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Electricity produced using biogas obtained from the recovery of organic waste in ecological landfills – a case study

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***Abstract* — The paper presents an applied technological study regarding the production of biogas and its subsequent use for the production of electricity, at the level of a developed rural agro-zootechnical area.**

One of the main energy recovery processes from agricultural organic residues is anaerobic fermentation at high temperatures which is the most efficient method of generating non-conventional energy from solid and liquid organic waste, animal droppings and vegetable mass. anaerobic fermentation occurs naturally in a wide range of cases, from within the digestive system to the depth of effluent ponds and can be reproduced artificially in manmade containers called digesters. Through anaerobic fermentation, microorganisms break down organic matter, releasing a series of metabolites, fermentation products, including carbon dioxide and methane. The mixture of these two metabolites, with the predominance of methane which also includes small amounts, up to traces, of other gaseous metabolites, constitutes biogas.

The use of the biological mass potential generated by anaerobic digestion within a rural ecological deposit, its transformation into biogas together with the avoidance of pollution represents a current strategic option and at the same time, a technical solution for the future.

This case study consists in the determination of the biogas requirement, according to the community requirements, the calculation of the amount of biomass needed by type and ratio of raw material used and the design of some main components of the biogas production station.

Keywords—biogas, anaerobic fermentation, cogeneration

I. INTRODUCTION

Biogas is an energetic gas, produced by the anaerobic fermentation of biomass [1]. The main feedstocks for biogas production are agricultural substrates (specifically grown energy crops as corn or sugar beet, as well as cover crops, vegetable waste), manure, wet waste fractions from the food industry sector, sludges from water treatment and other organic wastes from households [2]. The raw materials influence the gas composition and the methane content in the gas.

Pre-treatment of the material to be fed into the digester depends on the nature of the feedstock and it involves the removal of non-digestible materials (plastics, metals, glass), washing, milling, and pressing, for the agricultural feedstock. All biomass fractions, except for lignin, can be degraded by anaerobic microbes. For high fraction of, or lignocellulosic feeds as agricultural residues, it is necessary to use a pre-treatment to make the cellulose and hemi-cellulose available for the bacterial degradation.

Although microbes are involved in each step of the anaerobic digestion, there is little information about them, due to the lack of data about their phylogenesis and metabolism since most of them are unculturable microorganisms [3].

The anaerobic digestion process includes four main phases: hydrolysis, acidification, acetogenesis, and methanogenesis.

Hydrolysis is the first step of the process, in which complex organic polymers as polysaccharides, lipids, proteins are broken down to monomers as sugars, fatty acids, amino acids by hydrolases secreted by microorganisms.

Acidogenesis is the next step of anaerobic digestion, during which the products of hydrolysis are converted to non-gaseous short-chain fatty acids, alcohols, aldehydes and gases, such as carbon dioxide and hydrogen.

The third step, acetogenesis supplies substrates for methanogens. Acetogenesis provides the formation of hydrogen and carbon dioxide as a result of the transformation of the complex mixture of fatty acids into acetic acid.

In the final step, methane is produced from the products of the acetogenesis step. Methane formation is a complex process, requiring specific enzymes and cofactors. The course of the reaction depends on the substrates utilized by the methanogens.

Most biogas plants operate at a mesophilic temperature (35–42˚C), but there may also be plants that operate at a thermophilic temperature (50–60˚C). The period of residence in the fermenter depends on the type of substrate used and can vary between 20 and 70 days.

There are several factors which affect the digestion process and the biogas production: temperature, pH value, C/N ratio in the organic load, equipment, hydraulic retention time. A series of prerequisites must also be fulfilled for the efficiency of biogas production by anaerobic digestion [4].

The most important thing is to create an ecosystem that is favorable for the development and metabolic activity of the microorganisms involved in the process. It is often hard to find an ideal raw material, and a combination of substrates can be used to ensure that the feedstock fits the operational parameters. There are large differences in energy efficiency among the biogas obtained from various raw materials. The results are affected by the composition of the biomass, the water content or digestion technologies [5] Many publications investigated the combined treatment of agricultural and livestock waste and the optimum composition of biomass. [6]

Temperature is the important factor which affects the biogas production. At higher temperatures the production of biogas is maximized.

Effect of the carbon/nitrogen ratio. During hydrolysis ammonia is produced as a byproduct from nitrogenous compound. Ammonia is an important factor causing methanogenesis inhibition. Excess ammonia is also dangerous as it may lead to digester failure. Microorganisms generally utilize 25-30 times carbon than nitrogen during anaerobic digestion. Best carbon/nitrogen ratio in methane generation is in the domain 20-30.

The effect of pH is also a main factor in anaerobic digestion. If pH is greater than 5, production of $CH4$ is enhanced, and the highest biogas production is obtained for a pH between 6 and 7.

Hydraulic retention time is time holding slurry in digester. Shorter retention time means fewer active bacteria, and longer retention time needs a larger digester, and thus higher investment costs.

One of the biggest advantages is the fact that biogas is a carbon neutral energy source because plant and animal sources emit the carbon dioxide they have accumulated during their lifetime, and which would have been released by decomposition, increasing the greenhouse gases concentration. 1 kWh of electricity produced by biogas, prevents the release of 7000 kg of $CO2$ per year [7].

Other important advantages are reducing methane emissions, which is also a greenhouse gas, decentralized energy supply, production of high-quality fertilizers, creating energy autonomy, renewable energy source that can be produced 365 days a year, regardless of weather conditions [8].

When looking to install a biogas plant, the first question that should be answered is: How big is this plant? The answers to this question must also consider the criteria for installing a biogas production plant: ensuring the energy and heat needed by a certain number of consumers, ensuring the complete processing of locally available raw materials, ensuring the processing of raw materials from an area whose extent is established based on technical-economic criteria.

Although there are several types of biogas plants, any biogas plant has the following elements:

- organic waste deposit
- organic waste transport facilities
- tanks for biological substrate
- machines for shredding biodegradable solid waste
- the raw material supply system
- the pumping system
- fermentation basins (fermenters or digesters)
- biogas collection system
- the waste collection system
- heat unit and power plant.

The raw material is directed to a collection basin and is transferred via a pumping station to the separation plant. Mechanical separation of the liquid part from the coarse solids is almost always necessary and serves to remove the non-biodegradable parts. The solid part separated from the digester can be composted and used on agricultural land. The liquid part, rich in organic substances, will feed the digester. To operate in thermally controlled conditions, the walls of the digester must be well thermally insulated, and the inside of the digester is heated by a heat exchanger placed near the bottom, the heating agent being water heated by burning biogas in cogeneration. The produced biogas is compressed in the upper part of the digester through a roof in the shape of a gasometrical dome. The gasometrical dome is made with three overlapping membranes made of polymer fiber fabric. This three-membrane system can replace the gas meter and favors the dehumidification of the gas obtained.

The final preparation of the biogas takes place in a compact station. It consists of a gas dryer and a compressor. The gas dryer has the function of cooling and cleaning the gas. For this purpose, the condensate is cooled by means of a cooling unit and is stripped in a reactor. In this way, dirt particles are washed, and the gas is cooled. This drop in temperature leads to a more efficient separation of water from the condensate. Condensate that is not used for gas washing is pumped into the condensate well. The gas temperature is adjusted after the drying process. The gas compressor serves to reach a preliminary biogas exploitation pressure of $\Delta p = 80 – 120$ mbar.

The gas produced and recovered is directed towards a cogeneration plant that burns biogas to produce electricity and heat. Part of the recovered heat is used to maintain the temperature in the digester.

The digestate at the exit from the fermenter will be accumulated in a storage basin for use as agricultural fertilizer.

II. ENERGY AND HEAT REQUIREMENTS

The goal or our calculations is to ensure the energy and heat needed by the community, the determination of the biogas requirement, the calculation of the amount of biomass needed by type and ratio of raw material used, and the design of some main components of the biogas production station. A developed rural community has between 5000 and 7000 inhabitants, with an average of 2000 dwellings [9]. The average electricity consumption for a household in Romania is 2.4 MWh per year and the thermal energy required for heating the house is 12.92 MWh per year, with a maximum in the winter months of 2.5 MWh per month [10, 11]. So, the monthly necessary amount of energy in wintertime will be:

$$Q = 2000 \cdot (2.5 + 0.2) = 5400 \text{ MWh} \qquad (1)$$

The amount of biogas required will be calculated for an average value for thermal energy considering that heat is needed 8 months per year. The value taken in account is 1.67 MWh.

Biogas is a mixture of gases including methane 50–75%, carbon dioxide 25–50%, hydrogen 0–1%, nitrogen 0–10%, oxygen 0–2% and sulfur compounds (0–3%). Depending on the organic matter and the evolution of the fermentation process, biogas can contain significant amounts of hydrogen and carbon monoxide. The calorific value of biogas (LHV) is 18–26 MJ/m3 [12] (on average, about 6 kWh/m3), which corresponds to the calorific value of 0.6 liters of fuel oil or 1.3 kg of wood. For our calculations we will use a value of 5.87 kWh/m3.

Combined heat and power (CHP) are the simultaneous cogeneration of electricity and heat. Cogeneration is a particularly efficient form of energy transformation and by using gas engines it can provide primary energy savings of approximately 40%, compared to the separate purchase of electricity from the electricity network and gas to feed the boilers [13].

Combined heat and power plants are usually integrated close to the end user, thus helping to reduce transmission and distribution losses, and improving the overall performance of the electricity transmission and distribution network.

Centralized power supply systems use combined heat and power plants to produce electricity and heat for a group of residential or commercial buildings. For energy consumers for whom security of supply is an important decision factor in the selection of energy production equipment and if the availability of gas is high, gas cogeneration systems are ideal as self-generating plants.

As a localized source of energy production, they increase the resilience of a location in the event of a power grid failure, while also offering the possibility of operating in isolated mode.

In Table I. are presented the parameters used to calculate the electrical and thermal power of the cogeneration plant [14].

TABLE I.

Parameter	Value	Measurement unit
Biogas calorific value	5.87	kWh/m3
Biogas density	1.28	kg/m3
CHP electrical efficiency (load average of 75%), η_e	41.10	%
CHP thermal efficiency (load average of 75%), η_t	43.20	%
No. average operating hours annual	8016	hours
No. average operating hours monthly	668	hours

The remaining thermal energy available to be delivered to an external consumer will be 62.37% of the total amount produced by biogas plant. The rest is used for heating the digester and for the sanitation installation [15].

The amount of thermal energy required to be produced per month for the 2000 households:

$$Q_t = \frac{1.67}{0.6237} = 5355.13\,\text{MWh} \qquad (2)$$

The maximum thermal power

$$P_t = \frac{Q_t}{\eta_t} = \frac{5355.13}{0.432} = 12396.13\,\text{MWh} \qquad (3)$$

Thus, the maximum electric power will be:

$$P_e = 11770\ \text{MWh} \qquad (4)$$

Knowing the total energy production (electrical and thermal), as well as the global efficiency of the cogeneration plant, the amount of energy embedded in the fuel (in biogas) Q_{comb} is further determined:

$$Q_{comb} = \frac{P_t + P_e}{\eta_{tot}} = \frac{24166.13}{0.843} = 28666.82\,\text{MWh} \qquad (5)$$

$$\eta_{tot} = \eta_e + \eta_t = 0.411 + 0.432 = 0.843 \qquad (6)$$

This amount of energy can be provided by:

$$V_{biogas} = \frac{Q_{comb}}{LHV} = \frac{28666.82}{5.87 \cdot 10^{-3}} = 4.88 \cdot 10^6\ \frac{\text{m}^3}{month} \qquad (7)$$

III. BIOMASS COMPOSITION

The composition of the biomass can vary extensively and depends on the available resources. Being in a rural zone, the main possible resources are animal manure and vegetable remains. In Table II. is given the estimation of the amounts of biogas resulting from the fermentation of different organic materials [16]

TABLE II.

Type of resource	Dry content (%)	Organic content (% dry content)	C/N ratio	Biogas yield (m3/t)
beef manure	12 - 14	68-85	18	200 – 280
swine manure	2.5 – 9.7	60-85	13	260 - 450
liquid poultry droppings	28	75 -77	15	200 - 400
sheep solid droppings	25-30	80	29	240 - 500
horse solid droppings	28	75	24	200 - 400
corn	34	86	57	350 - 390
hay	86 -93	67-98	25	500
clover	20	80	41	300-500
straw	85 -90	85-89	87	180 - 600
corn cobs	86	72	950	300 - 700
rotten apples	2 -4	94-95	35	330
molasses	80	95	72,3	300
whey	4 -6.5	80-92	50	330
vegetable remains	2 -20	76-90	68	350

To correctly calculate the ratio between animal droppings and agricultural vegetable remains it is necessary to provide a carbon/nitrogen ratio in the domain 20 – 30. At the same time, the biogas yield resulting from the fermentation should be as high as possible. In this paper, the following composition of the raw materials was proposed: bovine manure 2 parts, poultry droppings 1 part, swine manure 3 parts, corn cobbs 1part, straw 1 part, vegetable remains 2 parts. For this composition the carbon/nitrogen ratio is 29.6. Using the properties given in Table II and the composition of the mixture it is possible to calculate the average dry content, 22.5% and the average biogas production of the raw material, 343.5 m3/t. The necessary amount of raw material is:

$$M = \frac{V_{biogas}}{Biogas\ yeld} = \frac{4.88 \cdot 10^6}{343.5} = 14206.69 \text{ t/month} \quad (8)$$

To reduce the percentage of dry content down to 8 % an amount of 25742.4 tons water will be added so the total mass of raw material will be 39949 t/month.

Assuming the digestor is fed each 30 days, the necessary quantity fed is 39949 t/charge which will include 25742.4 tons water, 8521.6 tons of animal manure and 5685.09 tons vegetable mixture.

The average density of vegetable mixture is 450 kg/m3, and the average density of the manure is close to the density of water, 950 kg/m3. Thus, the volume of the storage tanks can be calculated, considering a filling coefficient of 80%. The necessary volume for the manure storage tank:

$$V_1 = \frac{8521.6 \cdot 10^3}{950 \cdot 0.8} = 11212.63 \text{ m}^3 \quad (9)$$

For the storage of the vegetable mixture

$$V_2 = \frac{5681.1 \cdot 10^3}{450 \cdot 0.8} = 15791.91 \text{ m}^3 \quad (10)$$

So, the storage tank volumes will be 2 × 5000 m^3 for the manure and 3 × 5000 m^3 for the vegetable mixture respectively.

The fermenter will be considered as a vertical reactor. The digestor represents a fermentation basin in which the necessary amount of biomass is brought and during the period of approx. 30 days, biogas is released and rises to the upper part of the fermenter. The reactor has three compartments, the biomass fermentation chamber, a gas collection volume, and a sludge sedimentation volume.

Thus, the total volume of the fermenter is determined with the relationship:

$$V = V_{gc} + V_f + V_s \quad (11)$$

where V_{gc} is the volume for the gas collection, V_f is the volume necessary for fermentation and V_s is the sludge sedimentation volume. Usually, the fermentation volume is about 80% of the total digestor's volume. The volume of the fermenter can be determined by knowing the volume of the fermentation chamber, which depends on the mass of the raw material. The quantity fed is, as previously stated, 39949 tons and consists of water, vegetable mixture and manure. The volume of the biomass fed and thus, the volume of the fermentation chamber is 47337 m^3. The volume of the fermenter will be:

$$V = \frac{47337}{0.8} = 59171.25 \text{ m}^3 \quad (12)$$

which means that there will be 6 fermenters with the volume of 10000 m^3 working in parallel.

IV. Conclusions

The present paper addressed the energy recovery from organic waste within an ecological deposit, had in mind the fulfillment of the specific objectives defined by the production of biogas in an installation located on the outskirts of a set of residential houses in a developed rural area.

It was possible to determine the biogas requirement for the mini-thermoelectric power plant, based on the average heat and electricity consumption of a dwelling. A composition of the biomass used was proposed based on the optimum C/N ratio, and as a function of this composition the amount of biomass needed to provide the necessary biogas was calculated. Of course, the composition can widely vary, as a function of the raw materials available on each site.

The generation of biogas has a double role, apart from providing a quantity of renewable energy, it contributes to reducing pollution due to agricultural activities. Therefore, the use of the biological mass potential generated by anaerobic digestion in a rural ecological deposit related to a locality with 2000 households, and respectively its transformation into biogas, represents a current strategic option and at the same time, the technical solution of the future that must be adopted and generalized.

The study also resulted in the need to develop the specific infrastructure for the use of the biogas obtained, through a mini-thermoelectric power plant (mini-CET) on biogas, intended to produce electricity and thermal energy, at the level of the reference rural locality.

The sustainable use of biogas energy requires the encouragement of biogas production through investment and technology development together with the creation of demand through measures that encourage consumption of biogas in an energy market that offers cheaper nonrenewable options [17]. In conclusion, the biogas thermoelectric plant represents a feasible project proposal and constitutes a source of renewable energy.

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