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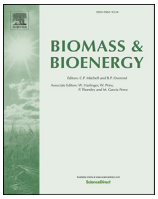

Research paper

Economics of GHG emissions mitigation via biogas production from *Sorghum*, maize and dairy farm manure digestion in the Po valley

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ABSTRACT

The Greenhouse gas (GHG) emissions and economic feasibility of electricity production from the anaerobic digestion of different substrates are studied in this paper. Three realistic substrate options for the climatic and soil conditions of a modelled farm in the Po Valley in Italy are analysed: manure from a dairy farm, *Sorghum* and maize.

A detailed cost analysis is performed with field data provided by farmers and suppliers and literature sources. The capital costs (CAPEX) and the operational costs (OPEX), disaggregated by their components, are presented. Investment payback time is then calculated for the different substrates and technologies, while taking into account the Italian government feed-in tariff scheme for biogas plants implemented in 2013.

In the specific conditions assumed, electricity production via anaerobic digestion of manure and co-digestion of manure with at most 30% *Sorghum* (no till) provide both GHG savings (in comparison to the Italian electricity mix) and profit for economic operators.

The anaerobic digestion of silage maize or *Sorghum* alone, instead, provides no (or very limited) GHG savings, and, with the current feed-in tariffs, generates economic losses.

Both economic and environmental performance are improved by the following practices: cultivating *Sorghum* instead of maize; implementing no till agriculture; and installing gas-tight tanks for digestate storage. A tool allowing a customised calculation of the economic performances of biogas plants is provided.

1. Introduction

European Member States are committed both to increase their share of renewable energy sources and to reduce their GHG emissions [1]. Within the Renewable Energy Directive [1]), mandatory sustainability criteria are defined for biofuels, but only voluntary recommendations were defined for biomass used for power and heat production.

In Italy the incentives for electricity production from Anaerobic Digestion (AD) have fuelled, in the last 5 years, a rapid growth of investments in biogas plants and biogas production technologies and a significant diversion of maize crops to bioenergy [2].

However, debate over actual GHG emission savings of biogas pathways [3–5] and concerns over indirect land use change [6] have culminated in EU recommendations or mandates capping the use of food crops for bioenergy purposes [7,8].

Starting in 2013, the Italian law [9] concerning the tariffs and subsidies for renewable electricity from anaerobic digestion was modified to respond to the sustainability concerns; feed-in tariffs are now linked to biogas plant capacity, the specific substrate used, and to the technologies employed to reduce the environmental

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impacts.

Chinese et al. [10] analysed the effects of previous and current support schemes on the optimal plant size, substrate mix and profitability in Italy. They concluded that new plants are likely to be manure based and due to the lower energy density of such substrate, wider supply chains are expected although optimal plant size will be smaller. They concluded that the new support scheme will most likely eliminate past distortions but also slow down investments in agricultural biogas plants.

At the end of 2012, there were 994 biogas plants in Italy with a total installed electric power capacity of 756 MW. Of these, 17.7% used only livestock manure as their substrate, 20.1% used only energy crops, and 62.2% used both types of biomass and other agro-industrial waste streams. However when these shares are calculated on the basis of installed capacity, the picture is very different; 74.2% of the installed capacity was based on co-digestion, 22.4% on energy crops only, while just 3.2% on manures only [11].

According to the Italian National Renewable Energy Action Plan (NREAP), Italy is committed to reach an installed electric power capacity of 1.2 GW for biogas-fed power plants in 2020, complemented by 11.1 PJ of heating/cooling final energy consumption covered by biogas in the same target year [12].

Several authors analysed the economic performance of biogas plants in Italy [13–15]. Schievano et al. [14] provided on-field data on the production costs of electricity from biogas using different dedicated energy crops cultivated along the Po Valley (northern Italy) and concluded that in order to compete with traditional fossil fuels and other forms of renewable electricity, the production cost of electricity from biogas must be reduced as much as possible in the near future with biomass supply being the most important cost item. Only by introducing organic wastes and residues could production costs be lowered sufficiently to compete with other energy sources.

Scholz et al. [16] analysed the GHG emissions mitigation costs for biogas plants in Germany and found a wide range of potential CO_2eq mitigation costs from 95 € t^{-1} to 378 € t^{-1}.

Biogas can be produced from nearly all kinds of biological materials deriving from the primary agricultural sectors and from various industrial and domestic organic waste streams.

The production and use of biogas is normally perceived as a clean and sustainable energy generation option that can guarantee significant GHG savings if compared to fossil fuels [1]. However, the environmental impacts associated with AD are strongly dependent on many factors, mainly: the choice of substrate, the technology adopted and the operational practices [3–5].

Currently, no mandatory sustainability criteria at European level have been formulated for solid biomass and biogas used for power and heat production. However, the European Commission (EC) provided recommendations to Member States to develop criteria similar to the ones designed for transport biofuels [17]. A recent document from the EC presented the state of play of bioenergy in the EU [81] and introduced updated typical and default GHG emissions values for a large selection of bioenergy pathways, including several pathways for the production of power by anaerobic digestion of manure, maize and biowastes [5]. This document suggests the application of a GHG emission savings threshold of at least 70% for all biogas pathways compared to a specific fossil fuel comparator. According to JRC data [5] which accompanied the EC document [8], only manure based plants would reach such a threshold. However, with the suggested suspension of the mass balance approach for biogas plants and, therefore, the possibility to 'average' the GHG emissions among co-digested substrates, the use of about 30% (wet mass) of maize substrate in co-digestion plants with a gas-tight storage for digestate would still allow a facility to comply with the criteria [5].

In previous work the environmental impacts associated with several biogas systems employing a variety of substrates and technologies [3–5,18] were analysed. It was found that on-farm biogas production from manure shows high potential to mitigate some of the environmental impacts associated with intensive dairy farming, especially as a consequence of the emissions avoided from manure management. However, local impacts (i.e. photochemical ozone formation) may actually worsen with the introduction of a biogas plant [18]. On-farm manure anaerobic digestion is an effective method to significantly reduce GHG emissions and non-renewable energy consumption; however, it was found that GHG emissions of biogas electricity are strongly influenced by the actual plant design, with GHG savings (referred to the emissions of the European electricity mix) ranging from more than 100% for manure based systems (thanks to credits for avoided methane emissions from raw manure storage) to 3% for maize-only based systems with open storage of the digestate [4].

In a recent study, the environmental impacts of three biogas systems based on dairy manure, *Sorghum* and maize, in the Po Valley were analysed [35]. This research found that GHG emissions for maize and *Sorghum*-based systems, instead, are similar to those of the Italian electricity mix; maize-based systems cause higher environmental impacts than *Sorghum*, due to more intensive cultivation practices [3,19].

These studies have confirmed, thus, that: i) manure digestion is the most efficient way to reduce GHG emissions, although there are trade-offs with other local environmental impacts; ii) that the management of digestate, specifically having an open or a gas-tight storage tank, is an essential element to reduce GHG emissions; iii) that biogas systems based solely on energy crops have very high GHG emissions, equal or barely lower than the current power generation mix.

This work builds on the previous research of this team, mainly on the work of Agostini et al. [3], and expands upon it to include the economic analysis of the biogas plants.

In [3] the results of the environmental analysis are reported for all possible mixtures of the three substrates analysed (maize, *Sorghum* and manure). However, for simplicity, as the Italian law [9] that defines the criteria for biogas feed-in tariffs allows the mixtures with up to 30% wet mass of energy crops to benefit from the same tariff granted to biogas produced from residues only, this work was limited to plants running only on manure, *Sorghum* and maize, or on a mixture of manure and 30% energy crops.

In this work, as in [3], manure refers to the untreated excretion of dairy cattle (sometimes referred to as slurry).

The aim of the economic analysis is to calculate the Net Present Value (NPV), Internal Rate of Return (IRR) and payback period of the plants analysed to evaluate the feasibility of the investments. Calculating the production costs shows whether the support tariff is sufficient (break-even analysis), and by combining the units costs of the electricity produced with the GHG emissions calculated in [3], the unit cost for the reduction of GHG emissions via biogas production from different substrates is calculated, which is the final aim of this work. This will provide guidance to policy makers on the most cost-effective way to pursue the objective of mitigating climate change by exploiting the anaerobic digestion of biomass and on-site electricity production.

2. Materials and methods

2.1. Systems description

The economic analysis is performed on the same biogas systems defined in Agostini et al. [3]. The systems analysed are biogas plants producing electricity from different substrates (manure, maize, *Sorghum*), with different cultivation management (conventional till, CT or no till, NT) and different ways of storing the digestate (in an open or gas-tight tank). In addition, as the Italian tariffs scheme gives the same incentives to the plants digesting only waste/residues or waste/residues with up to 30% energy crops in fresh matter weight, we modelled plants co-digesting manure from a dairy farm with 30% mass fraction of energy crops on a fresh mass basis.

The 18 systems deriving from the combination of the different options are reported, together with the main characteristics, costs and feed-in tariffs provided by the Italian government in DM, 2012 [9], in Table 1. The set of systems chosen reflects, as in [3], the most common configurations. Manure based biogas plants are normally small, to avoid the transport of manure over long distances. Manure transport is very expensive because of the very low energy density due to the high water content. On the other hand, with energy crops, economies of scale are possible; therefore the average size of the systems, thanks also to the legislative threshold, is about 1 MW installed electrical capacity.

The initial investment includes the capital costs of all the fixed assets (e.g. construction buildings, plant and machinery) and non-fixed assets (e.g. start up and technical costs such as design/planning/authorisation). The CAPEX for the cultivation machinery are not included as local tariffs for all the agricultural practices were used. In this way all the costs (labour, machinery depreciation, diesel etc) are included in the OPEX as cultivation costs. The lifetime of the investment is 20 years (which equals the economically useful life of the plant and the duration of the Italian feed-in tariff). The depreciation charge is calculated assuming an interest rate of 5%. No residual value was given to the plant (the time horizon equals the economic lifetime of the plant) as well as no decommissioning costs.

The investment cost figures for biogas plants reported in literature vary broadly, on the basis of the technology and the various equipment included (pre-treatment, storage and handling modules of different input substrates). Variations of 20–30% or higher are noted [20].

The investment costs are taken from the Italian decree [9], in which reference typical investment costs for biogas plants are reported in Table 1 of Annex 2 [9]. The investment costs are reported because only those plants which invested a given amount of the reference investment cost in refurbishing the biogas plant can apply for the new subsidy scheme.

The costs reported in the DM 2012 [9] are in line with the costs of other sources. The Politecnico of Milan performed two surveys [21,22] and found investment costs similar to those of the DM 2012 [2]. Also Riva et al. [8] used similar investment costs. Chinese et al. [3] analysed the relationship between the size and the cost of biogas plants. The assumptions here fit quite well in the cost curve they found. The investment cost values used by the EC in their energy systems modelling tools are also similar [23].

For informational purposes, the most important costs are reported and commented on in Table 2. All other costs, together with the main assumptions, explanations and calculations, and references are presented in the Supplementary Material.

The total cost of energy crops per t of fresh matter is reported in Table 3, while the contribution analysis is reported in Fig. 1.

The manure substrate does not incur costs, not even for transport, as it would be produced and stored and returned to the fields anyway.

The practices used in energy crops cultivation are detailed in [3] and can be summarized as follows:

- maize and *Sorghum* share the same cultivation technique apart from the level of irrigation and fertilization;
- maize was irrigated three times, while *Sorghum* was grown under rain-fed conditions;
- maize was fertilized with 120 kg ha^{-1} of nitrogen, while *Sorghum* with only 60 kg ha^{-1}, in addition to the organic fertilizer from the biogas plant .
- maize and *Sorghum* average biomass yields (55.2 and 58.0 t ha-1 respectively) were assumed not to change under CT or NT conditions.

Estimates of cultivation costs include land rent, harvesting, transport and ensiling, and digestate management. They are net of the revenues received from the Common Agricultural Policy (CAP).

The total costs for maize cultivation are about 2670 €ha^{-1} in conventional agriculture and 2330 € ha^{-1} in no till conditions; for *Sorghum* the costs are approximately 2000 €ha^{-1} and 1650 € ha^{-1} in conventional and no till conditions respectively.

The cost of maize production is higher than *Sorghum* production mainly because of the cost for irrigation which is the major component in the total cost amount of maize in both conventional till and no till.

For *Sorghum* the main contribution to the total cost is given by the "harvesting, chopping, transport and ensiling" component (see Fig. 1), followed by digestate management.

In conventional agriculture higher costs are due to the

Table 1
Main characteristics of the systems analysed.

Substrate	Agricultural practice	Digestate storage	Installed capacity (kW)	Capital cost[a] (€ kW^{-1})	Feed-in tariff
Manure		Open	50	5700	236
		Closed	50	5700	236
Maize	Conventional till	Open	1000	4000	140
		Closed	1000	4000	140
	No till	Open	1000	4000	140
		Closed	1000	4000	140
Sorghum	Conventional till	Open	1000	4000	140
		Closed	1000	4000	140
	No till	Open	1000	4000	140
		Closed	1000	4000	140
Manure + 30% maize	Conventional till	Open	1000	4000	178
		Closed	1000	4000	178
	No till	Open	1000	4000	178
		Closed	1000	4000	178
Manure + 30% *Sorghum*	Conventional till	Open	1000	4000	178
		Closed	1000	4000	178
	No till	Open	1000	4000	178
		Closed	1000	4000	178

[a] Excluding the cost of covering the digestate storage.

Table 2
Some of the main costs. References are reported in the Supplementary Material.

Membranes	The cost of the membranes needed to recover the biogas generated during the storage of the digestate (and relative installation civil works) were set to 60 € m^{-2}. The sizing instead was based on the actual amount of digestate produced, assuming that only the first digestate tank would be covered.
De-silaging machine	We assumed that the self-propelled de-silaging machine costs 120,000 euros, and its lifetime is 10 years
Personnel	The cost of the personnel was set to 25 € per hour (medium skilled worker). The daily work need for the two sizes of the plants differs. We assumed the smaller plant requires 1 h of work per day, while the bigger 4 h per day.
Maintenance	The plant maintenance is set to 300 € kW^{-1} $y^{-1}$of installed capacity, while the maintenance of the desiling machine is set to 50% of its initial cost for its whole life cycle.
Insurance	The biogas plant insurance costs is assumed to be 50 € kW^{-1} $y^{-1}$of installed capacity

Table 3
Substrates costs per tonne of fresh matter, own calculation (see Supplementary Material).

Substrate	Agricultural practice	Substrate (fresh mass basis) cost (€t^{-1})
Manure		0
Maize	Conventional till	48.3
	No till	42.2
Sorghum	Conventional till	34.3
	No till	28.4

ploughing and harrowing components as shown in Fig. 1.

Further details on the cultivation costs and the references used are reported in the Excel file provided as Supplementary Material.

The cost of substrate is the one with the greatest contribution to total production costs for the systems where 100% energy crops substrates are used (see details on total annual costs in the Excel file provided in Supplementary Material, various tables for each system), in line with the results provided by Schievano et al. [14].

The share of this factor varies between 60 and 65% of the total annual cost for maize based plants (in no till close storage and conventional agriculture open storage respectively). When *Sorghum* is used as substrate, the cost for substrate production ranges from 53% to 59% of total annual cost.

The contribution is obviously lower when the plants are co-digesting a mixture of manure and 30% energy crops: for maize, the contribution falls to 52%–57% of the total cost (in no till close storage and conventional agriculture open storage respectively) and for *Sorghum* it represents between 45% and 52% of the total annual costs.

2.2. Environmental impacts

A detailed inventory of input–output flows of the systems, including all the related environmental impacts weighted according to the Life Cycle Impact Assessment methods recommended by the ILCD [24,25] is reported in Agostini et al. [15].

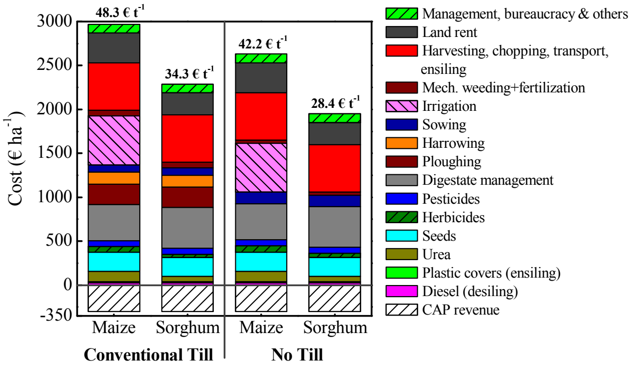

Fig. 1. Cultivation costs contribution analysis (€ ha^{-1}).

In order to calculate the potential GHG savings as mass of CO_2 eq, the Italian electricity mix as provided by the Gabi database (150 g CO_2 eq kWh^{-1}) was chosen as the reference [26].

GHG savings are high when manure substrate is used (more than 500% compared to the reference) but they become negative when energy crops are used as substrates (see Fig. 2). They vary between 80% and 170% when a mixture of manure and crops are used in the biogas plants. GHG savings higher than 100% indicate that anaerobic digestion reduces GHG emissions in absolute terms; that is even without considering the potential fossil energy substitution. This is due to the fact that management of raw manure as organic fertilizer causes very large emissions of methane; when manure is digested and the biogas combusted for bioenergy, CO_2 instead of methane is released with significant mitigation of the climate impact of the system.

Further details can be found in [3] and in the Supplementary Material.

2.3. Methodology: economic analysis of the biogas plants

The economic analysis of the different systems was carried out considering a number of key indicators that will enable a comparison of performances.

The financial attractiveness of the projects were first examined. The annual cash flows (inflows and outflows) of the plants, applying the discounted cash flow (DCF) method were calculated. This method integrates the effect of time on future cash flows by adopting an appropriate discount rate to estimate their present value [27,28]. The discount rate reflects the opportunity cost of capital [28].

A 5% discount rate was used according to the recommendation of the European Commission for project appraisal [28]. In [28] it is recommended to use a 4% discount rate (in real terms) for the opportunity cost of capital in the long term. For a private investor it is reasonable to assume a higher value. The same discount rate of 5% is used in [29].

The financial net present value of the investments (NPV) and the internal rate of return (IRR) were calculated and compared. These figures were used to measure the extent to which the project net revenues are able to repay the investments regardless of the sources of financing [28].

The net present value (NPV) is defined as the sum of the present values of the individual (yearly) cash flows. A project is financially feasible when the NPV is positive. The higher the NPV, the more profitable the project [30,31]. The NPV is expressed as follows:

$$NPV = -C_0 + \sum_{t=1}^{n} \frac{\left(R_t - C_t^{O\&M}\right)}{(1+r)^t} \qquad (1)$$

where NPV is the financial net present value of the project, C_0 is the initial investment, R_t is the revenue in time period t, $C_t^{O\&M}$ is the operating cost in time period t, r is the discount rate (%), and t is the

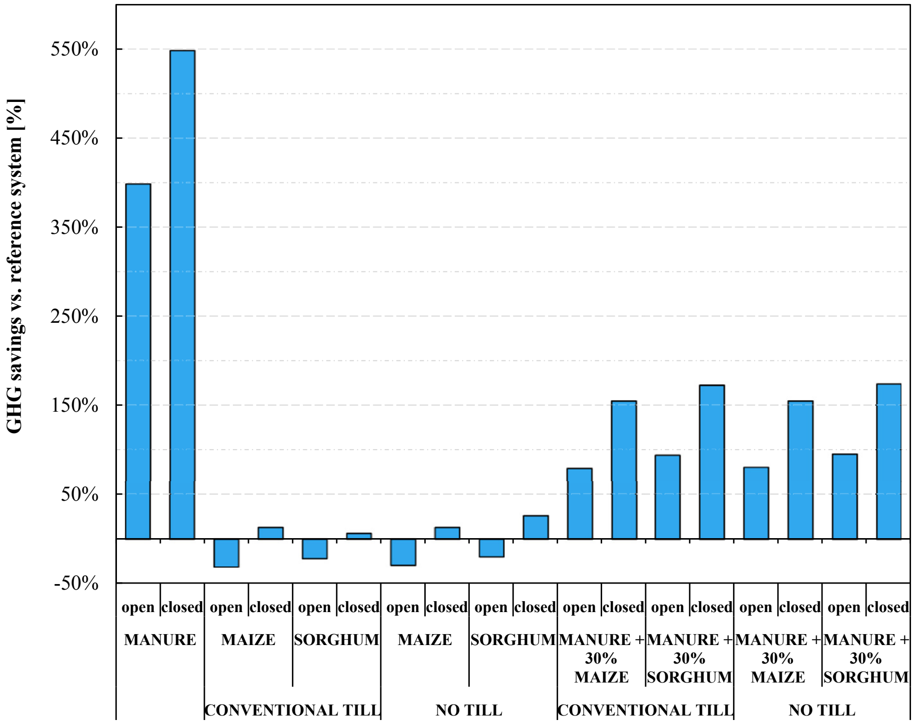

Fig. 2. GHG savings calculated with the Italian electricity mix as reference (own calculation based on Agostini et al. [15]).

time period from 0 to n (years).

The internal rate of return (IRR) is defined as the discount rate at which the NPV becomes zero, which means that the present value of future revenues equals the present value of costs. The IRR allows the judgement of the future performance of the investment in comparison to other projects, or to a benchmark required rate of return [28]. Hence, the IRR is defined as:

$$0 = -C_0 + \sum_{t=1}^{n} \frac{\left(R_t - C_i^{O\&M}\right)}{(1+IRR)^t} \tag{2}$$

where IRR is the financial internal rate of return, C_0 is the initial investment, R_t is the revenue in time period t, and $C_t^{O\&M}$ is the operating cost in time period t. The advantage of IRR is that, unlike NPV, its percentage results allow projects of vastly different sizes to be easily compared. If the IRR is higher than the discount rate, the project should be viable, otherwise it should be rejected. In general, the higher the IRR, the more desirable it is to undertake the project [30,31].

The payback period is defined as the time at which the NPV becomes zero. A payback calculation determines the length of time required to recoup the initial investment. The shorter the payback period, the more economically attractive the investment becomes [31].

The profit margins (for a year) of the various systems are calculated by the difference between the revenues and costs (before taxes).

A feed-in tariff was determined which corresponds to the point at which total cost equals total revenue and the profit margins are equals to zero. This figure is defined as the break-even tariff.

Combining the GHG savings estimated in Agostini et al. [3] along with the cost analysis for the substitution of fossil resources with biogas to produce electricity, an estimate of the CO_2eq mitigation costs is performed.

The CO_2eq mitigation costs are calculated according to IEA [32] and Scholz et al. [16]. They are given by:

$$CO_2 mitigation\ cost = \frac{C_i - C_{ref}}{E_{ref} - E_i} \tag{3}$$

where C_i is the production costs of the electricity produced by the biogas plants; C_{ref} denotes the production costs of the electricity mix produced in Italy (which is the reference technology); E_i represents the emissions resulting from the electricity produced by the biogas plants; and E_{ref} denotes the emissions resulting from the reference technology being considered.

3. Results and discussion

3.1. Financial NPVand IRR

The financial NPV for all systems are shown in Fig. 3. They are estimated applying a discount rate of 5%. Investment costs are shown in the same graph.

Most of the systems being considered have a negative NPV. This means the revenues are unable to repay the investments. Therefore, the investments are not feasible and should not be carried out.

On the other hand, the NPVs are positive in the systems where manure is used as substrate with both ways of storing the digestate (in an open or closed tank). NPVs are positive also in the systems digesting a mix of manure and *Sorghum* (30%), but only when the cultivation practice for *Sorghum* is no tillage. The cost of substrate in this case is lower than in conventional agriculture as shown in Section 2.1. The NPV is negative in all systems where maize is used, as Fig. 3 shows.

For manure based systems, Fig. 4 shows the payback time period, which is the length of time required to recoup the initial investment. It is 7 years in the open storage systems and 6 years in the close storage systems respectively.

The gas-tight cover for the digestate allows the recovery of additional biogas and hence generation and the sale of more

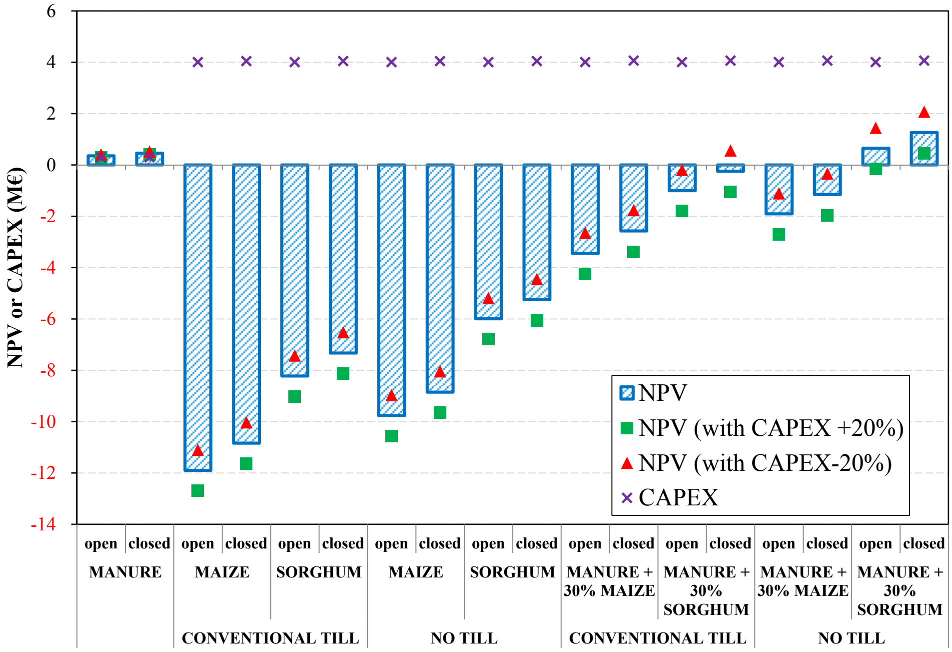

Fig. 3. Net Present Values of the systems considered. The CAPEX is reported to facilitate the evaluation of the performances.

electricity. The additional revenues are able to more than repay the additional investment necessary to cover the digestate.

The Internal rate of return confirms the results reported above. Table 4 shows the systems where the IRR is positive. The IRR shows that the systems where manure is used are more attractive than all the others. It should be considered that while manure and manure-*Sorghum*-no till systems have a similar NPV, the manure based systems have a higher IRR, and therefore they are more attractive investments.

Table 4
Internal rate of return.

		IRR
Manure	Open	17.2%
	Close	19.9%
Manure + 30% *Sorghum* (conv till)	Open	1.9%
	Close	4.3%
Manure + 30% maize (no till)	Close	1.5%
Manure + 30% *Sorghum* (no till)	Open	6.8%
	Close	8.4%

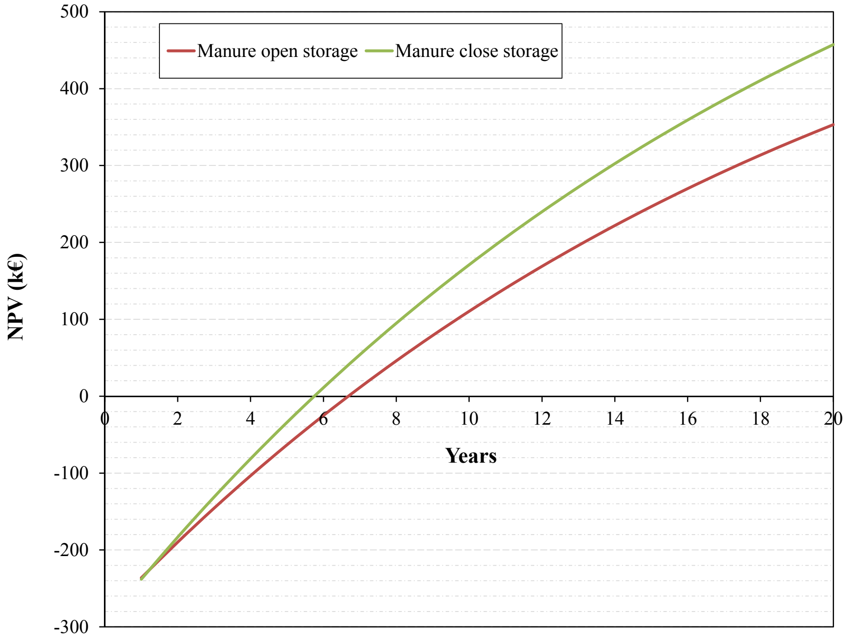

Fig. 4. Net present value for manure based biogas plants.

3.2. Profit margins and break even tariff

The profit margins strictly depend on the incentive that is paid for the production of electricity from renewable sources which is provided by the Italian subsidy scheme [9]. Profit margins for all system are reported in the Supplementary Material.

The feed-in tariff which corresponds to the point at which the profit margins of the systems are equal to zero (break-even point) was calculated.

The break-even tariff is shown in Fig. 5 in comparison with the actual tariff adopted according to the Italian scheme. For the systems where the break-even tariff is higher than the actual tariff the profits are negative and the revenues are unable to cover the costs.

The only systems which are profitable are the ones which use manure and the ones which use manure combined with *Sorghum* (30%).

The systems which use energy crops (maize and *Sorghum*) as substrates are not economically feasible with the current feed-in tariff. The subsidy scheme discourages the use of only energy crops as substrates for the biogas plants in order to avoid the competition of agricultural land with food and feed markets and as a consequence the risk of indirect land-use change.

The use of maize is not convenient even if used as a percentage (30%) combined with manure.

The break-even tariffs vary between 150 €MWh^{-1} and 139 € MWh^{-1} of electricity sold in the manure systems (open and close storage, respectively), between 229 € MWh^{-1} and 259 € MWh^{-1} when maize is used as substrate, and between 193 € MWh^{-1} and 223 € MWh^{-1} with *Sorghum*. For the plant co-digesting manure and an energy crop, the breakeven tariffs vary between 165 € MWh^{-1} and 213 € MWh^{-1}. The lowest break even tariffs are associated with no till cultivation practices and closed digestate storage.

Further details for all the considered systems can be found in the Excel file provided as Supplementary Material.

3.3. Mitigation costs

One of the main goals of the paper is to combine the environmental and economic analysis to evaluate if anaerobic digestion is an efficient instrument for GHG emissions reduction compared to other technologies.

According to the literature, biomass-based technologies offer a broad range of potential mitigation costs. Some studies identify CO_2eq mitigation costs of energy production, based on biogas combustion (used to generate electrical and thermal energy), between 95 and 378 € t^{-1} CO_2eq [16]. Mitigation costs are calculated in this section applying Eq. (3) (Section 2.3).

The GHG savings estimated in [3] and discussed in Section 2.3 are used as denominator.

For the numerator of Eq. (3), the production cost of the electricity generated by the biogas plants presented in previous sections is compared with the production cost of the Italian electricity mix. As a proxy of this cost, the wholesale price of electricity in Italy in 2013 was considered which was 49.5 € MWh^{-1} according to EC-DG ENER [33]. The wholesale element covers capital expenditures (CAPEX) and operating expenses (OPEX) as well as costs related to the operation of wholesale trading activities [34].

The CO_2eq mitigation costs are reported in Fig. 6 only for the systems which save GHG emissions, and for which the cost per tonne of CO_2eq avoided is not out of scale (therefore the systems where energy crops are used 100% as substrates are excluded, but are reported in the Supplementary Material). For these systems, the range of mitigation costs varies between 30 and 380 €t$CO_2$$eq^{-1}$ saved (see Fig. 6).The lowest GHG emissions mitigation costs are associated with the manure based systems which have feedstock cost equal to 0 and have large GHG savings thanks to methane emissions avoided from raw manure storage. The highest costs are found for the system with open storage of the digestate in which manure and 30% maize are the inputs (380 € t$CO_2$$eq^{-1}$ in conventional tillage and 338 €t $CO_2$$eq^{-1}$ for no till respectively) followed by the system with manure

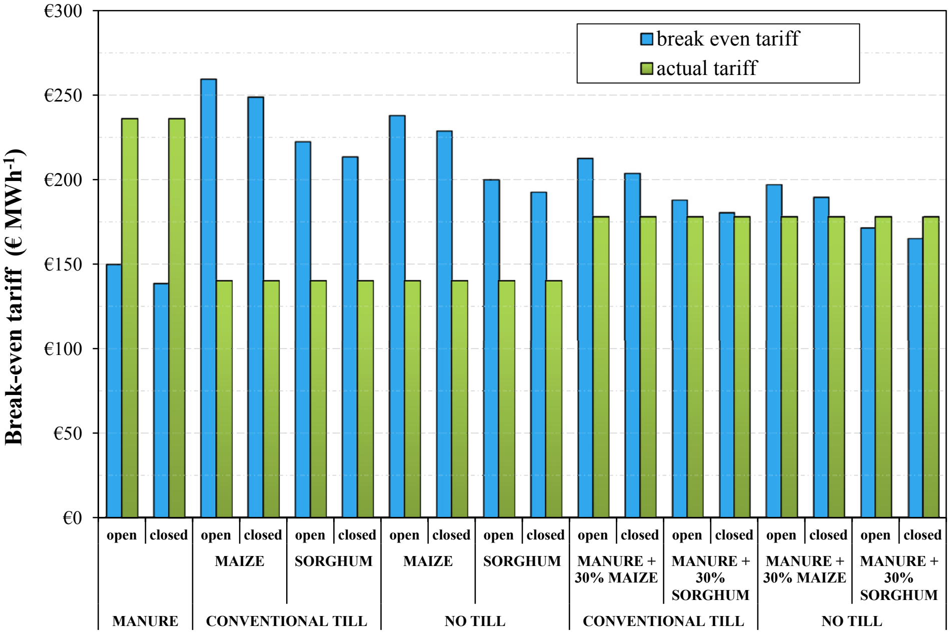

Fig. 5. Actual and break even tariff for all systems.

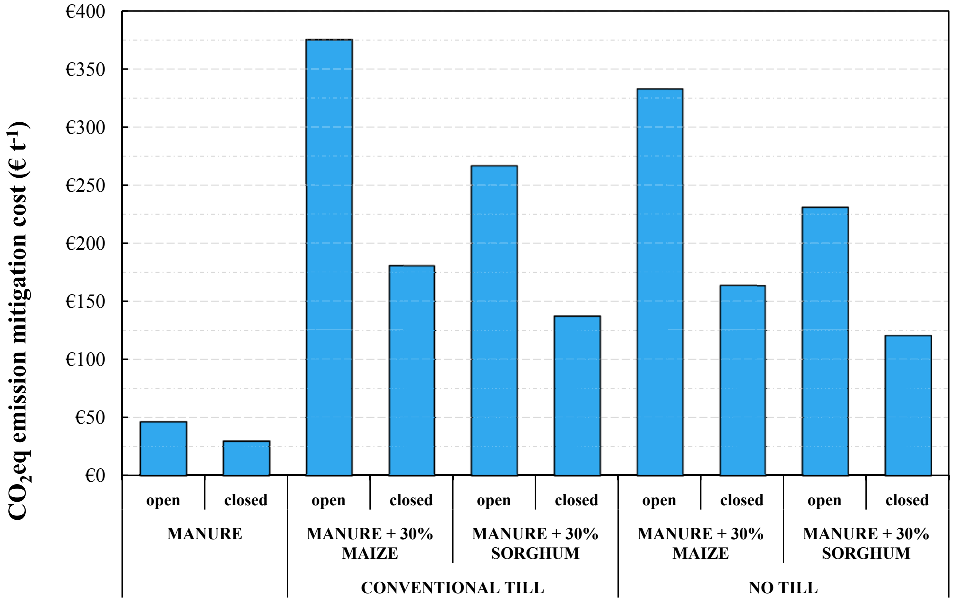

Fig. 6. GHG emissions mitigation costs (€ t CO_2eq^{-1} saved).

and 30% *Sorghum* (272 € t CO_2eq^{-1} in conventional tillage and 235 € t CO_2eq^{-1} for no till respectively).

In general, systems considering gas-tight digestate storage have lower GHG mitigation costs than open ones, and *Sorghum* shows lower mitigation costs than maize.

3.4. Sensitivity

Both the capital and the operational costs of biogas plants are highly variable. There is a multitude of technologies that can be adopted for use in biogas plants, performing differently, and having different initial costs. The same applies to the cultivation of energy crops, which, besides the fragmentation of the market for relatively wet substrates such as silages, may be affected by the specific practices adopted by the farmers, and also by local conditions of soils, climate and competing uses.

The economic margin of biogas projects is highly sensitive to these widely variable parameters (especially the cost of a plant itself, the substrate costs and the maintenance costs).

The impact of the biogas plant capital cost on its economic performance is shown in Fig. 3. By varying the CAPEX of ± 20%, only in one case, when manure is co-digested with 30% *Sorghum* NT with closed digestate storage, the NPV changes to negative or positive, respectively. This demonstrates that, rather than the CAPEX, it is the annual cash flow which makes the difference between viable and non-viable projects. Actually, the costs of the substrate and the feed-in tariffs are the main parameters in the economics of a biogas plant.

Since the sale of electricity normally provides the only revenue for the biogas plant, the feed-in tariff has a dominant role in determining the economic performance of a biogas to power project. Obviously, only when the feed-in tariff is higher than the break-even tariff a biogas project is viable.

Regarding the substrate costs, a sensitivity analysis was carried out by comparing the 9 different substrates. It was found, as mentioned above, that the economic performance of biogas plants are particularly sensitive to substrate costs. In fact while plants running solely on energy crops are not economically feasible, when energy crops are mixed with manure, only the cheapest feedstock, that is grown without soil cultivation and irrigation, makes the project profitable. The plants running on manure are also profitable, which has zero cost. Given the difficulty in analysing the influence of all the possible parameters affecting the costs and revenues of biogas plants, in the Supplementary Material a calculation tool has been provided that can be used to assess the impact on the economic performance of a change in any parameter used in this analysis.

4. Conclusions

Under the specific conditions analysed, electricity generation via anaerobic digestion of dairy cattle manure and co-digestion of manure with up to 30% *Sorghum* (no till) in Italy provides GHG savings (in comparison to the Italian electricity mix) and profit for economic operators. The anaerobic digestion of energy crops alone, instead, provides no (or very limited) GHG savings, and with the current feed-in tariffs leads to economic losses.

In general, it can be concluded that *Sorghum* performs better than maize both economically and environmentally and that, especially thanks to lower diesel consumption, no till agricultural practice improves both the economics and the environmental performance of energy crops for biogas plants production chains.

Furthermore, although some systems co-digesting manure and energy crops can still be economically profitable, the costs of mitigation of GHG emissions are very high, reaching values above 230 € t CO_2eq^{-1} when open digestate tanks are considered.

Nonetheless it appears that with the current feed-in tariffs from the Italian government (valid since 2013), all systems based on energy crops are rendered un-economic. Future capacity expansion will have to rely on the use of feedlot manures and other agricultural residues in order to be profitable.

A win–win option is clearly the adoption of the gas-tight cover of the digestate, which, by recovering the additional biogas produced, can payback the additional investment and lower the GHG emissions, improving both the economics and environmental performances of biogas plants.

A tool has been provided (see SM) that can be used by decision makers and economic operators to perform economic evaluations of potential investments in biogas plants.

It should be noted that sustainability is a much broader concept than simply GHG emissions, and policy recommendations should encompass all the aspects of sustainability (such as for example other environmental impacts, energy security and diversification of energy supply, impacts on employment and rural development, etc.).

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.biombioe.2016.02.022.

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