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Bioenergy recovery from waste: comparison of different treatment scenarios by LCA

Elena Albini[a], Donata Bacchi[a], Giovanni Ferrara[b], Giovanni Francini[a], Giovanni Galoppi[b], Lidia Lombardi[c], Isabella Pecorini[b*], Caterina Susini[d]

[a]*PIN S.c.r.l., Servizi didattici e scientifici per l'Università di Firenze, Piazza G. Ciardi 25 - 59100 Prato, Italy*
[b]*DIEF, Department of Industrial Engineering, University of Florence, Via Santa Marta 3 - 50139 Florence, Italy*
[c]*Niccolò Cusano University, Via Don Carlo Gnocchi 3, 00166 Rome, Italy*
[d]*SEA Risorse S.p.a., Via dei Comparini 186, 55049 Viareggio, Italy*

Abstract

Anaerobic digestion of sewage sludge generally produces an amount of biogas that is not enough to cover the energy requirements of the digester. One possibility to increase the biogas production is to co-digest, together with sewage sludge, other substrates, for istance the organic fraction of municipal solid waste. Alternatively, a preliminary step of dark co-fermentation of those mixed substrates can be applied. In this work, such possible cases are compared by Life Cycle Assessment approach. The study was carried out with reference to the Viareggio wastewater treatment plant, Italy. Anaerobic co-digestion of sewage sludge and the organic fraction of municipal solid waste emerges as the best treatment option in terms of environmental impacts. However, also dark co-fermentation presents, albeit less, benefits and a reduction in environmental burdens. The robustness of the results is explored by the sensitivity analysis with respect to the effective thermal energy use.

Keywords: sewage sludge, food waste, Life Cycle Assessment, anaerobic digestion, dark fermentation, biohydrogen, biofertilizer

* Corresponding author. Tel.: +39-055-2758718; fax: +39-055-2758755; e-*mail address:* isabella.pecorini@unifi.it

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1. Introduction

The bioeconomy concerns the recovery of raw materials of biological origin, playing an important role in industrial ecology. Within this frame bio-waste has an enormous potential as an alternative to chemical fertilizers or for conversion into bio-energy [1]. The sewage sludge (SS) valorisation through anaerobic digestion (AD) is a crucial step to produce renewable energy in a wastewater treatment plant (WWTP). Moreover, AD is a technology for energy recovery from the organic fraction of municipal solid waste (OFMSW), originated from the separate collection. The SS thus can be used together with the OFMSW in a process of anaerobic co-digestion (AcoD) to produce fertilizers and energy, in order to replacing the use of non-renewable sources [2]. In this respect, biohydrogen production through dark fermentation (DF) can be considered the new borders of AD process development [3]. The coupling of DF in the first step and AD in the second step, can increase the process sustainability and the treatment of the organic waste. Thus, in order to improve the economic sustainability of DF, AD could provide an appealing solution [4].

In this study, the two possibilities of applying AcoD or DF coupled with AD were investigated with reference to a specific study case, related to the WWTP of Viareggio in Tuscany (IT). The two alternative treatments of SS and OFMSW were evaluated from the environmental point of view, by Life Cycle Assessment (LCA), and compared with the current management for SS and OFMSW. LCA can identify the environmental impacts of a product or process at each stage of its life cycle and also it is generally adopted as a tool for supporting policies particularly concerning bioenergy [5]. Of course, not only the enviromental issues can guide the final decision about innovative technologies. For this reason a preliminary analsysis of investement costs for the different compared cases is reported in this work.

Nomenclature

AcoD	anaerobic co-digestion
AD	anaerobic digestion
DF	dark fermentation
EE	electric energy
ICE	internal combustion engine
LCA	life cycle assessment
MCFC	molten carbonate fuel cell
OFMSW	organic fraction of municipal solid waste
SGP	specific gas production
SS	sewage sludge
TE	thermal energy
TS	total solid
Turb	gas turbine
TVS	total volatile solid
WWTP	wastewater treatment plant

2. Scenarios and methods

Based on standard criteria defined by the International Standard Organisation [6,7], the LCA analysis is performed in agreement with the LCA steps: goal and scope, inventory analysis, impact assessment and results interpretation.

2.1. Goal and scope definition

The purpose of this work is the comparison of the environmental impact of the different scenarios for the treatment of OFMSW and SS, with reference to the WWTP of Viareggio study case. The compared scenarios are:

1. *Reference Scenario*: SS are processed by simple AD, commonly used in several WWTP, including the Viareggio plant; OFMSW is composted; the biogas obtained from the SS AD is used in a boiler, thus producing thermal energy (TE) for the anaerobic digester;
2. *Scenario #1*: AcoD of SS and OFMSW; two possibilities for energy recovery (both in terms of electricity and heat) were considered for the produced biogas: *(i)* Scenario #1-ICE, with an internal combustion engine (ICE); *(ii)* Scenario #1-Turb, with a gas turbine (Turb);

3. *Scenario#2*: anaerobic DF of SS and OFMSW, producing what is commonly called the biohydrogen (which is a gas mixture rich in H_2, but also containing CO_2), followed by a second step of AD; two possibilities for biofuels recovery were considered: *(i)* Scenario #2-ICE, with an ICE for the energy recovery from biogas and a molten carbonate fuel cell (MCFC) for the energy recovery from the hydrogen-rich gas; *(ii)* Scenario #2-Turb, with a Turb, for the energy recovery from the mixture of both biogas and hydrogen-rich gas.

The LCA boundaries of the analyzed scenarios include: pre-treatments, the core biological treatment, the expected production of energy and soil improver, the transports, the treatment of the produced wastewater, the landfilling of residues obtained from the pre-treatments and the generated emissions from the various devices. As regards the production of biogas and hydrogen-rich gas, experimental data were used for the inventory.

System expansion was used in order to avoid the need to allocate multi-functional processes. The substitution method was applied because of the production of soil improver, electric energy (EE) or TE and the use of equivalent products was avoided [8].

The reference functional unit for the proposed scenarios is defined as: the treatment of the total annual amount of SS (189 000 t/y) and OFMSW (15 500 t/y) from the city of Viareggio. The characterization of the OFMSW was obtained from the average characterization in the area in which the study is located. The following average composition of the organic waste was considered: organic food (67%), organic (non-food) (3%), paper (3%), cardboard (6%), high density plastics (2%), plastics films (6%), textile materials (1%), glass (4%), ferrous metals (1%), non-ferrous metals (1%), hazardous (1%) and inert (5%). Furthermore, the OFMSW has a total solid (TS) content of 37% and a total volatile solid (TVS) of 68%, while the SS, collected from the municipal WWTP of Viareggio, has a TS content of 0.7% and a TVS content of 70%.

2.2. Inventory analysis

In the inventory phase the studied systems must be necessarily described in a quantitative way in terms of input and output streams. Primarily, the data was obtained by the Viareggio management plant society and they were integrated with laboratory notions, literature data and database information (SimaPro software).

2.2.1. Reference Scenario

A mechanical sorting process is considered to remove all the undesirable materials from the OFMSW. 15 kWh/t of EE [9] and 1.3 liters/t of diesel [10] are required for this process. As can be seen in Fig. 1, OFMSW is sent to a biological composting, whose production of compost is 0.43 kg/kg OFMSW [11]. The assumption was made not considering green waste in addition to the process and considering a consumption of EE equal to 38 kWh/t [10].

The SS, after a thickening phase, moves towards the AD for biogas production with a 2% of TS. Biogas lower heating value is 22 750 kJ/Nm^3 and its composition is: 65% CH_4, 0.5% H_2S, 32% CO_2 and 2.5% H_2O [12] (operating parameters of AD are reported in Table 1). The sludge AD needs EE and TE, 111 MWh/y and 2058 MWh/y respectively [12]. A boiler (efficiency of 85% [13]) produces TE which is not enough to cover the totally demand: an input of natural gas equal to 630 MWh/y is estimated. The composting of digestate coming from the AD is inventoried using the same consumptions as the OFMSW composting.

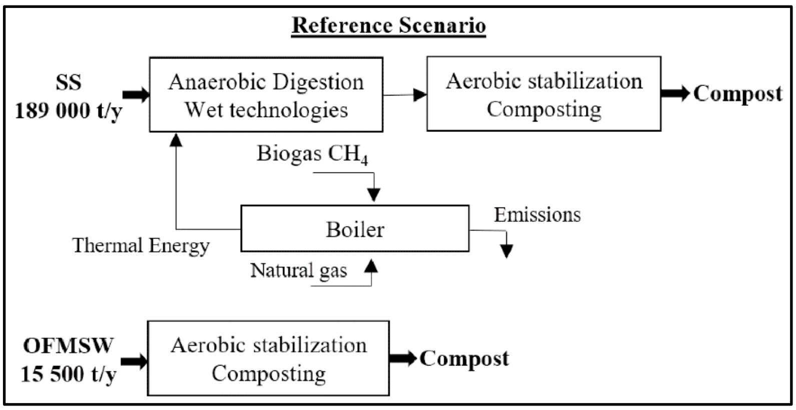

Figure 1. System boundary of Reference Scenario

2.2.2. Scenario #1

The OFMSW is sent to an extruder press which required an amount of diesel of 20 000 l/y [12]. After the pre-treatment, the OFMSW has 4.8% of TS content. SS has 5% of TS after the thickening. The mixture of pre-treated OFMSW and SS are sent to AcoD. As a preliminary approach, biogas production was estimated considering the specific gas production (SGP) obtained separately for SS (in the real plant) and OFMSW (in laboratory tests), being not yet available results for the SGP of AcoD tests (operating parameters of AD are reported in Table 1).

The produced biogas is recovered according to two possible routes (Fig. 2): a 600 kW power ICE (EE efficiency of 0.42 and TE efficiency of 0.43 [14]) or a 600 kW Turb (EE efficiency of 0.33 [15] and TE efficiency of 0.55 [12]). The self-sufficiency of the process is guaranteed by both devices, being the AcoD energy consumptions equal to 475 MWh/y of EE and 2620 MWh/y of TE, and ensuring net energy outputs [12].

The final treatment for the exiting from the AcoD consists of mixing it with other substances, such as peat, to produce a soil improver. Production process for peat was not included into the system boundary (it is anyhow produced and used for soil improvement purposes). An annual consumption of 110 MWh/y [16] was assumed for the mixing process.

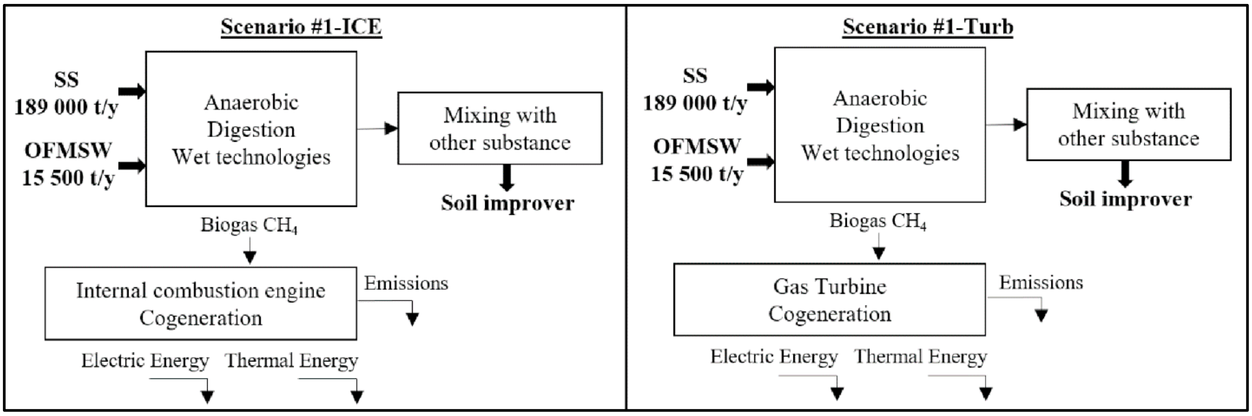

Figure 2. System boundary of Scenario#1

2.2.3. Scenario #2

In Scenario#2 the SS and OFMSW are mixed and sent for DF, producing hydrogen-rich gas (operating parameters of DF are reported in Table 1). The output from the DF is further processed in AD, producing biogas and digestate.

Table 1. AD operating parameters in the Reference Scenario and Scenario#1 and DF operating parameters in Scenario#2

Parameters	Reference Scenario	Scenario#1	Scenario #2 (only DF)
Reactor volume	3000 m^3 [12]	4500 m^3 [12]	818 m^3 [3]
Hydraulic residence time (HRT)	17.84 d	20.69 d	3.8 d
Volumetric organic load (OLR)	0.85 kg TVS/m^3 d	1.95 kg TVS/m^3 d	10.73 kg TVS/m^3 d
Specific gas production (SS)	0.289 Nm^3 biogas/kg TVS [3]	0.289 Nm^3 biogas/kg TVS [3]	0.06 Nm^3 H_2/kg TVS [3]
Specific gas production (OFMSW)	-	0.678 Nm^3 biogas/kg TVS [3]	0.06 Nm^3 H_2/kg TVS [3]
Biogas produced	730 Nm^3 biogas/d	5540 Nm^3 biogas/d	526.5 Nm^3 H_2/d

The consumptions for the DF step are: EE equal to 78 MWh/y and TE equal to 2290 MWh/y [12]. The produced biofuels are recovered according to two possible routes (Fig. 3): the hydrogen-rich gas in a MCFC (EE efficiency of 0.45 [3]; TE recovery is not considered for the MCFC) and the biogas in a 600 kW power ICE (same efficiencies of Scenario#1); alternatively, the mixture hydrogen-rich gas and biogas is used in a 600 kW Turb (same efficiencies of Scenario#1). The self-sufficiency of the process is guaranteed in both cases and ensuring net energy outputs.

The digestate produced from the second stage of AD is assumed to be mixed with peat, according to the same assumptions previously described for Scenario#1.

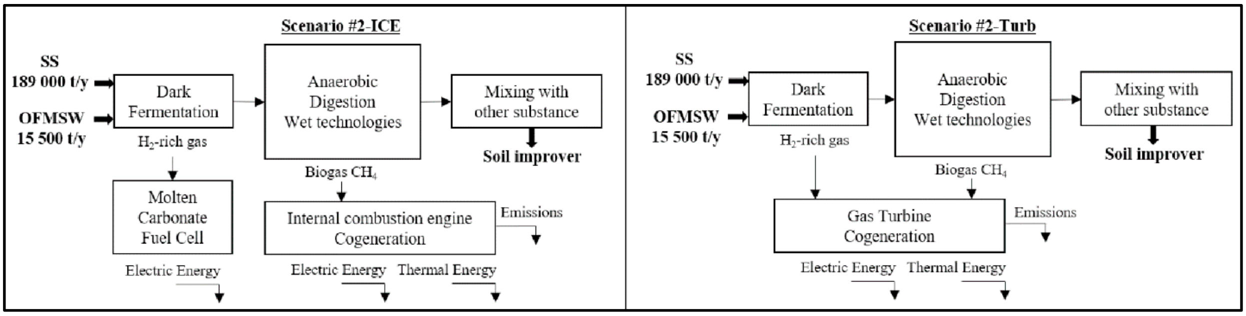

Figure 3. System boundary of Scenario#2

2.2.4. Energy production, emissions and use of soil improver

The excess of EE is sent into the electricity grid while the TE surplus is presumed to be used by a thermal user near the plant. In the Ecoinvent archive, the following records were chosen for the EE and TE: Electricity, medium voltage {IT} and Heat, central or small-scale, Natural gas {Europe without Switzerland} | heat production, natural gas, at boiler modulating <100kW. The emissions of all devices were determined by using the emission factors reported in Table 2. The stoichiometric calculation is adopted for CO_2 (biogenic) and SO_2 emissions, estimated in 2.75 kg CO_2/kg CH_4 and 1.88 kg SO_2/kg H_2S respectively.

Table 2. Devices emission factors

Pollutants	Boiler	ICE	Gas Turbine
NO_x	4480 kg/(10^6) Nm^3 CH_4 [17]	250 mg/Nm^3 [14]	18 mg/Nm^3 [15]
CO	1344 kg / (10^6) Nm^3 CH_4 [17]	8.29E-04 kg/Nm^3 [18]	100 mg/Nm^3 [15]
PM	121.6 kg/(10^6) Nm^3 CH_4 [17]	1.91E-05 kg/Nm^3 [18]	115.2 kg/(10^6) Nm^3 CH_4 [19]

No information was provided regarding the nutrient characteristic of the compost/soil improver at the end of the processes, therefore the following composition from literature was assumed [20]. Contents of 18 g/kgTS of N (as TKN), 30 g/kgTS of P (as P_2O_5) and 18.5 g/kgTS of K (as K_2O) were assumed for compost; while for soil improver it was estimated a composition of 50 g/kgTS of N (as TKN), 40 g/kgTS of P (as P_2O_5) and 4 g/kgTS of K (as K_2O).

The produced compost is used for 25% replacing peat, 68% substituting mineral fertilisers and 7% without any substitution [21]. The Ecoinvent records selected are: Peat moss {RoW}| peat moss production, horticultural use, Nitrogen fertiliser, as N {GLO}| field application of compost, Phosphate fertiliser, as P_2O_5 {GLO}| field application of compost, Potassium fertiliser, as K_2O {GLO}| field application of compost. In the case of soil improver production, the replacing of peat was not considered, therefore the 93% of substitution is for mineral fertilisers.

3. Results

The results are presented according to the CML-IA baseline V3.02/ EU25 method, Institute of Environmental Sciences of the Leiden University (NL) [22]. The results are here reported only for the following indicators: Abiotic Depletion, Global Warming and Terrestrial Ecotoxicity, for conciseness reasons.

3.1. Impact assessment

Fig. 4 shows, for the three selected indicators, the values of percentage difference calculated for Scenario#1 and Scenario#2 with respect to the Reference Scenario. As can be seen in Fig. 4, the use of AcoD is advantageous and the use of an ICE (or an ICE+MCFC in the Scenario#2) instead of a gas turbine determines a better behavior in terms of impacts. These environmental performances are due to the better energy balance obtained in the AcoD case, also because of a larger energy demand, especially in terms of TE for heating the digesters, characterizes the scenarios with co-fermentation (see in Fig. 5 the energy consumption of the DF+AD in Scenario#2 compared to the energy consumption of only AD in Scenario#1). Moreover, the recovery of EE is more favorable than the recovery of TE: an

ICE produces much more EE compared to a turbine, giving greater avoided impacts. The contribution given by EE and TE for Abiotic Depletion indicator are respectively 8.63 and 4.27 MJ per kWh of produced energy.

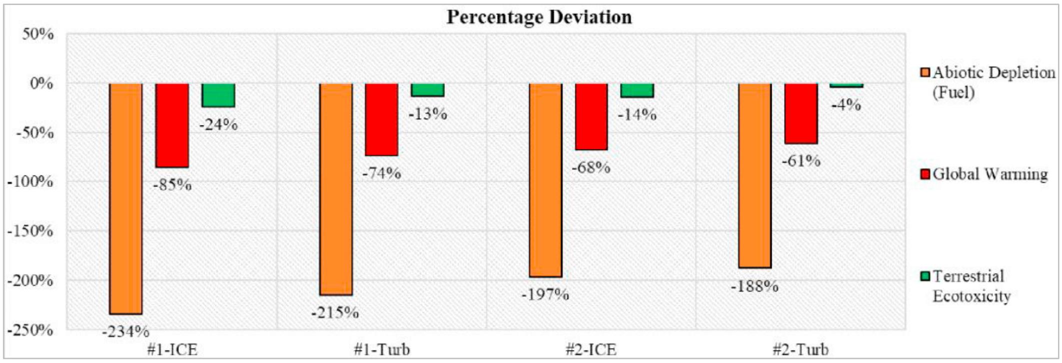

Figure 4. Results of the analysis in terms of percentage difference calculated with respect to the Reference Scenario

The mixing phase, in which the production of soil improver represents a saving, allows lower impacts. For the Terrestrial Ecotoxicity indicator the values are: 0.00025 kg 1.4 DB eq per kg of replaced peat, 0.169 kg 1.4 DB eq per kg of replaced N, 0.086 kg 1.4 DB eq per kg of replaced P_2O_5, 0.067 kg 1.4 DB eq per kg of replaced K_2O.

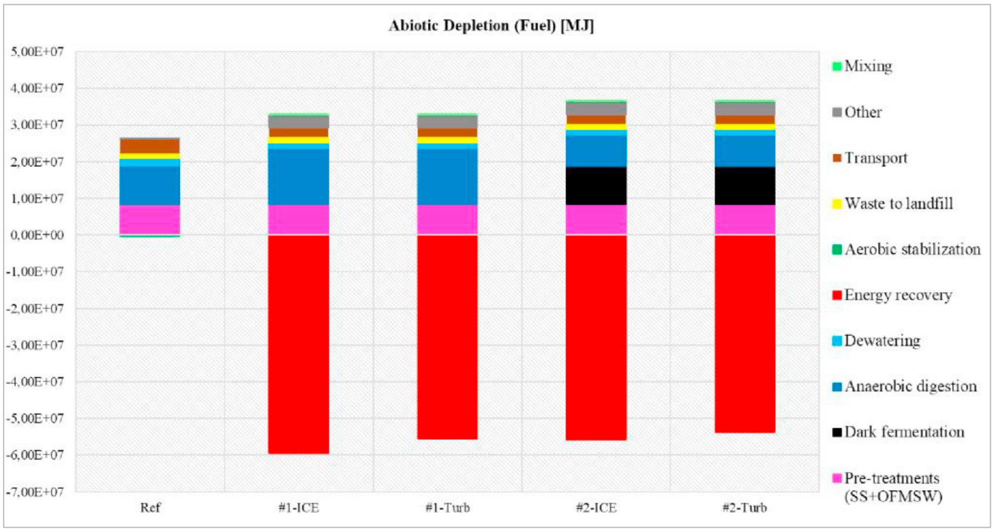

Figure 5. Sub-processes abiotic depletion impacts

3.2. Interpretation and uncertainty analysis

The comparison between the AcoD and the dark co-fermentation scenarios shows that DF does not appear very advantageous. In fact, the energy recovered is lower and the produced digestate is lower, giving less soil improver and therefore less avoided impacts. In the Scenario#2, the MCFC does not imply a significant EE profit; this is because the production of hydrogen-rich gas is not very high.

It should be noted that the possibility of effective TE use outside the plant is linked to the territorial context. The energy recovery is a key figure for the results of this analysis. Therefore, it was decided to evaluate how results can change if the net produced TE is not used (i.e. an external thermal is not available). Fig. 6 shows for the Abiotic Depletion indicator, the values of percentage difference calculated for Scenario #1 and Scenario#2 with respect to the Reference Scenario. When TE is not effectively used, the performances of the ICE scenario are decreased more that the gas turbine's ones. These results are linked to the fact that the TE recovery from turbines is lower that TE recovery in ICE, thus the scenarios using ICE are more influenced by the elimination of net TE use.

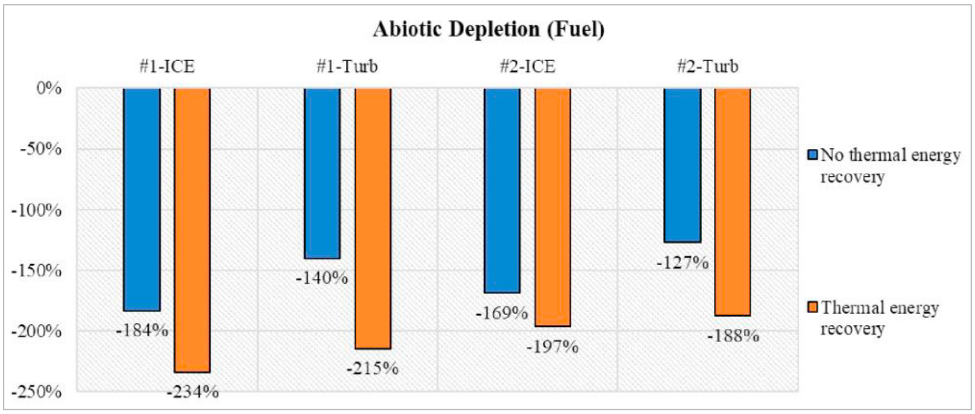

Figure 6. Sensitivity of abiotic depletion indicator with respect to the thermal energy recovery

4. Capital investments

Beside the environmental assessment, it is interesting to estimate the costs that characterize the analyzed processes. Capital investments costs for each scenario were estimated and reported in Table 3, to give a preliminary idea of the investment that the study case plant should face for the upgrading of the existing layout with the necessary additional equipment. For example, the digesters and the cogeneration unit were considered. Data was obtained by the Viareggio management plant society. The highest investment cost of Scenario#2 is justified by the costs of the co-fermentation reactor and the MCFC (Scenario#2-ICE). A detailed economic analysis is referred to future studies.

Table 3. Capital investments of each scenario (the same investment cost was assumed for Scenario#1-ICE and Scenario#1-Turb)

	Reference Scenario	Scenario#1-ICE	Scenario#1-Turb	Scenario#2-ICE	Scenario#2-Turb
Investment [€]	-	3 147 000	3 147 000	3 706 000	3 556 000

5. Conclusions

The main results, obtained from the Life Cycle Assessment applied to the case of co-processing sewage sludge and the organic fraction of municipal solid waste, show that the anaerobic co-digestion case provides better performances that the dark co-fermentation case, mainly because of the higher energy recovery. Additionally, it was found that, even if the combustion of the biogas in an internal combustion engine produces higher emissions, its contribution to energy recovery is higher, providing better results than in the cases using gas turbines. However, it is important to highlight that both the co-processing scenarios (co-digestion and dark co-fermentation) offer the possibility to cover the in-plant energy demand, also generating net outputs, thus deleting the energy import requirements of the simple anaerobic digestion of only sludge. Beneficial results are also significantly influenced by the effective possibility of recovery the net thermal energy, as shown by the sensitivity analysis. After all, the results may be sensitive to the assumptions made in the inventory phase. Based on some preliminary experimental data, it is expected that dark fermentation might increase the gas production of the subsequent anaerobic digestion phase. If such an increase will be confirmed in the future, the inventory data will be updated and an improvement in scenarios with dark fermentation is expected.

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