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CARBON FOOTPRINT OF ELECTRICITY FROM ANAEROBIC DIGESTION PLANTS IN ITALY

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Abstract

In the context of biogas sustainability assessment, a promising way to reach greenhouse gases (GHG) reduction and fossil energy savings is the anaerobic digestion (AD) of both animal manure and energy crops.
Nowadays, more than 1,100 AD plants are working in Italy, mostly located in Northern Regions. To those plants with an electrical power lower than 1 MW, strong public incentives were given, therefore, several of them have been put into operation; this entailed increasing cereal silage prices, feedstock transportation distance and issues about digestate management and heat valorization.
In this study the Carbon Footprint (CF) of electricity production from biogas has been evaluated considering five AD plants located in Lombardy and Piedmont. A Life Cycle Assessment (LCA) approach and a cradle-to-grave perspective have been considered. Different plant sizes (100, 250, 300, 300 and 998 kW) and feeding rate (maize and pig slurry, only maize, only pig slurry and only cow slurry) have been studied.
The CF was calculated for a 100-year time frame based on GHG emissions, indicated as mass of CO_2 equivalents (kg CO_2eq), according to IPCC. The Functional Unit (FU) is 1 kWh of electricity fed into the electric grid. The CF saving for electricity produced by the AD plants ranges from -0.208 to -1.07 kgCO_2eq/kWh, being mainly related to the substitution of energy production from fossil fuel. Electricity from biogas has a big potential to reduce GHG emissions: valorization of surplus heat and reduction of transport distance can support the lower GHG emissions achievement of this bioenergy system.

Key words: anaerobic digestion, climate change, Greenhouse Gases, renewable energy, LCA

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1. Introduction

The interest in Renewable Energy Sources (RES) has strongly increased due to the need of reducing fossil energy consumption and Green Houses Gases (GHG) emissions. Considering that the profitability of food crops is generally decreasing (Bacenetti et al., 2015a), RES represent a good opportunity for the agricultural sector. Within the "Green Economy" context, Common Agricultural Policy (CAP) highlights both the need to contrast environment alteration and the RES development as the main challenges for the agricultural sector (De Cara et al., 2005, Mateescu et al., 2008). In particular, the micro-energy generation model (small-size and widespread plants) is suggested to achieve the "multi-functionality" of the modern agriculture as well as to improve the farmer's income (Bacenetti et al., 2013b; Duan et al., 2014; Li et al., 2012; Wu et al., 2014). At the moment, in Italy, biogas production from agricultural biomass is having a strong appeal on farmers who are looking for diversifying their income sources. In fact, to the electricity generated through Anaerobic Digestion (AD) of biomass, strong public subsidies are applied.

In this context, the production of energy from biomass represents an interesting business-opportunity for many livestock farms; actually, they

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can: (i) directly manage the whole add-value coming from energy production, and (ii) sell their whole production (electricity) to a single customer (grid company), at a fixed rate, for a long-period (15 years), which explains the, significant agricultural biogas production increase in the last two decades. At present, more than 1,100 agricultural biogas plants are operating, mainly located in northern regions of Italy. At the end of 2012, the installed power was 756 MW: nearly 1.65% of Italian electricity consumption was generated in agricultural biogas plants (Bacenetti and Fiala, 2014; Negri et al., 2014).

However, biogas production can generate significant impacts to the environment, especially focusing on global warming, acidification, eutrophication, etc. For this reason, environmental sustainability and performance of biogas production systems were object of numerous studies and researches (Hoppe and Sanders, 2014; Li et al., 2012; Wu et al., 2015). In particular, special attention has been paid on Carbon Footprint (CF) related to the electricity (EE) produced by AD plants (Dressler et al., 2012; Lijó et al., 2014a, 2014b; Meyer-Aurich et al., 2012; Rehl and Muller, 2013; Tricase and Lombardi, 2012).

The goal of this study is to estimate, using a Life Cycle Assessment approach, the CF of EE co-generated in 5 CHP (Combine Heat and Power) systems fuelled with biogas produced in AD agricultural plants fed with different agricultural feedstock. The AD plants have been selected considering feeding: in more details, to better highlight the impact of the different feedstock, four of the five selected AD plants are mainly fed with animal wastes (pig and cow slurry). The CF of these plants, characterized by low electrical power (maximum 300 kW), is compared to that of the electricity produced from fossil fuel but also to the CF of the 5th AD plant fed only with maize silage. Although several studies highlighted that environmental benefits are achieved from AD, only few researches in Italy have focused the attention on AD plants fed with by-products (Bacenetti et al., 2015b; Battini et al., 2014). In fact, given the subsidy framework, the major part of AD plants are fed with cereal silages and have an electrical power close to 1 MW. Although in Italy there are several natural gas fuelled cars, the attention of this study was paid on electricity generation because this is by far the most widespread utilization pathway for the biogas produced by agricultural AD plants. Due to the lack of a proper and clear legislation, the development of the "bio-methane sectors" is limited to few pilot plants.

2. Case studies

2.1. Process description

The analysis considers a cradle-to-grave system boundary; therefore, all the processes (and the related inputs) involved throughout the life cycle have been taken into account: (i) energy crops production, (ii) feedstock transport to the biogas plant, (iii) anaerobic digestion and biogas use, and (iv) digestate storage and management. Information concerning the agricultural biogas plants and the feedstock digested are reported in Table 1.

In more details:

i) **Plant A** – **Pavia 1** has an electrical power of 300 kW; it is located in Pavia district (Lombardy), has 2 digesters (1 for the storage of digestate) and is fed with maize silage produced on farm and pig slurry coming from nearby breeding farms.

ii) **Plant B – Lodi** has an electrical power of 250 kW; it is located in Lodi district (Lombardy), has 2 digesters (1 for digestate storage) and digests pig slurry only, produced on farm.

iii) **Plant C** – **Pavia 2** has an electrical power of 300 kW; it is located in Pavia district (Lombardy), has 2 digesters (1 for digestate storage) and is fed with pig slurry and maize silage.

iv) **Plant D** – **Cremona** has an electrical power of 100 kW, is located in Cremona district (Lombardy Region), has 2 digesters (1 for digestate storage) and is only fed with cow slurry.

v) **Plant E** – **Novara** has an electrical power of 998 kW, is located in Novara district (Piedmont), has 4 digesters (2 for digestate storage) and digests only maize silage.

The biogas-to-electricity process can be divided into:

i) Subsystem 1 - Feedstock: it includes maize cultivation and harvest as well as pig slurry transport. Table 2 reports details about maize cultivation.

ii) Subsystem 2 - Transport and storage: it includes maize transport and ensiling and slurry transport and storage at the biogas plant. Both pig and cow slurries are transported by means of slurry tanks; distances between the breeding farm and the digesters are 0.8, 2.2, 3.0 and 0.3 km for Plant A, B, C and D, respectively, whereas in Plant E no slurry was transported.

iii) Subsystem 3 – Energy production: the conversion of feedstock into biogas and of biogas in energy (electric energy - EE- and thermal energy - ET) has been considered. Table 3 reports further details concerning the microbiological biogas production inside digesters. Among the different feedstock, maize silage shows the highest dry matter content and, consequently, the highest biogas production. Between the animal wastes, cow slurry has a dry matter content 2.5 times higher than pig slurry and, approximately, a 2 times higher methane production.

Fig. 1 shows the system boundaries for the five biomass-to-energy processes. The animal slurry production has been excluded from the system boundaries due to the fact that it is a waste belonging to the pig meat and cow milk production processes.

2.2. Data collection

Background data for the production of seeds, diesel fuel, fertilizers and pesticides were obtained from the Ecoinvent Database (Ecoinvent Database, 2015; Frischknecht et al., 2007; Nemecek and Käggi, 2007; Spielmann et al., 2007).

Data concerning the agricultural AD plants running parameters (e.g. biomass consumption, biogas production, EE and ET self-consumptions), were obtained through daily direct monitoring over 12 months (from September 2012 to August 2013), gathering the following information:

i) feedstock consumptions (t/day);
ii) temperature inside the digester (°C);
iii) organic loading rate ($kg_{VS}/m^3 \cdot day$);
iv) biogas production and composition (m^3/day; CH_4 % vol.);
v) gross EE production, EE self-consumption and net EE production (kWh per day).

In the five AD plants assessed, biogas losses were considered, both from digesters and biogas treatment devices (1.0%) and from the CHP (0.5%) (Dressler et al., 2012).

Emissions data from biogas combustion in Combined Heat and Power (CHP) devices are assumed from National Environmental Research Institute (NERI, 2010).

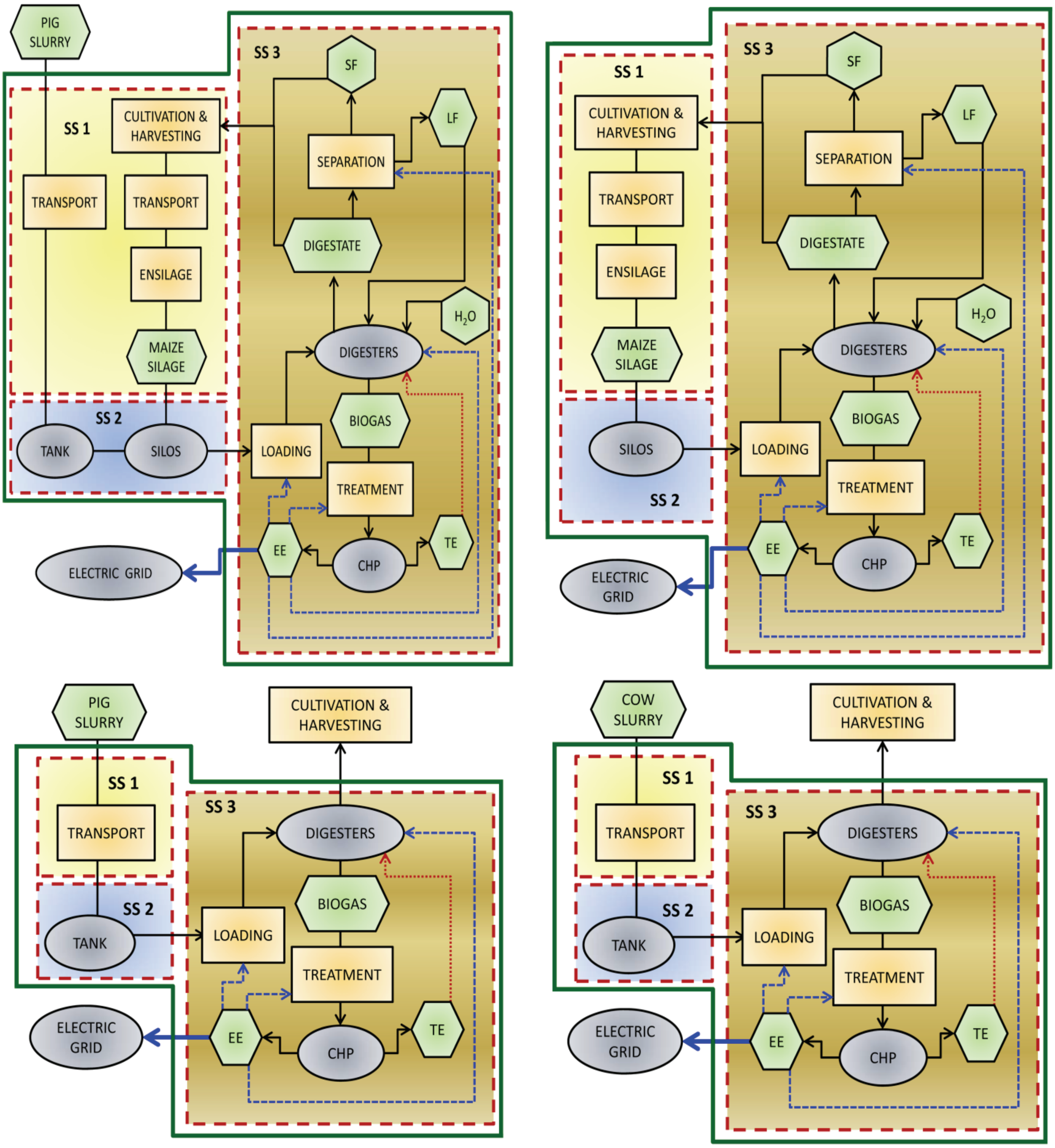

Fig. 1. Biomass-to-electricity process for the five agricultural biogas plants: on the top: plant A&C (left) and plant E (right); on the bottom plant B (left) and plant D (right). Green lines are the system boundary; red lines are the sub-subsystems boundary. (SS1 = Feedstock production and recovery; SS2 = transport and storage; SS3 = Conversion; EE = electricity; TE = heat)

Table 1. Main technical data for the five biogas plants

Biogas plant	*Engine power*	*Electric efficiency*	*Thermal efficiency*	*Maize silage*	*Pig slurry*	*Cow slurry*
	kW	*%*	*%*	*t/day*	*t/day*	*t/day*
A - Pavia 1	300	39.0	50.8	14	45.0	0
B – Lodi	250	36.0	50.5	0	175	0
C – Pavia 2	300	38.6	49.5	13	35	0
D - Cremona	100	35.0	48.0	0	0	33.0
E – Novara	998	40.9	44.0	55	0	0

Table 2. Maize cultivation: field operations and the production factors

Field operation	*Means*	*MECHANIZATION*						
		Tractor 4WD + Machines	*Mechanical Power*		*Field Capacity*	*Diesel Consumpt.*	*APP. rate*	*Times*
			TR[a]	*OM*[a]				
			(kW)		*(ha/h)*	*(kg/ha)*		
Cutting up field sides	-	Rotary tiller	74	35	2.0	4.18	-	1
Organic fertilization	Solid Fraction (SF) of digested matter	Front loader, 2 m^3	100	25	0.1	3.65	-	1
		Manure spreader 20 m^3	132	55	0.5	27.21	15 t/ha (N slurry content = 8.60 kg/t)	1
Ploughing	-	Four-furrow plough	180	110	1.3	22.61	-	1
Harrowing	-	Rotary harrow 4 m	130	85	0.8	23.69	-	1
Precision seeding	Seed	Precision seeder (8 lines)	100	70	1.0	13.4	11 kg/ha	1
Soil sanification	Chemical						12 kg/ha	
Local fertilization	Diammonium phosphate [b]						200 kg/ha	
Pre-emergence weed control	Herbicide	Sprayer 3 m^3	74	40	2.5	3.52	4 kg/ha	1
Post-emergence weed control	Herbicide (mix)	Sprayer 3 m^3	74	40	2.5	3.52	1.6 kg/ha	1
Top fertilization	Urea	Fertilizer spreader 1 m^3	74	50	2.0	6.06	210 kg/ha	1
Irrigation	Water	Pump + sprinkler system	100	70	0.5	22.4	400-500 m^3/ha	3
Harvest	-	Self-propelled forager	-	300	1.0	76	-	1

[a]TR = tractors, OM = operative machines; [b]= Typical formulation is 18-46-0 NPK

Table 3. Feedstock characteristics

Feedstock	*Total Solid Content (TS)*	*Volatile Solid Content (VS)*	*Specific biogas production*	*Methane content*
	% of fresh matter	*% of total solid*	*m^3/t of VS*	*%*
Maize silage	33.0	90.0	650	60.0
Pig slurry	3.5	85.0	450	53.0
Cow slurry	9.0	83.0	325	58.0

3. Methodology

The Carbon Footprint of EE produced from the different agricultural biogas plants was calculated for a 100-year time frame based on GHG emissions indicated as CO_2 equivalents (eq) (IPCC, 2006). The Functional Unit (FU) is 1 kWh of electricity fed into the electric grid.

The software Simapro® was used to organize and process data. GHG emissions were calculated according to the following 100-years factors expressed in kg CO_2 equivalents, CO_2: 1; CH_4: 25; N_2O: 298 (IPCC, 2007). The GHG emissions (EM_{GHG}; (kg CO_2eq/kWh electrical) derived from the proposed bioenergy processes have been calculated considering that - in accordance with the guidelines of IPCC (2006) - the CO_2 removed from the atmosphere through photosynthesis offsets the CO_2 released during Anaerobic Digestion and biogas combustion. The Carbon Footprint of EE generated from biogas derives from a balance between GHG emissions that occur during the bioenergy process and credits that can be attributed to it (e.g., for the substitution of energy production from fossil fuels, avoided GHG emissions from the storage of animal slurry in open tanks, etc.).

The considered GHG emissions are connected to:

i) maize silage production (Plants C and E) and animal slurry recovery (Plants A, B, C and D);

ii) energy and materials consumption -in addition to feedstock- that occurs in Subsystem 3 (diesel fuel for maize silage loading, lubricants for CHP, additive substances for digesters, EE for plant self-consumption). Considering that the ET self-consumption of plants are met by CHP, no emissions have been considered for heat generation;

iii) methane losses from digesters, pipes, biogas treatments devices and CHP utilization. Due to high GWP of CH_4, these losses -although small- have a strong impact on environmental performances of the process.

Emissions of GHG due to the production of both farm equipment (e.g., tractors, machines) and biogas plant and infrastructure (e.g., roads and trucks) were not included in the system boundaries. For these production factors, Hartmann (2006) reported a small contribution (4% approximately of the total GHG emission).

Background data for the production of seed, diesel fuel, fertilizers, pesticides as well as for transport were obtained from the Ecoinvent database v.3 (Ecoinvent, 2015).

Emissions from digestate were not considered because of the use of covered tanks.

To the biogas system are attributed credits for:

i) the substitution of the EE otherwise produced mainly using fossil fuels. In more details, the EE from biogas replaces the production of the same amount of electricity produced with the Italian mix of energy sources. Therefore this EE has been credited with the GHG emissions that characterize the actual Italian electricity production (currently, 541.7 g CO_2eq/kWh);

ii) the substitution of ET otherwise produced using fossil fuels. In more details, considering that plant self-consumption is covered by CHP, these credits are granted only for the net thermal energy cogenerated;

iii) the avoided GHG emissions due to anaerobic digestion of animal wastes. AD of slurry reduces CH_4 emissions compared with an uncovered storage tank (IPCC, 2006); in accordance with Lansche and Müller (2012), it has been assumed that these avoided emissions from animal slurry are equivalent to 16% of the potential biogas production. More details about the calculations of these credits are reported by Bacenetti et al. (2013a). With regard to the effect of AD credits on the CF, a sensitivity analysis has been carried out (alternative scenario 2).

Credits due to the mineral fertilizers replacement - the digestate is used as organic fertilizer at the end of the process - have not been considered because: (i) in biogas Plants A and B the digestate is completely spread on maize fields and, (ii) in biogas Plants C and D, the amount produced by the animal slurry is used as fertilizer in fodder production and, hence, is excluded from the analysis because it would be spread also in absence of the biomass-to-energy process.

3.1. Alternative scenarios

In addition to Base Scenario (BS), three Alternative Scenarios (AS1 and AS2) have been proposed and evaluated in this report. In AS1, the impact of heat valorization has been assessed using the credit approach; the credits were attributed to the biomass-to-energy process, assuming the full valorization of ET produced by CHP net thermal energy (Tashima et al., 2014).

The heat is credited considering the GHG emissions entailed in a fossil-based energy generation plant (0.226 kgCO_2eq/kWh thermal) (Capponi et al., 2012). In AS2 no credits for AD have been taken into account in order to assess their impact on CF.

4. Results and discussion

Fig. 2 shows the results for the five agricultural AD plants and for BS, AS1 and AS2. In baseline scenario (BS) the CF of electricity produced from biogas ranges between -0.208 kgCO_2eq/kWh to -0.930 kgCO_2eq/kWh. The differences are mainly due to the credits attribution and, secondarily, to feedstock production and recovery. The lower values of CF are achieved in the AD plants fed with animal slurries (Plants A, B, C and D) and, consequently, credited with high credits for AD of animal slurry. Without the accounting of credits for AD (AS2), the CF varies from -0.263 kgCO_2eq/kWh for the Plant C (Lodi, fed with pig slurry) to -0.476 kgCO_2eq/kWh for the Plant E (Novara fed only with maize).

The considerable differences between the two AD plants fed only with slurry (B and D) are due to the transport distance: in Plant D the slurry is available on the farm, while in Plant B it must be transported for 3.0 km. With regard to GHG emissions, it must be underlined that in all the AD plants about 20% of the total is due to methane losses. The comparison among the different scenarios highlights that, with respect to the BS:

i) the attribution of credits for heat valorization entails a reduction of CF. This reduction is lower for Plants B and D that are fed only with animal slurry and, consequently, characterized by a higher heat self-consumption. On the contrary, Plants C and E -mainly fed with energy crops- digest feedstock with a high energy density, have a lower heat consumption and, consequently, more credits for heat valorization;

ii) the credits for AD of animal slurry have a strong impact on the CF for the Plants (A, B and D) where the digesters are fed with a high amount of these feedstock. In BS, these credits represent 66%, 75%, 47% and 51% of GHG savings, respectively for biogas plant A, B, C and D.

The CF differs considerably between the biogas plants fed with maize silage (C and E) and the ones in which slurries are utilized (A, B and D). The feeding of the digesters with slurries involves high thermal self consumption and, therefore, low credits for heat valorization; furthermore, when these feedstock are transported high GHG emissions occur.

The results are similar for the ones recorded by previous studies (Bacenetti et al., 2012; Bacenetti et al., 2013b; Bachmaier, 2010; Lijó et al, 2014a, 2014b; Meyer-Aurich et al., 2012; Pöschl et al., 2010; Poeschl et al., 2012; Szabó et al., 2014; Schumacher et al., 2010), which show that EE from biogas is an effective solution to reduce GHG emissions. Moreover, the utilization of the cogenerated heat can substantially improve the CF of electricity production from biogas. Further improvements can be achieved by using animal waste as feedstock. Animal slurry as feedstock can partially substitute energy crops and avoids GHG emissions from undigested manure. However, compared with cereal silages, the use of animal slurry involves higher thermal energy self-consumption for heating the digesters and, consequently, lower credits are available for heat valorization.

4.1. Sensitivity analysis

Considering that the credit granted for the substitution of EE produced from fossil fuels has a deep impact on CF of EE produced in the 5 agricultural biogas plants, a sensitivity analysis was carried to this regard. In more details, CF has been assessed considering the possibility that, in addition to the Italian electric mix, the EE from biogas replaces the electricity produced from different fossil sources (coal, natural gas and oil) and from different technologies (e.g., combined cycle plant). The CF of electricity from coal, natural gas and oil have been taken from the Ecoinvent database (Ecoinvent, 2015). Table 4 shows the results of the sensitivity analysis.

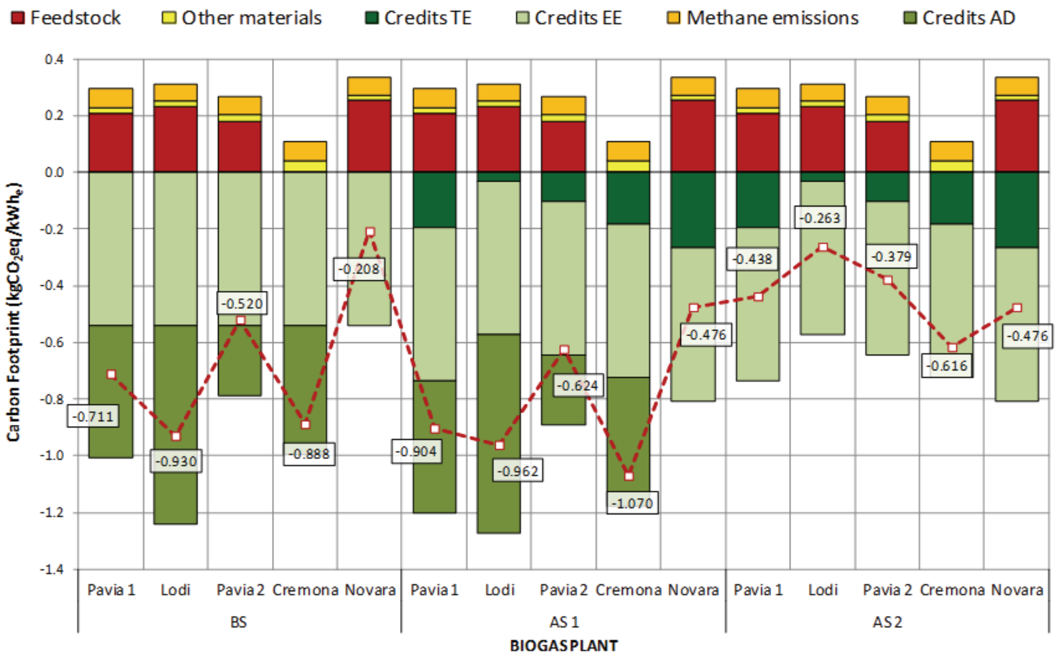

Fig. 2. Carbon Footprint for the five considered agricultural biogas plants, under different scenarios (BS, AS1 – credits for thermal energy valorization and AS2 – no credits for anaerobic digestion of animal slurries)

Table 4. Results of the sensitivity analysis: absolute and comparative (with respect to Baseline Scenario – BS) values

CASE	***Unit***	***BIOGAS PLANT***				
		Pavia 1	***Lodi***	***Pavia 2***	***Cremona***	***Novara***
Electricity mix ITA (BS)	kg CO_2eq/kWh	-0.711	-0.930	-0.520	-0.513	-0.208
Coal	kg CO_2eq/kWh	-1.204	-1.418	-0.921	-0.819	-0.696
	% respect BS	169%	152%	177%	160%	335%
Natural gas “combined cycle plant”	kg CO_2eq/kWh	-0.421	-0.813	-0.316	-0.214	-0.091
	% respect BS	59%	87%	61%	42%	44%
Oil	kg CO_2eq/kWh	-1.054	-1.268	-0.771	-0.669	-0.546
	% respect BS	148%	136%	148%	130%	263%
Natural gas “old technology”	kg CO_2eq/kWh	-0.833	-1.047	-0.550	-0.448	-0.325
	% respect BS	117%	113%	106%	87%	156%

As expected, the replacement of EE produced from different fossil fuels affects the CF of EE from biogas: the more the GHG emissions of the replaced EE are high, the more the CF of electricity from biogas is interesting (higher GHG savings). The highest benefits are achieved when EE from biogas replaces electricity from coal and oil. As regard to electricity from natural gas, it is interesting to underline that, when electricity produced from natural gas in combined cycle plants is substituted, the CF of EE from biogas shows lower GHG savings with respect to the baseline scenario.

5. Conclusions

In this study, we evaluated the carbon footprint (CF) of five agricultural biogas plants characterized by different electrical power and fed with different feedstock. The results showed that electricity production from biogas has huge potential to reduce GHG emissions.

The results highlight the environmental sustainability of anaerobic digestion based on agricultural feedstock as a bearable solution to produce electricity: for all biogas plants evaluated, the CF of EE is negative. Nevertheless, it should be underlined that the favorable CF of biogas bioenergy process is mainly related to the credits obtained from the substitution of electricity generation from fossil fuels. In fact, the biogas process does not sequestrate GHG but it just produces EE substituting the current technology characterized by high GHG emissions. To further improve the environmental sustainability of this bioenergy production process, slurry transport must be minimized and as much as possible of the surplus heat should be valorized substituting heat generation from fossil sources. If possible, instead of feeding the AD plants with cereals silage, they should be fed with animal slurries and agro-food industry by-products. Actually, considering that intensive livestock activities are carried out in some Italian areas (e.g., Lombardy, Emilia Romagna, etc.), there is still availability of animal slurries for biogas production scopes. Therefore, in order to improve the CF of EE from biogas, until this last condition occurs, the feeding with cereals silage and other feedstock from energy crops should not be subsidized, above all in case of new agricultural AD plants.

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