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ScienceDirect

Energy Procedia 45 (2014) 333 – 341

Energy Procedia

68th Conference of the Italian Thermal Machines Engineering Association, ATI2013

An innovative small sized anaerobic digester integrated in historic building

Franco Cotana[a], Alessandro Petrozzi[a], Anna Laura Pisello[a], Valentina Coccia[a], Gianluca Cavalaglio[a], Elisa Moretti[b].

[a]*CRB-Biomass Research Centre - Department of Industrial Engineering, Via G. Duranti sn, Perugia 06125, Italy*
[b]*CIRIAF-Interuniversitary Research Centre on Phisical Agentes Pollution, Via G. Duranti 93, Perugia 06125, Italy*

Abstract

The CRB - Biomass Research Centre of the University of Perugia has developed an innovative anaerobic batch plant for the biogas production consisting on polyethylene bags, conventionally used for agriculture silage storage, converted and used as anaerobic digesters. Bags equipped with piping systems, become biocells: hence the name of the plant, biocells biogas plant.
The biocells, filled with biomass residues and manure, allow the disposal of residual agricultural biomass and manure, with a reduced cost for plant and a quick return on investment, thanks to the incentives for electric production from renewable sources, particularly advantageous for small biogas plants, according to the last Ministry Decree.
The tests carried out on the biocells system detected the critical issues in order to implement a new prototype of a small size plant, more flexible and adaptable to other contexts different than the rural one.
Unlike previous systems that worked for farms, the new plant will be integrated into a civil building: the stables of the Fortress of Saint Apollinare, located in the municipality of Marsciano (PG), currently under renovation in order to create an office structure at service of the fortress, that will be rehabilitated to host a research and education centre, with classrooms, dining areas, offices, rooms and canteen.
The plant will be fed by waste from the canteen residues and the pruning or residual biomass from the maintenance of the green and the neighbouring municipal wastewater from the septic tank. The thermal production is partially absorbed to maintain the temperature for the biological reactions in the digester; electrical energy is injected into the grid to take advantage of incentives from renewable sources.

Keywords: Biogas, biocells, pilot plant.

doi:10.1016/j.egypro.2014.01.036

1. Introduction

The central Italy, and Umbria in particular, is characterized by small farms spreading in the rural territory in which it is difficult to organize a complete chain for the biogas production for heat and electricity enhancement by biomass plants. The local rural economy and the small extent of the farms does not yield enough biomass for the construction of a biogas plant of medium to large size, allowing for a safe economic investment.

The CRB - Biomass Research Centre of the University of Perugia has recently designed, patented and built, an innovative small sized biogas plant, which allows small farmers to access to the renewable energy production and cash from energy selling, by the use of local residual biomass produced in several agricultural or zootechnical activities [1]. Installing farms sized biomass plants makes possible to ensure the correct disposal of animal waste produced daily by breeding, or the biomass residues from agriculture activities, which can constitute high potential energy source in the form of biogas production otherwise thrown away, even with large costs [2].

The access system to the incentives of the Italian Government predicts higher values the smaller the size of the biogas plant. So it is guaranteed the economic return of the investment in a reasonable time with respect to the life of the plant [3]. This allows the farmer to gain from the use of a renewable source of energy and also to re-use of the digested matter produced, as fertilizer instead of chemicals.

In addition, the prototype developed and tested by the Biomass Research Centre used huge polyethylene bags as digesters, to reduce investment and management costs.

This batch pilot plant, using big plastic bags, renamed “biocells plant”, is constructed with polyethylene bags commonly used for herbaceous storage, reconverted as digesters and filled with seasonal biomass such as olive husk, pruning, manure, herbaceous matter, and straw, reducing the installation costs. The prototype plants were built twice close to a farm in S. Angelo di Celle, near Perugia, in Italy; now it will be replicated in integration of a residential buildings complex in S. Apollinare di Marsciano.

The idea is to create a system of small size, low cost, that would enable an incentive to finance the renovation of the fortress, disposing of organic waste produced in the surrounding area. The thermal energy produced by the CHP, net of consumption in order to maintain the biological reactions in the plant, will be used to power the heating system of the office building, which runs every day of the year.

The stable building in particular, will be the object on the International LEED certification program, as an important International protocol aimed at designing innovative and sustainable solutions for new and existing buildings [4-6].

2. The biocells biogas plant in S. Angelo di Celle

2.1. The biocells biogas plant

The biogas chain in Italy is structured mainly on the co-digestion of several kinds of biomass: zootechnical slurry from breeding and herbaceous biomass from dedicated energy crops. They represented, in 2011, the 70.4% of the total energy production from biogas in Italy [7]. Focusing on the mini biogas plants, under the threshold of 100 kW electric power, they are mostly fed by manure or seasonal matters such as husks, pruning, residues of squeezing [8].

The majority of the installed biogas plants has electrical power of 501÷1000 kW (55.5%), a little part, 52 plants (10.4%), with power under 100 kWe, have an average power of 52 kW [7].

The biocells biogas plant is innovative because bags are currently used by the municipal manager of waste to store the organic fraction before the disposal in treatment plants [9]; but there are not examples of direct use as part of the plant itself. Therefore, there are spread applications and experimentations of big plastic bags for the digestion chamber but for domestic use and small sized, often without engine but only for the production of biogas.

The biogas biocells pilot plant is composed by great polyethylene bags, about 3- 3.5 meters in diameter and with length definable by the machinery operator (maximum 60 m), filled with the collected solid biomass: seasonal pruning, litter cattle, herbaceous matter, dedicated crops products and straw (Figure 1-a).

After the bags are produced, they remain sealed and partially inactive: biocells can be biologically activated when needed, by liquid zootechnical slurry injection from more points distributed at the top of the biocell. From a well, the liquid biomass is heated to the requested temperature for the biological activation [10]; then it is injected from the top of the biocell and it drains across the biomass inside the bag to the bottom, refilling the loading well, where it is heated again and re-loaded by the pump inside the biocell digester.

The 400 liters well is provided with 2 pumps: the first one to load the cold slurry to the heat exchanger recovering heat from the CHP engine and the other pump to reload the draining hot slurry to the biocell top to obtain a continuous liquid biomass flow. During the start up of the plant, liquid slurry is heated by an electric 1.5 kW resistance then, when engine starts working fed by biogas, heat is provided by CHP unit by heat exchanger.

The CRB has carried out continuous monitoring and studies for the activation of the biocells in not advantageous thermal conditions [11], such as in winter with high thermal dispersions, developing a PLC system which makes the system completely automatic and active, thanks to the presence of pressure, level and temperature sensors. When the temperature stabilizes at mesophyll conditions, the aerobic phase ends and anaerobic conditions begin, with the production of biogas.

At steady conditions, the biogas produced by bacteria accumulates at the top of the biocell bag; then, once reached a given pressure, a manometer makes a valve in opening and biogas is aspired by a blower to pass across the dehumidification and desulphurization systems before the engine combustion (Figure 1-b).

All the features are organized inside a compact box loadable to be transported everywhere. Inside the box a Personal Computer allows the plant to perform automatic control thanks to the PLC systems.

Fig. 1. (a) The biocells as biomass digester; (b) Dehumidification unit and 30 kW powered CHP engine.

2.2. Biomass for biocells

The second version of the biocells plant was constructed in S. Angelo di Celle on February 2012 at service of a zootechnical farm. The company owns 1,000 fattening pigs and slaughter makes two cycles per year. The animals are housed to a weight of 25 kg and can weigh about 165-170 kg. The increase in weight of the animal is 140 kg during a cycle time of 7 months.

The monitoring campaign, before the plant construction, has allowed us to calculate the consumption of feed, which is counted as three times its growth (420 kg). To this quantity, the water consumption must be added which, although varying with the season, can be quantified to the extent of twice the weight of feed consumption (840 kg).

Therefore, compared with a consumption of 1.260 kg of material per cycle, it produces the equivalent in weight of the quantity of wastewater net assimilated for growth. Thus is produced a quantity of 1.120 kg per animal for each cycle. Considering a herd of 1.000 head, it is possible to obtain a production of 1.120 t of wastewater per cycle, equivalent to about 5 tonnes per day. For the fresh pig slurry, there is coincidence between volume and weight are occupied in volume 5 m^3 per day. In addition of the biomass from the farm, in order to arrive at a consistency shovelable, can be used for the co-digestion the straw that composes the litter. It is estimated that 500 q of straw are consumed by 1,000 pigs in the litter box for each cycle, equivalent to 0.25 t per day. In addition to the straw, it is possible to dispose any type of vegetable residue from cultivation or other activities.

A fundamental characteristic of this biomass is that it presents low cellulose content such as green pruning, and hay which is not suitable for animal feed as rotting, corn cobs, corn stalks, etc.

The first biocell was 50 m length, 3.5 m diameter. The biomass volume that can be stored inside a biocell depends on the type of compaction that is given to the biomass at the time of his load inside the bag; the experience of the CRB is that a quantity of 3 t/m is a typical value for this type of biomass. Therefore, the quantity by weight of biomass that can be loaded into the bio-cell in order to exploit all the available volume, reaches up to 165 t. With these considerations, counted the material produced daily, a biocell provides storage for one month.

It should be noted that the slurry and manure production is not constant the same for each month, but it undergoes seasonal variations with external temperature and with the age of the animals. The calculation is carried out with prudent assumption. Therefore, it is possible to consider one biocell load for each month of the year. Any reduction in livestock production can, as mentioned, be integrated with crop production also seasonal or temporarily stored, which can be obtained as waste or of the neighboring business.

Each biocell is connected to the system via the piping, for biogas capture and liquid injection, and its biological activation for the production of biogas is by placing the inoculum liquid.

2.3. Biogas production

Regarding the biogas production, monitoring was conducted through a portable meter, allowed to monitor and represent the production trend in time of the relative concentrations of the gases that make up the biogas. The machine can be applied to a tee pipe derived by the biogas adduction to the engine.

The biocell activation, on February 2012, was monitored in detail. The methane concentration was around 50% and the same value for carbon dioxide, with the maximum percentage of 57% contained. It depends on the organic substrate characteristics [10, 12-13] and by the biological stability reached by bacteria, depending by temperature maintenance.

To estimate the burnt biogas volume, the engine can be programmed setting the cubic meters aspired by the blower: the engine ignition occurs when the manometers on biocell record a high pressure, which indicates that the bag is full of gas: valves can open and the biogas can flow to the engine ensuring a flow rate between 7,5 and 9 Nm^3/h. If the biogas insufflations is under the lower level, engine automatically switches off. Therefore, fixing the maximum threshold of biogas inlet, engine can cyclically work only if a certain biogas volume in ensured in the bags and quoted by pressure manometers.

The table below (Table 1) shows the values monitored and processed by the machine that is the number of hours in which the operation took place, of course, even intermittently, operating more cycles. The cumulative hours of operation and the cumulative volume of biogas burned (Figure 2).

Table 1. The cumulative biogas produced and burnt by the engine.

Day	Time Engine (*h*)	Time Engine cumulative (*h*)	Biogas Volume cumulative (m^3)
0	0	0	0
8	26	26	233
10	14	40	361
14	57	97	875
16	25	122	1101
19	39	162	1455
21	71	233	2096
23	36	269	2422
24	14	283	2547
25	9	292	2632
26	10	303	2726
27	7	310	2786
29	1	311	2798

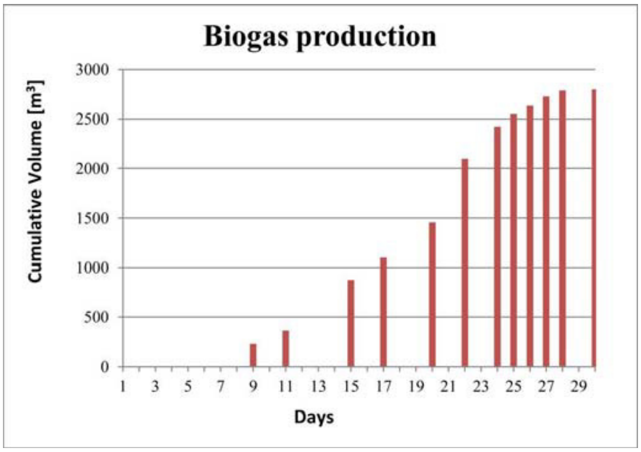

Fig. 2. Cumulative biogas production by biocells plant.

3. Application of the biocells biogas plant to the S. Apollinare stable

The fortress that represents the case study of this work consists of an historical building edified in X century in order to protect the adjacent existing monastery.

The main building is represented by a large U-shape complex which surface is around one thousand square meters. An adjacent building, which was constructed for stable use, represents another construction of the group, which is object of retrofit intervention as well.

Both of the buildings will host an International research center with classrooms, offices, accommodations and other services useful for research and teaching activities.

3.1. Energy efficiency upgrading of the stable

To reduce heat loss, the construction of an outer coat is expected; it will cover the external masonry which is not valuable and it will be made with EPS panels with graphite additives, characterized by a high heat-insulation potential, resistance and non-sensitivity to thermal expansion. After the installation of the panels, a reinforced plaster will be built over the surface.

Since there are not present in the building elements such as terraces or balconies, it is not necessary to provide for the elimination of further thermal bridges produced by such discontinuity. Nevertheless, there is the problem of thermal bridges created by the sill of the fixtures. The thermal cutting of these elements will be executed by breaking into two parts the sill at the casing and by interposing between the two parts an element in expanded polystyrene. Another element in hard expanded polystyrene will be also interposed between the piece of internal sill and the masonry. Even the fixtures that are going to install will need to ensure an adequate thermal insulation. To this end, we will install a frame with thermal break hard PVC, multi-chamber. The triple glazing, fitted with spacers, will be low-emissivity ensuring a high thermal insulation.

A wooden ventilated roof is involved for the advantage of a lower energy cost for summer air conditioning, thanks to a greater thermal inertia, which allows the leveling of the temperature of the interior in a longer time. The overall retrofit intervention is designed in order to optimize the indoor thermal comfort conditions and energy efficiency of the complex, which is previously evaluated through dynamic simulation tool [14]. Additionally, specific peer network monitoring facilities will be installed in order to minimize the use of energy when it is not required, thanks to the occupants' awareness sensitivity campaign [15]. The choise of materials and methods will be carried out in order to maintain the historic heritage of the building [16]. The overall complex intervention is subject to LEED certification application, which is on-going at the moment of the writing of this contribution.

3.2. The biomass from the area of the fortress

The fortress and the stables are located within an area of landscape value, managed by the Foundation for Agricultural Education in Perugia. Among other promotion activities in the field of agriculture, the Foundation is involved in research on zootechnical field. The breeding has 800 pigs, whose wastewater is currently being used as fertilizer in the fields of the company by transport. The idea is to transport the waste from pigs to the fortress by truck and to install a biocells plant at about 200 m from the stable, in a small dedicated area (2,000 m^2) near the cultivated field (Figure 3). The chosen area is adjacent to the fields, owned by the same Foundation. In this way, they can be easily transport the green residual biomass produced from agricultural activities to the plant; furthermore, the digestated matter produced by the system will be used on the same site as fertilizer. In fact, once the biocell exhausts its potential in terms of biogas, the piping is removed and a new biocell ready for use is installed. The old biocell, now containing stabilized organic matter, sealed is left and it can be only opened during the warm season, to allow the biomass drying and to facilitate the spread on the fields. Concerning the liquid biomass, from an economic point of view, to load it into trucks and take it to the biocells biogas plant would be very expensive. Therefore, the solution is to leave Casalina the current fertigation system that already use for disposing of the swine slurry and find another source of supply, which could compensate for the reduced quantity of wastewater produced from pigs in Casalina.

The fortress will host a canteen and then organic waste will be produced and it must be disposed in the biogas system. It is also thought to take the sludge from septic tanks at least once a month, and feed the biocells.

These quantities, once taken and finely shredded together, will be conveyed from the stable to the plant, through a pipe. Also other biomass from the maintenance of green, pruning, in the fortress may be added into the shredder. The high potential of organic waste mixed with the municipal wastewater, contributes with a high intake staff.

The table below (Table 2) summarizes the quantities.

Table 2. Biomass available from the fortress.

Kind of biomass	Daily quantity (*kg*)	Monthly quantity (*t*)
Sewage slurry	7.6	0.23
Food waste	4.0	0.12

Another piping system connects the plant to the stable: the hot water produced by the CHP plant is sent, through an insulated pipe, to the stable; the return water descends to the facility in order to be re-heated. At the stable there is a control system with expansion vessels and the distribution system via manifold area to the terminal elements.

Fig. 3. The stable and the plant insert in the surrounding area.

3.3. Energy enhancement for thermal needs

The Biomass Research Centre of the University of Perugia has, in recent years, developed expertise in the field of renewable electricity production and, in the case of batch systems for the production of methane, such systems are coupled to fuel Cells for the production of electricity [17-20].

The stable heating, cooling, hot water requirement were evaluated through a dynamic simulation engine (EnergyPlus), by taking into account the final designed configuration of the façade materials and occupancy of the building. Therefore, the estimated energy consumptions correspond to the post-retrofit scenario. The ex-ante scenario took into account the non-insulated façade and roof structure, where the thermal transmittance of the two layer masonry was 1.448 W/m^{2}K, calculated as prescribed in BS EN ISO 6946. The post retrofit façade is a 4 layer structure that was described by EnergyPlus simulation engine through: (i) cement based plaster – 0.02 m, (ii) EPS insulation – 0.12 m, (iii) masonry dry block – 0.4 m, and (iv) gypsum internal plaster – 0.02 m. The before-retrofit configuration only considers (iii) and (iv) layers. The final calculated transmittance value is 0.269 W/m^{2}K. The dynamic simulation was run from January 1st to December 31st. The temperature setups are 20°C and 26°C for winter and summer, respectively. The thermal control is carried out on air temperature of the thermal zones. The occupation schedules described in the model are typical of training and learning areas from Monday to Friday, national holiday excluded. The internal gains in classrooms are 4.74 W/m^2 with 20% of radiant fraction, and 0.2034 person/m^2 density is considered with 0.9 metabolic rate. In labs, a density of 0.1063 person/m2 is considered with 0.9 metabolic rate. The internal gain level was considered as 8.73 W/m^2, with 20% of radiant fraction. For office and consulting areas, a 0.0979 person/m^2 density was modeled with 0.9 metabolic rate. The internal gain was 10.49 W/m^2 with 20% radiant fraction. The year-round simulation is run with a 2/hour time step, by using the Typical Meteorological Year of the area in Perugia, Italy, where the building is located. No Inter-Building Effect is taken into account, given the low density construction level of the rural area [21-22].

For the air conditioning in summer, a system of controlled mechanical ventilation will be installed, and it has been modeled: it takes air from outside, distributing it, expelling stale air. As seen from the monthly values of the heat consumption, the demand reaches peak of 2,200 kWh in January (Figure 4). The biogas plant has a thermal power of 70 kW. From the simulations carried out in winter conditions, with maximum heat loss to the outside, two thirds of the power must be committed for heating the fluid for biological reactions in the biocells. It therefore remains a useful thermal output of 23 kW which appears fully compatible with heat consumption. Whereas Perugia, Italy, is in climate zone E, with 2289 degree days, in a month with heating system at full load, well 10,000 kWh of heat is available. A 2,000 liters puffer will be mounted to ensure an adequate accumulation also in function of the frequent cycles of machine downtime of the plant induced by the discontinuity of the burning of the biogas.

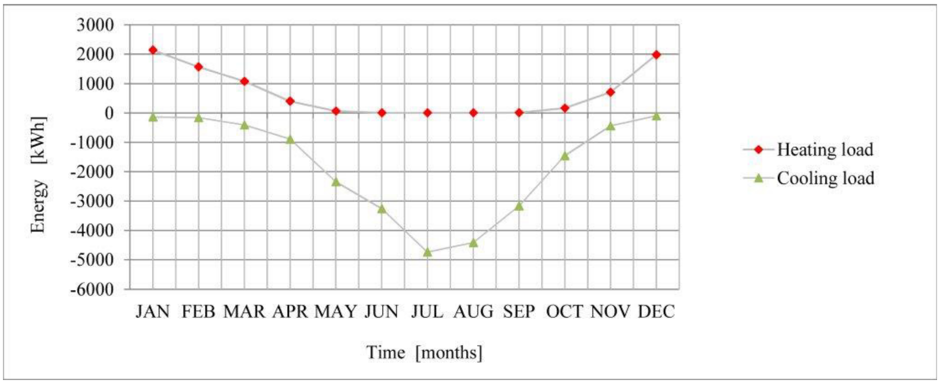

Fig. 4. Heating and cooling monthly requirement.

4. Economic analysis

4.1. Investment and operating costs

The total sum of costs for the entire biocells biogas plant, machinery and equipment, the automation system via PLC, is estimated to be about 154,000 €, as shown in detail in the Table 3 below. The machinery for bagging is already possessed by farmers managed by the owner Foundation.

All the operating costs related to personnel can be considered negligible because it uses existing member of staff in the company and in charge of transporting and loading the livestock waste.

Other operating costs are: the consumption of electricity energy for the start-up phase of the plant, the fuel costs for the loading of biomass by roto-bagging machinery, the 12 bags. The total amount is about 1,000 € per year.

Table 3. Investment costs for a biocells biogas plant.

Equipment	Cost (€)
CHP 30 kWe engine	55,000
Piping nets	30,000
Automation PLC system	20,000
Gasometer	15,000
Dehumidifier	25,000
Loading well and pumps	7,000
Heat exchange	2,000

4.2. Revenues

Biocells biogas plants allows little farms or other similar companies, to cash from incentive by electric energy selling produced by biogas enhancement.

The Italian legislation for the authorization of biogas installations [24] provides that, if a rated power is less than 50 kW, the procedure consists of a communication to the municipality where the facility in installed. The timing of authorization are practically almost immediate.

The incentive fee, a feed-in tariff, according to the recent legislation, is evaluated taking into account the range of power that remains below the threshold of 300 kW and depends on the type of biomass that is used to feed the plant. In our case, we refer to Table 1-A of the decree [25] that identifies the incoming biomass as a by-product obtained from breeding wastes and biomass residues from pruning and private green. Considering these characteristics of the system, the incentive is 0.236 €/electric kWh. The electric energy produced at the net of auxiliaries consumptions (about 11% of the total production) is about 74,000 kWh per year, which allows annual revenues of more than 17,500 €/y.

5. Conclusions

The future activities of the research group will consist in taking samples of the different biomass and simulate in the laboratory some mix, in order to identify the best possible combination that optimizes the production of biogas [26-28].

The biocells biogas plant, already widely experienced to serve farms, for the first time will be applied to a residential building complexes; this application, as well as providing a significant contribution in terms of quality of life and improvement of the environment, is a viable alternative for the production of electricity and thermal energy in insulated rural buildings.

Therefore this applied research contribution aims to demonstrate the real feasibility of small-scale biomass power plants, still too undeveloped, with high potential especially in Italian rural territory. At the same time, this technology could represent an effective solution to several environmental problems, thanks to the incentives, a source of income to boost the rural economy currently in crisis.

Acknowledgements

The authors thank the Italian Ministry of Agriculture for supporting the project. The authors also thank the students of the Architecture Degree Course at University of Perugia, for performing in-field measurements: Alessio Bonci, Alessia Tasso, Alessandra Curina, Federica Bistocchi, Laura Becchetti, Eleonora Minelli.

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