.e., H_2-rich gas and biogas, respectively), and v) dewatering treatment of the AcoD residues. In particular, four different scenarios were investigated (Fig. 1):

- Scenario 1 (Reference Scenario): biogas and H_2-rich gas are mixed together and burned in an internal combustion engine (ICE), thus cogenerating heat and electricity.
- Scenario 2: 81% of the produced biogas undergoes an upgrading process to biomethane, while the remaining part of biogas and the H_2-rich gas are burned in an ICE, thus cogenerating heat and electricity.
- Scenario 3: 90% of the produced biogas undergoes an upgrading process to biomethane, while the remaining part of biogas and the H_2-rich gas are burned in a boiler, thus generating heat.
- Scenario 4: 100% of the produced biogas undergoes an upgrading process to biomethane, while the H_2-rich gas is burned together with methane from network in a boiler, thus generating heat.

Scenario 1 and Scenario 4 represent the two extreme conditions, in which all the produced biogas is used for CHP or biomethane production, respectively. Conversely, the percentages of biogas sent to the ICE, in Scenario 2, or boiler, in Scenario 3, correspond to the amount needed to maintain the digester temperature at 37 °C, based on mass and energy balances.

System boundaries included all the flows of materials, chemicals, energy and transports involved in the treatment stages and recovery processes carried out, comprising the aerobic composting of dry digestate to an external plant and landfilling of waste generated during the pre-treatment step (Fig. 1). In addition, system boundaries were expanded to consider avoided impacts associated with material and

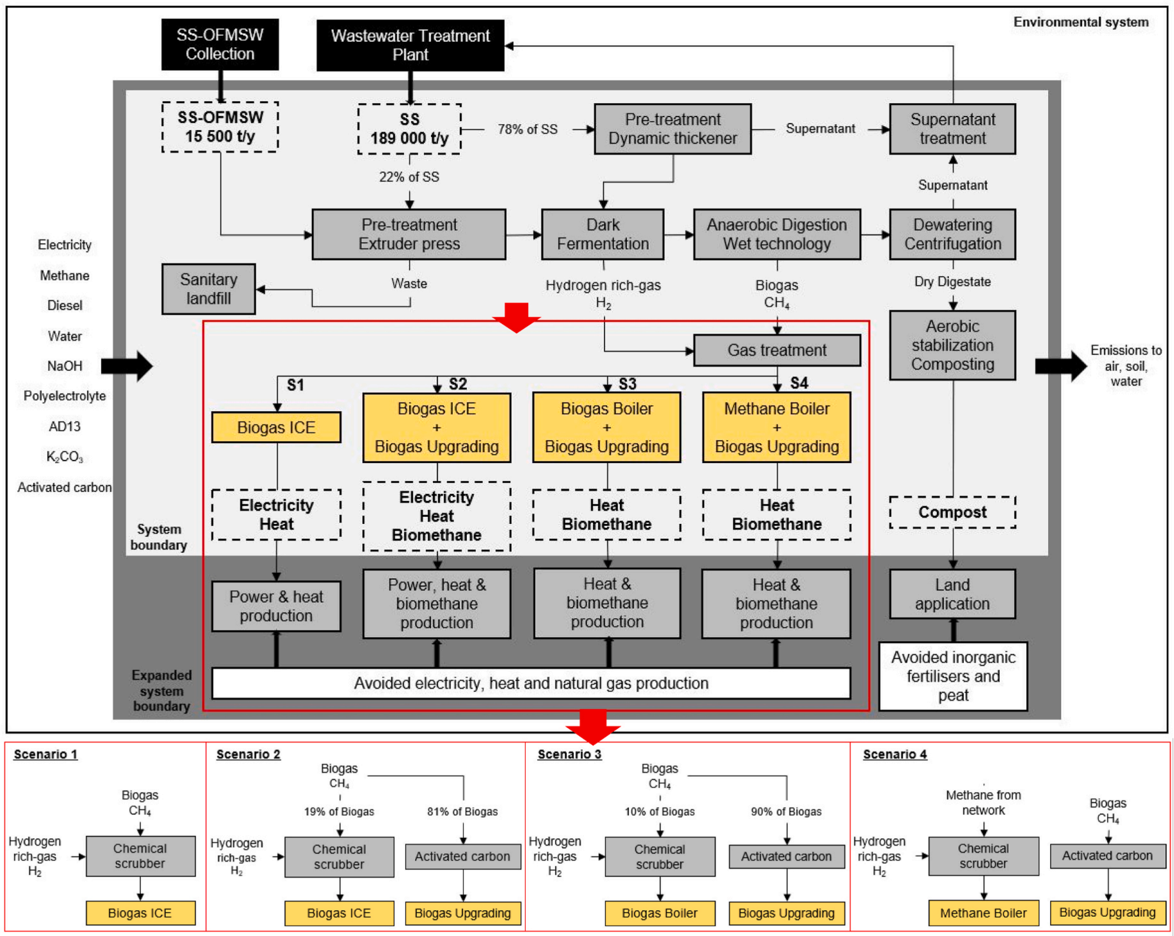

Fig. 1. System boundaries and investigated scenarios.

energy recovered, which were considered as equivalent substitutes for conventional products (Cornejo et al., 2016).

Stuck emissions due to the combustion of biofuels and air emissions due to the composting process were also included; however, CO_2 emissions from these processes were assumed to be of biogenic origin and were not considered, as they should not contribute to global warming (Evangelisti et al., 2017). The treatment of the supernatants produced during the pre-treatment and dewatering stages was accounted for. It should be noted that the supernatants are recirculated to the top of the WWTP once treated; however, their eventual contribution to SS in terms of nutrients was excluded from the study.

Processes due to the construction and decommissioning phases of the WWTP, machinery and equipment were not included, since it has been proven that the potential environmental impacts associated with these phases can be considered negligible compared to the operational steps (Arias et al., 2020).

The annual amount of treated waste was adopted as functional unit (FU). Mass-related units are the most used FUs in LCA waste management studies (Mulya et al., 2022). Specifically, in the study case facility, 189,000 t/y of SS and 15,500 t/y of OFMSW are processed, based on design data (year 2017). Table 1 shows the main characteristics of waste. As reported, the average composition of OFMSW shows the presence of undesired fractions; however, it is consistent with other Italian case studies (Micolucci et al., 2018). After the pretreatments, the SS and OFMSW are mixed in order to achieve a total solid (TS) content of 6.5%, thus obtaining a suitable consistency for mesophilic wet anaerobic reactors and a daily ratio of TS between OFMSW and SS ratio equal to 80:20, which is recognized as an optimal ratio for both co-fermentation and co-digestion processes (Tyagi et al., 2018).

Table 1
Properties of the SS and OFMSW treated.

Parameter	Unit	Value	Reference
Properties of SS			
TS content	% w/w	0.70	*
Total volatile solids (TVS) content	% TS	70	*
Properties of OFMSW			
TS content	% w/w	24	*
TVS content	% TS	78	*
Average composition of OFMSW			
Food and organic waste	%	88	*
Green waste	%	6.5	*
Plastic waste	%	3	*
Paper/cardboard waste	%	2	*
Metal waste	%	0.15	*
Inert and glass	%	0.35	*

*Provided by the study case facility.

Concerning the LCC, a conventional analysis was performed. Conventional LCC is based on purely economic evaluation and includes various costs associated with the life cycle of a product. In general, the analysis is carried out by the perspective of a single actor, which is often the producer or the user (Ilyas et al., 2021). Only internal costs are considered, which refer to the direct monetized costs (such as planning, construction, management, maintenance, disposal) for a person or company undertaking an activity (Ilyas et al., 2021).

Because of the above, the investment, operating, maintenance and disposal costs associated with the activities included within the system boundaries were taken into account. Cost data was provided by the study case facility and processed by a calculation software. On the other hand, external costs refer to the economic concept of uncompensated social or environmental effects (such as the cost of healthcare due to pollutant emissions), and were excluded from the analysis, as they are generally included in the environmental LCC (Ilyas et al., 2021).

Finally, two sensitivity analyses were performed. In the first analysis, named sensitivity analysis 1, different uses of the recovered biomethane were explored. In the second analysis, named sensitivity analysis 2, the default LCA study was carried out considering the future composition of the European electricity mix, expected by 2050.

2.2. Inventory analysis

In inventory analysis, every input and output of the system were collected, according to the adopted FU, in order to describe each quantitative flow within the system boundary both in terms of materials and energy. Foreground data was site-specific where possible, provided by the company in charge of the WWTP; alternatively, data retrieved from the literature and experimental laboratory tests on the concerned substrates were used (Francini et al., 2019). Backgorund data were collected from the ecoinvent 3.8 database, which is currently the most up-to-date version of the database.

2.2.1. Waste treatment

Fig. 1 shows the treatment plant of the two specific substrates. Initially, the OFMSW is pre-treated by an extruder press, able to separate materials such as plastics, paper, metals and inert that could affect the following DF process. OFMSW handling is possible through the use of specific vehicles fuelled by diesel, assuming 1.1 L/t OFMSW (provided by the study case facility). A subsequent refining step, with a fraction of the incoming SS (22%), remove possible plastics and inert still in the biodegradable sludgy flow coming from the extruder press. At the end of the OFMSW pretreatment line, sludgy flow TS is equal to 7%.

The wastes generated from the pretreatment of OFMSW (20% of the incoming OFMSW) are disposed of to landfill. The wastes composition was directly provided by the plant and it is: paper and cardboard (7%), green and food waste (65%), glass and inert (3.5%), plastics (23.5%) and metals (1%). The final disposal of each material is modelled with a specific ecoinvent record, leaving out the system boundaries the electricity production from the collected biogas. A distance of 80 km was assumed between the landfill and the study case facility.

The incoming SS is divided into two flows (Fig. 1): 78% of the SS is fed to a dynamic thickener and 22% of the SS is mixed with OFMSW for the refining step, previously described. Polyelectrolyte consumption equal to 5 g per kg_{TS} of incoming SS was assumed for the thickening step. At the end of the SS pretreatment line, TS is equal to 5%.

The following DF process receives the sludgy flow by the OFMSW pretreatment refining step and thickened SS. The specific hydrogen production (SHP) for the DF process was assumed from laboratory tests on the described mixture (Baldi et al., 2019), and it is reported in Table 2. The DF step produce a liquid/solid output substrate fed to an AcoD process, whose specific gas productions (SGPs) were assumed from laboratory experiments on the substrates (Baldi et al., 2019) (reported in Table 2).

DF process is mainly affected by environmental factors such as temperature and pH, which should be maintained in a given range of values (5–6) for an optimal H_2-rich gas production. Indeed, DF process can lead to an accumulation of volatile fatty acids (VFA), due to the high loads involved, increasing the acidity of the substrates (Micolucci et al., 2014). When pH value drops below 5, DF process is driven by fermentative metabolism and the production of hydrogen is disadvantaged; therefore, it was assumed that 20% of the digestate from AcoD is recirculated to the head of the DF process, in order to exploit the residual buffer capacity of the digestate and avoid the use of chemicals for pH control (Micolucci et al., 2014).

The digestate from the AcoD process is treated by a dewatering

Table 2
Inventory data of the DF and AcoD processes.

Parameter	Unit	Value	Reference
DF			
Feeding ratio	t SS/t sludgy flow	0.34	*
TS content	%	6.5	*
Reactor volume	m^3	300	*
Hydraulic Retention Time	Days	1.5	*
Specific Gas Production	$Nm^3_{H2\text{-rich gas}}/kg_{TVS}$	0.062	(F. Baldi et al., 2019)
Specific Hydrogen Production	Nm^3_{H2}/kg_{TVS}	0.012	(F. Baldi et al., 2019)
Organic Loading Rate	kg_{TVS}/m^3d	32.5	*
H_2-rich gas production	Nm^3/year	221,457	*
H_2-rich gas composition	%	$H_2 = 20.2$; $H_2S = 0.04$; $CO_2 = 79.76$	(F. Baldi et al., 2019)
Lower Heating Value	kJ/Nm^3	2,182	*
AcoD			
Reactor volume	m^3	4,500	*
Hydraulic Retention Time	days	22.75	*
Specific Gas Production	Nm^3_{biogas}/kg_{TVS}	0.668	(F. Baldi et al., 2019)
Specific Methane Production	Nm^3_{CH4}/kg_{TVS}	0.488	(F. Baldi et al., 2019)
Organic Loading Rate	kg_{TVS}/m^3d	2.00	*
Biogas production	Nm^3/year	2,151,633	*
Biogas composition	%	$CH_4 = 73.1$; $CO_2 = 26$; $H_2S = 0.03$; $H_2O = 0.87$	(F. Baldi et al., 2019)
Lower Heating Value	kJ/Nm^3	25,746	*
TS of digestate	%	2.85	*

*Provided by the study case facility.

process through a centrifugation step able to increase the TS content of the digestate up to 25%. Polyelectrolyte consumption equal to 11 g per kg_{TS} of digestate was assumed for this process. A supernatant with phosphate and nitrogen content is produced by the thickening and dewatering processes. The supernatant is fed to the WWTP oxidation tank and it was modelled with the proper ecoinvent process.

Finally, the dry digestate is aerobically bio-stabilized in a composting process through enclosed vessel biocells with a specific compost production equal to 0.39 $kg_{compost}$ per kg of digestate (Bustamante et al., 2012). The composting specific consumption was assumed equal to 38 kWh/t of treated digestate (Bernstad & La Cour Jansen, 2012). A distance of 270 km was assumed between the composting plant and the study case facility. A biofiltration step is provided for the exhaust air from composting reactors; however, N_2O and CH_4 emissions equal to 0.1 kg/t OFMSW and 0.025 kg/t OFMSW were assumed, respectively (Boldrin et al., 2009). In a composting process, a lignocellulosic waste is required as structuring materials, in order to allow the appropriate aeration to the composting process; nevertheless, this aspect was not included in the system. In any case, they are supposed to be composted with or without digestate. According to data retrieved from the study case facility, the water consumption of the whole plant was assumed equal to 0.02 m^3/t of waste treated (incoming SS + incoming OFMSW).

2.2.2. Biogas valorization scenarios

The energy recovery from biofuels changes according to the considered scenario. Incondensable gas such as O_2, N_2, H_2, predominantly remain in biomethane after the upgrading process. That’s why H_2-rich gas from DF is always fed to boiler or ICE, in order to respect the Italian regulatory limits on the biomethane composition after the biogas upgrading process.

H_2-rich gas and biogas, before being supplied to a boiler or an ICE, are treated into a chemical scrubber using NaOH and a mixture of iron trichloride, water, carboxylic acids called AD13 in order to absorb contaminants such as H_2S. The NaOH and AD13 consumptions were assumed respectively equal to 0.59 g/Nm^3 and 1.76 g/Nm^3 of incoming gas. Differently, H_2S removal through activated carbon (800 kg/year every 100 ppm of H_2S contained in the biogas) was considered before the biogas upgrading process. A landfill disposal with the proper ecoinvent process was assumed for the exhausted activated carbon.

According to EPA (U.S. Environmental Protection Agency, 1995b), the flue emissions for the boiler were assumed equal to 1.60E-03 kg NO_x/Nm^3, 1.34E-03 kg CO/Nm^3, 1.22E-04 kg PM/Nm^3, 8.80E-05 kg VOC/Nm^3 of CH_4 within the entering biogas. The flue emissions for the ICE were assumed equal to 5.00E-04 kg NO_x/Nm^3 (Jenbacher, n.d.), 8.29E-04 kg CO/Nm^3 (Carnevale and Lombardi, 2015), 1.91E-04 kg PM/Nm^3 (Carnevale and Lombardi, 2015), 1.16E-03 kg VOC/Nm^3 (U.S. Environmental Protection Agency, 1995a) of entering biogas. Natural gas combustion implies a CO_2 emission equal to 2.75 kg CO_2/kgCH_4 (stoichiometric factor). H_2S content entering the energy recovery device implies a SO_2 emissions equal to 1.88 kg SO_2/kgH_2S (stoichiometric factor).

The biogas upgrading process is made through a chemical absorption with an aqueous solution with 30% of K_2CO_3 by weight. After the H_2S and H_2O removal, the biogas is fed in an absorption column where it is washed by the K_2CO_3 solution, in order to separate CO_2 from the biogas. A consumption of 0.12 kg water/Nm^3 biogas was assumed for the upgrading process. Very limited CH_4 losses, equal to 0.038% of CH_4 in the entering biogas, characterize this upgrading technique. A waste-water equal to 0.07 kg/Nm^3 biogas is produced by the upgrading processes.

The layout configuration and energy balance of the investigated scenarios are described below. Mass and energy balances for each component were computed as shown in supplementary material. The multifunctionality of the systems was solved by the expansion of the systems; thus, the obtained products were considered equivalent substitutes for commercial products (avoided impacts) and were allocated as reported in supplementary material.

2.2.2.1. Scenario 1. In the first scenario, all the biogas and hydrogen produced was sent to an internal combustion engine to produce electricity and heat for the digestion. Sludge enters the plant and is heated up in a regenerator to recover the heat of digestate. Sludge regeneration reduces the heat required to increase the temperature of sludge up to digestion temperature.

After regenerator, sludge is mixed with hot sludge from the digester. The mixing loop has a high recirculation ratio (sludge recirculation mass flow is 23 times higher than incoming sludge mass flow) to keep the temperature of the sludge within acceptable biological limits in the sludge heating system. The heating systems takes part of the heat rejected by engine in the coolant and in flue gas to heat sludge. After heating, sludge enters in the dark fermentation digester and then in the anaerobic digesters to produce hydrogen and biogas respectively. After a residence time of 17 days, the digestate is removed by digesters and sent to the sludge regenerator before the disposal. In this scenario, the two products (i.e., hydrogen and biogas) are mixed together and, after purification, are sent to the engine to produce electricity and heat, as mentioned. The amount of hydrogen produced during dark fermentation is very low (about 1.9% Vol.) and the mixture obtained can fuel the engine as it is. The engine chosen in this scenario is a Jenbacher JGS 316 GS-B. L, with a nominal electric output of 703 kW, and a nominal electric efficiency of 41.7%. Fig. 2 shows the layout configuration and energy balance in Scenario 1.

2.2.2.2. Scenario 2. In the second scenario, sludge line and digesters are the same as scenario 1. The difference lies in the presence of an upgrading system which separates CO_2 to produce biomethane. The upgrading system considered is a commercial product which absorbs CO_2 in a solution of potassium carbonate. The system requires about 0.59 kWh/m^3 and 0.2 kWh/m^3 of treated biogas as thermal and electric energy respectively. About the 75% of the thermal energy introduced at the temperature of 120 °C is recovered and made available at the temperature of 80 °C for sludge heating. The upgrading system is fed by biogas from AcoD. The hydrogen from dark fermentation is completely sent to the engine together with the remaining part of biogas and not injected in the gas grid: in fact, by considering Italian standards for

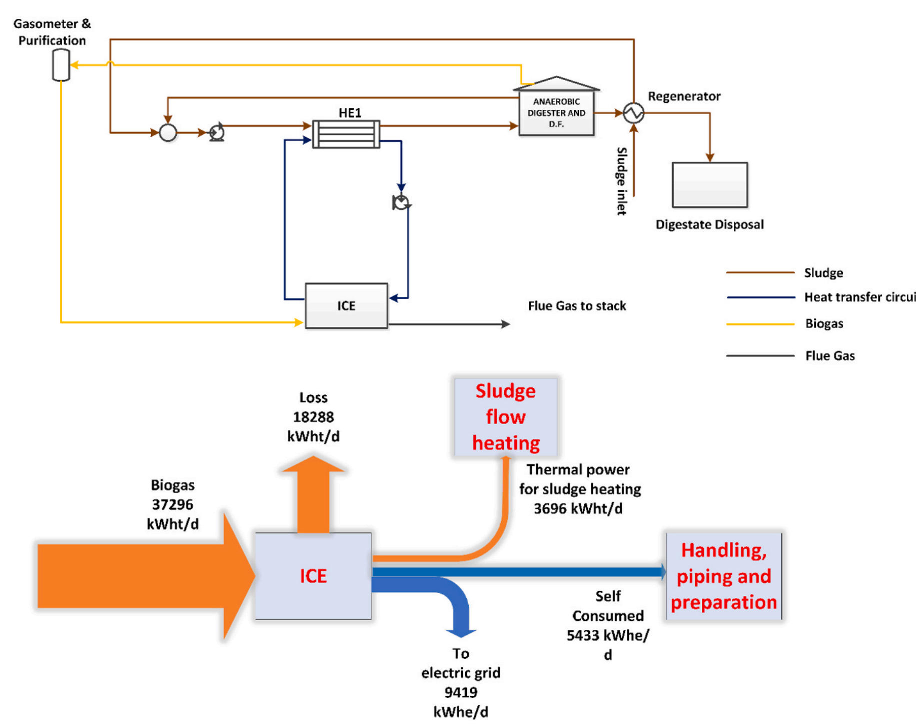

Fig. 2. Layout configuration (above) and energy balance (below) in Scenario 1.

natural gas grid, the maximum acceptable concentration of H_2 must be lower than 0.5% Vol. The engine, a MAN E2676 LE 212 is operated in thermal follow mode, in order to provide the minimum heat necessary to operate the plant (sludge heating and upgrading system). Fig. 3 shows the layout configuration and energy balance in Scenario 2.

2.2.2.3. Scenario 3. In the third scenario, the cogeneration unit is replaced by a heater to produce the thermal power requested by sludge and upgrading system. Electric power necessary to the plant is assumed to be purchased from the electric grid. In this way, the amount of biomethane produced increases, due to the high thermal efficiency of the heater, to the detriment of the lack of electric energy production. In analogy to the previous configuration, the whole amount of H_2 from dark fermentation is burned in the boiler. Fig. 4 shows the layout configuration and energy balance in Scenario 3.

2.2.2.4. Scenario 4. This configuration is very similar to configuration 3. The only difference is in the heater feed, being natural gas and hydrogen from dark fermentation adopted as fuel for the heater. All the amount of biogas produced is delivered to the upgrading system to be injected in the gas grid. Fig. 5 shows the layout configuration and energy balance in Scenario 4.

2.2.3. Sensitivity analysis on life cycle assessment

In the first analysis, named sensitivity analysis 1, the total emissions of CO_2 equivalent associated with the investigated scenarios were computed by assuming the use of biomethane in the sector of transport. Specifically, three different uses of the recovered biomethane were studied: replacement of diesel, replacement of petrol and replacement of liquefied petroleum gas (LPG), thus avoiding the environmental burdens associated with their production and combustion (no assumptions were made for the engine application, which were considered out of scope).

The substitution ratios were calculated based on the heating power supplied from the amount of biomethane recovered, considering a lower heating value equal to 35,220 kJ/Nm^3. In this case, the use of liquefied natural gas was assumed; therefore, for the liquefaction of biomethane, an electricity consumption of 0.749 kWh/kg$_{CH4}$ was taken into account (Pasini et al., 2019).

In the second analysis, named sensitivity analysis 2, the total emissions of CO_2 equivalent associated with the default LCA study were computed considering the European electricity mix expected in 2050. A realistic scenario, based on acknowledged projections of the future energy market in Europe, was taken into account to assume the shares of energy sources (Table S3) (Parisi et al., 2020).

2.2.4. Life cycle costing

Similarly to the LCA perspective, LCC has the purpose to assess a system or a product, from an economic and financial perspective, during its life span. For this case study, a life span of 20 years was assumed for the LCC analysis.

The LCC analysis includes costs items such as capital expenditure, operational and disposal expenses. In Table S4, the operational and disposal expenses are reported, which were assumed to be the same in all four systems, in order to estimate the inputs/outputs of each scenario from a financial perspective. No profit from compost sale was considered because of its variation and its usual low revenues. 330,000 €/y of personnel cost were assumed in all scenarios. According to the data retrieved from the study case facility, the maintenance costs, excluding the energy recovery devices (ICE, boiler, upgrading), were assumed equal to 300,000 €/y in each scenario. The ICE specific maintenance costs were set equal to 17.6 €/MWh of electric energy produced (U.S. Environmental Protection Agency, 2017). The specific maintenance

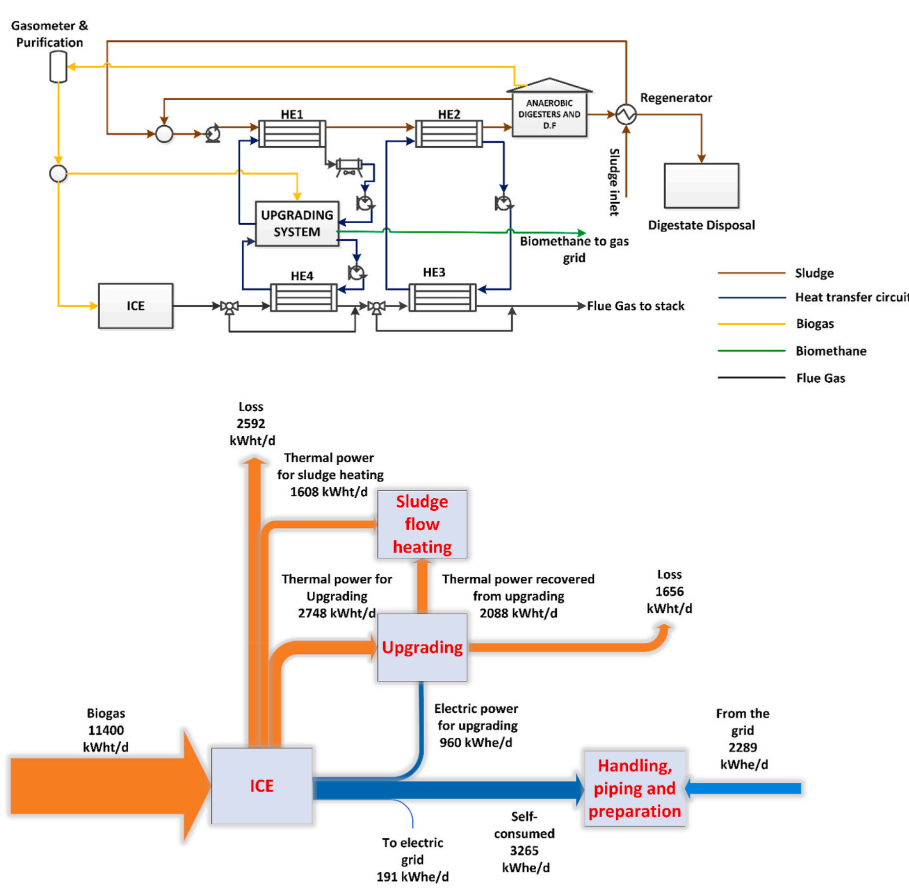

Fig. 3. Layout configuration (above) and energy balance (below) in Scenario 2.

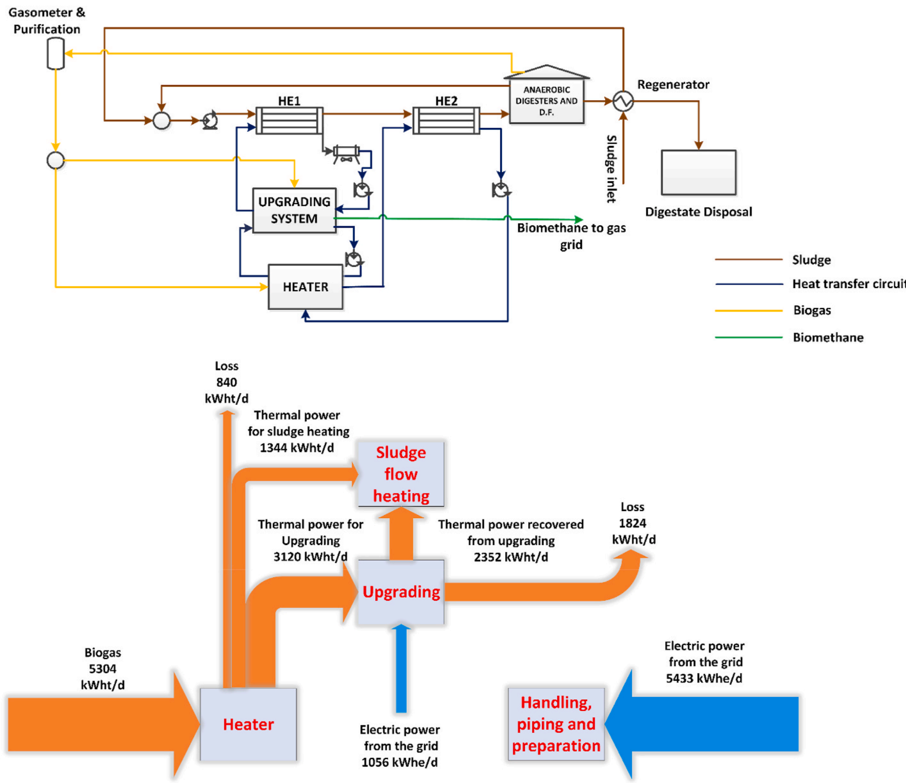

Fig. 4. Layout configuration (above) and energy balance (below) in Scenario 3.

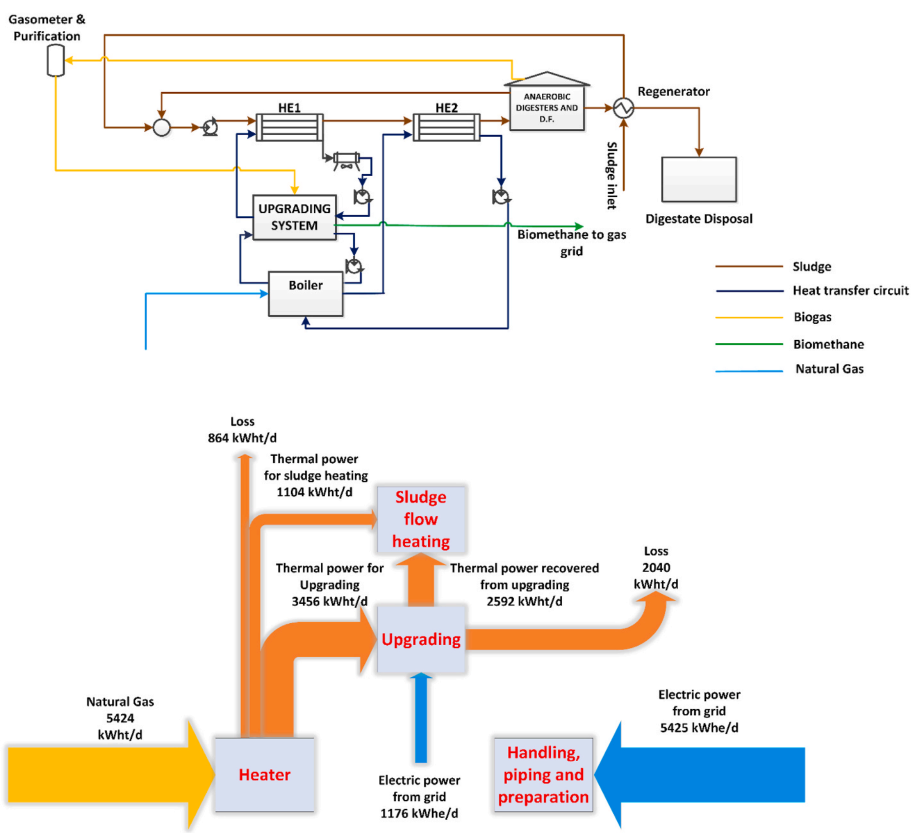

Fig. 5. Layout configuration (above) and energy balance (below) in Scenario 4.

costs of boiler and upgrading devices was assumed equal to 2.5% of their initial capital investment.

According to the data retrieved from the study case facility, the investment costs, excluding the energy recovery devices (ICE, boiler, upgrading), were assumed equal to 5,761,000 € in each scenario. The aerobic composting plant was considered to be an external existing one. In Table S5, the investment costs of the energy recovery devices were reported for each scenario.

To perform the LCC analysis and evaluate the cost-effectiveness of each scenario, the NPV and IRR were computed. The NPV is a method to estimate the current value of a certain future number of cash flows deriving from an investment. The NPV was calculated by subtracting to the present value of the incoming cash flows (revenues), the present value of the outgoing cash flows (expenses, comprising investment costs), as shown in Eq. (1):

$$NPV_{(i,N)} = \sum_{t=0}^{n} \frac{R_t}{(1+i)^t} \tag{1}$$

where N is the total number of years considered (20 years, as assumed), t is the period (1 year, based on the adopted FU), R_t is the cash flow of every period and i is the interest rate, which was assumed to be 1.5%, as it refers to an ordinary financial situation in Italy (Bank of Italy, 2019). Whereas, the IRR is the interest rate (i %) that sets the NPV equal to 0 and is used to assess the profitability of a potential investment.

2.3. Life cycle impact assessment

Life cycle impact assessment was implemented in Simapro 9.3 software. The environmental impacts were quantified using the CML-IA baseline method (Guinee, 2002), developed by the Institute of Environmental Sciences of the Leiden University.

The CML-IA baseline method estimates the potential environmental impacts at midpoint level (Corominas et al., 2020), showing results through 11 impact categories.

Contribution analysis was discussed in detail for three impact categories: abiotic depletion (fossil fuels) potential (ADP), global warming potential (GWP) and acidification potential (AP). The last two categories were selected because of their importance and popularity in solid waste management studies (Mulya et al., 2022), the first one was chosen to highlight the influence of biomethane recovery processes.

The CML-IA baseline method is widely used in LCA studies of solid waste management systems (Laurent et al., 2014). Recently, CML-IA baseline was recognized as one of the most consistent methods for life cycle impact assessment in this research area (Mulya et al., 2022).

In life cycle impact assessment, avoided impacts due to the avoided production of energy, biomethane and material were credited as emissions subtracted from the system, thus considering the advantages deriving from the replacement of conventional products (Francini et al., 2019).

Endpoint analysis was not performed due to high statistical uncertainties (Corominas et al., 2020), preferring a broad overview of midpoint level environmental impact trade-offs.

3. Results and discussion

3.1. Life cycle assessment analysis

The results obtained from the LCA analysis are shown in Table 3. The negative values indicate that the avoided impacts are greater than the direct impacts (positive values) generated by the systems, based on previous assumptions. The percentage differences in the potential environmental impacts generated by Scenario 2, Scenario 3 and Scenario 4, compared to Scenario 1 (Reference Scenario), are shown in Fig. S2.

Scenario 1 was the most environmentally sound in 8 out of 11 impact categories. At the same time, Scenario 1 was the most impactful configuration in the remaining three categories, which represent significant environmental indicators: GWP, ozone layer depletion potential and ADP.

Table 3
Life cycle impact assessment of the investigated scenarios.

Impact category	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Abiotic depletion [kg Sb eq.]	−7.06E+00	−3.13E+00	−1.61E+00	−7.95E-01
Abiotic depletion (fossil fuels) [MJ]	−1.67E+07	−4.00E+07	−3.66E+07	−3.15E+07
Global warming [kg CO_2 eq.]	1.32E+06	−1.14E+05	1.78E+05	1.00E+06
Ozone layer depletion [kg CFC-11 eq.]	−1.42E-01	−4.73E-01	−4.48E-01	−4.51E-01
Human toxicity [kg 1,4-DB eq.]	3.35E+05	7.33E+05	8.91E+05	9.83E+05
Fresh water aquatic ecotoxicity [kg 1,4-DB eq.]	4.74E+06	5.20E+06	5.39E+06	5.44E+06
Marine aquatic ecotoxicity [kg 1,4-DB eq.]	1.92E+09	3.05E+09	3.50E+09	3.60E+09
Terrestrial ecotoxicity [kg 1,4-DB eq.]	1.18E+03	5.54E+03	7.24E+03	7.47E+03
Photochemical oxidation [kg C2H4 eq.]	4.54E+02	5.77E+02	6.69E+02	7.46E+02
Acidification [kg SO2 eq.]	−4.70E+03	1.19E+02	2.72E+03	3.57E+03
Eutrophication [kg PO4 eq.]	1.05E+04	1.24E+04	1.33E+04	1.35E+04

The best environmental performance in these three categories were reported by Scenario 2, in which 81% of biogas undergoes an upgrading treatment to biomethane, while the remaining part was assumed to cogenerate heat and electricity.

Compared to Scenario 2, the increase in biomethane production did not provide better environmental results. In each impact category, Scenario 3 (90% of biogas converted into biomethane) resulted to be a worse configuration than scenario 2. With the exception of GWP, ozone layer depletion potential and ADP, Scenario 4 (100% of biogas converted into biomethane) reported the highest environmental impacts in all indicators provided by the CML-IA baseline method, resulting the worst configuration in 8 out of 11 categories. As will be highlighted in the next sections, the recovery of both heat and electricity, while modest, made Scenario 2 a better setup than Scenario 3 and Scenario 4.

In general, Scenario 1 and Scenario 2 achieved the best results. From an environmental point of view, the outcomes found so far suggested that the optimal configuration may lie in the combined recovery of biomethane, electricity and heat, balancing the rates of biogas to be used for CHP and biomethane production.

3.1.1. Contribution analysis to abiotic depletion (fossil fuels) potential

Scenario 1, which considered the generation of heat and electricity from biogas, was the least advantageous configuration. However, in each scenario, avoided impacts were higher than direct impacts (positive values) (Table 3). The avoided electricity production was the main component in Scenario 1, accounting for 78% of the avoided impacts; conversely, avoided natural gas production represented the most beneficial aspect in the other scenarios (89–92% of the avoided impacts). The avoided production of inorganic fertilisers and peat generally provided a scarce contribution to the avoided impacts (22% in Scenario 1; 10% in Scenario 2; 9% in Scenario 3; 8% in Scenario 4).

Concerning the direct impacts (positive values), electricity consumption was the main contributor to ADP in Scenario 2, Scenario 3 and Scenario 4. In Scenario 2, where a small part of biogas is used for CHP, the direct impacts from electricity consumption represented 51%; whereas, the contribution associated with the use of electricity increased to 71% of the direct impacts in Scenario 3, as electricity production from biogas was not involved in this configuration. In Scenario 4, in addition to the contribution of electricity consumption (47% of the direct impacts), an important share (34%) of the direct impacts came from thermal energy consumption, as thermal energy was retrieved mainly by methane from network.

On the other hand, the electricity produced in Scenario 1 exceeds that required by the plant, and the impact due to waste transport was the main cause of fossil fuel depletion. It should be noted that Scenario 1 generated the least direct impacts (positive values); however, Scenario 2, Scenario 3 and Scenario 4 were more environmentally beneficial thanks to the contribution of the avoided natural gas production, confirming the importance of biomethane recovery for this impact category (Fig. 6a).

3.1.2. Contribution analysis to global warming potential

Similarly to ADP, the recovery of biomethane had a particular impact on GWP (Ardolino et al., 2018); as a consequence, Scenario 1 was the worst configuration even in this case (Table 3).

Biomethane production accounted for a large share of the avoided CO_2 equivalent emissions (82–86%) in Scenario 2, Scenario 3 e Scenario 4; however, avoided impacts were higher than direct impacts (positive values) only in Scenario 2, showing that the combined recovery of heat, electricity and biomethane was essential to mitigate the impact of GWP.

Unlike ADP, the avoided production of inorganic fertilisers and peat accounted for a more significant part of the avoided impacts (32% in

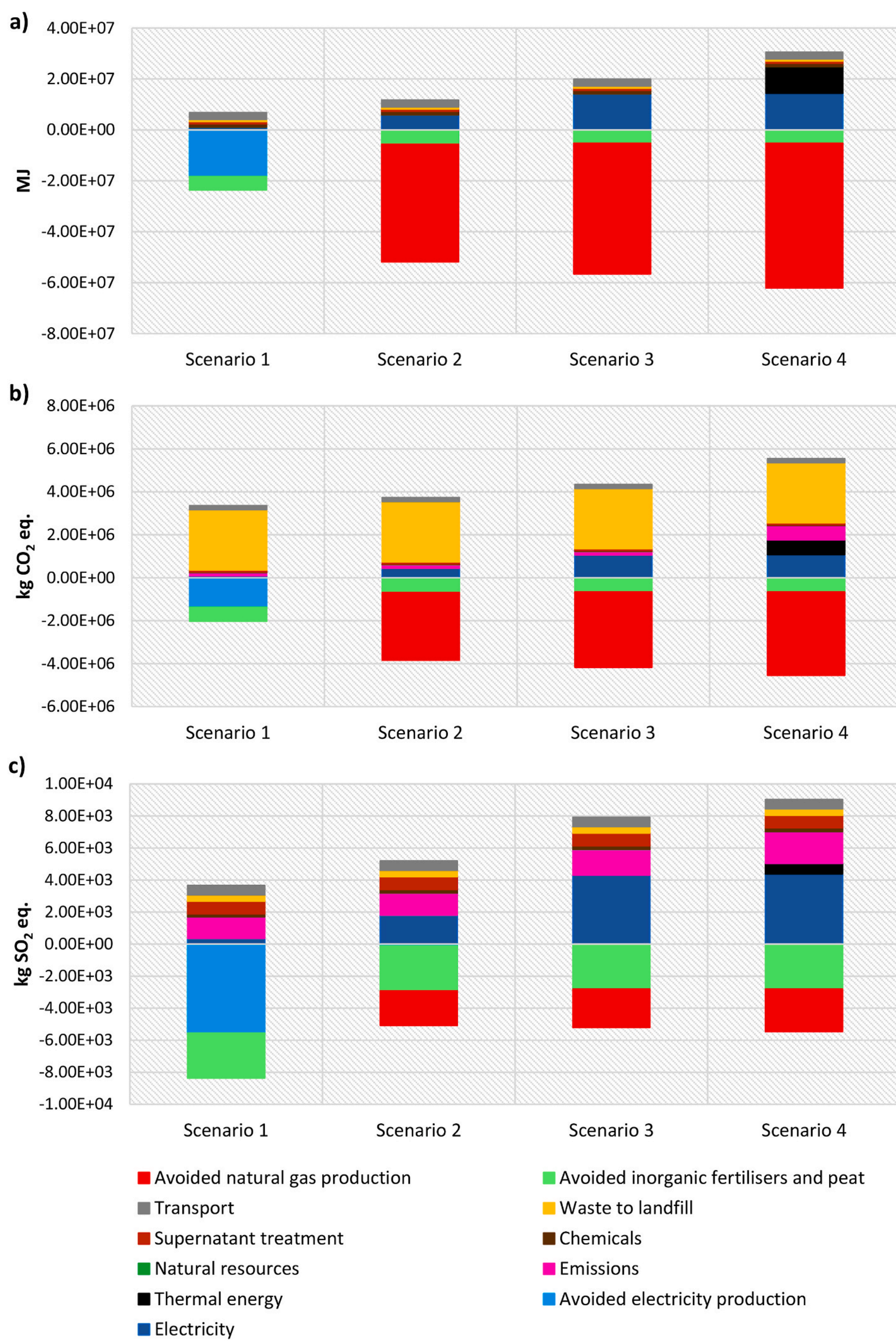

Fig. 6. Contribution analysis to abiotic depletion (fossil fuels) potential (a), global warming potential (b) and acidification potential (c).

Scenario 1; 17% in Scenario 2; 16% in Scenario 3; 14% in Scenario 4). This is because GWP is less affected by the avoided productions of electricity and natural gas than ADP. Anyway, the avoided electricity production was the main component in Scenario 1, representing 68% of the avoided impacts.

On the other hand, in each scenario, the treatment of waste to landfill was the main component of direct impacts (84% in Scenario 1; 75% in Scenario 2; 65% in Scenario 3; 51% in Scenario 4). The contribution of electricity consumption was not negligible in Scenario 3 and Scenario 4, representing 24% and 19% of the direct impacts (positive values), respectively, as well as the consumption of thermal energy in Scenario 4 (12% of the direct impacts), due to the use of methane from network for the boiler. Furthermore, the combustion of natural gas increased the CO_2 emissions of fossil origin in Scenario 4, based on the assumptions explained in section 2.2.2; therefore, air emissions showed a not neglectable contribution in this configuration, accounting for 12% of the direct impacts (Fig. 6b).

3.1.3. Contribution analysis to acidification potential

Aspects related to the production/consumption of electricity played a crucial role in this impact category. Not surprisingly, Scenario 1 (biogas used for CHP) was the most ecological configuration for AP (Table 3) (Colzi Lopes et al., 2018). In addition, avoided impacts were higher than direct impacts (positive values) only in Scenario 1. Anyway, the avoided electricity production represented 67% of the avoided impacts in Scenario 1.

On the other hand, the recovery of biomethane was not so decisive for AP. Indeed, in terms of avoided SO_2 equivalent emissions, the environmental benefits from natural gas production (43% in Scenario 2; 46% in Scenario 3; 49% in Scenario 4) were slightly lower than those from the avoided inorganic fertilisers and peat production (55% in Scenario 2; 54% in Scenario 3; 51% in Scenario 4). In general, it should be noted that the avoided production of inorganic fertilisers and peat provided a notable contribution for AP, accounting for 33% of the avoided impacts also in Scenario 1.

Concerning direct impacts (positive values), SO_2 equivalent emissions associated with electricity consumptions were the main contributors to AP in Scenario 2, Scenario 3 and Scenario 4 (35%, 54% and 49%, respectively), followed by air emissions (27%, 20% and 22%, respectively).

In general, air emissions showed a relevant contribution for AP, due to the emissions of NO_x and SO_2 from biofuel combustion, and represented the main source of direct impacts (positive values) in Scenario 1 (37%). Anyway, the contributions of supernatant treatment, transport and waste treatment to landfill were not negligible in each investigated scenario (Fig. 6c).

3.1.4. Contribution analysis to abiotic depletion potential

Scenario 1 was the best configuration. Abiotic depletion potential is strongly affected by electricity consumption (Fig. S3), and the avoided production of electricity played a key role in Scenario 1 (−3.35E+00 kg Sb eq.).

In each scenario, avoided impacts were higher than direct impacts (positive values) (Table 3). The recovery of inorganic fertilisers and peat represented the most relevant avoided contribution (−6.66E+00 kg Sb eq.), while environmental credits from the avoided production of natural gas were modest.

3.1.5. Contribution analysis to ozone layer depletion potential

In each scenario, avoided impacts were higher than direct impacts (positive values) (Table 3). Biogas upgrading-based scenarios (Scenario 2, Scenario 3 and Scenario 4) were better configurations than Scenario 1 (biogas used for CHP), because of the huge avoided impacts generated from natural gas production (up to −6.95E-01 kg CFC-11 eq. in Scenario 4, Fig. S4).

Nevertheless, the increase in biomethane production did not provide better environmental results: the consumption of electricity was not negligible for this impact category, and Scenario 2 was the best option as CHP was included (Fig. S4). Indeed, environmental credits from the avoided electricity production were considerable in Scenario 1.

3.1.6. Contribution analysis to human toxicity, fresh water aquatic ecotoxicity, marine aquatic ecotoxicity and terrestrial ecotoxicity potential

In all ecosystem toxicity categories, direct impacts (positive values) were higher than avoided impacts (Table 3). In these categories, the disposal of waste to landfill generated the highest contributions, especially in fresh water aquatic ecotoxicity potential and marine aquatic ecotoxicity potential, accounting for 90–96% (Fig. S6) and 74–91% (Fig. S7) of the positive impacts, respectively. At the same time, supernatant treatment accounted for non-negligible positive impacts in human toxicity potential (15–21%, Fig. S5) and in terrestrial ecotoxicity potential (21–31%, Fig. S8).

However, the consumption of electricity generated significant impacts on these categories; therefore, Scenario 1 was the best option in each category, due to the avoided production of electricity. Conversely, avoided impacts from natural gas production were almost negligible; therefore, Scenario 2 was the best configuration among the biogas upgrading-based scenarios due to CHP.

3.1.7. Contribution analysis to photochemical oxidation potential

In photochemical oxidation potential, the situation was similar to that of ecosystem toxicity categories. Contrary to the situation described above, the production of natural gas generated significant avoided impacts (up to −2.19E+02 kg C_2H_4 eq. in Scenario 4, Fig. S9); however, Scenario 1 was confirmed as the best configuration due to the avoided electricity consumption, which had a greater influence (−2.51E+02 kg C_2H_4 eq., Fig. S9).

3.1.8. Contribution analysis to eutrophication potential

Eutrophication potential was dominated by the disposal of waste to landfill and supernatant treatment, accounting for 66–75% and 18–21% of the positive impacts, respectively. However, as shown for ecosystem toxicity categories, Scenario 1 turned out to be the best option, as the avoided production of electricity generated much higher environmental credits than the avoided production of natural gas (Fig. S10).

3.1.9. Literature comparison

As shown in previous section, the use of biogas for CHP (Scenario 1) was the best option in 8 out of 11 impact categories. These findings contrast with the results found by Ardolino et al. (2018), in which the production of biomethane for road transport was always a better solution.

Our findings were somewhat closer to that of Colzi Lopes et al. (2018), who stated that the preference for a specific scenario depended on the impact categories prioritized. Similar to our study, biogas upgrading-based scenario reported lower impacts in ADP, GWP and ozone layer depletion potential; while scenario based on CHP represented the best option in photochemical oxidation potential and AP.

Considering biogas upgrading-based scenarios, we found that the increase in biomethane production did not provide better environmental results. This was due to the fact that environmental benefits deriving from the production of biomethane were not be able to compensate for the internal energy consumptions. In this context, a similar outcome was noticed by Venkatesh and Elmi (2013), who showed that the increase in biomethane production cannot lead to best-case scenarios, when it comes at the expense of energy recovery.

3.1.10. Sensitivity analysis

3.1.10.1. Sensitivity analysis 1.

Fig. 7a shows the total CO_2 equivalent emissions generated by the investigated scenarios, assuming the use of

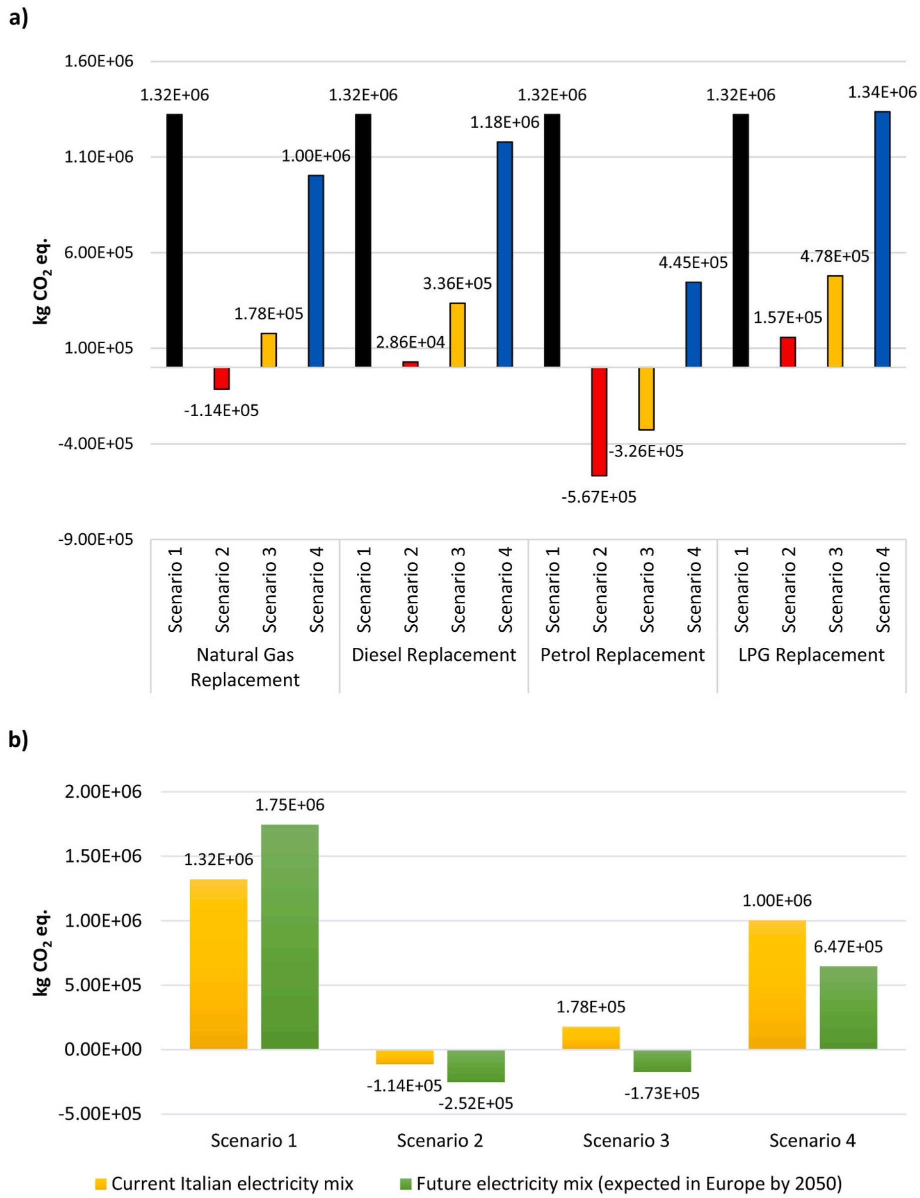

Fig. 7. GWP considering different uses of the recovered biomethane (a) and GWP considering a realistic European electricity mix expected in 2050 (b).

the recovered biomethane to replace natural gas (default LCA), diesel, petrol and LPG.

From the point of view of GWP, Scenario 2 was the most environmentally sound configuration in each study case, followed by Scenario 3. In any biogas upgrading-based scenario (Scenario 2, Scenario 3 and Scenario 4), the use of biomethane to replace petrol was the best option against climate change, followed by natural gas replacement (default LCA), diesel replacement and LPG replacement, respectively. In particular, considering the replacement of petrol, the avoided impacts were higher than the direct impacts (positive values) in both Scenario 2 and Scenario 3. However, as happened in default LCA, avoided impacts were lower than direct impacts in most of the analyzed cases; therefore, the overall CO_2 equivalent emissions were positive.

Scenario 4 was always the most impactful configuration among the biogas upgrading-based scenarios. Furthermore, considering the use of biomethane to replace LPG, it should be noted that Scenario 4 represented a worse solution than Scenario 1 (biogas used for CHP).

3.1.10.2. Sensitivity analysis 2. Fig. 7b shows the total CO_2 equivalent emissions generated by the investigated scenarios, considering the current Italian electricity mix (default LCA) and the European electricity mix expected in 2050.

The future European electricity mix represented a worsening condition in Scenario 1, where it was assumed the use of biogas for CHP. In fact, as shown in Table S3, the composition of the adopted electricity mix should encourage the use of renewable sources, thus causing lower environmental burdens for electricity production. At the same time, the benefits deriving from the avoided electricity production will be lower. Therefore, although the production of electricity was far higher than that required in Scenario 1, considering the future electricity mix, the system was less affected by the avoided CO_2 emissions from electricity production.

Conversely, the future European electricity mix led to an improvement in the configurations aimed at biogas upgrading to biomethane (Scenario 2, Scenario 3 and Scenario 4). In particular, as happened in previous analysis, Scenario 2 was the best configuration for GWP, followed by Scenario 2 and Scenario 3, respectively. Avoided impacts were higher than direct impacts (positive values) in both Scenario 2 and Scenario 3.

Table 4
Net present value (NPV) and internal rate of return (IRR) of the investigated scenarios.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
NPV (€)	3,424,958	10,518,291	8,674,168	8,685,600
IRR (%)	5.94	16.62	15.98	16.56

3.2. Life cycle costing analysis

In Table 4, the estimated NPV and IRR of the investigated scenarios are reported, according to the assumptions assumed in section 2.2.4.

In general, all the proposed configurations represented economically sustainable projects, as each scenario showed positive NPV in 20 years (Fig. 8a). As shown, biogas upgrading-based scenarios (Scenario 2, Scenario 3 and Scenario 4) achieved higher NPV values than Scenario 1 (biogas used for CHP). In addition, in Scenario 2, Scenario 3 and Scenario 4, the positive NPVs were achieved approximately 7 years earlier than in Scenario 1.

However, Scenario 2 had a higher NPV than Scenario 3 and Scenario 4, thanks to biomethane revenues and electricity sales, despite the latter being modest. Scenario 1 was the least economically advantageous configuration.

Finally, the NPV of each scenario, considering different interest rate (*i* %), is reported in Fig. 8b. Furthermore, it should be noted that the intersection between the NPV variation curves and the abscissa axis represents the IRR. As shown, Scenario 2, Scenario 3 and Scenario 4 continue to be economically viable projects even with interest rates (*i* %) higher than 6%, representing the IRR of the Scenario 1.

4. Conclusions

This study performed the LCA and LCC of different scenarios for the valorization of the biogas produced from the AcoD of SS and OFMSW, pre-treated by a DF process.

Four configurations were compared, exploring the recovery of one or more of the following: heat, electricity and biomethane. Furthermore, two sensitivity analyses were performed on LCA analysis, considering the use of the produced biomethane as a fuel for transport and the European electricity mix expected by 2050, respectively.

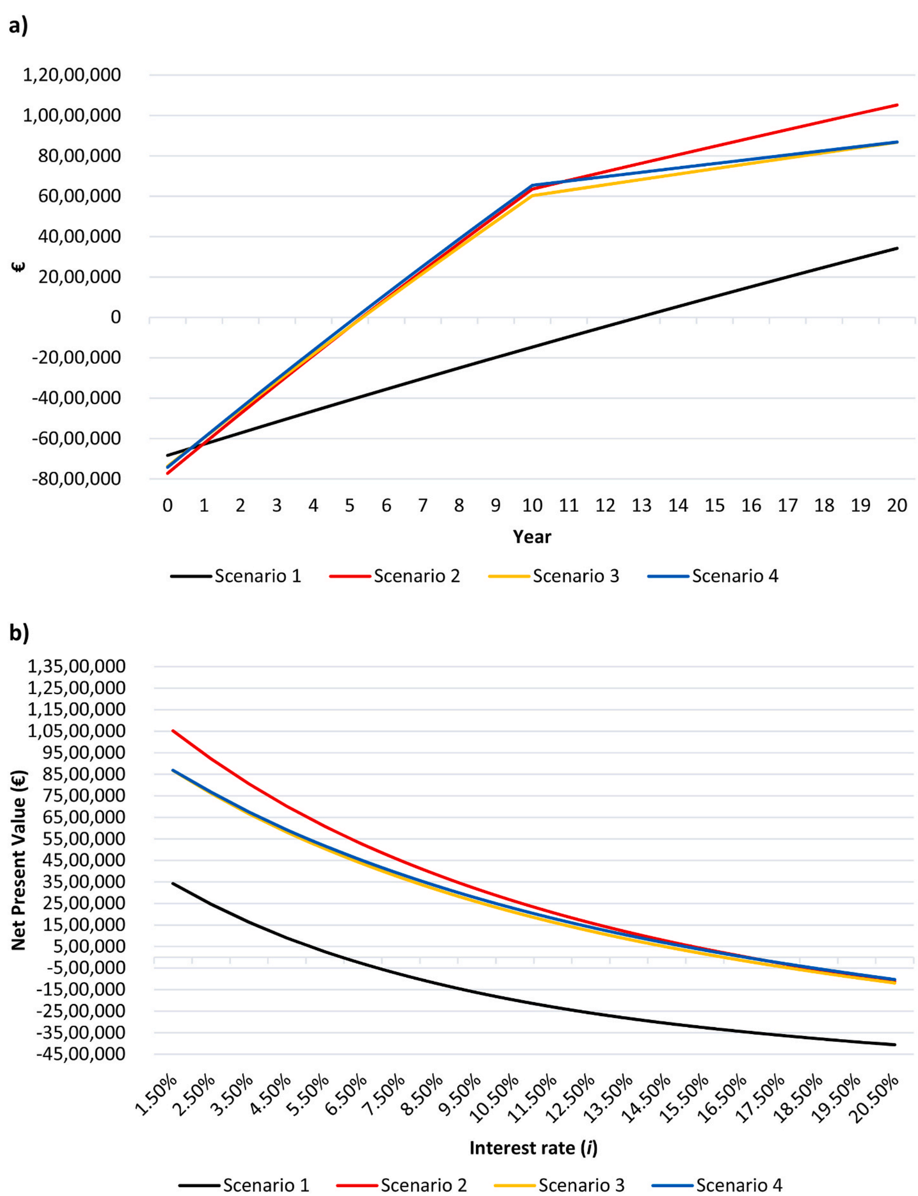

Fig. 8. Cumulative net present value (NPV) in 20 years (a) and NPV considering different interest rates (b).

Contrary to most of the previous studies in the literature, we found that CHP should not be neglected, as the optimal configuration may lie in the combined recovery of biomethane, electricity and heat, both from an environmental and economic point of view.

Sensitivity analyses confirmed that the biogas upgrading processes should have generally a lower impact on climate change than CHP systems. Furthermore, the use of biomethane to replace petrol resulted to be the best option in terms of global warming potential.

Future research efforts should focus on developing systematic frameworks and models aimed at optimizing and maximizing energy recovery from SS, thus contributing to the process of decarbonization as much as possible.

CRediT authorship contribution statement

Francesco Pasciucco: Methodology, Software, Formal analysis, Data curation, Writing – original draft, Visualization. **Giovanni Francini:** Conceptualization, Methodology, Software, Formal analysis, Resources, Writing – review & editing. **Isabella Pecorini:** Conceptualization, Validation, Formal analysis, Investigation, Resources, Writing – review & editing, Supervision, Project administration. **Andrea Baccioli:** Conceptualization, Software, Investigation, Resources, Writing – review & editing. **Lidia Lombardi:** Methodology, Validation, Supervision. **Lorenzo Ferrari:** Conceptualization, Validation, Supervision, Project administration.

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

No data was used for the research described in the article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.136762.

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