# The sustainability of Anaerobic Digestion plants: a win-win strategy for public and private bodies

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# The sustainability of Anaerobic Digestion plants: a win-win strategy for public and private bodies

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**Abstract**: Energy production from the anaerobic digestion of organic waste is widely recognized as a social and environmental opportunity, since it allows reducing waste disposal and making waste management economically profitable. However, profitability of these plants is strongly affected by the quantity and the quality of wastes, as well as by the availability of local subsidies. The key role of incentive policies in the economic success of investments in biomass to energy plants is highly recognised and has led EU governments to promote the deployment of these plants. Incentive policies adopted in EU countries differ significantly. In this paper, an evaluation model based on cost-benefit analysis is developed in order to identify the production-based incentive rates making investments in anaerobic digestion plant economically feasible without reducing social and environmental positive impacts. The model has been applied to the case of energy production plants from anaerobic digestion of cattle manure. In order to investigate the influence of the plant size on the investment profitability, different waste collection areas have been considered. Environmental performances of the plants have been evaluated by adopting a life cycle assessment approach. Results obtained confirm the environmental benefits achievable through the energy production from the anaerobic digestion of cattle manure. However, the current production-based incentive rates provided in most EU Countries revealed an inadequate balance between private and public interest, since they make profitable the investments only in case of small plants.
**Keywords**: Anaerobic digestion, cattle manure, LCA, incentive policy.

## 1 Introduction

Biomasses, classified in Italy by the D. Lgs. 387/03, are a Renewable Energy Source (RES). In the last few years, energy production from biomass plants has spread, and they now represent a potential profit centre (Dolan *et al.*, 2011). Nowadays many processes are available to obtain energy from biomasses: incineration and combustion, pyrolysis and gasification, fuel cells as well as anaerobic digestion (Kastner e*t al.,* 2012). In traditional anaerobic digestion (AD) plants high moisture content and lower heating value biomasses are treated to jointly produce a gaseous energy carrier (biogas) with an additional end-product (digestate) which can be used as fertilizer after an aerobic composting process. More recently, alternative technologies have been developed as the dark anaerobic fermentation in order to obtain hydrogen from carbohydrate-rich substrates (Bakonyi *et al.*, 2014; Gottardo *et al.*, 2013). Hydrogen produced can be used as transport fuel or in fuel cells to produce energy (Alves *et al.,* 2013), or mixed with methane for feeding internal combustion engine and turbine commercially available (Martinez-Perez *et al.*, 2007). Biogas is mainly used for Combined Heat and Power (CHP) application (Kastner *et al.,* 2012; Tricase and Lombardi, 2009). Many biogas upgrading processes have been developed to upgrade biogas and to obtain biomethane suitable for both in feed into the natural gas grid as well as for vehicle fuelling (Caponio *et al.*, 2013) which has expanded biogas utility (Pöschl *et al.,* 2010). An emerging alternative technology is the production of biohydrogen from biogas for its use in loading fuel cells (Bakonyi *et al.,* 2014; Alves *et al.,* 2013). In this paper the conversion of biogas into electrical and thermal energy (CHP) is considered.

Biomasses suitable for the AD process differ in their moisture content, Biochemical Methane Potential (BMP), availability (both from a quantity and supply continuity point of view), and intrinsic economic value (De Wit and Faaij, 2010; Schievano *et al.*, 2009). Biogas yield, geographical availability, unit cost, and tractability (the need of pre-treatments included) affect the suitability of biomasses for the AD process (Appels *et al.*, 2011; Jingura and Matengaifa, 2009, Qiao *et al.*, 2011). Energy conversion of biomass reveals economic justification in case biomasses are spatially concentrated and available with continuity throughout the year. On the contrary, when they are spread over and/or are discontinuously supplied, collection, transport and warehousing activities are more difficult and expensive (Amon *et al.,* 2007).

The economic success of investment in AD plants is strictly related to incentive policies adopted in the Countries. From a public point of view, sustainability of energy conversion plants has to be investigated jointly considering economic as well as environmental, energy, and local aspects, mainly because of the incentives provided to private investors.

The AD process, as well as the biogas energy conversion process, require energy, and are characterised by air pollution. In order to evaluate the effective sustainability of the bio-energy supply chain, in the cost benefits analysis of these plants an overall environmental balance has to be considered (Wang *et al.*, 2014; Lijó *et al.*, 2014). In the evaluation, emission avoided, as well as emission generated during plant operation (energy consumption, transport) and during its overall life cycle have to be considered.

The goal of this paper is to evaluate the sustainability of a bio-energy supply chain in the cattle livestock sector, in which biogas obtained from the AD of manure is converted into energy (electrical and thermal ones). An evaluation model based on a cost-benefit analysis has been defined and adopted for AD plants of farm manures. Scenarios differing for the manure collection field area extent (and hence for the installed power) have been considered. An LCA approach (ISO 14040, 2006) has been adopted for the sustainability evaluation of the AD process, in order to identify the scenario characterised by the best performances (energy and environmental). Environmental performances have been measured considering four main impact categories (global warming, acidification, eutrophication, and PM formation).

The paper is structured as follows: in Section 2, the economic and environmental viability of biomass conversion plants is investigated, and incentive policies available in EU countries for AD plants are illustrated; in Section 3, results of an economic and environmental analysis of biomass conversion plants of different sizes are presented and discussed, and the minimum values of the production-based incentive rates making economically viable investments in this renewable energy projects are evaluated for different biomass collection area extents; conclusions of this work are in Section 4.

## 2 Materials and methods

In this section, the economic viability of farm manure AD plants and their environmental performances are investigated. Different scenarios have been considered, differing in the extent of the farm manure collection area, and hence in the plant size. Moreover, incentive policies adopted in EU countries for these plants are illustrated and compared.

### *2.1 Economic viability of biomass conversion plants*

In order to investigate the economic viability of an AD plant, investment and operating costs, as well as biomass transport costs have to be evaluated. As far as AD plants investment costs are concerned, the following cost elements have to be quantified:

- cost of biomasses storage and conditioning section: in this section the biomass is pre-treated; mixing, removing of unsuitable matter, chopping or diluting by means of homogenising tanks are carried out; biomass consistency affects the choice of handling equipment to be adopted (diggers, silos, pumps);
- cost of digester feeding system: depending on the biomass type and quantity, volumetric pumps, centrifugal systems, hoppers with insertion screw, mixer screw with pumps or dosing loaders can be adopted;
- cost of digester: size, number and shape of digesters to be adopted depend on the type and quantity of the biomass, as well as on the hydraulic retention time required;

- cost of CHP (Combined Heat and Power) devices (fed with the produced biogas);
- cost of digested handling and conditioning section: this section contains the solid-liquid separation tank (if needed), storage tanks for the liquid phase, storage area for the solid phase, ammonia reduction equipment (it is a significant part of the plant cost), and machines for spreading compost onto the soil;
- cost of infrastructures: buildings, access ways, enclosures, piping, electrical connections, auxiliary plants such as automated supervising and control systems, fire protection systems, sewer collection systems, pollution and odour abatement systems.

The previous costs depend on:

- the size of the AD plant: in the evaluation of the optimal AD plant size, two contrasting economic effects have to be considered: investment and operating costs decrease with the increase of the plant size as a result of the unit cost reduction (economies of scale); at the same time, an enlargement in the biomass collection area leads to an increase in transport costs;
- the nature of the biomass (e.g., pure farm manure, farm manure mixed with energy crops or agro industrial wastes, organic fraction of municipal solid waste);
- the specific process adopted (simplified processes, patented processes).

With regard to operational costs, biomass collection and transportation costs, as well as the operation and maintenance costs of both the AD plant and the CHP device, have to be assessed. Starting from available technical reports on manure AD plants (Mezzadri and Francescato, 2012; COLDIRETTI, 2008; Francescato and Antonini, 2007; Provincia di Venezia, 2010; Confcooperative Bologna, 2012; ENAMA, 2010; C.R.P.A., 2008a; Birkmose *et al.*, 2007; Buratti *et al.*, 2009; C.R.P.A., 2008b; C.R.P.A., 2011; van Asselt, 2007; Jacobsen *et al.*, 2013), data in Fig. 1 have been elaborated. Data adopted are comparable with those available in scientific literature (Tricase and Lombardi, 2009; Walla and Schneeberger, 2008; Cavinato *et al.*, 2010; Karellas *et al.*, 2010). A regression analysis has been carried out in order to shape both investment and operational costs as a function of the plant size (expressed as annual tons of biomass treated). Data adopted for the regression analysis, results obtained and corresponding mean square error values are shown in Figure 1 for both investment and operational costs.

Costs of biomass transport ($C_{transp}$) from farms to AD plants have been evaluated in the hypothesis of transport (round-trip) carried out by a truck with a capacity of 24 [t] (GVWR - Gross Vehicle Weight Rating in class 34÷40 [t]) by means of the following relationship:

$$C_{transp} = c_u \cdot L, \qquad (1)$$

with

• $c_u$ denoting the unit transport cost [€/km],
• $L$ indicating the overall transport distance (round-trip) [km].

Unit transport costs are evaluated by means of the following relationship:

$$c_u = c^1{}_u + \frac{G}{C} \qquad (2)$$

with

• $c^1{}_u$ being the sum of the unit cost of maintenance, insurance, tyre, labour and organisation [€/km];
• $G$ indicating the fuel cost [€/l];
• $C$ denoting the fuel consumption, assumed as 2.8 [km/l].

The $c^1{}_u$ value adopted in this work was obtained from the official publication of Italian Department of Infrastructures and Transport (www.mit.gov.it) on the operating cost of logistic companies; it has been considered constant over time. Fuel price increase was estimated based on the data on historical time series of fuel prices published by the Italian Department of Economic Development (dgerm.sviluppoeconomico.gov.it).

As far as financial analysis is concerned, for each scenario considered, the economic viability of the investment has been evaluated by means of the Net Present Value (NPV), which was evaluated for a 20 year period:

$$NPV = \sum_{i=1}^{20} \frac{p_e EE_{net}(i) - c_{op}(i) - c_{transp}(i)}{(1+r)^i} - I_0 \qquad (3)$$

with:

- $I_0$: investment cost;
- $p_e$: electricity unit selling revenue;
- $EE_{net}$: amount of electricity sold to the provider, evaluated as the difference between the quantity produced and that consumed by the plant;
- $c_{op}$: plant operating cost;
- $c_{transp}$: biomass transport costs;
- $r$: discount rate.

The weighted average costs of capital (WACC) has been adopted here as discount rate value. It is evaluated as the weighted average of the cost of equity and debt, using the following formula:

$$WACC = \left(\frac{D}{D+E}\right) \cdot k_d \cdot (1-t) + \left(\frac{E}{D+E}\right) \cdot k_e \qquad (4)$$

with:

- $D$: share of debt;
- $E$: share of equity;
- $k_d$: interest rate on debt;
- $t$: tax rate (assumed as 31%);
- $k_e$: return on equity.

The capital structure considered here is of 70% debt and of 30% equity. According to Kost *et al.* (2013), an interest rate on debt of 4.5% and a return on equity of 9% has been assumed. With reference to the Italian taxation system, the tax rate (31%) has been obtained as the sum of national (27.5%) and regional (Apulia, 3.5%) levies. The resulting WACC value is 4.87%.
The annual cost of debt (mortage payment) has been evaluated by means of the French depreciation plan for a 10 years period:

$$P = \frac{C \cdot i}{1-(1+i)^{-t}} \qquad (5)$$

with:

- $C$: loan capital;
- $i$: interest rate on debt ($k_d$);
- $t$: 10 years.

***2.2 Sustainability of biomass conversion plants***

In case of farm manure, no disposal process is adopted, but it is directly spread onto the soil, thus generating a large quantity of methane emissions (DIIAR, 2006). The adoption of a biomass AD technology allows an energy vector (biogas) to be produced from biomass, whilst enabling stabilisation of the biomass treated, thus avoiding the emission of methane. In order to assess the environmental benefits of the adoption of biomass conversion plants, the impacts of the plant operation have to be evaluated. In the environmental analysis, both direct and indirect emissions have to be considered. The adoption of the LCA approach led to the evaluation of the impacts in each of the biomass to energy process phases, and to identify the scenario characterized by the minimum impact. Processes included in the system boundary (see Fig. 2) are the transport and the methanisation (AD) of the biomass, the conversion of the biogas obtained into electricity and heat, and the aerobic composting process of the digestate. Avoided emission due to the conventional management of raw manure (soil spreading), as well as the electricity production using fossil fuels have been evaluated (De Vries *et al.,* 2012).
In this work, a simplified LCA analysis was carried out, and the following hypotheses were adopted:

- the functional unit adopted in the LCA is the ton of biomass fed into the AD plant ($t_{FU}$); this unit has been selected in order to compare scenarios characterised by different plant sizes;
- emissions of the following pollutants have been quantified: $CO_2$, $CH_4$, $N_2O$, CO, NOx, $SO_2$ and PM10 (DIIAR, 2006);
- system boundaries considered are those depicted in Figure 2;
- it is assumed that biogas chemical composition is the same in all scenarios considered;
- $CH_4$ emissions due to the warehousing of manure before they are fed into the digester have been considered negligible;
- emissions due to the production of equipment and machines adopted in in the plant have not been considered;
- biogas leakages from gasometer have been considered negligible;
- impact categories considered in the LCA analysis and the related equivalent unit are: 100-year time horizon Global Warming Potential ($GWP_{100}$) - [kg $CO_2$eq], Eutrophication Potential (EP) - [kg $PO_4^{3-}$eq], Acidification Potential (AP) - [kg $SO_2$eq], and PM formation - [kg $PM_{10}$eq].

The following relationship has been adopted to calculate process emissions:

$$B_j\left(\frac{kg}{t_{FU}}\right) = \sum_{i=1}^{N} bc_{i,j} \cdot x_i \qquad (4)$$

with:

- $B_j$: mass emission per functional unit ($t_{FU}$) of the $j$-th pollutant from the $i$-th activity ($i$ = 1, …, $N$; $j$ = 1, …, $M$);
- $bc_{ji}$: emission factor of the $j$-th pollutant from the $i$-th activity;
- $x_i$: mass or energy flow in the $i$-th activty.

Emissions $B_j$ were then converted into the equivalent unit corresponding to the impact categories considered by means of the characterisation factors $ec_{j,k}$, (k = GWP, EP, AP, $PM_{formation}$):

$$E_k\left(\frac{kg}{t_{FU}}\right)=\sum_{j=1}^{M} ec_{j,k}\cdot B_j \qquad (5)$$

Characterisation factors values adopted were from Azapagic *et al.* (2004) and Goedkoop *et al*. (2009), and are listed in Table 1.
Transport emissions have been evaluated from data in Probas database (www.probas.umweltbundesamt.de).

CHP emissions factors adopted in this work are from the National Environment Research Institute (NERI), and are listed in Table 2 (DIIAR, 2006). CHP emission factors are expressed as mass ([g]) of emitted pollutant per unit volume ([$Nm^3$]) of biogas burnt. A percentage of methane of 60% (White *et al.,* 2011) and a Lower Heating Value (LHV) of 5.7 [$kWh/Nm^3$] for the biogas have been assumed. In Table 2, the carbon dioxide emission factor is zero because it is sequestered by the animal feedstock, and hence the net emission is null (González-García *et al.*, 2013).

With regard to avoided emissions (thanks to the electricity fed into the national grid), emission factors from the Ecoinvent Database (2004) related to the electricity produced by carbon-fed thermal power plants were adopted in this work. Moreover, carbon transport avoided emissions were computed.

The monetary value of the equivalent emissions in the four impact categories considered was obtained by adopting the corresponding shadow prices (see Section 3.5) as:

$$C_k\left(\frac{€}{t_{FU}}\right)=E_k\cdot shadowprice_k \qquad (6)$$

where $C_k$ is the monetary value of the $k$-th emission per functional unit ($t_{FU}$).
Monetary values obtained have been adopted to evaluate the Economic Net Present Value (ENPV) of the investment (see Section 3.5).

In cases where costs are greater than revenues, ENPV assumes negative values. In renewable energy production investments, this happens frequently. Thanks to public incentives, however, these investments are found to be profitable. Incentive policies currently adopted in EU Countries are presented and discussed in the following Section.

### *2.3 Incentive policies in EU Countries*

Support policies for renewable energy in EU Countries significantly differ. In some EU Countries, different support measures are available, and they are continuously updated. In EU Countries, four main different support schemes are adopted:

• Feed-in tariff

All of the electricity produced and fed into the national electrical grid is paid at a conventional tariff not depending on the electricity market prices. The tariff could be considered as the sum of the selling price and the incentive. It is guaranteed for a long period. Feed-in tariff values for different EU Countries are listed in Table 3.

• Feed-in premium

Electricity fed into the national grid is paid at the wholesale market electricity price, and the public authority provides an additional production-based "premium". In Italy, this measure has been adopted for the photovoltaic energy.

• Obligations based on Tradable Green Certificates (TGCs)

In the tradable green certificate system, suppliers are required to derive a certain percentage of final energy production from renewable sources. Green certificates are assigned to producers of renewable energy based on the effective quantity of energy produced on a yearly basis. They are tradable, and can be acquired from suppliers to comply with the obligation. The trade of TGC contributes to setting their price.

• Tender or competitive auction: for a given area, with renewable energy production potential, the Government or a regulator holds competitive auctions in which the desired amount of renewable energy source (RES) capacity is defined and the least expensive, most attractive offers are selected.

In the graphs of Figure 3, the tariffs provided in some EU countries are plotted against the installed electrical power. As can be observed, different public support schemes are adopted in different EU Countries. In all Countries, in order to guarantee the same financial support to plants of different size, the incentive values decreases with the increase of the installed electric power. The trend adopted should balance the economy of scales.
In Italy, incentive values significantly decrease when installed power exceeds 0.3 [MW]. Nevertheless, the Italian incentive policy is the most favourable in cases of biogas production plant with an installed power of less than 1 [MW].
In Slovenia, the tariff is quite constant until the installed power is less than 1 [MW], and a limited reduction of the tariff (9.6%) is applied for plants with an installed power greater than 1 [MW].
In the other Countries considered in the tariff comparison shown in Figure 3, a continuous and limited reduction of the tariff is applied.

In cases where the installed power ranges from (1÷10) [MW], the most favourable tariffs are provided in the Eastern European Countries, in particular in Bulgaria and Slovenia. In these Countries, the renewable energy market is still "young", and offers good opportunities for private investors: high tariffs, simplified authorisation processes, low industrial costs, and the availability of EU funds (Rotondi *et al*., 2012).
The attractiveness of the East renewable energy market is also due to the lower tariff offered in "mature" renewable energy markets such as in Germany, France, Italy and United Kingdom.
Finally, in cases with an installed power greater than 10 [MW], only Italy, Germany and Austria provided an incentive tariff.
In Italy, incentive tariffs for renewable energy production were updated in 2012 and are defined in "*D.M. del 6 luglio 2012 del Ministero dello Sviluppo Economico*" ("*Decree*" in the following).
In the next Section, the Italian incentive scheme is detailed.

### *2.3.1 Italian incentive scheme*

In Italy, for renewable energy production plants that started operating in 2014, a basic incentive tariff (*Tb*) is defined on the basis of the renewable source and the installed power. Moreover, an extra-incentive (*Pb*) can be obtained in cases where the plant is compliant with specific operation requirements. *Tb* values are shown in Table 4.
Both tariff and premium are production-based, and are applied to the quantity of electricity that is effectively fed into the national grid.
Starting from *Tb* and *Pb*, a feed-in tariff or feed-in premium is adopted depending on the installed power category:
• In cases where the installed power is less than 1 [MW], a feed-in tariff system is applied. The tariff is evaluated as:

$$To = Tb + Pr \qquad (7)$$

All of the electricity fed into the national grid is managed by the national electricity authority (GSE).
• In cases of an installed power greater than 1 [MW] (and less than 5 [MW]), plant owners have to choose between the feed-in tariff mentioned above and a feed-in premium. In the last case, electricity is available for the producers (he can consume or sell it), and a premium (*I*) is provided. The premium is evaluated as:

$$I = Tb + Pr - Pz \qquad (8)$$

with *Pz* being the local hourly price of the electricity (with reference to the area in which the plants is operated).
• In cases with an installed power greater than 5 [MW], a competitive auction system is adopted.

## 3 Results and Discussion

In this Section, the results of the economic, financial, and environmental analysis discussed in previous Sections and carried out in case of an AD plant of farm manure in which the biogas obtained is fed into a CHP system are presented and discussed.
Between farm manure, that from cow/buffalo livestock is of practical interest, since it is spatially concentrated and has sufficient moisture content (Colonna *et al.*, 2009).
The main benefits of the AD of cow/buffalo manures are:

- sanitising of the manure, by reducing biological oxygen demand (BOD) and chemical oxygen demand (COD), pathogen reduction, and odour abatement by up to 90% (EC Oregon, 2009);
- biogas production, which is a renewable energy source allowing the avoidance of $CO_2$ emissions of substituted fossil fuels (Chavez-Vazquez and Bagley, 2002);
- by-production of a digester effluent that is adoptable as a fertiliser, thus reducing the mineral and organic resource consumption required to produce traditional fertilisers (such as peat) (Pantaleo *et al*., 2013);
- avoiding the methane emissions characterising the direct spreading of manure onto soil (González-Avalos and Ruiz-Suárez, 2001).

The main goal of the analysis was to evaluate the effect of the absence of incentive policies on economic feasibility of this kind of renewable energy production plant. Environmental evaluations have been obtained by adopting an LCA approach.

### *3.1 Biomass availability*

Biomass quantities available for the AD process have been estimated on the basis of previously published data (Colonna *et al.*, 2009) on the solid/liquid manure potential of cow/buffalo livestock. The area of interest in this work has been limited to three Regions (Puglia, Campania, Basilicata), since it has been assumed that the AD plant will be located in south east Italy.
Data provided by ISTAT on the VI agriculture census have been adopted in order to identify, in the area of interest, the size and the location of cow/buffalo livestock. An upper limit of 70 [km] has been considered for the manure supply distance in order to guarantee traceability of the supply chain (as stated in "Decreto Mipaaf del 2 Marzo 2010").

Starting from manure data, biogas potential in [$Nm^3$/year] was estimated. Data in the "Italian biomass atlas", a WEB-GIS based territorial information system, have been elaborated in order to obtain the results in Figure 4.

### *3.2 Technical issues*
The AD technique considered here is a wet process, which is adopted when the level of dry solids in the substrate is less than 10% (as in the case of manure) (Ahn *et al.*, 2010).
Anaerobic digesters can be of complete mixed or Continuous Stirred Tank Reactor (CSTR) type, in which biomass fed into the reactor is mixed with partially digested biomass by means of a mixing device. CSTR provides homogeneity to the digester content (Bakonyi *et al.,* 2014).
The anaerobic digestion of organic material is accomplished by a consortium of microorganisms working synergistically. Digestion occurs in a four-step process: hydrolysis, acidogenesis, acetogenesis, and methanogenesis, in which $CH_4$ is produced (see fig. 5). Reactor operating conditions affect methanogenesis phase (Chen *et al.*, 2008). Mixing the fed biomass with the partially digested one, already involved in a methanogenesis process, ensures
- the development of the methanogenesis processes in the fresh biomass, thus increasing fermentation speed;
- process stability, thanks to a homogenous substrate in the reactor.

Anaerobic digester is operated at mesophilic temperatures. Although CSTR is not the most efficient digester configuration, it is characterised by low investment and operating costs when compared with other configurations. More details can be found in Baldwin *et al*. (2009).

The main AD process parameters, such as biogas yield, and electrical and thermal energy consumptions have been estimated on the basis of values observed in plants adopting the CSTR configuration digester (Mastrullo *et al.*, 2011). The main electricity consumptions of the plant are due to the feeding system, mixing system, and the solid/liquid separator of the digested effluent.
The process diagram of the plant considered is shown in Figure 6.

### *3.3 Economic—financial analysis*
Economic viability of the AD plant has been evaluated in the hypothesis of feeding electricity produced into the national grid, and of the adoption of the "*Ritiro dedicato*" revenue system. Currently, in Italy, when renewable energy producers adopt this option, the electricity that they feed into the national grid is "picked up" directly from the national electricity authority (GSE). Electricity is paid at a different tariff depending on the plant's installed power. In case of an installed power of less than 1 [MW], electricity will be paid to the producer at a conventional (the maximum) price. The reference price is the "single weighted national price" (PUN). It is obtained, on a monthly basis, as the average of electricity zonal prices weighted on the zonal consumptions. The advantage of this option is that GSE guarantees a minimum price applied on a yearly basis to a certain amount of electricity fed into the national grid. The amount varies with the renewable source adopted. In the case of biomasses, the minimum price is guaranteed for the first 2 [GWh] fed into the grid per year. In the case of an installed power greater than 1 [MW], electricity is paid at the zonal price (PZ), which varies hourly. PZs vary significantly with time and location, and contribute to PUN formation.
Due to difficulties in forecasting zonal prices, in the analysis carried out, only the PUN was considered, even in cases of installed powers greater than 1 [MW]. In order to forecast the PUN in the next 20 years, a regression analysis has been carried out to shape the PUN as a function of the overall national electricity consumption. Historical data yearly published by the Italian Energy Markets Authority (GME, www.mercato elettrico.org) have been adopted to carry out the regression analysis. Results obtained led to shaping the PUN as a linear function of the Italian annual electricity consumption:

$$y = 1.7538 + x \cdot 2.1575 \cdot 10^{-7} \qquad (9)$$

with $y$ being the PUN [€/MWh], and $x$ denoting the annual consumption [MWh/year].
As far as the annual consumption is concerned, an increase of 1.2% has been considered for each of the 20 years (Terna Rete Italia, 2012).
The compost obtained from the aerobic digestion of the solid phase of the digested effluent is of high quality thanks to the particular biomass fed into the system. Generally, this kind of compost has a market in the rural area close to the plants. However, in the analysis carried out, it is assumed that no revenues are obtained from it.
Economic and technical parameters adopted in the analysis are summarized in Table 5. Biogas yield as in (Piccinini and Fabbri, 2012) has been assumed. CHP data adopted here are from the technical specifications of a commercial dealer.

In the hypothesis mentioned above, an economic model has been defined in order to estimate costs and revenues of the plant in its working life (set at 20 years) for different manure collection distance. For each distance, the annual amount of collectable manure has been evaluated, as well as the CHP installed power and the related electricity revenues. As shown in Figures 7 the costs are higher than revenues for each collection distance considered.

A negative NPV is obtained for each collection distance considered. Discounted Pay Back Period (DPBP) and Internal Rate of Return (IRR) values confirmed the results obtained through the NPV analysis: DPBP greater than the plant working life (20 years) and a negative value of IRR have been obtained for all of the collection distances considered.

### *3.4 LCA Analysis*

In the LCA analysis, both direct and indirect emissions, as well as avoided emissions have been evaluated. With regard to the electricity production, emissions avoided are those generated from a carbon power plant producing the same amount of electricity fed into the grid by the AD plants. Two main emission sources have been considered: the carbon transport (assuming a transport distance of 10000 [km]), and the energy production process. The required carbon quantity was evaluated assuming a carbon LHV of 9.11 [kWh/kg] (Demirel, 2012), and an overall power plant yield of 37.3% (DIIAR, 2006). The same emission factors have been adopted in order to evaluate the emissions due to the plant electricity consumption. As far as transport is concerned, emission factors of a bulk carrier with a DWT (Dead Weight Tonnage) of 120000 [t] have been considered. Emission factors adopted are from the Probas database [http://www.probas.umweltbundesamt.de]. Emission factors of the energy production process are from (DIIAR, 2006).
Further avoided emissions are due to the missed direct manure spreading on the soil. In this process, manure is stocked in an opened tank for 180 days before being spread on the soil. In this situation, $CH_4$ emissions can increase to up to 20 [kg/year] per head of cattle. (EMEP - CORINAIR, 1999). Emission factors assumed for each process considered in the LCA analysis are listed in Table 6.

The impacts ($GWP_{100}$, AP, EP, and $PM_{10}$) of each process considered for different collection distances are in Figures 8 to 11.

Results obtained from the LCA analysis showed that the main impacts are addressed to the CHP process. This is due to the high value of the $NO_x$ emission factors of this process. The avoided electricity production leads to relevant values of avoided emission. Direct manure soil spreading significantly impacts only the $GWP_{100}$, since avoided emissions considered consist only of $CH_4$.
In Fig. 12, the net impacts, sum of the produced and the avoided emissions for each process considered, are plotted for different collection distances. Results confirmed the high level of environmental sustainability of cattle manure AD process mainly in terms of $GWP_{100}$. Only in case of EP, direct emissions exceed avoided ones due to the biogas combustion process in CHP devices.

### *3.5 NPV versus ENPV*

Costs related to impacts due to the AD and CHP processes have been evaluated by adopting shadow prices in Table 7. Two different approaches can be adopted to compute shadow prices. In the "abatement costs method", the unit cost of emissions is evaluated as the required cost to improve abatement technology in order to meet public reduction goals. In the "damage cost method", the unit cost is evaluated on the basis of the economic damage to the environment caused by the relative (unit) emission. The latter method is commonly adopted by economists to compute externalities costs (De Bruyn *et al*., 2010). In the analysis carried out here, prices computed with the "damage cost method" were adopted.

Emission monetary values allow to evaluate the Economic Net Present Value (ENPV). In the ENPV evaluation, shadow prices have been assumed to be constant in the 20 years plant working life.
NPV versus ENPV comparison is plotted in Figure 13 for different collection distances.

As expected, ENPV values exceed NPVs for each collection distance considered, since the overall environmental costs are negative due to the sustainability of the process (avoided emissions are greater than direct ones).

### *3.6 Sensitivity analysis*

Generally, the evaluation of the NPV requires the use of parameters that are subject to uncertainty. Therefore it is necessary that the decision makers know what the risks of a particular choice are. The use of sensitivity analysis allows to govern this phenomenon. This analysis identifies and monitors the oscillations of the NPV to changing one or more parameters used. So, it is possible to identify the factors having the greatest impact on the outcome of the analysis. The problem of the uncertainty of the results obtained with cost- benefit analysis can be solved through the construction of different scenarios.
The sensitivity analysis was applied to the scenario that involves the supply of manure from a distance of 20 [km]. To determine the NPV, it was assumed that the electricity was paid with the Italian incentive (231.28 [€/MWh]).
The analysis aims to identify the effects of a change in the tax rate and in the shares of debt and equity, both affecting the WACC and the NPV values. The analysis has been carried out considering a percentage of debt and equity of 70% and 30%, respectively. The impact of the shares of debt and equity on the WACC value has been investigated by considering a fixed tax rating of 31%. Table 8 shows the results obtained.

The NPV values obtained for each case considered in the sensitive analysis are plotted in Fig. 14. Variation in share of debt proved to severely impact WACC values rather than NPV ones. On the contrary, tax rate values have a greater impact on NPV values.

### *3.7 The incentive fee evaluation*

The proposed evaluation model has been used to calculate the Minimum Incentive Fee (MIF [€/MWh]) aiming at a balance between profitability and public interest in the cattle manure supply chain.

The evaluation of MIF has been carried out by considering the incentive fee that makes the NPV equal to zero for a fixed value of the WACC (4.87%).

Figure 15 shows the variations in the MIF that can vary the length of the supply chain (calculated as the radius of the manure supply) and the nominal electric power of cogeneration.

Figure 15 also shows a comparison between the MIF and incentive fees proposed by the Italian Decree (a standard fee plus the premium for the cogeneration).

The “Decree fee” assures the profitability of the investment only in the case of 140 [kW] of electric power of cogeneration.

In case of an installed power of 1.3 [MW], the “Decree fee” differs from the MIF of about 45%.

In Figure 16, the variations in the MIF values with the installed power in case of a fixed collection distance (equal to 0 [km] – it is assumed that the biomass is available in the plant site) are shown. For each value of the installed power two MIF values have been calculated, by assuming a tax rate of 25% (WACC 5%) and 40% (WACC 4.6%), respectively. These values are compared with incentives in Italy, Germany, Bulgaria, Luxembourg, Slovenia and Austria. Only in the case of Italian, Bulgarian, and Austrian incentives values the investment revealed to be viable. On the contrary, the incentives values available in the others Countries are far from the MIF ones. As it can be observed, negligible differences in MIF values are obtained even in case of different tax rate values considered.

In case of a collection distance of 20 [km] (see Figure 17) is considered, the MIF values obtained are higher due to the manure transport costs. In this case only Italian and Bulgarian incentives values prove to be greater than the MIF ones.

In case of a collection distance of 30 [km] (see Figure 18) only Bulgarian incentives are greater than the corresponding MIF values, but only in case of a cogeneration power greater than 1 [MW]. For higher collection distance values the MIF is greater than all available incentives values available in EU Countries.

Results obtained lead to conclude that current EU production-based incentive schemes reveal inadequate in making AD plant investments economically viable in case of biomass transport is required, even in case of small collection distance. As a direct consequence, in livestock low-density areas, a manure management different from the direct soil spreading reveals not feasible. The shifting towards an avoided emission-based incentive scheme could lead AD plant investments economically viable even for these areas, thus reducing the impacts due to large quantities of direct soil spread manure.

## 4. Conclusions

The reduction of the environmental impacts due to the energy production from fossil fuels requires the development of energy production systems with better environmental performances. Renewable energy production is widely recognized as a sustainable solution. Investor decisions, however, often do not take into account the social benefits deriving from renewable energy projects. Incentive policies adopted in EU Countries should financially support private investors, thus making renewable energy projects economically viable, and achieving at the same time their social and environmental benefits. The aim of the analysis proposed in this paper was the evaluation of the sustainability of energy production from the anaerobic digestion of cattle manure from both public and private perspectives. A model that combines cost benefit analysis and LCA is proposed as a reference model to calculate the profitability of public and private investments.

Starting from the evidence that anaerobic digestion is not convenient in the absence of a public incentive, in this paper an analysis of the incentive schemes proposed in Italy and in other EU countries has been carried out in order to verify their ability to guarantee a balance between private and public interest.

The approach was applied to a specific case study in the South of Italy, but the results obtained are quite general.

The profitability of the investment depends on the availability of cattle manure that influences both the plant size (the electric cogeneration power) and the transport costs (the length of the supply chain).

From the public point of view, the environmental and social impacts are reduced by the shorter supply chain. This evidence led Italian laws to design incentives to favourite small-size plants.

In Italy, the biogas production from cattle manure will be very interesting for farm industries, in particular for plants with an installed power that is less than 1 [MW]. Moreover, the Italian incentive fee seems to lose its effectiveness when the biomass is not available close to the AD plants (in the proposed case study about 30 [km]).

This confirms the validity of the proposed incentive scheme to promote only small size plants with a short supply chain.

As far as the environmental performances of AD plants are confirmed, no limits in terms of collection distance and/or installed power have been identified. The AD of farm manure leads to a significant reduction of environmental impacts for each collection distance considered (up to 70 [km]) when compared with the traditional spreading of manure onto the soil.

The results obtained suggest that, in order to promote the deployment of renewable energy, the actual production-based incentive schemes are inadequate, and a different approach has to be adopted, shifting towards an avoided emission-based incentive scheme, thus driving the design and operation of renewable energy source plants towards maximum sustainable configurations.

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