Modeling and Analysis

Greenhouse gas emissions of electricity and biomethane produced using the Biogasdoneright™ system: four case studies from Italy

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Abstract: We reported previously on the Biogasdoneright™ system for on-farm biogas production. This innovative system employs sequential (year-round) cropping to produce both food and energy from agricultural biomass, primarily cellulosic materials. This paper uses a marginal analysis approach to estimate the life cycle greenhouse gas emissions (GHGs) of electricity and biomethane produced by four currently operating Italian biogas plants that process various agricultural feedstocks, residues, and by-products. The biogas is burned on-farm to generate electricity that is then exported to the grid. The marginal lifecycle GHGs of this farm-produced electricity range from -335 to 25 grams CO_2 per kilowatt hour (kWh). By comparison, the marginal GHGs of electricity generated by fossil fuels in the European Union (EU) is 752 grams CO_2 per kWh. The biogas might also be upgraded to produce pipeline-quality biomethane, a direct substitute for natural gas. The marginal lifecycle GHGs of biomethane potentially produced from the Biogasdoneright™ plants range from 10 to -36 grams CO_2 per megajoule (MJ) while the corresponding figure for a conventional biogas plant is 27 grams CO_2 per MJ. Natural gas in the EU produces 72 grams CO_2 per MJ and marginal fossil fuel in the EU generates 115 grams CO_2 per MJ. Negative GHG emissions arise largely from avoided emissions of agricultural effluents and residues. © 2017 Society of Chemical Industry and John Wiley & Sons, Ltd

Supporting information may be found in the online version of this article.

Keywords: anaerobic digestion; biogas; Biogasdoneright™; carbon footprint; greenhouse gas emissions; life cycle assessment

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Introduction

Bioenergy has been criticized as interfering with food production, the so-called food versus fuel argument.[1-5] Furthermore, according to the indirect land-use change (iLUC) theory, bioenergy must be held responsible for the greenhouse gases (GHGs) that are emitted when additional agricultural feedstocks are produced to replace feedstocks used for bioenergy production.[6,7] Some critics of bioenergy note that using existing agricultural feedstocks for energy production does not generate additional carbon savings or carbon sequestration to offset rising atmospheric carbon dioxide levels. In essence, these critics argue that carbon-neutral biofuels are insufficient. Instead, bioenergy should create very large sinks for atmospheric carbon.[8-10]

Without necessarily accepting these objections, our purpose in this paper is to show how it is possible to reconcile all these objections to bioenergy by applying existing technologies that are easily accessible to many farmers. This set of innovations is called Biogasdoneright™ (BDR) and is being practiced by over 600 Italian farmers who are now producing about 1.4 gigawatt of renewable electricity. There is no food versus fuel issue; these farmers are producing food and fuel. There is no mechanism for iLUC because food production continues as before. Finally, additional carbon is produced and some of that carbon is sequestered in the soil in highly stable forms. The BDR system is therefore a bioenergy with carbon capture and storage (BECCS) system.

Local climates and soils, locally available biomass resources, and prevailing food/feed markets define how BDR principles are applied in particular situations, as illustrated here using actual case studies involving four separate Italian farms. Prior to BDR, these farms produced traditional food and feed products, but no energy products. After instituting BDR, these farms continue to produce traditional food and feed products and also grow additional feedstocks to produce biogas via on-farm anaerobic digestion. This raw biogas is burned to produce electricity and exported by the electric grid.

The aim of the study is to assess the carbon footprint of electricity and natural gas produced in three real-case biogas plants operating in different Italian regions and following the BDR system. To quantify the environmental sustainability of the BDR model, these results are compared with a conventional first-generation biogas plant using life cycle assessment (LCA).

Currently these farms only produce renewable electricity. However, biogas might also be upgraded to biomethane and then exported from the farm via the natural gas grid. Unlike the electric grid, the natural gas grid also provides substantial energy storage capacity. The biomass required to support bioenergy production is generated by growing additional biomass on seasonally unused bare land (via double-cropping, also known in the EU as sequential cropping) on the same farms.

The overall BDR approach is illustrated in Fig. 1. Anaerobic digestion, ensiling, and double-cropping are well-established, relatively low-cost technologies with no intellectual property barriers to application. The innovation in this system is to feed the ensiled double crop to the digester and then to return the digestate liquid to the farm, thereby recovering mineral nutrients and recycling very stable carbon to the soil. In addition to the double crop, the digester can also process locally-available byproducts including livestock manures, crop residues and failed crops such as frost-killed or drought-killed immature maize. Digestate liquid also serves as a source of irrigation water during times of drought. Farming for traditional food/feed crops continues as performed prior to BDR.

To illustrate how this is done, Figs 2 and 3 summarize two representative 38-month-long planting cycles that are actually used on these farms. The first planting cycle (Fig. 2) is a conventional farming rotation of traditional wheat, maize, and soybeans. In this particular cycle, the ground is bare about 17 months out of the 38 total months of the cycle, or 45% of the time. The land could be growing something during these months but it is not. Farmers are not growing additional food and feed crops because those food/feed markets are already saturated and depressed. Producing additional food and feed crops would only further depress crop prices. Importantly, the farmer's primary capital asset, land, is not providing any return on investment when the land is bare.

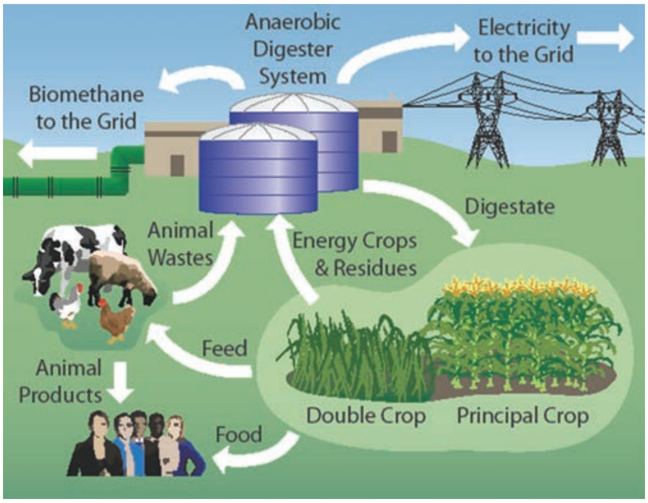

Figure 1: Outline of the Biogasdoneright™ system.

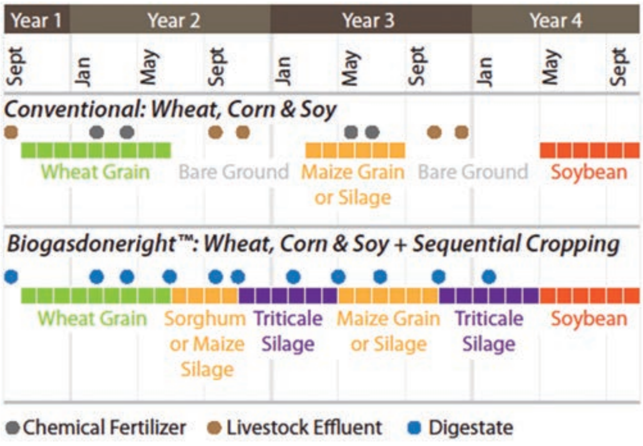

Figure 2. Representative 38-month cropping cycle showing conventional and Biogasdoneright™ cropping systems plus timing of chemical fertilizers, livestock effluents and digestate application.

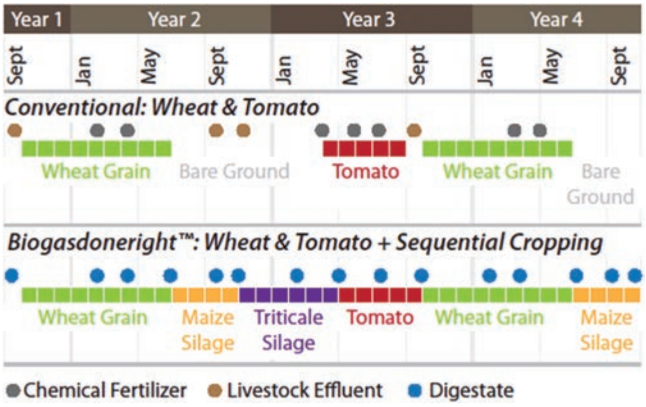

Figure 3. Another representative 38-month cropping cycle showing conventional and Biogasdoneright™ cropping systems plus the timing of chemical fertilizers, livestock effluents and digestate application.

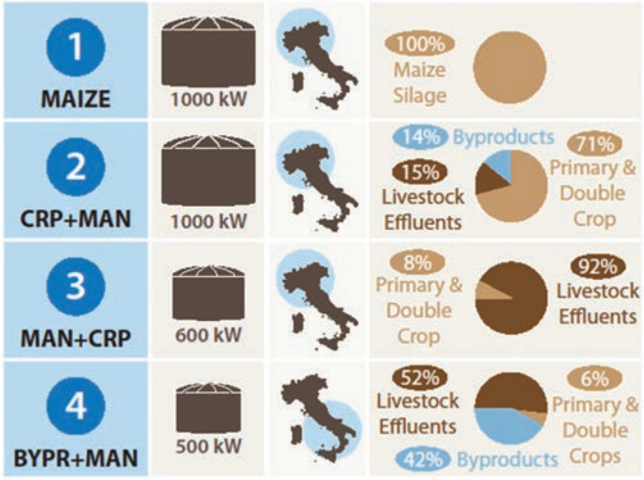

Figure 4. Four Italian biogas case studies: one conventional biogas plant and three plants following Biogasdoneright™ principles.

In contrast, demand for bioenergy enables production of additional crops via sequential cropping, that is, essentially continuous use of the land. Various crops (e.g. triticale, maize, or sorghum) are planted during these months when the land would have otherwise been bare. These crops are then ensiled to provide feed for the digester. Because the land is continuously planted, application of digestate as fertilizer is much less likely to produce the potent GHG nitrous oxide (by microbial metabolism of nitrogen fertilizers). Also, less nitrate and phosphorus are lost to ground and surface waters than when chemical fertilizers or livestock effluents are applied on bare ground. Soil carbon levels are enhanced by the stable carbon resulting from microbial metabolism in the digesters. Other agricultural practices such as strip tillage, precision application of digestate, etc., can further enhance positive environmental outcomes and improve farm economics.

A second representative planting cycle, this one producing wheat and tomatoes, is given in Fig. 3. In this case, the 38-month planting cycle consists of 15 months in which the ground is not planted, or about 39% of the total time. Following the BDR principles. maize and triticale silage are planted during these times when the ground would have otherwise been bare.

It is worth noting that even if the wheat or tomato food crop fails (due to frost, flood, hail, drought, etc.), it can still be harvested, ensiled, and fed to the digester, thereby reducing the farmer's losses while continuing to produce both energy and environmental services.

BDR farms produce both food and bioenergy. Thus, the environmental burdens of the system are allocated among the food and bioenergy products to estimate GHGs for bioenergy production. In Fig. 4 a graphic description of the feedstocks for the 4 AD plants object of the study is presented. We use the marginal approach to allocation: the land, energy, and other inputs required to produce electricity and biomethane from biogas are separated from the inputs required to produce food and feed. From these data, the greenhouse gas emissions of electricity and biomethane are calculated. Details of the calculations are given herein.

Methods

Anaerobic digestion plant cases

Table 1 summarizes four case studies that are investigated in this paper to estimate GHG emissions of electricity and biomethane.

Table 1. Extended acronym clarification for the case studies.

Case study	Acronym	Feedstocks
Case 1	MAIZE	MAIZE
Case 2	CRP+MAN	CROP + MANURE
Case 3	MAN+CRP	MANURE + CROP
Case 4	BYPR+MAN	BYPRODUCT + MANURE

Case 1: MAIZE

The first case is essentially a conventional or reference biogas system that grows only energy crops – but not food or feed crops. This conventional system is an anaerobic digestion plant located in Northern Italy (Lombardy region), for which maize silage is the only feedstock. In this case, the maize silage energy crop is a traditional animal feed crop that is diverted to bioenergy production. Thus, this farm no longer produces food or feed, but only bioenergy. The biogas plant size is 1000 kW, and maize silage is supplied from 285 ha of croplands. The digestate is stored in a closed tank and is used as a fertilizer for subsequent maize silage crops. The average distance from croplands to the anaerobic digestion plant is 2.5 km. Mineral fertilizers along with digestate are also used to meet the nutrient requirements for maize production in this region.

The feedstock and operating characteristics of this and of the following case studies are summarized in Tables 2 – 5.

In contrast to Case 1, the following three cases represent various embodiments of the BDR principles applied in specific areas with particular climates and locally available feedstocks.

Case 2: CRP+MAN

This 1000 kW anaerobic digestion plant in Northern Italy (also the Lombardy region) is located at a 600-head dairy cattle farm, including 280 lactating cows. Feedstock for the digester is a mixture of energy crops (mostly maize silage), cattle manure slurry, and by-products from nearby cereal grain mills and potato processing plants. The digestate is used as fertilizer on the farm. Digestate is applied under best practices and using machines that minimize nitrogen losses. The use of mineral fertilizers (nitrogen, phosphorus, and potassium) is very limited. About 65% of the nitrogen requirements of the crops are met with recycled digestate, and essentially 100% of the potassium and phosphorus requirements.

This farm has 255 ha of cropland divided up into seven different plots. Of these seven plots, 80 ha are used for a monocrop of maize silage (50% for animal feed and 50% for the digester), 160 ha are for maize silage in double cropping (sequential cropping) with a winter cereal (triticale or ryegrass), used as forage for the animals, and 15 ha are used to grow perennial forage (alfalfa) for cattle.

Table 2. MAIZE case: Feedstock and load characteristics.

	MAIZE plant		
Parameters	Unit	Feedstocks	
		Corn silage monocrop	Total
Crop area	ha	284.6	284.6
Biomasses load	t per year	17 945	17 945
Biomasses TS content	% f.m.	35%	35%
Biomasses VS content	% TS	96%	96%
Biomasses VS load	t VS per a	6006	6006
VS degraded in digestion	%	89%	89%
N content biomasses input	g/kg f.m.	4.38	4.38
Biogas yield	m^3 per kg VS	0.679	0.679
% CH_4 in biogas	%	53%	53%
BioCH_4 yield	Nm^3CH_4 per kg VS	0.360	0.360

TS = Total Solids; VS = Volatile Solids; f.m. = fresh matter

Figure 5 summarizes the somewhat complex land use patterns for this particular farm. Some acreage on this farm is used exclusively for food/feed production, some is used exclusively for biogas production, and some is used both for food and biogas production. Note also that not all the farm land is used sequentially according to BDR principles. Some land is left bare part of the year because the current legal structure for the feed-in tariff for renewable electricity in Italy does not provide market access for all the electricity the farm could generate. This farm could produce significantly more biogas and electricity than it does at present.

As summarized in Figs 2 and 3, digestate is applied at the following times (and using specific equipment) during the cropping cycle: (i) prior to sowing the next crop (using an umbilical system and strip distribution with combined equipment), (ii) during weed control (via digestate injection), and (iii) during crop growth (using fertigation or pivot distribution with drip lines). Pictures and links to movies of this equipment in use are found in the Supporting Information.

Table 3. CRP+MAN case: Feedstock and load characteristics.

CRP+MAN plant									
Parameters	Unit	Feedstocks							
		Cattle slurry	Potato scraps	Cereal by-products	Corn silage monocrop	Corn silage 2° crop (after ryegrass)	Corn silage 2° crop (after triticale)	Triticale silage 2° crop	Total
Crop area	ha				40.0	30.0	130.0	70.0	270.0
Biomasses load	t per year	14 600	1825	913	2522	1746	6936	3395	31936
Biomasses TS content	% f.m.	8%	8%	92%	35%	35%	35%	33%	23%
Biomasses VS content	% TS	83%	96%	97%	96%	96%	96%	94%	93%
Biomasses VS load	t VS per a	994	140	814	844	584	2321	1055	6753
VS degraded in digestion	%	55%	87%	78%	89%	82%	82%	78%	78%
N content biomasses input	g/kg f.m.	3.85	1.06	13.69	4.38	4.38	4.38	3.80	4.15
Biogas yield	m^3 per kg VS	0.429	0.656	0.616	0.679	0.623	0.623	0.594	0.597
% CH_4 in biogas	%	56%	52%	56%	53%	53%	53%	53%	54%
BioCH_4 yield	Nm^3CH_4 per kg VS	0.240	0.340	0.345	0.360	0.330	0.330	0.315	0.320

TS = Total Solids; VS = Volatile Solids; f.m. = fresh matter

Table 4. MAN+CRP case: Feedstock characteristics and load.

MAN+CRP plant							
Parameters	Unit	Feedstocks					
		FYM manure	Poultry droppings	Cattle slurry	Sorghum silage monocrop	Sorghum silage 2^{nd} crop	Total
Crop area	ha	0.0	0.0	0.0	20.0	20.0	40.0
Biomasses load	t per year	13 177	1843	30 271	873	776	46940
Biomasses TS content	% f.m.	22%	42%	8%	30%	30%	14%
Biomasses VS content	% TS	84%	71%	82%	95%	95%	83%
Biomasses VS load	t VS per a	2435	552	1986	248	221	5442
VS degraded in digestion	%	55%	70%	50%	78%	78%	56%
N content biomasses input	g/kg f.m.	5.28	21.00	3.76	3.45	3.45	4.85
Biogas yield	m^3 per kg VS	0.428571	0.554	0.393	0.594	0.594	0.443
% CH_4 in biogas	%	56%	56%	56%	53%	53%	56%
BioCH_4 yield	Nm^3CH_4 per kg VS	0.240	0.310	0.220	0.315	0.315	0.246

TS = Total Solids; VS = Volatile Solids; f.m. = fresh matter

Case 3: MAN+CRP

This anaerobic digestion plant is located in Northern Italy (Veneto region), and its power capacity is 600 kW. This plant is owned by a consortium of farmers and is fed with livestock manure from these farms (cattle and poultry manure) and a relatively small amount of sorghum silage. The digestate is stored in a closed tank and is returned to the farms for use as a fertilizer.

Table 5. BYPR+MAN case: Feedstock characteristics and load.

		BYPR+MAN plant								
Parameters	Unit	Feedstocks								
		Citrus pulp	Olive vegetation waters	Olive pomace	Whey	FYM manure	Cattle slurry	Poultry droppings	Corn silage	Total
Crop area	ha	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.7	15.7
Biomasses load	t per year	253	1230	5783	1025	1846	4593	5044	835	20610
Biomasses TS content	% f.m.	20%	3%	30%	6%	22%	8%	40%	33%	24%
Biomasses VS content	% TS	98%	91%	90%	77%	84%	82%	75%	96%	83%
Biomasses VS load	t VS per a	49	38	1561	44	341	301	1513	264	4112
VS degraded in digestion	%	84%	85%	57%	86%	55%	50%	73%	89%	65%
N content biomasses input	g/kg f.m.	3.00	0.51	6.00	0.84	5.28	3.76	20.00	4.13	8.17
Biogas yield	m^3 per kg VS	0.622	0.731	0.446	0.667	0.429	0.393	0.571	0.679	0.509
% CH_4 in biogas	%	50%	65%	56%	54%	56%	56%	56%	53%	56%
BioCH_4 yield	Nm^3CH_4 per kg VS	0.311	0.475	0.250	0.360	0.240	0.220	0.320	0.360	0.284

TS = Total Solids; VS = Volatile Solids; f.m. = fresh matter

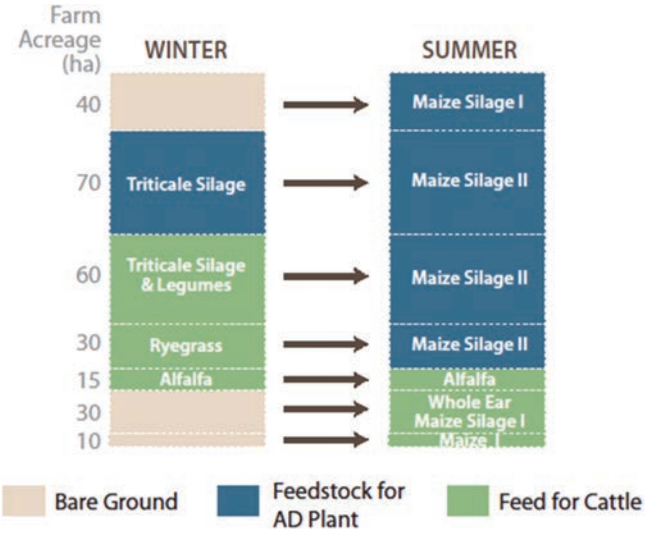

Figure 5. Land-use practices for the northern Italy farm represented by Case 2.

The average transport distance for livestock manure and digestate is 4 km.

Case 4: BYPR+MAN

This 500 kW plant is located in Southern Italy (Puglia region) on a farm with a variety of livestock (dairy cattle, laying hens and broilers), olive trees, and grape vines, and also access to food processing wastes from cheese, citrus, and olive oil processing plants. The plant receives all the livestock manure from the farm, a minor amount of maize silage from a nearby farm, and a significant quantity of by-products from the processing of milk, olive oil and oranges including olive pomace, olive vegetation waters, whey, and some citrus pulp. The digestate is stored in a closed tank and is used to fertilize the olive grove and the vineyards.

Life cycle assessment

There are two different functional units to describe this bioenergy system, namely one kW h of electricity and one MJ of biomethane. Since the BDR system delivers multiple functions (i.e., food/feed, electricity and biomethane), the environmental burdens associated with the system must be assigned to either electricity or biomethane to estimate their respective carbon foot prints. The marginal approach rather than other procedures (e.g. physical property or economic-based allocations), is used to avoid allocation as recommended by ISO standards.[11,12] The MAIZE case does not deliver any food/feed functions; hence no allocation is required.

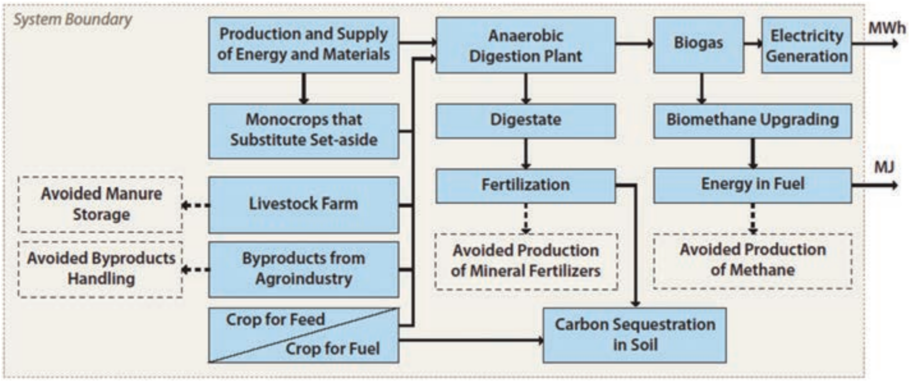

Figure 6. System boundaries for analyzing electricity or biomethane production from on-farm anaerobic digestion systems.

The system boundaries are illustrated in Fig. 6. System boundaries include all the relevant processes from the cradle-to-gate of the biomethane or electricity production systems: cropping systems, anaerobic digestion and biomethane upgrading plants, electricity generation, upstream processes, and avoided processes as appropriate. The approach from cradle-to-gate instead of cradle-to-grave is chosen as the energy distribution stage and other downstream processes cannot be managed by these farmers and should be similar in any event.

The overlapping processes between the BDR systems and the reference systems are not included in the system boundaries to simplify the calculations. The upstream processes are fuel and material production. The avoided processes are processes that would be phased out or displaced due to the BDR system. For example, the manure storage process is eliminated when manure is used as raw material in the anaerobic digestion plant, and the environmental burdens associated with the manure storage process would be avoided in the BDR system. The digestate displaces mineral fertilizers which were applied in the reference system; hence the avoided processes for the digestate are nitrogen and phosphorus fertilizer displaced by the digestate.

The 100-year time horizon global warming potentials (GWPs)[13] are used to estimate the carbon footprints for electricity and biomethane. Carbon sequestration, N_2O emissions (both direct and indirect), and methane fugitive losses along with GHG emissions released from the processes within the system boundaries are included in the carbon footprint. No environmental burdens are assigned to manure and agri-food by-products. Primary data related to the technical features of the anaerobic digestion and biogas upgrading plants, and the cropping systems were collected in the year 2015.

Table 6. Data sources for emissions.

Emissions	Data source
Emissions from livestock manure and digestate storage facilities	IPCC Guidelines[14], Marelli[15]
Soil N_2O emissions	IPCC Guidelines[14]
Carbon sequestration	Angers[16], Toderi[17], Rossi[18]
Fugitive emissions in the anaerobic digestion plant	Marelli[15]
Fugitive emissions in the upgrading plant	Baxter[19]
CH_4 emissions in the fumes of the CHP plant	Nelles[20]

The data for the upstream processes are obtained from the Ecoinvent v.3 database. The environmental burdens associated with infrastructure and equipment in the anaerobic digestion, electricity generation and biogas upgrading plants are also obtained from the Ecoinvent v.3 database, with appropriate up or down-scaling. Some emissions (e.g. carbon sequestration, nitrogen losses, fugitive emissions) are estimated based on the 2006 IPCC method[14] and literature, and their data sources are summarized in Table 6. The detailed calculations for those emissions are now described.

Emissions from livestock manure and digestate

As mentioned previously, manure storage facilities are not included in the analysis because manure is immediately fed to the anaerobic digestion plant without intermediate storage to avoid organic matter losses that would reduce the biogas yield and increase emissions. The emissions from manure storage facilities (i.e., CH_4 and N_2O) are therefore avoided emissions (hereinafter named manure

Table 7. Methane conversion factor (MCF) by average temperature and different manure management systems.[14]

System	MCFs by average annual temperature (°C)		
	13°C (cool)	16°C (temperate)	25° (digestate)
Solid storage	2%	4%	4%
Liquid/slurry, with natural crust cover	14%	18%	41%
Liquid/slurry, without natural crust cover	22%	29%	65%
Poultry manure	1.5%	1.5%	

credits). Based on the 2006 IPCC methodology,[14] CH_4 emissions are:

$$CH_4 \text{ emissions} = VS \cdot B_0 \cdot d_{CH4} \cdot MCF \qquad (1)$$

where VS is the volatile solids fed to the storage system (kg VS per year), d_{CH4} is the density of methane (kg per m^3), and B_0 is the maximum methane production capacity for manure produced by the specified livestock category (m^3 CH_4 per kg VS). MCF is the methane conversion factor, which depends on the manure management and the ambient temperature. In this study, two different climatic conditions are considered: the Po Valley in Northern Italy (average temperature: 13°C) and the Puglia region in Southern Italy (average temperature: 16°C). The MCFs for the manure management systems in the study are listed in Table 7. Cattle slurry is assumed to form a crust covering 80% of the surface of the slurry.

The emission factors for direct N_2O emissions from manure management in the 2006 IPCC methodology[14] are used. To quantify indirect N_2O emissions from manure management, it is assumed that about 12.7% of nitrogen compounds from the storage facilities are volatilized,[15] but only 1% of volatized nitrogen is converted to $N\text{-}N_2O$.[14]

In the anaerobic digestion plant, digestate is stored until it is applied as fertilizer, and CH_4 and N_2O emissions are released during digestate storage depending on the type of storage used – either closed or open systems. The BDR system uses closed storage. Since the open storage system is still used in several anaerobic digestion plants, we perform a sensitivity analysis on both storage systems to determine the effects on the carbon footprint of CH_4 and N_2O emissions released during digestate storage.

CH_4 emissions from the digestate tank are estimated in a similar manner to those of the livestock manure,[14] but considering that the B_0 of digestate is much lower than that of fresh manure. A residual biogas yield of the digestate of 0.090 m^3 CH_4 per kg VS is assumed, based on measurements carried out in an Italian laboratory.[21] N_2O emissions from the digestate tank are also estimated by IPCC 2006,[14] considering that the digestate forms a surface crust less easily than cattle slurry. In the case of digestate, it is assumed that 20% of the surface has a natural crust. In the covered digestate storage tank, CH_4 and N_2O emissions from the storage are considered to be zero. CH_4 is recovered, and N_2O is not formed in the covered storage tank due to anaerobic conditions. The CH_4 emissions in the open storage tank are quantified according to the 2006 IPCC factors,[14] and the average ambient temperature is 25°C, considering the fact that digestate is warm when released from the digester.

N_2O emissions from the agronomic use of livestock manure are considered equal to those of the digestate produced, because the digestion process does not change the nitrogen content. The nitrogen efficiency when digestate is applied to soil is assumed to be 65% compared to 40% for the undigested manure[22,23] due to mineralization of the organic nitrogen by the anaerobic digestion process. This difference enables reduced application of synthetic fertilizers, and the reduction is accounted as a fertilizer credit. The fertilizer use reduction when using the digestate from energy crops as fertilizer is not counted as a fertilizer credit because these crops are not produced in the absence of the anaerobic digestion system.

Emissions from crops

GHG emissions associated with crop production are considered, including seeds, fertilizers, agrochemicals, fuels for transportation of materials from suppliers to farm, tillage, planting, application of fertilizers and digestate, plant protection treatments, irrigation, harvesting, transportation within the farm, water consumption related to agricultural operations, and N_2O emissions from nitrogen fertilization (direct and indirect). The applied agrochemicals are 5–7 kg per ha, depending on the crops. The nitrogen application rate is estimated based on a simplified N-balance.

N_2O emissions from nitrogen fertilization are estimated according to the 2006 IPCC method,[14] in which the direct emissions are equal to 1% of the input of nitrogen from organic and mineral fertilization and from both above-ground (AG) and below-ground (BG) crop residues. The AG crop residues are estimated at 1.25 dry t per ha in the case of maize and sorghum, and 0.7 dry t per ha in the case of triticale. The BG crop residues and the nitrogen content of residues are also estimated by the 2006 IPCC method and factors.[14]

Indirect N_2O emissions are equal to 1% of the nitrogen losses in the form of N-NH_3 + NO and 0.75% of N losses by leaching and runoff, estimated at 30% of nitrogen applied. Emissions of NH_3-N and NO from the agronomic use of livestock effluent and synthetic nitrogen fertilizers are quantified as 20% of N applied for livestock manure and 10% for urea if used.[14] For the digestate, the nitrogen losses are reduced proportionally by its nitrogen efficiency compared with the nitrogen efficiency of livestock manure.

Carbon sequestration

Adding digestate and organic matter from crop residues arising from double (sequential) crops increases soil organic carbon (SOC), compared to the reference system. A mass balance approach is used to quantify the SOC change by applying digestate and organic matter of crop residues from double crops. About 12% of organic matter (OM) from digestate and crop residues is converted to SOC.[17,18] Thus, the annual increase of SOC is 0.2–0.3 t C per ha. These values are close to those obtained from field trials using conservation agriculture practices. [24,25]

Fugitive emissions and capital equipment-related emissions

GHG emissions associated with producing the infrastructure and equipment in the anaerobic digestion plant, the electricity generator, and the upgrading process are included. The service lifetime of capital equipment is assumed to be 15 years. Fugitive CH_4 emissions in the anaerobic digestion plant are assumed to be 1% of the biomethane produced,[15] while fugitive CH_4 emissions in the upgrading process are assumed to be 1.5%[19] (i.e., a conversion efficiency of 98.5%). Different electricity generation efficiencies are considered within the range of 38–41%, depending on the installed power, and CH_4 emissions in the fumes of the generator are assumed to be 0.5% of the methane combusted.[20] The thermal energy in excess of that used to regulate the digester temperature is not utilized and is not counted as an energy output.

Results and discussion

Figure 7 summarizes the estimated GHG emissions for renewable electricity produced by each of these four case studies compared with emissions from electricity generated and supplied to consumers using fossil fuels. All three BDR case studies, representing real farms and their associated digesters, achieve either very low or net negative GHG emissions. In the most extreme example, the MAN+CRP case study achieves a net reduction of nearly 1100 grams of CO_2 equivalents per kWh of electricity compared to marginal fossil-fuel based electricity in the EU.[15] The negative GHG emissions produced here are driven primarily by avoided emissions from animal manures or other residues that would otherwise decay and release GHGs without providing any corresponding energy services.

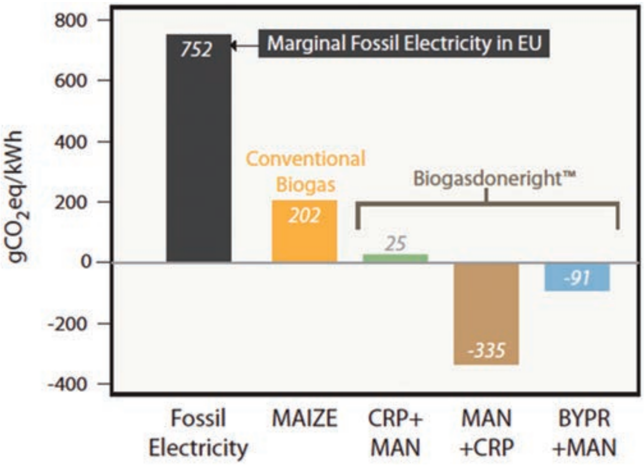

Figure 7. Greenhouse gas emissions of renewable electricity produced from four different biogas systems versus marginal fossil electricity supplied to consumers.

A sensitivity analysis indicates that the key factor affecting the GHG emissions systems is the loss of methane and nitrous oxide from uncovered digesters. For example, uncovered digesters would increase the emissions of the CRP+MAN case by about 85 g CO_2 eq per kW h, from 25 to approximately 110 g CO_2 eq per kW h. Nonetheless, the reduction compared to fossil electricity is still very large. An uncovered digester changes the reduction in GHGs for biogas-based renewable electricity versus fossil electricity in the CRP+MAN case from 97% to 85%.

The specific environmental impacts of the various plants depend primarily on the relative amounts of each type of biomass feedstock utilized (Table 8, Fig. 8).

For example, in the MAN+CRP plant heavy use of manure avoids CH_4 and N_2O emissions from the manure storage pit resulting in negative GHG emissions. As another example, soil organic carbon accumulation increases in the CRP+MAN case due to the additional biomass produced and left in the field (roots and crop residues) and because digestate is returned to the soil. Finally, in the BYPR+MAN plant, a large fraction of by-products is recovered without environmental burdens (except

Table 8. Contribution of the emissions and avoided emissions/sequestration on the carbon footprint of the AD plants.

Portions of the System	Carbon Footprint [gCO_2eq/kWh]			
	MAIZE	CRP+MAN	MAN+CRP	BYPR+MAN
Biomass production	*118.2*	*88.2*	*13.6*	*9.8*
Feedstock transport	*3.6*	*4.9*	*30.3*	*1.2*
Biogas plant	*80.2*	*79.4*	*81.4*	*85.0*
Fertilizers credits	*0.0*	*-6.5*	*–42.8*	*–30.3*
CH_4+N_2O manure credits	*0.0*	*–105.1*	*–415.2*	*–156.7*
Soil carbon sequestration credit	*0.0*	*–35.5*	*-2.3*	*0.0*
Total emissions	202.0	172.5	125.2	96.0
Avoided emissions/Sequestration	0.0	–147.1	–460.3	–187.0
Balance	**202.0**	**25.4**	**–335.0**	**–91.0**

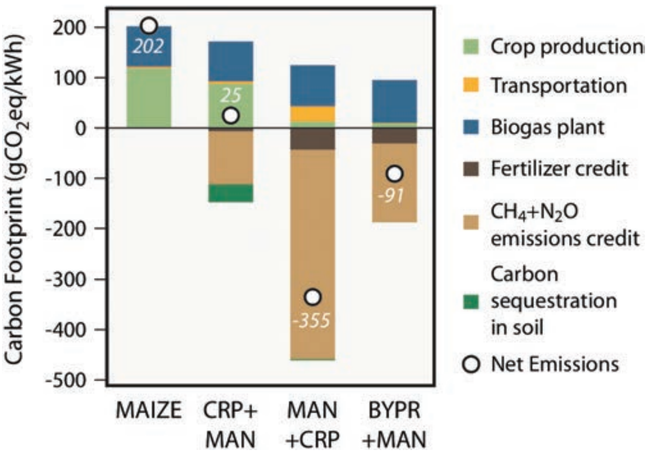

Figure 8. Contribution analysis of the carbon footprint of the energy produced by the AD plants of the four case studies (emissions and credits are included).

transport) so that feedstock production for the AD plant has a limited environmental impact.

Our results show that it is critical to close the digestate storage tank and recover the residual methane produced, as this can significantly improve the GHG budget. Many other researchers[15,26,27] have also concluded that the emissions from open digestate storage play a major role in the carbon footprint of the biogas production pathways.

In this study, the avoided GHG emissions of the raw manure storage dominate the overall emissions profile for plants relying primarily on this feedstock, as shown in other European and Italian case studies [15,27-29]. For AD plants exclusively fed by manure, “manure credits” are 4-10 times as large as all other GHG emissions[15,27].

Crop production, including N_2O field emissions and direct and indirect CO_2 emissions from the agricultural operations, represents a large share of the overall emissions, particularly when energy crops dominate the organic matter supply to the AD plant. The CO_2 emissions of diesel used for field operations is a minor component (10-15%) of the GHG emissions of crop production, which are dominated by the N_2O emissions of the N-fertilizers applied (65-75% of the total).

Methane leakage from digesters (and from the biogas upgrading plant in the case of biomethane) also has an important impact on the emissions and should be minimized in order to improve the system sustainability. Construction of infrastructure and machinery play a very minor role in the emissions, while transportation emissions are sometimes important for by-products not directly available at the biogas plant and which must be hauled from a distance.

GHG credits due to the mineral fertilizers replacement, achievable by an improved nitrogen use efficiency with an optimized use of digestate instead of raw slurry, can also significantly reduce the carbon footprint of biogas production, particularly when animal effluents represent a large fraction of the feedstock.

Credits for increased SOC content from crop cultivation and digestate application are seldom considered in biogas production LCA studies, mainly because an established evaluation methodology is not available and uncertainty regarding the rate, level, and duration of SOC sequestration processes. In a Swedish study[30] assessing the GHG performance of different crop-based biomethane systems, the impact of including the SOC contribution was evaluated for various crops and approached about 8 g CO_2 eq per MJ biogas for ley, a mixture of ryegrass and clovers (legumes) and hemp crops. Here we adopted a more conservative approach. We considered only the contribution to SOC due to the use of sequential crops that produce additional organic matter in the crop residues and in the digestate compared to mono-crops cultivation. Doing so we found that SOC sequestration reaches 5 g CO_2 eq per MJ in the most favorable case, the CRP+MAN plant. Organic carbon accumulation in the soil represents an important contribution to the GHG budget that can be increased improving the fraction of sequential crops in the farm's crop rotation practices. Increased SOC has many other benefits including more fertile soils, improved drought and flood tolerance and better utilization of crop nutrients.

The carbon footprint of the energy produced by anaerobic digestion is estimated in many European and studies both at European and international studies[27]. However, comparing results is difficult due to different methodologies, parameters chosen and assumptions such as multifunctionality aspects, functional units, system boundaries, iLUC inclusion, reference systems and so forth. Thus, the results vary widely and range from minus (negative) a few thousands to plus some hundreds of g CO_2-eq per kW h[27]. Several studies analyzed the case of a single feedstock used for digestion, while in reality, codigestion of different substrates is the normal practice. Limiting the comparison only to studies that consider real plants in Italy, we still observe a very large variation in results, ranging from -1440 to 550 kg CO_2 eq per MW h. Lower values are typical for AD plants using only livestock effluents and higher values are more representative of energy crops with open digestate storage, as we observe here.

Our results fall in the mid-range of literature values, and tend to confirm that the higher carbon footprint better represents conventional AD plants fed exclusively by maize silage, while the use of livestock manure and agricultural by-products significantly reduces GHGs. Moreover, including carbon credits due to SOC accumulation, achievable by the sequential cropping system and the improved cultivation techniques of the *Biogasdoneright* approach, makes anaerobic digestion essentially carbon neutral.

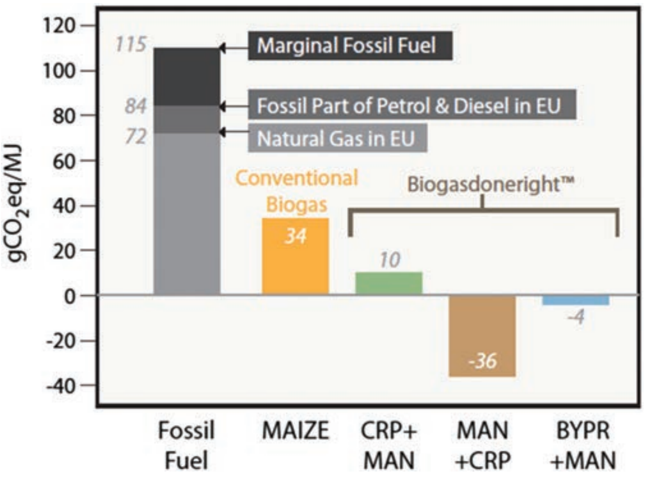

Figure 9. Greenhouse gas emissions of biomethane that might be produced from four different biogas systems versus various fossil energy sources.

Considering the biomethane pathway, Figure 9 summarizes the GHG results for biomethane hypothetically produced from the *Biogasdoneright* case studies compared with fossil natural gas in the EU[31] and other fossil energy sources within the EU[32,33]. Conventional farm-based biogas, which does not coproduce food and feed, nonetheless reduces GHG emissions by about half compared to natural gas in the EU. By comparison, the CRP+MAN case achieves an 86% reduction in GHGs for this specific *Biogasdoneright* case study compared to fossil gas. The other BDR cases considered here reduce GHGs compared to fossil gas by more than 100%.

Conclusions and perspectives

Our study on four real AD plants in Italy confirms that anaerobic digestion of agricultural feedstocks to produce energy (electricity, biomethane) has great potential to reduce greenhouse gas emissions associated with fossil energy use. The BDR system consists of feedstocks grown under sequential cropping that continuously covers the soil, use of animal manures and agricultural residues, recycling digestate to the farm using innovative techniques to substitute for mineral fertilizers and increase soil organic matter. Using these feedstocks and approaches, negative CO2-eq emissions per unit of energy produced can be achieved. This positive environmental result is especially due to avoided emissions from the storage of animal manures or other residues, to the improved nitrogen efficiency of digestate with respect to livestock manures, to the increase in the soil organic carbon stock due to the regular supply of digestate produced by sequential cropping and the improved agricultural practices favored by the BDR model.

Following the BDR model guarantees the higher photosynthetic and nutrient use efficiency compared with growing food crops alone, and thus food and feed production coexist with renewable energy production to their mutual advantage. The model also promotes improved soil quality and carbon sequestration. Moreover, BDR is consistent with the 4pour100 (4‰) Initiative, launched by France (4p1000.org), which aims to demonstrate that agriculture, and agricultural soils in particular, can play a crucial role in slowing climate change.

None of the farms participating in the Italian BDR consortium is currently involved in producing pipeline quality biomethane, but this is certainly possible in the future. The technology to upgrade raw biogas to biomethane is well-known. Obviously, the additional capital and operating inputs required to produce biomethane from biogas reduce the GHG benefits somewhat compared to direct on-farm electricity production from biogas.

However, biomethane represents a dispatchable, storable renewable energy carrier that can penetrate additional markets beyond on-farm electricity generation. Biogas converted to biomethane can be stored in the existing EU natural gas grid which has a storage capacity of about 1582 TWh,[34] whereas the EU electricity grid storage capacity can be estimated, combining batteries, spinning reserve and synchronous generators between 0.04 and 0.4 TWh.[35] The storage capacity of the gas grid thus exceeds that of several orders of magnitude.

Biomethane could compete directly in all current industrial and domestic heating and cooking applications with fossil natural gas, provide a raw material for the chemical industry, be used in many different vehicles to provide mobility, provide energy for mobile work platforms such as tractors, plows and crop harvesting equipment and, obviously, it could be burned in existing, conventional generators to produce electricity at locations far distant from the biogas-producing farms.

In this latter application, biomethane to electricity, the potential of biomethane seems particularly great. Biomethane could complement other renewable electricity sources such as solar and wind by serving as a dispatchable source of renewable electricity to help reconcile varying temporal and spatial demand for electricity with production of electricity by wind and solar, which also vary with time and location, thereby enabling the further spread of solar and wind power. In fact, conversion of biogas to biomethane might not be necessary to realize this benefit of dispatchable power. Biogas might possibly be stored on farm, for example in large inflatable bags, and then burned as needed to provide dispatchable electricity. In farming locations with high wind production potential, another interesting possibility suggests itself: namely, farms as sources of both wind and biogas-derived electricity.

These and other economic and environmental questions surrounding the uses of biomethane and biogas are interesting topics for further studies.

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