Economical Analysis of Alternative Uses of Biogas Produced by an Anaerobic Digestion Plant

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Abstract
In the frame of the Italian market and regulations, some alternative uses of biogas produced by an anaerobic digestion plant fuelled by zootechnical effluents, integrated with corn silage, are investigated. In particular, on the basis of an existing plant, the following alternatives to the use of the generated biogas are analyzed and compared under the economical point of view:

- use of a cogeneration plant to produce electric energy (self-consumption and sale of the surplus to the power supply network operator) and thermal energy (digester and post-digester heating, and feeding of a cereal dryer);
- use of a trigeneration plant to produce electric energy (self-consumption and sale of the surplus to the power supply network operator) and thermal/refrigeration energy (heating of the digester and post-digester, and air conditioning of the company's warehouses);
- use of a regenerative water-based scrubbing plant for up-grading the quality of the produced biogas, obtaining biomethane for direct sale to the network operator.

This comparison is carried out considering the technical differences between the three alternatives, as well as the related investment and operative costs. A sensitivity analysis on the main parameters influencing the payback time of the three alternatives has been also carried out, showing that the most important parameter to consider is the cost of energy (as either electric or biomethane vector). On these grounds, using the Net Present Value approach, an assessment of the most convenient option in terms of shortest payback time and highest returns is made.

Article Highlights

- **On the basis of an existing anaerobic digestion plant, the following alternatives to the use of the generated biogas are analyzed and compared under the economical point of view:**
  - **use of a cogeneration plant to produce electric and thermal energy;**
  - **use of a trigeneration plant to produce electric and thermal/refrigeration energy;**
  - **use of a regenerative water-based scrubbing plant for up-grading the quality of the produced biogas, obtaining biomethane for direct sale to the network operator.**
- **Using the Net Present Value approach, an assessment of the most convenient option in terms of shortest payback time and highest returns (in the frame of current Italian laws and regulations) is made.**

Keywords Anaerobic digestion · Animal sewage · Corn silage · Biogas · Biomethane · Trigeneration

Introduction

The continuous growth of the world's energy demand has set the conditions for the blooming of various forms of distributed energy generation plants. Among the multitude of possible sustainable energy sources, zootechnical effluents

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are a target of choice, due to their wide availability, low cost, potentially high energy yield (Gunaseelan 1997; Angenent et al. 2004; Ward et al. 2008; Cantrell et al. 2008). Moreover, the combination between increasing world population and growing demand for meat in developing countries is expected to generate an increase of 70% with respect to the currently available livestock, to feed a population estimated to reach 9.6 billion by 2050 (FAO website), with the consequent huge availability of zootechnical effluents all over the world.

A further condition encouraging a sustainable use of livestock sewage is that the increase of world population is leading also to an agricultural intensification, which requires appropriate crop fertilization methods. Animal sewage can be used for this purpose, but excessive concentrations can be harmful for crops and even humans, due to both too high amounts of nutrients delivered to the crops, and to the ubiquitous presence of heavy metals, hormones, antibiotics and pathogens in these livestock by-products (Gupta and Gupta 1998; Goss et al. 2013; Khanal et al. 2006; Tyrrel and Quinton 2003). Among several methods reportedly able to reduce the amounts of these pollutants in animal sewage (Vanotti et al. 2007; Chen and Lin 2004; Borghi and Palma 2014), anaerobic digestion is an approach which shows multiple advantages: it produces biogas that can be used for direct electricity generation, thermal energy generation or subsequent use for industrial chemistry processes (Cantrell et al. 2008), it avoids the use of fossil fuels (hence reducing the global greenhouse gases emission) (Zaks et al. 2011), it is carried out on a starting compound which is both widely available and inexpensive, and for which appropriate disposal methods are actively seeked for (Weiland 2010; Holm-Nielsen et al. 2009), and its use in rural areas it may contribute to alleviate energy crises and to boost economic growth, contributing to an overall reduction of global warming (Zheng et al. 2010). Moreover, while the effectiveness and environmental friendliness of the resulting digestate as a valid fertilizer is still under active discussion (Möller and Müller 2012; Nkoa 2014; Insam et al. 2015), anaerobic digestion of animal sewage avoids the extensive use of purely vegetal feed for biogas production, saving valuable large amounts of agricultural lands for edible vegetables cultivation. Finally, anaerobic digestion of animal sewage can provide solution also to the non-negligible problems caused by the progressively more stringent regulations aimed to limit the pollution caused by indiscriminate and environmentally disrespectful disposal of sewage (Bloem et al. 2017).

In this frame, in the last 20 years a myriad of anaerobic digestion plants using zootechnical effluents for producing biogas have been realized all over the world (Gunaseelan 1997; Angenent et al. 2004; Ward et al. 2008; Cantrell et al. 2008). These plants have reached a technological-productive maturity which is not showing further evolution, although a lot of research work is being carried out over the characterization and monitoring of the digestion process taking advantage of zootechnical effluents (Cantrell et al. 2008; Weiland 2010; Holm-Nielsen et al. 2009; Alvarez and Liden 2008; Buhr and Andrews 1977; Seghezzo et al. 1998; Mata-Alvarez et al. 2000; Madsen et al. 2011; Mudhoo 2012; Vavilin et al. 2008). Nonetheless, the assessment of the economic convenience of different approaches to the use of biogas is still a point of interest in the field, due to technological advances that continuously change the landscape of the viable options. In particular, there are several ways for using biogas; in addition to the traditional cogeneration plants (Caputo et al. 2005; Ahrenfeldt et al. 2013), it is possible to use it in trigeneration plants (Huang et al. 2011; Lian et al. 2010; Bruno et al. 2009) or to transform it into biomethane by purification in an up-grading plant, and then by feeding it to a network (Muñoz et al. 2015; Ryckebosch et al. 2011; Molino et al. 2013). However, to our knowledge, the technical and economic feasibility of these alternatives in the practical use of biogas has not been analyzed in detail, yet.

This paper will hence give quantitative evaluations of costs and returns of anaerobic digestion plants for biogas generation characterized by different uses of the generated biogas, i.e. (a) cogeneration, (b) trigeneration, and (c) purification of the biogas to biomethane. The economical considerations will be based on an existing digestion plant, taken as a model case, with the aid of a sensitivity analysis carried out over the main parameters influencing the final payback time of each proposed solution.

Description of the Model Anaerobic Digestion Plant

The considered anaerobic digestion is already existing and it was built 5 years ago on the basis of a consolidated design (Mudhoo 2012; Hessami et al. 1996). It is located in a farm in the Italian province of Udine. The farm activities consist in breeding of swines (1900 head of cattle for 1.6 cycles per year) and chickens (150,000 head for 4 cycles per year) and farming of cereals (maize, grain, barley, etc.). It operates in mesophilic mode (temperature of 42 °C) and it is fed with zootechnical waste from poultry and fattening pigs, integrated with corn silage. The plant provides approximately 3400 Nm^3/day of biogas, with a methane percentage of 51–54% by volume.

The production process of the anaerobic digestion plant, which has the potential of approximately 250 kWe, is sketched according to Fig. 1.

The plant scheme is given in Fig. 2.

The process can be divided into the following operational phases:

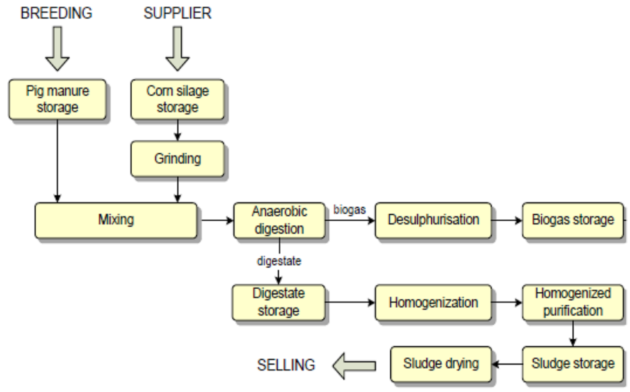

Fig. 1 Logical blocks sketch of the considered anaerobic digestion plant

(a) storage of zootechnical effluent resulting from pig farms

It is realized with a reinforced cylindrical concrete tank with a capacity of 24 h (182 m^3), corresponding to 32.7 tons/day of zootechnical effluent produced;

(b) storage of chicken manure

It is made of a parallelepipedal tank (60 m length × 3 m width × 15 m height), capable of collecting 4 m^3/day of chicken manure;

(c) corn silage storage

It is made of galvanized sheet metal silos with a storage capacity of 24 h (56 m^3), equivalent to 10 tons/day of corn silage;

(d) corn silage shredding

The shredder is fed from the silos by gravity and its production capacity is 417 kg/h;

(e) biomass loading systems

The non-shovellable biomass (pig effluent) from the storage tank is introduced into the digester by means of a hydraulic circuit, while chicken manure and corn silage are introduced using a conveyor belt and a loading hopper. The amount of corn silage is equal to 4.76% of the total, while the quantity of treated mixture that feeds the digester is about 210 tons daily;

(f) anaerobic digestion

It is carried out using two elements, a digester and a post-digester with a cylindrical shape, having, respectively, a volume of 1665 m^3 and 2814 m^3, a diameter of 20 m and 26 m, and the same height of 6 m. The operating temperature is 42 °C. After the loading phase, a continuous stream of corn effluent-corn silage mixture substitutes the output of the same amount of material (digestate at the bottom and biogas at the top). The retention time is 90–100 days;

(g) storage system with gasometric covers for both the digester and the post-digester dome

The biogas storage system is realized in tarpaulin. This system allows the accumulation of the produced biogas, using a double variable membrane. The produced biogas is at 42 °C and at a slightly higher pressure than the atmospheric one (1.1 bar). A plastic mesh network acting as a

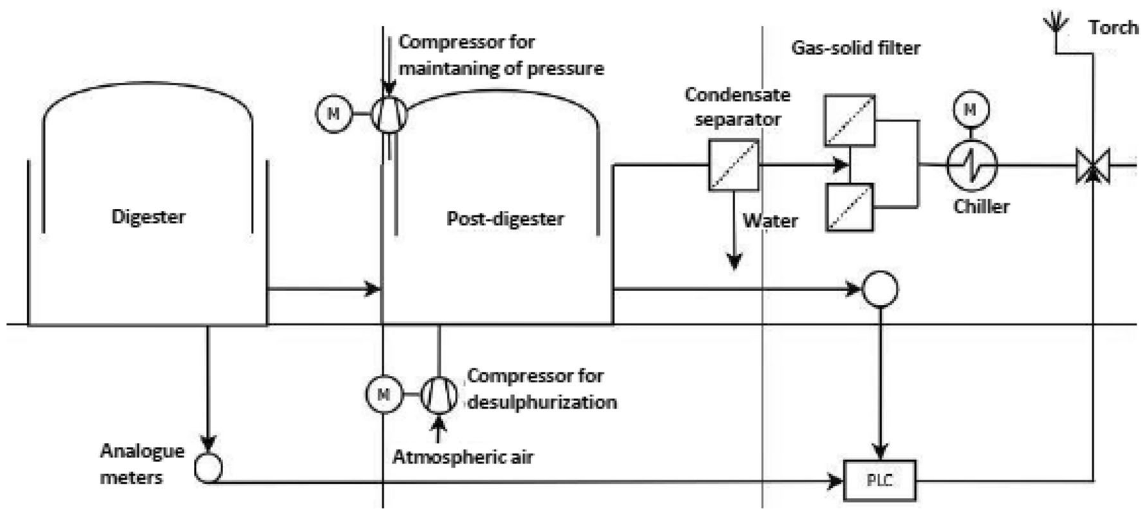

Fig. 2 Technical scheme of the considered plant

Table 1 Chemical composition and chemical-physical properties of the considered biogas

Biogas components	Biogas properties
CH_4 = 45–75% volume	Lower calorific power = 23 MJ/Nm^3
CO_2 = 22–47% volume	Wobbe Index = 27 MJ/Nm^3
O_2, H_2 e H_2O < 1% volume	Relative density = 1.2 kg/Nm^3
H_2S = 1000 ppm	Minimum temperature
NH_3 < 100 ppm	Maximum temperature

support for bacteria that perform biological desulphurization in situ is placed within the cover of the post-digester. Biogas has a highly variable chemical composition and chemical-physical properties [in function of the animal feed, periods of the year, conditions of the animals, etc. (Di Bernardo et al. 2017)] (Table 1). For this reason it is unsuitable both for sale in the methane gas network and for energy-generation use, unless it is subjected to appropriate treatments ("upgrade");

(h) digestate homogenization

The digestate undergoes homogenization in a system consisting of a cylindrical reactor equipped with a double mobile helix, made in stainless steel sheet (volume of 8.1 m^3). This helix allows to transform the incoming semi-solid fluid with BOD equal to 25,000 mg/dm^3 in a semifluid organic substance with BOD of 50–60,000 mg/dm^3, by the addition of sodium hydroxide in a quantity equal to 10% of the homogenizer volume. The reactor is continuously fed with digestate. The homogenized digestate accumulates at the bottom of the reactor;

(i) storage and purification of the homogenized digestate

The homogenized digestate is conveyed in the actual biological purifier, which is a truncated conical reactor built in reinforced concrete (volume of 40 m^3), and it is there purified for a minimum time of 5 days. At predetermined intervals, the system requires that compressed air is introduced into the reactor to move all the contained material and to stimulate the production of sludge, which is accumulated in the bottom of the purifier, by aerobic bacteria. The sludge is sent to the activated sludge storage. The clarified water at the top of the purifier is sucked and sent to the sewer or to surface waters;

(j) storage and drying of the activated sludge before spreading it on agricultural lands

The activated sludge are stored and stabilized by pit drying or, forcedly, on a drying belt, for subsequent sale as fertilizer for agricultural purposes;

(k) technical room, where the machines used for the anaerobic digestion process or for preliminary operations are housed.

Seasonal Yield of the Model Anaerobic Digestion Plant

Based on the collected data, to keep a constant biogas yield the anaerobic digestion process constantly requires different amounts of matrices (zoological reflux or high-energy crops), depending on the different operating parameters of the system.

The seasonal quantity of each feedstock provided for biogas production has been analyzed, in relation with the amount of produced biogas, as is visible in Fig. 3.

From this analysis it is possible to appreciate that:

- chicken manure is most widely used in the winter, with a decreasing trend towards warmer seasons, as nitrogen content is higher;
- in the spring, summer and autumn seasons, corn silage is used almost constantly thanks to its wide availability (especially in summer, when this cereal is harvested);
- the use of pig manure has a descending trend from winter to autumn, since the warmer months require less of this feedstock due to the change in water content of the corn silage during this seasonal cycle.

Overall, the anaerobic digestion process is discontinuous with respect to seasonality, as the amount of heat absorbed by digester and post-digester (which influences the activity of the bacteria) varies depending on the atmospheric conditions and, in particular, on the outside temperature.

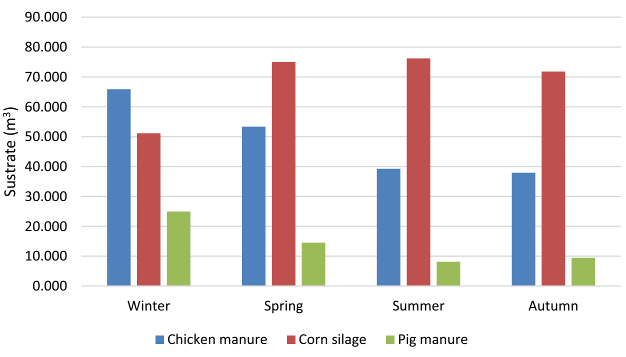

Fig. 3 Amount of produced biogas seasonally

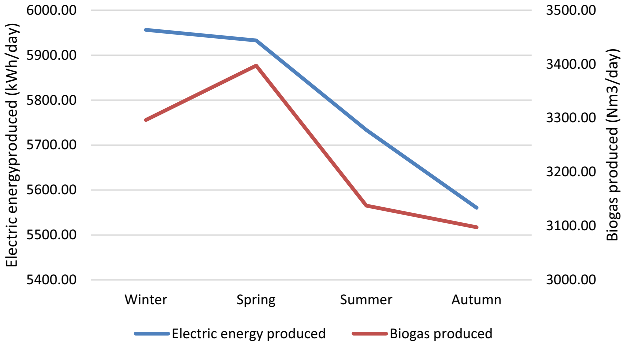

Fig. 4 Seasonal trend of production of energy and biogas

Figure 4 highlights the seasonal trend of production of energy and biogas. In particular, it is possible to notice that:

- in spring, a larger amount of biogas is produced, because in that period bacterial flora is more active (more efficiency bacteria);
- moving from spring to autumn, with respect to the winter production, there is a 6.27% decrease in electric energy production, and a 8.81% of biogas production, because bacterial flora becomes less efficient with decreasing external temperatures;
- the amount of produced electric energy is maximum in winter, because in this period the plant has a higher degree of control of the temperature of the bacteria, thanks to a larger flow of heating water. This allows to keep more constant the internal temperature of the reactor, boosting the bacterial flora productivity.

Different Alternatives for Biogas Use

The economic viability of the possible alternatives in the use of the produced biogas is analyzed using the methodology reported by different authors (Caliano et al. 2017; Farzad et al. 2017; Hahn et al. 2014; Naqvi et al. 2017). The used data and costs are those of the considered farm, including the "up-grading" hereafter described, taking into account some previous studies (Jonsson 2009; Persson 2003) and the values provided by the Italian Authority for electric energy and gas (https://www.arera.it/it/inglese/index.htm).

The technical and economic characteristics of the above described plant will be analyzed in three different applicative situations: (a) cogeneration, (b) trigeneration, (c) biogas purification and immission in the methane network. The presented data are the result of theoretical calculations carried out on the basis of the above described model anaerobic digestion plant, to which the technical and process modifications needed case by case are ideally applied, calculating the effect of these changes using well known thermodynamics and fluidodynamics formulas.

Table 2 Properties of the starting anaerobic digestion plant

Operating parameter	Values
Daily biogas production	3405 Nm^3/day
Percentage of methane found in the produced biogas	55%
Yearly energy of biogas produced	5978 MWh/year
Power needed to heat the substrate of the digester and the digester itself at 42 °C	92 kW
Yearly thermal energy required by the digester substrate and by the digester itself at 42 °C	807 MWh/year
Yearly produced electricity	2742 MWh/year

(a) Cogeneration plant powered by biogas coupled to dryers for treatment of different types of agricultural crops

In this case, the system added to the digestion plant consists of an endothermic engine with a displacement of 16.6 dm^3 with 8 cylinders in line, rotational speed of 1500 rpm and biogas consumption at nominal conditions of 142 Nm^3/h. The electrical efficiency of the cogenerative group is 38.1% and provides a power of 249 kWe.

The engine is installed in a structure that protects it against weather, working at full duty with regular maintenance every 8700 h (annual maintenance time of 60 h).

Due to the aforementioned seasonality characteristics, it is expected that during the winter season 90% of the thermal power of the cogenerative group will be used (164 kW, equivalent to 3936 kWh/day). This value will be reduced to about 20% in the summer period, as derived from the average of a series of measurements in existing anaerobic digestion plants (Di Bernardo et al. 2017).

Considering 8700 h of annual plant operation, the main operative parameters reported in Table 2 can be estimated.

To maximize the recovered heat, two heat exchangers for the engine have been designed.

The first one recovers heat from the water–glycol cooling system of the engine block, and it works mostly in summer (for estimated 60 days). The water–glycol used for cooling the engine block achieves a power of 164 kW, equivalent to 3936 kWh/day. During the summer period (average temperature, relative and specific humidity of ambient air 23.3 °C, 66.76% and 11.6 g/kg_{AS}, respectively) the total thermal power achieved is 276.6 kW, while during the winter period (average temperature 3.5 °C, relative humidity 75.41% and specific humidity of ambient air 11.6 g/kg_{AS}, respectively) the thermal power available is equal to 161.8 kW.

The second exchanger recovers heat from combustion products (fumes), and it will work all year round.

Combustion products develop a power of 129 kW, equal to 3096 kWh/day.

Overall, the mass flow rate of the combustion gas cooling battery will remain approximately constant throughout the year, while the mass flow rate of the engine block cooling battery in the two limit cases (summer and winter) will differ, and it is necessary to calculate these values.

Using the summer data, the first water–glycol exchanger provides a potential of 129.58 kW with an exchange surface of 97.68 m^2, a volumetric flow rate of 12,960 m^3/h ($m_1 = 15{,}339$ kg/h) and an increase in temperature between input and output from the exchanger by 29.6 °C, with constant humidity content. In winter the difference of temperature is not very different, therefore, these figures will be kept constant.

With respect to the exhaust fumes exchanger, the exhaust gas flow of 1067 m^3/h and a gas temperature at the inlet and outlet of 478 °C and 180 °C, respectively, make for a potential energy recovery of 54.82 kW (considering an exchange surface of 97.97 m^2 and a volumetric air flow rate of 298.4 m^3/h ($m_2 = 739$ kg/h) with an increase in temperature between input and output from the exchanger of 262 °C on a constant humidity content (Fig. 5).

By placing the two heat exchangers in parallel and considering the adiabatic process, a mixture of the two quantities of air obtained.

Another important parameter to be considered for the cogeneration plant optimization is the water content of the silage. The extraction of water vapour from cereal grains requires energy that will be provided by conveying hot air onto the silage. The drying plant will be designed considering corn as main feedstock, as the other cereals have lower water content and/or the specific surface is higher. It will operate between June and October, close to the summer air characteristics. The drying air temperature is fixed at 100 °C with a mass flow of about 15,000 kg/h. The required mass flow rate m_1 will be hence 14,261 kg/h after the passage; before mixing with the capacity m_2 (14,261 kg/h) it must be heated to 90.4 °C. The supplied thermal power is 353.5 kW in winter and 153.8 kW in summer.

Considering that the productivity of the ideally considered farm is 2000 tons/year of corn and that the drying plant can work also on behalf of third parties, a treatment potential of 55 tons/day (2291.67 kg/h) of dry product can be estimated. The technical parameters of the drying plant are given in Table 3.

The Dry-aeration process allows a contraction of both stress cracks (7.4%) and the percentage of broken grains (6.7%) and that involves in the case under consideration a mass of removed water of 381.95 kg_{H2O}. The mass flow of dry air at the entrance is, therefore, of 14,747.1 kg_{AS}/h, corresponding to a volumetric flow of 15,853.13 m^3/h.

Neglecting the heat loss in the dryer, the heat required for the actual drying of the cereal (368.78 kW) is the sum of three contributions: sensible heat needed to heat the water from the initial solid temperature to the wet bulb temperature at which evaporation occurs (35.53 kW), latent heat to evaporate water (241.05 kW) and sensible heat needed to heat the dry solid from the inlet temperature of 20 °C to the output temperature of 60 °C (92.20 kW).

Overall, the required heat for attaining this condition is higher than that generated by the air flow rate of 14,747.10 kg/h with a 62.5 °C thermal leap. Therefore, a further source of heat must be added to the system. This source is identified in an additional natural gas burner able to increase the mass flow rate of hot air to 20,209.70 kg/h. By keeping the previously set operating conditions, the temperature of the mass flow m_1' becomes 92.97 °C, the adiabatic mixing will be followed at first and then the indirect burner will be activated. The thermal power supplied in this way will be 259.23 kW.

Given the required productivity and the available amount of energy, it has been concluded that the most convenient route to provide the plant the aforementioned

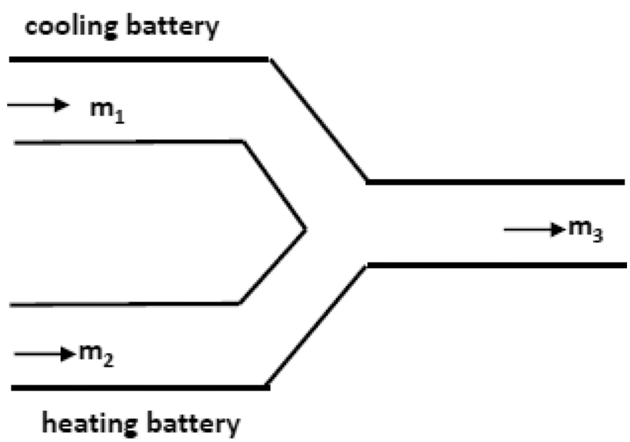

Fig. 5 Scheme of the air flows used of the heat exchange

Table 3 Assumptions for the mass balance of a cogeneration plant powered by biogas obtained from the considered anaerobic digestion plant coupled to dryers for different types of agricultural crops

Technical parameter	Value
Adiabatic drying process (equivalent to a linear process) time	1 h
Temperature of input drying air	100 °C
Specific humidity of drying air	11.6 g/kg_{AS}
Relative humidity of the air at the exit of the dryer	90%
Initial final grain moisture	28%
Final grain moisture required by the Dryaeration process	16%

drying capacity is to use a separated mobile drying machine, instead that building a dedicated drying unit in the plant.

To calculate the plant fixed costs, it must be considered that the necessary machineries will include: cogenerative group, sound-proof container, silencer, catalyst, ventilation system with air outlet silencer, heat sink working in excess air, automation with PLC and inverters for both engine and auxiliary services, supervisory Personal Computer, Low Voltage (LV)/Medium Voltage (MV) power transformer, MV transformer shields, MV line for energy transfer from container to delivery transformer room, booth MV framework, biogas treatment system, biogas dehumidification chiller and auxiliary. The total investment for these equipments is expected to be about 454,000.00 €.

The additional investment cost for the drying plant is given by the sum of the costs of mobile dredging (about 34,500.00 €), two heat exchangers (3000.00 €, divided into 1000.00 € for the exchanger operating with combustion products and 2.000,00 € for the heat exchanger working with digester heaters) and two silos needed to store the processed material, such as corn, soy or other seeds (for a total of 125,000.00 €, to which the 34,500 € of the mobile dredging unit must be added).

With this configuration, with a starting moisture content of 28%, then the drying costs will be of 292.00 €/kg corn. In more detail, for a 4-month operating period, the drying system consumes 30 kWh of electricity per hour corresponding to 108,000 kWh/year. Referring to an electricity cost of 0.050 €/kWh, this corresponds to a total annual cost of 5400.00 €. Since 32.91 Nm^3/h of methane is needed, corresponding to 118,476 Nm^3/year, and since the cost of methane is currently 0.21 €/Nm^3, an annual total cost of 24,879.97 € for the drying plant operation is obtained.

The silos depreciation coefficient is 8%, the coefficient of amortization of the cereal treatment machinery is 12.5% and that of the cogeneration plant is 11%.

The operating costs are quantifiable as reported in Table 4.

With the above mentioned costs, the total operation costs for the plant are 270,121.43 €/year.

To calculate the total annual revenues it must be considered that from selling the digestate spilling, at the current market prices (500 €/ton), about 46,770.88 €/year can be collected. Moreover, the produced electricity can be sold on the market to gain further 649,950.80 €/year (at a tariff of 0.28 €/kWh).

In a year, the prospected plant can process 3300 tons of corn, 1650 tons of soybean and 3300 tons of barley beet or leguminous seeds, from which an annual revenue of 262,960.00 € can be obtained.

The total revenue are hence 959.681,68 €/year.

In the event that the company invests the overall capital of 616,500.00 €, considering constant Italian taxes valued as 27.5% (IRPEF) and 3.9% (IRAP), the plant setup and operation has a payback period of 1.69 years and a Net Present Value of 2659,764.92 € after 15 years.

(b) trigeneration plant

A trigeneration plant is a power plant combining the production of Heating, Cooling and Electric Power: it is constituted by

- a combustion engine with high electrical performance connected to an electric generator or to an alternator;
- a heat recovery system working on the exhaust gas or on the primary engine cooling circuit, by means of a heat exchanger;
- a refrigerant fluid-generating system, consisting in a heat-absorbing machine for producing chilled water for conditioning or for industrial use.

For this plant, the main operating parameters deriving from the energy balance for 8700 h of annual operation are reported in Table 5.

The investment costs for a trigeneration plant able to satisfy the above mentioned operating parameters are around 1742,890.00 €, as detailed in Table 6.

For this type of plant, the estimated annual revenue is given by the sum of the incomes deriving from digestate spilling sale (46,770.88 €/year) and electricity sales

Table 4 Operating cost of the cogeneration plant powered by biogas coupled to dryers for the treatment of different types of agricultural crops

Item type	Yearly cost (€/year)
Total cost of biomass (maize silage, glucose, barley and triticale)	142,904
Total labour cost	17.720
Total cost of ordinary and extraordinary maintenance	39,150
Cost of managing the cogeneration system	26,100
Insurance (0.3% of the investment)	1362
Administration costs (0.5% of revenues)	3237
Other operating costs (digestate loading and spilling)	39.650
Worker cost (including wages, taxes and contributions) for 5 months a year	10,000

Table 5 Main parameters of the trigeneration plant

Item type	Value
Daily biogas production	3405 Nm^3/day
Percentage of methane in biogas	55%
Yearly energy of biogas produced	6978 MWh/year
Power needed to heat the substrate of the digester and the digester itself at 42 °C	92.1 kW
Yearly thermal energy required by the substrate of the digester and the digester itself at 42 °C	806.8 MWh/year
Yearly heat energy consumed to heat poultry farm at 20 °C	240 MWh/year
Yearly cooling energy produced by the chiller	151.2 MWh/year
Yearly electricity produced by the plant	2742 MWh/year
Yearly electricity self-consumed by the plant	142 MWh/year
Yearly surplus electric energy (saleable)	2600 MWh/year

Table 6 Investment costs for the trigeneration plant

Item type	Cost (€)
Digester, post-digester, cogeneration group, connection to an electric network and auxiliary	1,617,900
Heat exchanger for fumes	25,000
Two absorption chillers	50,000
Purchase and installation of fan coil systems	50,000

(all-inclusive tariff, 649,950.80 €/year), for a total revenue of about 696.721 €/year.

The heating and cooling savings deriving from the trigenerator characteristics must be considered to extract the total annual revenues. Moreover, some of the electrical energy produced by the plant will be used by the plant itself (self-consumption).

The annual savings in terms of thermal energy, that the plant will provide to a user, such as a farm, can be estimated upon the data provided in Table 5, yielding a saving of 6113.20 €/year. This figure is calculated considering that if the user should produce its own thermal energy burning commercial natural gas, it should buy it at a price of 0.27 €/Nm^3, and it should burn 22,641 Nm^3/year of it to match the thermal energy produced by the trigeneration plant. With a similar line of reasoning, the plant will provide electric energy savings for a user. These savings can be estimated to be equal to 8524.92 €/year, considering a cost of the electric energy at 0.06 €/kWh for 142,082 kWh/year.

Considering the above reported savings, the total saving achievable with a trigeneration plant is about 16,667.00 €/year.

With respect to the cooling system, it is assumed that the trigeneration plant will use a compression chiller with Energy Efficiency Ratio = 1.5, that would use electric energy for a final cost equal to 2028.96 €/year.

The operation costs of the trigeneration plant are quantifiable as reported in Table 7.

With the above mentioned costs, the total operation costs for the plant are 313,796.29 €/year.

Upon the above mentioned expenses and operating costs, If the company invests a capital of € 639,171.00 and the remaining amount of € 1103,719.00 is covered by a 15-year bank loan with a 6% interest rate and at constant rates, and considering that the company pays IRPEF and IRAP taxes at a rate of 27.5% and 3.9%, respectively, it has a payback period slightly above 2.34 years and a Net Present Value of 2029,487.56 € after 15 years;

(c) plant upgrade and immission of the biomethane in the network

It has been planned an anaerobic digestion system with a biogas depuration system with regenerative scrubbing water

Table 7 Operating costs for the trigeneration plant

Item type	Value (€/year)
Total cost of biomass (maize silage, glucose, barley and triticale)	142,904
Total labour cost	17.720
Total cost of ordinary and extraordinary maintenance	95,058
Insurance (0.3% of the investment)	5229
Administration costs (0.5% of revenues)	3237
Other operating costs (digestate loading and spilling)	39.650
Worker cost (including wages, taxes and contributions) for 5 months a year	10,000

and the introduction of biomethane into the network (Ryckebosch et al. 2011).

From the energy balance made for 8700 h of annual plant operation can be noted that reported in Table 8.

The investment costs for the plant upgrade and the infrastructure needed for the immission of the biomethane in the network are depicted in Table 9, and their sum is equal to 2335,000.00 €.

Annual revenues can be quantified upon sales of digestate spilling (46,770.88 €/year) and of purified biomethane (687,771.24 €/year), for a total revenue of about 734,542.12 €/year.

The operating costs are quantifiable as is reported in Table 10.

In this plant, the worker cost is zero because the upgrade equipment does not need dedicated personnel.

With the above mentioned costs, the total operation costs for the plant are 298,173.54 €/year.

If the company invests a capital of € 639,171.00 and the remaining amount, equal to € 1695,829.00, is covered by a 15 years bank loan with a 6% interest rate and at constant rates, it has a payback period slightly above 2.21 years and a Net Present Value of 2004,376.79 € after 15 years.

Table 8 Properties of the plant upgrade and immission of the biomethane in the network

Item type	Value
Daily biogas production	3405 Nm^3/day
Percentage of methane in biogas	55%
Biomethane losses during the up-grading	3%
Amount of biomethane sold	1816 Nm^3/h, 658,300 Nm^3/year
Calorific power of biomethane	10.6 MWh/Nm^3
Yearly energy of biomethane produced	6978 MWh/year
Power needed to heat the substrate of the digester and the digester itself at 42 °C	92.1 kW
Yearly thermal energy required by the substrate of the digester and the digester itself at 42 °C	806.8 MWh/year
Thermal energy consumed by the up-graded plant	370 MWh/year
Thermal energy consumed by the air conditioning unit for cooling the compressed biogas	41.5 MWh/year

Table 9 Investment costs for (1) plant upgrade and (2) immission of the biomethane in the network

Item type	Value (€)
Design and execution	20,000
Digester and post-digester construction	100,000
Electrical and thermo-hydraulic plant	85,000
Civil works	50,000
Plant upgrade (water scrubbing with recirculation)	950,000
Compressor, pump and heat exchangers of the air conditioning unit	135,000
Electrical installations	35,000
Pipes (400 m) for connection to the gas network (purchase and installation)	60,000

Table 10 Operating cost for (1) plant upgrade and (2) immission of the biomethane in the network

Item type	Values (€/year)
Total cost of biomass (maize silage, glucose, barley and triticale)	142,904
Total labour cost	21,586
Total cost of ordinary and extraordinary maintenance	43,877
Insurance (0.3% of the investment)	7005
Administration costs (0.5% of revenues)	3237
Costs of water, thermal and electric energy	46,485
Other operating costs (digestate loading and spilling)	39.650

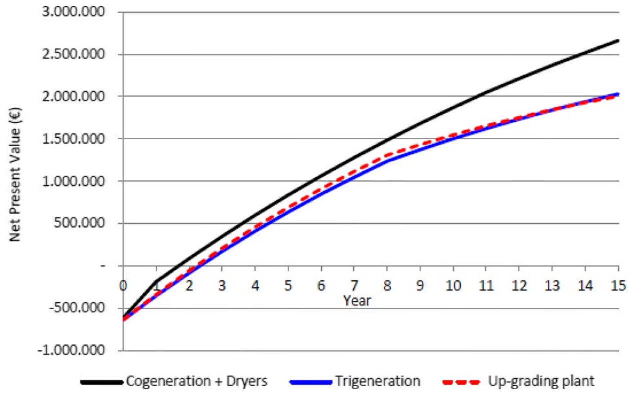

Fig. 6 Net present value for three considered plant improvement solutions

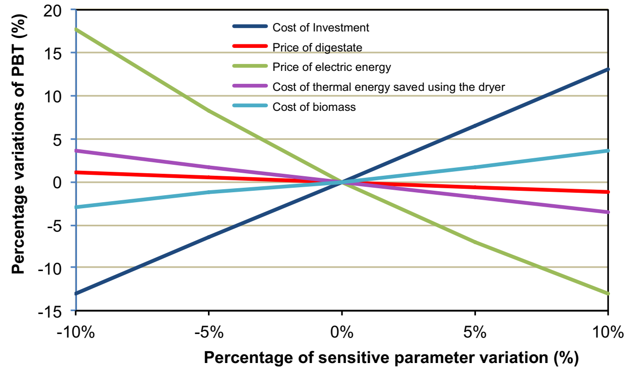

Fig. 7 Cogeneration plant (case a): graph of the sensitivity of payback time to the cost of investment (blue curve), price of digestate (red curve), price of electric energy (green curve), cost of the thermal energy saved using the dryer (violet curve), cost of biomass (cyan curve)

In the economic analysis it was assumed that the incentive scheme for biogas production will remain unchanged throughout the investment period (15 years).

A careful analysis of the economic results presented for the analysed individual solutions (Fig. 6) allows to assess that:

- the trigeneration plant and the up-grading plant with direct sale of biomethane to the network are not as profitable as the other solution, as they have a higher payback period (2.34 and 2.21, respectively, against 1.69) and a NPV lower than 15 years;
- the cogeneration plant with dryer is preferable to the simple cogeneration one because, although it has a slightly higher payback period or a NPV slightly lower than 15 years, the useful life of the dryer is much higher than 15 years and, therefore, the economic advantage is achievable even beyond this period. Moreover, if the dryer would be used for more than 5 months every year by exploiting other agricultural crops (e.g., greenhouse tomatoes), the benefit would be much higher.

Sensitivity Analysis for the Considered Plant Improvement Cases

To complete this study, sensitivity analyses have been performed on some relevant parameters of the considered possible plant improvements, in line with analogous approaches taken by other authors (Nixon 2016), but taking into account that the considered starting plant is already working at its maximum efficiency (i.e., the parameters of Tables 2, 5 and 8 are fixed). All the considered parameters have been varied by ± 10%, and the result of these variations have been examined in function of the overall payback time (PBT) for each of the presented plant upgrade cases.

Therefore, for the cogeneration plant powered by biogas coupled to dryers (case a) the following parameters have been considered: the plant improvement investment cost, the price of digestate, the price of the produced electric energy, the cost of thermal energy saved using the dryer and, finally, the overall cost of the biomass.

The results of this analysis are visible in Fig. 7. The price of digestate (red curve), the cost of thermal energy saved using the dryer (violet curve) and the cost of biomass (cyan curve) do not influence sizeably the overall payback time, as even changes of ± 10% of these parameters result in less than ± 5% variations in the PBT. On the contrary, the cost of the biomass (blue curve) has a relevant influence on the PBT, which can be reduced by almost 15% if the cost of biomass decreases of about 10%, and increases similarly if the cost of biomass increases by the same amount (being the relation between the two parameters linear). The price of the electric energy has an even higher influence: a decrease of the price of 10% results in an increase of the PBT of almost 20%, while this effect is slightly less important on the other side of the curve, where for an increase of 10% the PBT is decreased by about 13%.

Similar considerations can be made for the trigeneration plant (case b). In this case, the considered parameters are the amount of the initial investment, the price of the digestate, the price of the electric energy, the cost of the saved thermal energy, the cost of the biomass and the mortgage interest rate. As is visible in Fig. 8, the influence on the PBT of the amount of investment (blue curve), price of the digestate (red curve), cost of the thermal energy (violet curve) and mortgage interest rate (orange curve) is negligible. The effect of the change of the biomass cost is instead appreciable, with a ± 10% change that results in an about ± 5% variation of the PBT. The change of the electric energy price is important, as a − 10% of decrease of the price of electric

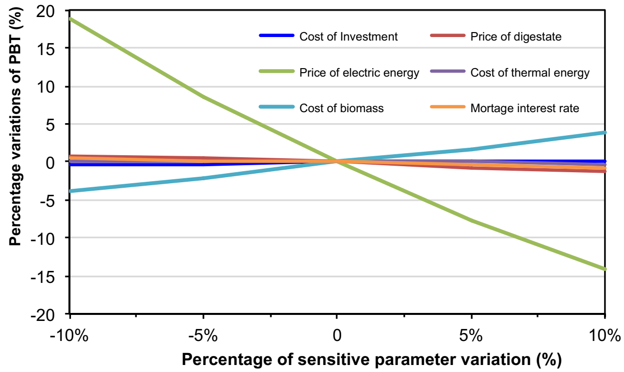

Fig. 8 Trigeneration plant (case b): graph of the sensitivity of payback time to the cost of investment (blue curve), price of digestate (red curve), price of electric energy (green curve), cost of the thermal energy (violet curve), cost of biomass (cyan curve), mortgage interest rate (orange curve)

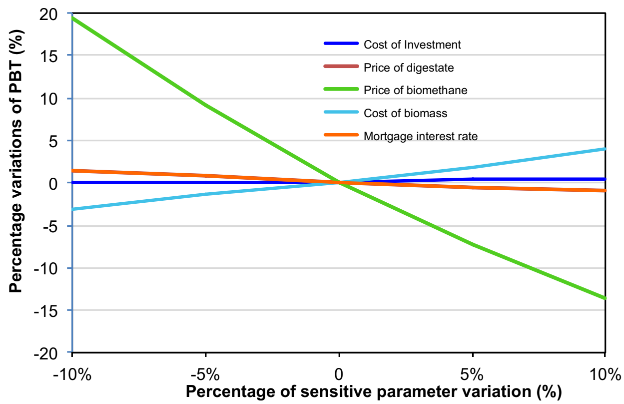

Fig. 9 Biomethane sale upon plant upgrading (case c): graph of the sensitivity of payback time to the cost of investment (blue curve), mortgage interest rate (orange curve), price of digestate (red curve, completely below the orange curve), price of biomethane (green curve), cost of biomass (cyan curve)

energy is reflected in an increase of almost 20% of the PBT, while a + 10% generates a decrease of about 15% in the PBT.

Finally, for the biomethane direct sale to the network (case c) the considered parameters are the amount of initial investment, the price of digestate, that of the sold biomethane, the cost of biomass and the mortgage interest rate. From this analysis it is evident (Fig. 9) that the amount of initial investment (blue curve), the price of digestate (red curve) and the mortgage interest rate (cyan curve) have a very small impact on the PBT, while a more relevant effect is caused by the change in the cost of the biomass (violet curve), which, however, contains the variation band in PBT to ± 5% upon changes of ± 10% in the parameter. The price of the biomethane is the most important parameter in determining the final PBT: with a decrease of 10% the PBT increases by almost 20%; viceversa, with the increase of the price, the PBT has a bit lower decrease, to a value of about − 15% for the + 10% increase of the biomethane price.

General Considerations Over the Environmental Impact of the Proposed Plant Improvement Solutions

The biogas produced by an anaerobic digestion plant powered by zootechnical waste, possibly integrated with maize silage, used with energy systems converting the energy potential into electrical and thermal energy, offers a significant environmental advantage over the traditional plants for the production of energy from fossil source.

The carbon dioxide emission differential has been assessed in the solution for the cogeneration plant associated with the drier for the treatment of different types of agricultural crops, both when using biogas integrated with methane, and when using methane for both plant systems.

In the first case, carbon dioxide is emitted only for the integration of the thermal power required by the dryer by activating a direct fire burner. In this case, methane consumption is 624 Nm^3/day, corresponding to a carbon dioxide emission of 1716 Nm^3/day.

When both the cogenerator and the integration energy of the drier are fed with methane, there is a consumption of methane from fossil origin of 1874.4 Nm^3/day and 624 Nm^3/day. This corresponds to an overall carbon dioxide emission of 6870.6 Nm^3/day. The positive balance of the plant powered by biogas is, therefore, 5154.6 Nm^3/day.

In a more general frame, several authors have analyzed the situation of a plant producing biogas from zootechnical wastes and/or cereals silage, by anaerobical digestion, mainly using the Life Cycle Assessment (LCA) technique. For example, Dressel et al. (2012) found that the production of biogas from maize and the subsequent transformation of the produced biogas into electricity have an environmental impact, under different categories (acidification, eutrophication, greenhouse gases emission, total fossil energy demand), strongly dependent from the geographical region in which the activity takes place, due to differences in irrigation, fertilization and general farming practices. Lijó et al. (2015)assessed the LCA of plants using swine sewages (as a waste from other farms, hence with the sewage production not included in the LCA process) and maize silages for the production of biogas, finding that these plants generate an environmental advantage with respect to traditional plants, and the use of the digestate as organic fertilizer is a supplementary benefit, with the caveat due to the eutrophication and acidification effects of the digestate matter. They also estimated the outcome of biogas production from mixed swine sewage/cereals silage using six potential impact categories (abiotic exhaustion, acidification, eutrophication, global warming, ozone depletion, photochemical oxidation), finding that this waste mix ensures evident environmental advantages and that the use of digestate as a fertilizer is of particular importance to reduce the global warming potential (Lijó et al. 2014). De Vries et al. (2012) have analyzed different categories of environmental impact (climate change, terrestrial acidification, marine and freshwater eutrophication, particulate matter formation, land use and fossil fuel depletion) upon the use of different combinations of animal (swine sewage) and vegetal (maize silage, maize silage and glycerin, beet tails, wheat yeast concentrate and roadside grass), finding that the best combination of wastes, in terms of reduced overall environmental impact, is that constituted by swine sewage and roadside grass. Jury et al. (2010) analyzed the LCA of biogas production from a monofermentation of energy crops, finding that the so-realized biogas is not economically competitive with the fossil-derived one, but that it is anyway more environmentally sustainable, in particular with respect to the climate change effect, the damage on natural resources and the fossil energy demands.

Overall, the here reported analysis appears to be well in line with the existing literature on the subject, confirming that the use of anaerobic digestion for the generation of biogas from animal or vegetal wastes generates an environmental advantage with respect to the traditional fossil fuels-based plants.

Conclusions

The paper analyzes the technical, economic and environmental feasibility of different technologically mature alternatives to the use of biogas produced by an anaerobic digestion plant powered by zootechnical waste, integrated by maize silage. These solutions are (a) cogeneration, (b) trigeneration, (c) biogas refining to biomethane upon plant upgrading.

For each alternative a comprehensive economical analysis have been carried out. The results of these analyses show that the options (b) and (c) are almost equivalent in terms of NPV at 15 years and payback times, while the option (a) is more advantageous, although not in a dramatic way (paybak time of about 1.7 years vs about 2.3 years for the other two options).

A sensitivity analysis over the main parameters influencing the payback time of the three presented plant improvement alternatives has been carried out, showing that in each case the most impacting parameter is the cost of the energy that the market can pay to the plant owner, being it under the form of electric energy (cases a and b) or of biomethane (case c).

The described analysis represents a valid starting point for considering possible upgrades of existing anaerobic digestion plants, leading to better management of the energy services in an agricultural business, and gaining obvious economic-environmental benefits.

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