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ScienceDirect
Energy Procedia 82 (2015) 666 – 673
Energy Procedia

ATI 2015 - 70th Conference of the ATI Engineering Association

Technical and economic analysis of a cogeneration plant fueled by biogas produced from livestock biomass

Francesco Calise[a], Cesare Cremonesi[b], Giulio de Notaristefani di Vastogirardi[c,*], Massimo Dentice d'Accadia[a]

[a]*Università degli Studi di Napoli Federico II – Department fo Industrial Engineering, P.le Tecchio, 80 – 80125 Napoli*
[b]*Cremonesi srl- Via Trecella 1 – Albignano d'Adda1- 20060 (MI)*
[c]*Mechanical Engineer – Via G. Donizetti 9 – 80127 Napoli*

Abstract

This technical report illustrates an anaerobic digestion plant for the production of biogas designed to be powered by livestock biomass, combined with a 330 kWe CHP unit co-generator, installed in a cattle farm located in the province of Reggio Emilia. The plant consists essentially of a pre-treatment system of the effluents to the load, two anaerobic continuously stirred tank reactors and heated under mesophilic regime sheltered with gasometric coverings with double membrane; at the end of the process of fermentation, the digestate converges in a solid-liquid separation system with helical compression and a storage tank of the clarified fraction, sheltered with a covering for the containment of residual gaseous emissions into the atmosphere. The produced biogas is collected in gasometers placed above the tanks and, after desulfurization, dehumidification and cooling, it fuels the co-generator. The report is determined to illustrate the experimental results for the first 12 months of operation of the plant that confirmed, both in terms of energy and from a financial perspective, the efficiency of biogas plants fueled only by livestock effluents.

Peer-review under responsibility of the Scientific Committee of ATI 2015

Keywords: biogas, anaerobic digestion, digestate, cogeneration

Introduction

The installation has been set up in a farm company named "F.lli Pedrotti of Reggio Emilia", a site where a cattle farming for the production of Parmigiano Reggiano are situated. The cattle are raised in two business sites located only 2 km one from the other. During the experimental period the company housed in their breeding 1,850 heads, in detail about 850 lactating cows, 200 heads in dry and 800 more

* Corresponding author. Tel.: +39 081 0130426 ; fax: +39 02 48630805.
E-mail address: giulio.denotaristefani@hotmail.it

Peer-review under responsibility of the Scientific Committee of ATI 2015
doi:10.1016/j.egypro.2015.12.024

heads including heifers, young heifers and calves. Depending on the season, the consumption of bedding straw varies from 3.2 kg/head/day for the confinement in crates to 6-8 kg/head/day for the usage of beddings. There are two milking rooms but only the washing waters of one of them are mixed with the effluents and this determines a difference in the chemical characteristics of the effluents coming from the two sites although it is possible to detect values in line with the results expected, as reported in Table 1. [1-3].

Table 1. Chemical Characteristics of effluents started to anaerobic digestion.

Kind of effluents	pH	Total Solids (g/kg)	Volatile Solids		Total Nitrogen		Ammonia Nitrogen (N-H4+)	
			g/kg	%t.s.*	mg/kg	%s.t.s.*	mg/kg	%NKT**
Sewage with washing water of 1st milking room	7,09	48,9	40,9	82,8	1493	4,6	656	43,9
Sewage without washing water of 2nd milking room	7,23	80,4	63,4	78,7	3097	4,3	1.585	51,2
Manure	8,02	163,9	137,3	83,8	4610	2,9	1.492	32,4

*s.t Total Solids - ** NKT Total Nitrogen

The amount of effluents measured during the observation period showed an average of approximately 115 t./day, with an increase during the summer up to 125 t./day, caused by the evaporative cooling system of the stables, which has produced a substantial dilution of sewage. The availability of total solids showed an average of about 11,000 kg /day, with an average percentage of volatile solids around 81%, equivalent to 12.3 kg / head of production (9.7 kg of volatile solids / head production).

1.1. Data of layout

The plant has been designed with the following purposes:

- allow the maximum supply flexibility to grant its future adaptation to the different matrices that may be available from time to time;
- minimize sand and solid bodies sedimentation inside the digester;
- optimize the conversion of organic substances into biogas by providing a digester with a processing temperature up to 44° C;
- to be dimensionally compatible with the production of biogas, in terms of quantities and characteristics, as indicated in Table 2 and in Table 3.

For the calculation of the volume of the tank reactors the following formula was applied:

$$V_{disp} = \left(Q + Q_{DR} + Q_{H_2O}\right) * HRT * k_r V_d \quad (1)$$

with Q= effluent rate (m^3/giorno), Q_{DR} = recycled digestated rate (m^3/day), Q_{H2O}= additional water rate (mc/day), HRT = hydraulic retention time (set equal to 30 days), $k_r V_d$= safety factor (set equal to 10%) [3]. The volume of biogas and the average percentage of methane it contains, produced with the available quantity of effluents, can be estimated using the stoichiometric model based on the relationship

$$\mathrm{CaHbOcNd} + \alpha\mathrm{H2O} \rightarrow \beta\mathrm{CH4} + \gamma\mathrm{CO2} + \delta\mathrm{NH3} \quad (2)$$

In eq.(2), CaHbOcNd is the biodegradable organic substance in the waste and we can calculate the stoichiometric coefficients setting the equality between the terms of the first and the second member [4].

Table 2. Data of plant load.

Matrix	Minimun annual flow rate to load (ton/year)	Minimun daily flow rate to load (ton/day)	minimum percentage of dry substance SST (%)	Ratio SSV/SST (%)
Cow Sewage	25.000	68	8	82
Cow Manure	9.500	26	24	82

Table 3. Plant characteristics and project parameters

Continuosly stirred tank reactors CSTR	Total gross volume of tank reactors (m^3)	Total net volume of tank reactors (m^3)	average volumetric organic load (kg s.v./m^3 day)	average hydraulic retention time (days)	Maximum production of biogas		Average percentage of methane in the biogas (%)
					(Nm^3/day)	(Nm^3/year)	
2	4.560	3.800	2,4	30	3.505	1.278.500	55

The two monolithic tanks of reinforced vibrated concrete (mix between the type C30/37 XA1, in volume of approximately 219 m3, and the type C12/15, in volume equal to about 37 m3) of dimensions Ø 22 m - h 6 m , volume 2,280 m3 (1,900 m3 fermentation volume), can be inspected and are insulated in XP 8 cm on the bottom and on the walls The two covering domes, running hemispherically, are air-supported with a blowing double membrane seal, double biological net, and over/under pressure valve.

Inside each tank there are 2 immersion Mixer Mod. GTWSI-Ex 204 (stainless steel Ø 820 mm Propeller) with stainless fixing system and vertical positioning system with a guide tube.

The process temperature of tank reactors (max 44°C) is kept stable with a system of insulated ring coaxial tubes internal to the digesters and fixed with brackets, the hot water distribution instead takes place thanks to manifolds. The energy parameters of the system are shown in Table 4; it should be kept in mind that the testing was performed for the first six months with the engine at 70% of its Pn, since, pending enlargement of the stables, the matrices available did not allow a production of biogas such as to generate the project power. The installation was developed following the scheme shown in Fig.1: it is possible to individuate a homogenisation tank called "kitchen", a system for pre-treatment of the effluents to the load, two circular anaerobic tank reactors continuously blended, heated under mesophilic regime and sheltered by gasometric coverings with double membrane, a helical compression solid-liquid separator for the treatment of the digestate and a storage tank of the clarified fraction sheltered by a covering for the containment of residual gaseous emissions into the atmosphere. The sewage produced by the two operation centers of the farm are conveyed in a mixing tank designed to be heated and inoculated with a part of the recirculation digestate. The load of the effluents in the "kitchen" is made through one automatic dispenser wagon, equipped with load cells to monitor the quantity; the shredding of the straw fractions, instead, is obtained thanks to a grinding pump equipped with a separator of solid elements such as stones, iron, wood, etc; after the mixing, the pump is programmed for dosing the load at regular intervals in the two fermenters. The biogas produced in the two fermenters is stored in the gasometers overlying the tanks and, after having been undergone to a predominantly organic desulfurization with controlled insufflation of air into the gasometric dome, it is dehumidified and cooled by a refrigeration system; later, it is sent to the cogeneration group (AB ENERGY - ECOMAX 3BIO 330 kWe, JENBACHER endothermic engine) and installed in a container that acts as a soundproofed utility room; the power of the plant has been identified in relation of the potential increase in cattle breeding.

Table 4. Main data of plant energetic performances.

electricity generation net of consumptions CHP (kWe)	workings hours (h/year)	Gross electricity generation (kWh/year)	energy need by the plant (kWh/year)	salable electricity generation (kWh/year)	engine thermal power (kW)	exhaust fumes thermal power (kW)	thermal power needed by the plant (kW)	thermal residual power (kW)
294	8.000	2.372.500	343.100 (1)	2.029.400	205	195	171(2)	122

(1) Calculated without steps of biomasses pre-treatment and digestate post-treatment
(2) Calculated with mesophilic process (44°C) and outside temperature of – 10°C

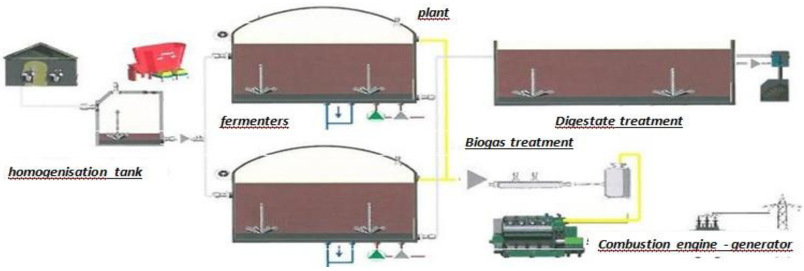

Fig. 1. Scheme of plant layout.

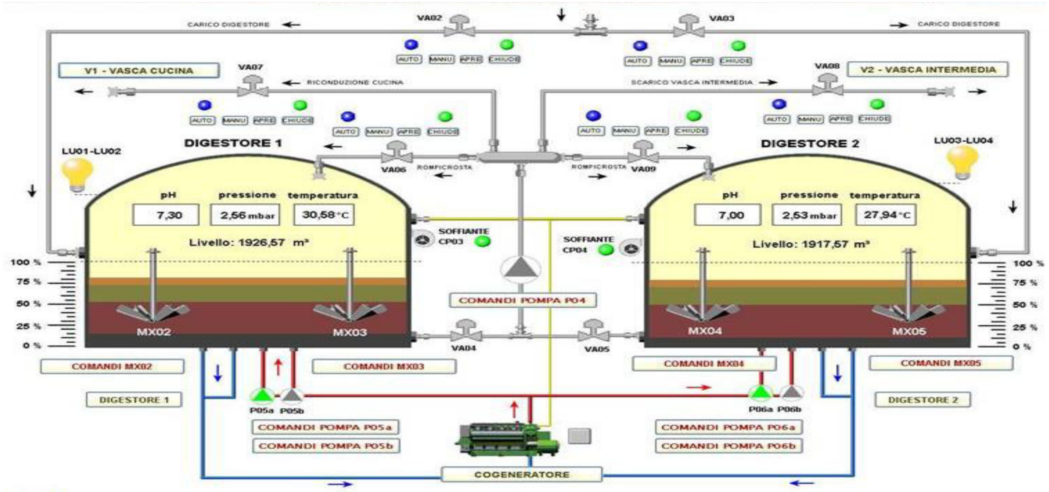

Fig. 2. Graphical user interface of management software.

The control PLC (see the picture shown in Fig.2) allows the complete management of the plant and, in particular, reveals the following functional applications:

- management of the pump and pneumatic shut-off valves;
- management of the mixers;
- management of the levels;
- management of the heating system;
- management of the systems for loading and unloading the digester.

In the first six months of the monitored period, operating data and performance requirements in the start-up phase and in the steady operation have been collected. Fig.3 shows the trends of the organic volumetric load and the hydraulic retention time HRT that shows the required days of fermentation of an "active" biomass in the anaerobic tank reactor in order to produce biogas anaerobically. During the starting phase, a period of 80 days characterized by a progressive increase of the organic load with consequent reduction of the retention time, the load of effluents has been progressively increased, with short intervals necessary to modify the set-point of the pretreatment system, mixing and load. Increasing load of the straw, it became necessary to calibrate the amount of digestate recirculation so as to ensure a correct pumpability of the mix. The organic volumetric load in the steady operation amounted on average to about 2.4 kg of s.v./m3 day.

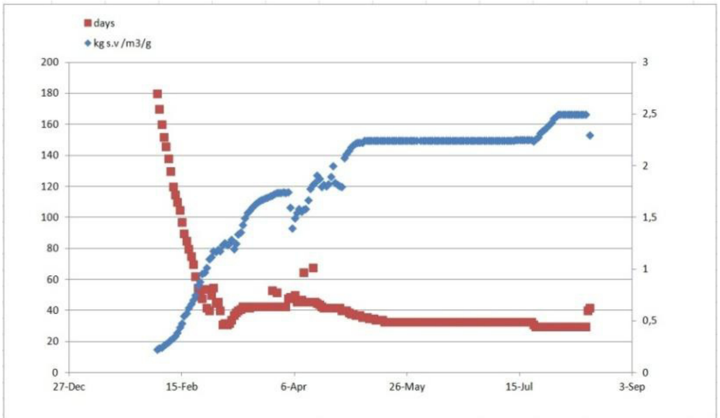

Fig. 3. Organic volumetric load and HRT.

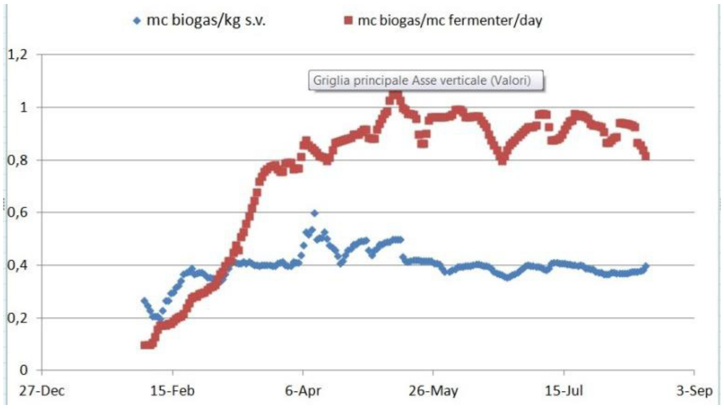

Fig. 4. Biogas production.

Fig. 4 shows the biogas specific production curves, related both to the effective volume of the tank reactors and to the amount of volatile solids loaded. In the curves it is possible to identify a first starting phase where, with the increase of the organic load and the set up of the biological process, there is a significant increase in specific performances which subsequently steadily boost until reaching a second phase where the trend looks stable. It was possible to move from the start-up phase to the standard phase by performing continuous adjustment of the main system parameters (temperature of the reactors, pressure, tuning of the engine); this in addition to a prudent variation of the load matrices obtained also by modifying the stable diets and the amount of straw used as bedding to balance the excessive dilution of the effluents caused by rains in the winter period [5]. The average volumetric production of biogas in the steady phase was equal to about 0.92 m^3 of biogas in relation to m3 of useful volume per day, while the production of biogas compared to the amount of volatile solids (s.v.) was approximately on average to about 390 m3 biogas/t/s.v. The average percentage of methane in the biogas produced was 55%, with a specific production of 0.22 m^3 / kg sv; the amount of ammonia in the biogas was about 300 ppm, while the emission of ammonia with the biogas was around 0.25% of the total nitrogen uploaded.

In Fig. 5 and Fig. 6, we can see that the plant has produced approximately 6.500 kWh/day, generating an average power of 272 kW; these values correspond, roughly, to a production of 0.30 kWe/head of cattle and 7.3 kWhe/head of cattle for day.

In Tab. 7 we can also see the monthly ignitions of the engine all due to machine downtimes for routine maintenance. In September there was a failure to an engine head, in November there was the maintenance of the 30,000 hours which caused a downtime of 8 days with a significant reduction of power generation.

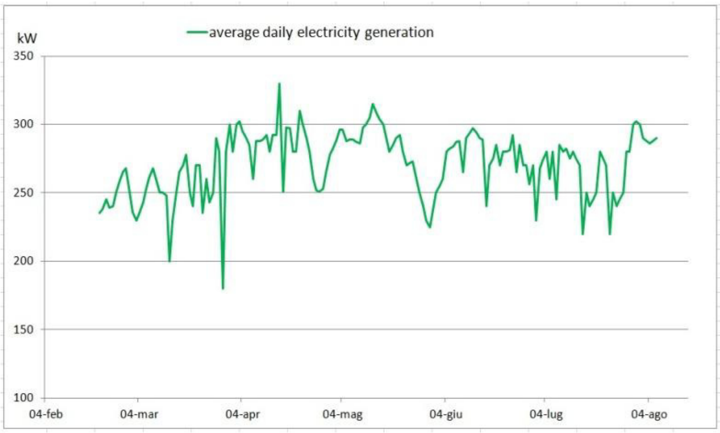

Fig. 5. Average daily electricity generation

Total own consumptions, calculated on the basis of the working hours of all the electric utilities closely linked to the production of biogas (excluding therefore the solid-liquid post-digestion separation phase), amounted to 940 kWh per day, equivalent to about 14, 4% of the total production; in particular the treatment phase of the mix preparation and the phase of load consumed an average of 325 kWh/day (5.0% of gross production), the utilities connected to the anaerobic tank reactors an average of 436 kWh/day (6.7% of the gross production) and the separation treatment with the pumping absorbed 124 kWh/day (1.9% of gross production).

The average daily net production was, therefore, equal to 5.790 kWh, for a total annual result of around 2.113 MWh, which generated a gross sale of 591.640 Euro with the benefit of 280 Euro / MWh given by the GSE all-inclusive incentive tariff.

The anaerobic digestion transforms part of the organic nitrogen into ammonia one; therefore, the concentration of total nitrogen present in the mixture to be loaded and the quantity that we can found in the digestate at the end of anaerobic process, remains almost unchanged while there is an increase in the quantity of ammonia nitrogen (from 1.422 mg / kg to 2,037 mg / kg). In the solid-liquid separation phase of the digestate produced during anaerobic digestion, the organic nitrogen is trapped in the solid fraction while the ammonia nitrogen stays mostly in the clarified fraction [6].

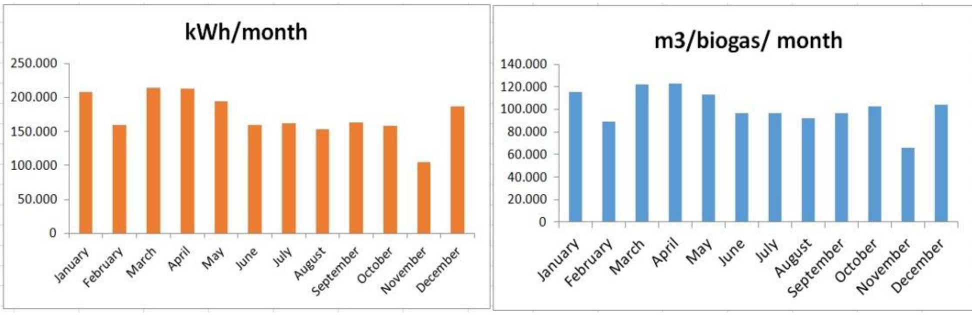

Fig. 6. Monthly electricity generator and biogas.

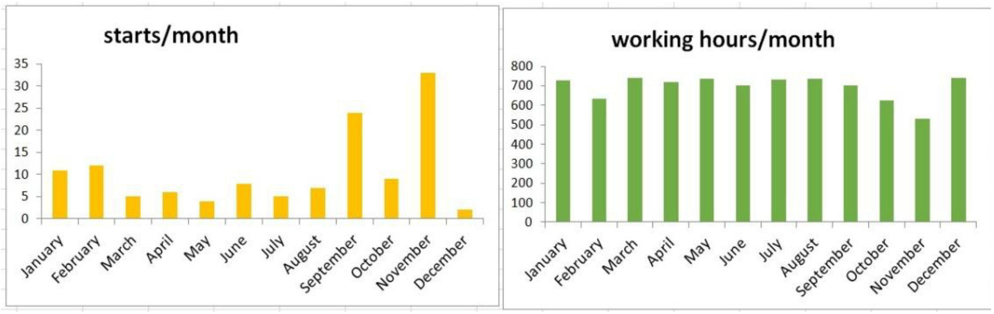

Fig. 7. Monthly working hours and starts of cogenerator

Table 5. Chemical characteristics of effluents load in the tank reactors and digestate produced

Kind of effluences	pH	Total solids (g/kg)	Volatile solids		Total nitrogen		Ammonia nitrogen (N-H4+)	
			g/kg	%s.t.*	mg/kg	%s.t.*	mg/kg	%NKT**
Average mixture to load	7,6	96	81,2	83,96	3.234	3,32	1.422	43,7
Digestate (n.=19)	7,8	54	4,7	73,23	3.400	5,5	2.037	60,3
Clarified Digestate (n.=2)	7,9	43	29,1	63,54	3.415	7,45	2.064	60,5
Solid Digestate	8,6	254	230	89,2	5.111	1,97	1.802	35,4

** s.t total solids - ** NKT Total Nitrogen*

Table 5 summarizes the characteristics of digestate and of the two fractions given by the solid-liquid separation. Considering the relationship volatile solids/total solids (initial and final) as 83.9% compared to 72.2%, it is possible to calculate a conversion efficiency of the organic substance of 50.4%. In the solid fraction the incidence of the various parameters detected in relation to the quantity treated was equal to 8.6% by weight, 36.8% in total solids, 45.2% in volatile solids, 12.9% in total nitrogen and 7,6% in ammonia nitrogen.

Results

The results here shown confirm that biogas plants fueled only by livestock effluents can produce very interesting results in terms of both energy and financial perspectives. The achievable profit with the organic substance available in the livestock effluents can reach approximately 60% of the average producible with the same amount of organic substance from a good corn silage, but free of cost of supply.

The problems experienced during the monitoring of the system are mainly due to the variability of the quantity of biomass available, resulting in higher self-consumption due to lower performances per unit of volatile solids and concentrations of dry matter. These can be overcome with a careful preliminary planning, reducing the consumption for handling and mixing. It was found, therefore, that the supply chain of biogas from livestock effluents presents some peculiarities that make it particularly attractive to the world of agriculture [6]:

- It is very flexible, allowing to take energy from a wide range of products and by-products that other sectors cannot use (livestock effluents, agro-industrial by-products damp and variable over time, animal by-products, etc.), reducing the competition for the supply of silage, etc;
- it is typically local, being born "short", as it uses products that cannot be very distant because of the high humidity, and must manage a residual moisture, the digestate, which for financial reasons must be placed in the immediate vicinity of the plant (10 km);
- is ecologically promising because it reduces the environmental impact of livestocks recovering part of the spontaneous emission of methane from the storage, and allowing the production of electricity and heat saving fossil fuels;
- it is one of the possible solutions to the problem of livestock effluents management (in consideration to the EU legislation on the environment), allowing to dispose of the separated solid digestate as fertilizer for agriculture, with good profit;
- it allows to eliminate the middlemen and to increase the value of all the agricultural land currently underutilized and/or agro-industrial by-products, which are usually managed in an expensive way.

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Biography

Giulio de Notaristefani di Vastogirardi completed a degree in Mechanical engineering at "Università degli Studi di Napoli, Federico II", specialised in design and management of renewable energy production plants, audit and energy efficiency of production systems, participated in research projects for the industrialisation of patents for installations.