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Replacing energy crops with bio-waste for an existing anaerobic digestion plant: Energetic and carbon footprint in a LCA perspective

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Abstract

The energetic and greenhouse gases emissions performances related to energy crops substitution with bio-waste for an existing anaerobic digestion (AD) facility were investigated in a life cycle assessment (LCA) perspective. For this reason two different scenarios were compared In the base scenario 17,667Mg/year of energy crops were processed in an existing AD facility generating about 7,700 MWh/year whereas 23,000 Mg/year of bio-waste were processed separately in an existing composting facility for organic fertilizer production. In this case the cumulative energy demand (CED) resulted of 11,000 MWh. In the modified scenario the whole energy crops were substituted by the bio-waste in the AD facility leading to the generation of about 5,000 MWh/year of energy with a correspondent CED of 8,600 MWh. The life cycle analysis detected an higher impact for the base scenario. On the other hand the amount of $kgCO_{2eq}$ generated per each kWh recovered resulted practically the same for both cases.

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Keywords: Anaerobic digestion, bio-waste, cumulative energy demand, energy crops, Life cycle assessment

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1. Introduction

Aerobic and anaerobic biological processes are widely exploited for the management of bio-waste and biomasses. In

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general aerobic processes such as composting are of particular interest because of their robustness and ability to return stabilized materials exploitable as soil improvers even if energetic consumption per unit of substrate processed resulted quite high [1]. On the other hand anaerobic digestion (AD) resulted characterized by higher investment and management costs [2], but returns two main output streams: a biogas composed mainly of methane and carbon dioxide exploitable as fuel for renewable energy production; a quite stabilized soil improver for agricultural use [3]. Furthermore AD is also an important process for achieving the 2020 EU objectives [4] concerning goals on greenhouse gas (GHG) reduction and renewable energy production. Concerning renewable energy production, waste materials like manure, crop residues, sewage sludge, the organic fraction of municipal solid waste (OFMSW) and fruit and vegetable waste are of particular interest since they do not compete with food crops as substrates for AD [5]. Several studies are available in literature concerning the AD of different biomasses as cheese whey an dairy manure [6] or animal waste, crop residues, energy crops and waste [7]. Also environmental benefits arising from the adoption of AD have been extensively reported in the literature. As example benefits arising from the agronomic exploitation of digestate was investigated by [8-10]. On the other hand [11] found that for the Danish context anaerobic digestion of OFMSW gave a higher net avoidance of GHG compared to incineration. These findings are in accordance with those of [12,13] concerning the AD of OFMSW compared to incineration in Singapore and Uppsala (Sweden), respectively. On the contrary, a similar study performed by [14] for an Italian waste management district gave opposite values, confirming the importance of taking the energetic context into consideration in environmental analysis studies. These findings highlight that there is a lack of knowledge on global energetic and environmental benefits achievable by AD and on which resulted the most suitable substrate. The present study aims to investigate the energetic and environmental consequences arising from the substitution of energy crops with bio-waste in an existing AD facility. The study was implemented on the basis of full-scale and experimental data using also a LCA approach.

2. Materials and methods

The comparative study was performed between two different scenarios. The first consisted in the separate treatment of OFMSW by composting and energy crops by AD. In the modified scenario the OFMSW was used for fully replacement of the energy crops in the existing AD.

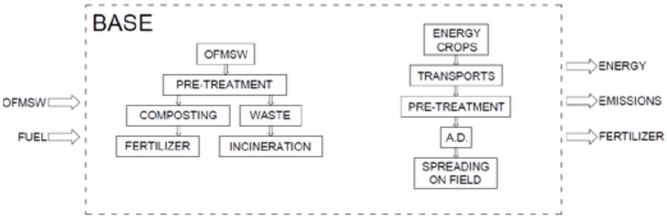

Fig. 1. System boundaries and flow chart of the base scenario

Table 1. Main features of the composting facility (2016)

Parameter	Amount	Unit
OFMSW	23,000	Mg
Waste	6,210 to incineration	Mg
Energy consumption	920	MWh
Energy from incineration of waste	300	kWh/Mg
N	14	kg/Mg compost
P_2O_5	6.74	kg/Mg compost
KO_2	19.3	kg/Mg compost
C_{sink}	201	kg/Mg compost

2.1 Base scenario

In the current scenario (Fig. 1) the 23,000 Mg/year of OFMSW are processed in an existing composting facility for recycling aims by the production of an organic fertilizer. Waste generated by this process, about 6,200 Mg were incinerated with energy recovery. As already reported in [14] considering the bio-waste composition and the average electrical efficiency of main incineration facilites operating the amount of energy recovered from the incineration of 1 Mg of Bio-waste resulted of about 300 kWh/Mg. Main features concerning this scenario are reported in Table 1.

Table 2. Main features of the AD facility (2016)

Parameter	Amount	Unit
Maize	6,332	Mg
Sorghum	5,802	Mg
Triticale	3,740	Mg
Alfalfa	1,793	Mg
Fuel for crops	69	Mg
Fuel for transport on fields	82	Mg
Fuel for spreading	23	Mg
Fuel for plant manag.	14.5	Mg
Fertilizer 60% N	155	Mg
40% diammonium phosphate		
Net energy	7,738	MWh
N	0.34	kg/m^3 digestate
P_2O_5	0.05	kg/m^3 digestate
KO_2	0.28	kg/m^3 digestate
C_{sink}	1.46	kg/m^3 digestate

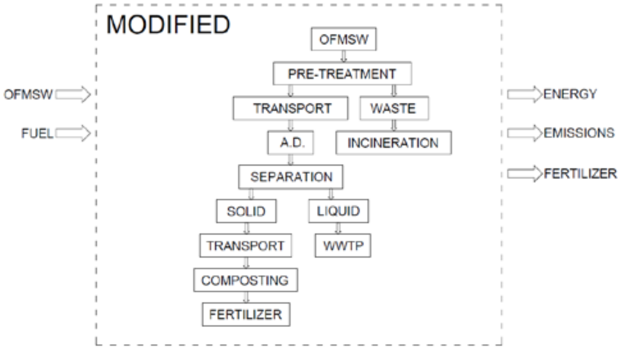

Fig. 2. System boundaries and flow chart of the modified scenario

On the other hand the AD facility, located about 50 km far from the composting one, processed about 17,700 Mg/year of energy crops (Table 2) generating about 4,000,000 m^3/year of biogas and about 8,000 MWh of electricity. AD digesters are of wet type operated with TS of about 9%. For diluting energy crops a given amount of digestate is recirculated after solid liquid separation. Both solid and liquid digestate are used as feriliazers.

2.2 Modified scenario

The modified scenario (Fig. 2) consisted in the substitution of the energy crop with the OFMSW for feeding the AD. After adequate pre-treatment the OFMSW is transported by truck to the AD (Table 3). Also in this case the waste generated by the pre-treatment, about 6,200 Mg, are incinerated with energy recovery. The resulting digestate is firstly separated in solid and liquid fractions, then the solid fraction is transported back to the composting facility. OFMSW is diluted up to 9%TS by a given amount of the liquid fraction of the digestate. The remaining amount is moved to waste water treatment plant (WWTP) located 130 km far.

Table 3. Modified scenario mean features

Parameter	Values	U.M.
OFMSW	23,000	Mg
Waste to incineration	6,210	Mg
OFMSW Pre-treat.	50	kWh/Mg
Solid digestate	0.909	Mg/Mg
Liquid digestgate to WWTP	0.091	Mg/Mg
Fuel for transports	68	Mg

2.3 Bio methane potential

Data related to the biogas generated and to the amount of energy recovered by AD of energy crops were referred to the year 2016 (Table 2). Otherwise the energetic potential of the OFMSW was determined by experimental tests. OFMSW was withdrawn in different period from the existing composting facility then ground after bulky materials removal. The bio-methane yield (BMP) (NLCH4/kgVS) was determined, on fresh OFMSW by digesting 100 ml of each substrate in 500 ml anaerobic bottles. TS concentration was maintained ≤4% w/w by dilution with demineralized water, if necessary. For the BMP test, inoculation was carried out with 300 ml of digestate (Table 4) coming from the full-scale digester in order to maintain a VS of inoculum to VS of substrate ratio of about 2. Anaerobic batch reactors were flushed with nitrogen before starting the run and shaken manually one time each day during the test. Bio-methane was determined by adopting a volume displacement system with a solution of 2N NaOH in demineralized water for CO_2 capture. The contribution of inoculum to bio-methane production was evaluated by the same method. All BMP runs were performed in triplicate in a controlled temperature chamber at a temperature of 35°C±2°C. TS (% w/w) and consequently moisture content (MC) (%w/w) were determined by measuring weight loss after heating at 105°C for 24h. VS (% TS) was determined by measuring the change in weight of TS after burning at 550°C for 24 h.

Table 4. Inoculum and OFMSW characterization

Parameter	Inoculum	OFMSW
TS (%w/w)	3.46	26.6±0.09
VS (%w/w)	86.2	90.3±0.03
pH	6.78	4.43±0.51
C (%TS)	39.5	43.7±3.67
N (%TS)	-	2.88±1.13
BMP ($NLCH_4$/kgVS)	-	523±95

2.4 Environmental analysis

From the environmental point of view the goal of the present study was to compare two different scenario. In the first scenario 23,000 Mg of OFMSW and 17,667 Mg of energy crops were processed separately by composting and AD, respectively (Fig. 1). In the second scenario the 23,000 Mg OFMSW substituted completely the energy crops in the AD facility (Fig. 2). System boundaries were expanded for taking into account multifunctionality of the systems and the life cycle inventory (LCI) framework was consequential. Background were represented by OFMSW, fuels and mineral fertilizers. Foreground were represented by energy, nutrients and emissions. LCI was retrieved from Ecoinvent 3.0 database [15] (Wernet et al., 2016) and adjusted on the basis of the experimental and direct observed data. Foreground were not able to influence the background for which average market values were used. In accordance with [16], natural gas was considered as marginal energy consumed or substituted with the one generated by AD and incineration. Main greenhouses emissions considered in the calculation of the GWP for the main activities and processes analysed were reported in Table 5. Larger specific emissions of $CO_{2,biogenic}$ were due to AD and WWTP with 2.73 (kg/m^3) and 2.085 (kg/m^3), respectively. Similarly larger specific N_2O and CH_4 emission, with a respective GWP of about 300 and 23 times higher of CO_2, were generated by WWTP

Table 5. Main greenhouses emissions from the processes analyzed.

Emission	AD (kg/m^3)	Compost (kg/kg)	Land spreading of digestate (kg/kg)	WWTP (kg/m^3)
$CO_{2biogenic}$	2.73	0.52	0.752	2.085
$CO_{2fossil}$	-	0.00843	0.051	-
N_2O	3.25E-4	0.000281	0.000182	0.0113
CH_4	2.78E-2	0.0101	-	0.0546
CO	-	0.00128	-	0.0185

2.4.1 Impact assessment method

As impact assessment method was used ILCD 2011+ midpoint [17]. Impact categories were (Table 6): Global Warming Potential at 100 years (GWP); Ozone Depletion Potential (ODP); Human toxicity, non-cancer effects (HTnc); Human toxicity, cancer effects (HTc); Particulate matter (PM); Photochemical Ozone Formation (POF); Acidification (A); Eutrophication Terrestrial (ET); Fresh Water Eutrophication (FWE); Fresh water ecotoxicity (FWec); Water resource depletion (WRD); Mineral, fossil and renewable Resource Depletion (RD). For obtaining an impression of which of the impact categories was most affected by the scenarios considered, normalization factors of the EU 27 domestic extraction of resources and emissions per person with respect to the year 2010 were used. Together with these impact categories also the cumulative energy demand (CED) (kWh) was quantified. This parameters represents the direct and indirect energy use through the life cycle including the energy consumed during the extraction, manufacturing and disposal of the raw and auxiliary materials [18]. Also an avoided CED was calculated on the basis of the energy recovered in the two scenario (i.e. AD and incineration). Primary energies considered by CED were grouped in non-renewable and renewable (Table 7), depending on the specific industrial process considered.

Table 6. Impact assessment categories.

Imp.cat.	Unit	Norm. f. EU27 (2010)	Unit
GWP	kgCO_2 eq.	1.10E- 04	kgCO_2 eq./a.
ODP	kgCFC-11 eq.	46.3	kgCFC-11 eq./a.
PM	kgPM2.5 eq.	2.63E -01	kgPM2.5 eq./a.
POF	kgNMVOC eq.	3.15E -02	kgNMVOC eq./a.
A	molc H^+ eq.	2.11E -02	molc H^+ eq./a.
ET	molc N eq.	5.68E -03	molc N eq./a.
FWE	kg P eq.	6.76E -01	kg P eq./a.
RD	kg Sb eq.	9.9	kg Sb eq./a.

Table 7. List of primary energies accounted for the cumulative energy demand (CED) calculation.

Energy group	Subcategory	Primary energy included
Non-renewable	Fossil	Har coal, lignite, crude oil, natural gas, coals mining off-gas, peat
	Nuclear	Uranium
	Primary forest	Wood and biomass from primary forest
Renewable	Biomass	Wood, food products, biomass from agriculture
	Wind	Wind energy
	Solar	Solar energy 8heat and electricicy)
	Geothermal	Geothermal energy (100-300m)
	Water	Run-of-river hydro power, reservoir hydro power

3. Results and discussion

In the base scenario the amount of electrical energy recovered from AD of energy crops and from incineration of waste from OFMSW pre-treatment were 7,738 MWh and 1,863 MWh, respectively. In the modified scenario the amount of energy recovered from the AD of OFMSW resulted of 4,109 MWh whereas the amount of energy recovered from incineration of waste from OFMSW was the same of the base scenario.

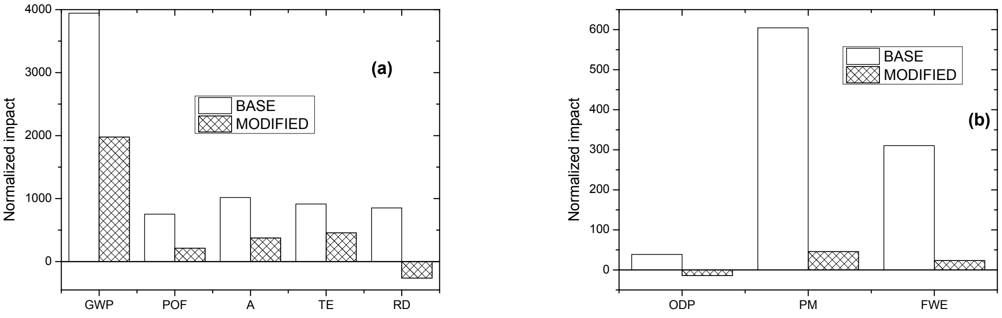

Fig. 3. Normalized values of GWP, POF, A, TE and RD (a) and ODP, PM and FEW (b).

Normalization procedure performed by dividing the values of the different impact categories by the correspondent normalization factor (Table 1) highlighted that the impact category most affected by the two scenarios was GWP.

From the environmental point of view the modified scenario showed lower level of impact (Figs. 3) and in some cases as for RD and ODP avoided impacts. Fuel consumption and mineral fertilizer production were the main causes of the higher PM value detected for the base scenario (Fig. 3b). Process emissions were the main causes of the high values detected for the GWP (Fig. 3a). As expected CED resulted higher for the base scenario (Fig. 4a). By the way, for giving an impression of global energetic benefits, also the avoided CED was calculated on the basis of the amount of energy recovered in the two scenarios (*i.e.* 9,600 MWh for the base and 5,972 MWh for the modified) (Fig. 4a). The higher biogas production per Mg of energy crop compared to the OFMSW was the main reason of the higher CED avoided detected for the base scenario.

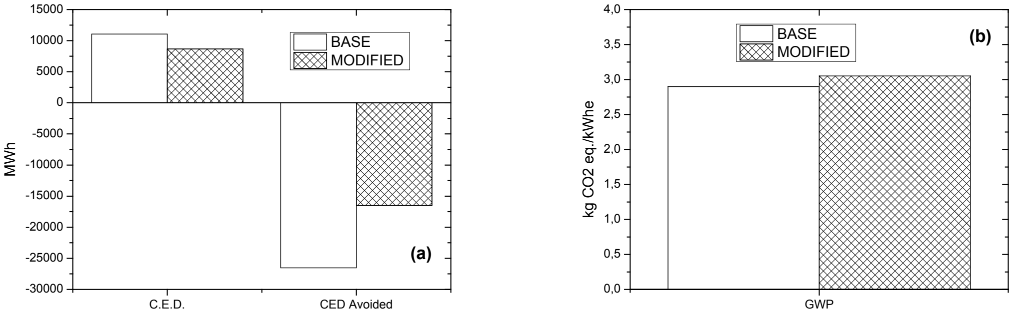

Fig. 4. CED and CED avoided (a) and specific GWP (b) for the base and modified scenarios

Similarly for giving an impression of the carbon footprint of the energy generation by the two scenario the specific GWP ($kgCO_{2eq}/kWh$) was also calcualted (Fig. 4b). Resulted showed that $kgCO_{2eq}/kWh$ resulted practically similar for the two scenarios, indicating a substantial similitude from this point of view.

4. Conclusion

Economic sustainability of existing anaerobic digestion (AD) facilites feed with energy crops will represent a serious problem to be faced at the end of the economic support period. Among the different possibilities under study the one represented by the total or partial replacement of energy crops with other substrate is among the most investigated. In particular replacing of energy crops with bio-waste resulted of particular interest since the possibility of total or partial integration of the economic incentives with the bio-waste treatment fee. By the way the replacement of such substrates implies also a modification of the legal framework under which the plant operates from the biomass to the waste one. For this reason it is of mandatory relevance the investigation of possible environmental benefits arising from this modification in particular for public authorities charged to release the necessary authorizations. The result of the present study, focused on a real case analysis, indicates that the replacement of energy crops with bio-waste leads to a general reduction of the different impact categories exploited for the life cycle analysis. On the other hand the lower amount of energy and of organic fertilizer recovered by the facility after the replacement of energy crops with bio-waste reduces the avoidance of primary energy sources consumptions compared to the base scenario. On the other hand the global warming emissions of the two scenarios referred to the single unit of electrical energy generated ($kgCO_{2eq}/kWh$) resulted practically similar.

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