Energetic Assessment of Biogas Plant Projects Based on Biowaste and Maize Silage Usage

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Abstract. Maize silage, in spite of its rising prize and technological problems of monoculture in Eastern Germany, is still the most popular substrate for biogas plants. However waste materials often generate income, because of the potential technological or ecological problems they cause. Such an approach seems to be more profitable even considering lower biogas yield of dose waste substrates. To compare these different scenarios energetic and economical assessment of waste fermentation processes such be conducted. In this paper, three different substrates will be evaluated to determine their suitability for agricultural biogas plant feedstock. The research was based on the modified German standards DIN and VDI, while chemical and physical analytical methods were based on the Polish Standard System. Economic analysis was performed using standard prices in the polish biogas market. The calculation was conducted for 500 kW installation. Based on the obtained results, it was proven that refood was characterized by the highest methane and biogas yield from the analyzed substrate group. Maize silage fermentation in the Polish condition is least profitable due to the approximately 50 % income reduction by the costs of obtaining silage. However due to the price received for treating waste materials, refood fermentation is the most economically feasible option.

1. Introduction
The development of renewable energy sources in the European Union is a non-reversible policy. The last decade has seen a remarkably rapid growth of various types of renewable energy, with particular emphasis on the wind and solar sector [1]. The energy produced from these renewable energy sources is becoming cheaper, and now it is less expensive than that generated from conventional sources, such as coal or natural gas [2]. However, the problem associated with the wind and photovoltaic sector is the irregular production of electricity. Against this background, the biogas sector performs very favorably, because electricity and heat are produced in biogas plants in predictable way, entirely under control [3].

1.1. New trends in the biogas sector
The biogas market has over 45 million installations worldwide [4]. The overwhelming majority of installations are small biogas plants located mostly on farms, in China and Southeast Asia [5]. In these locations, thanks to the warm climate, these small biogas plants do not require reheating, as is the case...
in Europe [6]. Nearly 20,000 biogas installations operate in the European Union [4]. These are usually industrial-type installations, automated, with production of electricity and heat, or possibly purified biomethane. Actually, the vast majority of biogas installations in Europe have focused on electricity production [7]. Besides, the use of heat produced in the cogeneration plant was a huge problem for most biogas plants. To sensibly use this heat, many biogas plants cooperated with other industrial or agricultural facilities such as: dryers, distilleries, greenhouses, storage halls, fish and other animal baths, or had a heat pipe connection with nearby buildings.

In recent years, in biogas sector, the installations to biogas purification for biomethane quality (over 97% of CH₄ content) has become increasingly popular in Europe [8]. The increasing demand for biomethane, especially produced from waste (this is particularly emphasized in the Renewable Energy Directive (RED II) [9]), has caused that more and more investors plan to build biomethane plants or convert existing biogas plants into biomethane production installations. This trend also resulted in increased investor interest to use biowaste as the substrate for biogas plant [10].

1.2. Substrates for biogas production

Currently, the primary substrate used in European biogas plants is maize silage and animal manure. Meanwhile, vast amounts of organic waste are produced in Europe. Over 80,000,000 tonnes of food waste is produced in Europe alone [11]. Organic waste is a material that usually has fairly high humidity. For this reason, organic waste thermal processing, such as combustion or pyrolysis, is not energy efficient, because a lot of energy is simply used to evaporate the water they contain. Many studies have shown that composting is a very effective way to manage organic waste [12], [13], [14]. In this technology, there is an intense decomposition of organic matter carried out by microorganisms, which leads to a sharp increase in temperature composted masses [15], [16]. Followed by the very high loss of water due to its evaporation, and CO₂ loss from decomposed organic matter. As a result of the composting process, a very large amount of energy is released in the form of heat, which, unfortunately in most cases, is irretrievably lost to the environment [17], [18]. Therefore, from an energy point of view, the best way to process organic waste is to put it in the methane fermentation process [19]. With this technology, the organic matter contained in biowaste is also broken down by microorganisms, but the final product is chemical energy in the form of easily stored methane, which is the main component of biogas [20], [21], [22]. There is a very wide range of different types of waste substrates. The higher is the dry matter content in the substrate, the higher is the methane yield, as a rule [23, 24]. However, it should be remembered that lignin is a compound that does not decompose in the methane fermentation process [25, 26, 27]. Therefore, substrates containing a high content of lignocellulosic compounds generally have lower methane production efficiency compared to materials with a higher fat, protein, or carbohydrate content [28, 29, 30].

The aim of this paper was to compare the different scenarios of energetic aspects of waste fermentation processes. In this paper, four different substrates (maize silage, food waste and bovine blood with flotation sludge) were evaluated in order to determine their suitability as agricultural biogas plant feedstock.

2. Methodology

The research experiments were carried out in the Laboratory of Ecotechnologies at the Poznan University of Life Sciences – the largest biogas laboratory in Poland (over 250 fermenters working in temporary or permanent mode). The analysis of the biogas efficiency of the substrate was based on a modified German norm DIN 38 414/S8 [31] and standardized biogas guidance issued by the Association of German Engineers in Dresden VDI 4630 [32]. Chemical analyzes were made in accordance with the Polish Standardization System.

2.1. The origin of the substrate and fermentation inoculum

The maize straw silage has been obtained from Przybroda Agricultural-Orchard Experimental Farm belonging to the Poznan University of Life Sciences (PULS). Food waste originated from collection made by Poznan City and bovine blood with flotation sludge from small slaughter house placed in
South Wielkopolska region. The mesophilic fermentative inoculum was gained by separating the liquid fraction of the digestate pulp from operating agricultural biogas plant.

2.2. Experimental Set-Up
The research tests on biogas efficiency of the substrates were carried out in a multi-chamber fermentation set-up designed and built in the Institute of Biosystems Engineering (PULS). Methane fermentation was conducted in the glass reactors with capacity of 2 dm$^3$. The tested substrates were placed in the reactors and then flooded with sufficient amount of inoculum. The reactors purged with nitrogen (creation of anaerobic conditions) were placed in a water bath with temperature of 39°C ± 1 (mesophilic fermentation) or 55°C ± 1 (thermophilic fermentation) to ensure optimal conditions for the methane fermentation process. The biogas produced in each reactor was transported throughout teflon wires to gas tanks constructed on the basis of inverted cylinder submerged in the water column and elevated liquid column. At the interface water – gas there was a liquid barrier preventing the dissolution of CO$_2$ in the water. All the trials have been repeated three times.

Economic assessment was conducted considering three different scenarios. First biogas plant feedstock was comprised of flotation sludge and bovine blood (W1), following by maize silage monofermentation (W2) with refood fermentation (W3) as a last scenario. Economic assessment was calculated using polish standard prices with US dollar exchange rate from December 4th 2019. The calculation was conducted for 500 kW installation.

2.3. Physical and chemical analyzes
In order to select the proper proportions between the tested substrate and inoculum, the following parameters were examined: total solids – TS (PN-75 C-04616/01), volatile solids – VS (PN-Z-15011-3), pH (PN-90 C-04540/01) and conductivity (BS EN 27888: 1999). These parameters were essential for the calculation of the biogas efficiency of the substrates into the units m$^3$/Mg FM; m$^3$/Mg TS; m$^3$/Mg VS. Moreover, every day, for the entire duration of the experiment, the pH of the fermentation trials have been analyzed. Substrate parameters are shown in Table 1.

2.4. Financial and energy calculations methodology and data
The methodology of financial and energy calculations bases on standard equations described in previous work [33]. The most important data and coefficients used for the calculations are shown in the table 1.

Table 1. The data and coefficient used for financial and energy calculations.

| Parameter                      | Value               | Parameter                      | Value               |
|--------------------------------|---------------------|--------------------------------|---------------------|
| Biogas plant size              | 0.5 MW              | Digestate storage time         | 4 months           |
| CHP unit efficiency            | 42%                 | Electricity price              | 141.75 US $/MWh    |
| Fermentation tank volume       | 1 250 m$^3$         | Plant energy consumption       | 15% of produced energy |
| Digestate mass reduction       | 10%                 | CHP unit working time          | 8 500 h/year       |
| 1 m$^3$ CH$_4$ total energy    | 0.009968 MWh        | 1 m$^3$ of methane             | 0.004187 MWh$_{el}$|
| value                          | Installation efficiency | 97%                              | Methane consumption 1 015 153 m$^3$/year |

3. Results
Since it was assumed that the substrate dosing system will use pumps, the batch mixtures were prepared so that the dry matter content of the batch was about 15%, thus ensuring their pumpability – WI (15.55%), WII (14.08%), WIII (15.56%). This assumption influenced several technological parameters and process parameters of individual variants.
Table 2. Initial parameters of tested substrate (TS – Total Solids, VS – Volatile Solids).

| Substrate        | pH  | TS [%] | VS [%TS] |
|------------------|-----|--------|----------|
| Bovine blood     | 6.78| 10.80  | 94.34    |
| Maize silage     | 4.00| 33.00  | 95.00    |
| Refood           | 4.72| 15.56  | 93.68    |
| Flotation sludge | 7.32| 20.90  | 82.07    |

3.1. Organic Loading Rate (OLR)
Due to the different biogas and methane yield of the substrates calculated as Mg VS (Table 2, 3), and also due to the differences in the percentage of methane in biogas generated from individual mixes, the organic loading rate differed significantly between individual variants. The lowest nominal OLR was characterized by WI and it amounted to 4.58 kg · m⁻³ · d⁻¹. In the case of the WIII OLR it was already 6.01 and in the WII up to 7.72 kg · m⁻³ · d⁻¹. It should be noted that the lowest OLR in practice is the easiest to maintain process stability, all the more so because it finds a very large connection with another important parameter i.e., HRT.

3.2. Hydraulic Retention Time (HRT)
Hydraulic retention time is the time to replace the entire batch in the fermenter. Due to the microbiological nature of the fermentation process, and thus the need to provide enough time for the bacteria to grow, it is good that HRT is as long as possible. Also, extending the residence time of the substrate in the reactor enables its better fermentation, which is particularly important in the case of substrates difficult to decompose. In the analyzed variants, the longest HRT was characterized by WI and it was 29 days. WIII was next in line (24 days). WII was characterized by the shortest retention time and it was 17 days. Such a short charge replacement time could threaten the stability of the process where it is not for the fact that in this variant, due to the high dry matter content in maize, the digestate was planned to be diluted to allow pumping. Along with the recycled digestate, the fermentation microflora is also recycled, which ensures the stability of biogas production.

3.3. Methane and biogas productivity
The results of biogas and methane fermentations are presented in the tables 3 and 4. For the real scale biogas plants operators, the most important parameter is the methane productivity from 1 Mg of FM (fresh matter) tested substrate.

Table 3. Biogas production from tested substrates

| Substrate       | CH₄ content [%] | Biogas [m³ / Mg FM] | Biogas [m³ / Mg TS] | Biogas [m³ / Mg VS] |
|-----------------|-----------------|----------------------|---------------------|--------------------|
| Flotation sludge| 74.24           | 123.71               | 591.90              | 721.21             |
| Bovine blood    | 67.12           | 62.13                | 575.15              | 609.66             |
| Maize silage    | 51.33           | 204.56               | 619.87              | 652.50             |
| Refood          | 58.94           | 91.62                | 588.79              | 628.50             |
It has to be underlined that most efficient substrate for methane generation – maize silage (table 4) – is typical agricultural product. In order to avoid the conflict between food and energy production, the waste-based substrate are better to use.

| Substrate          | CH$_4$ [m$^3$/Mg FM] | CH$_4$ [m$^3$/Mg TS] | CH$_4$ [m$^3$/Mg VS] |
|--------------------|-----------------------|-----------------------|-----------------------|
| Flotation sludge   | 91.84                 | 439.40                | 535.40                |
| Bovine blood       | 41.70                 | 386.04                | 409.21                |
| Maize silage       | 105.00                | 318.18                | 334.93                |
| Refood             | 54.00                 | 347.01                | 370.41                |

Additionally, the kind of substrate used has also strong influence of economic aspects of biogas plant operation, which is shown in table 5.

| Parameter                        | WI Bovine blood + flotation sludge | WII Maize silage | WIII Refood |
|----------------------------------|------------------------------------|-----------------|-------------|
| Required Lagoon size, m$^3$      | 4590                               | 2592            | 5562        |
| Digestate mass, Mg/year          | 13961                              | 7884            | 16918       |
| Income excluding operating costs, US $/year | 512 071                         | 512 071         | 512 071     |
| Feedstock cost, $/year           | 0                                  | 262800          | -704 906    |
| Total income, $/year              | 512 071                            | 249272          | 1 216 978   |

Looking from an economic point of view, it should be noted that the profitability of all three variants for the electricity produced would be the same, as they all tend to produce 12 MWh per day (maximum limit for 0.5 MW electric power biogas plant). The differences in economics will, therefore, be caused by the costs associated with the acquisition of substrates, or also by the revenues associated with their utilization in a biogas plant. Therefore, taking into account the adopted assumptions, it should be calculated that in WI scenario, due to reliance on the company's waste substrates, no costs related to the purchase of substrates will be incurred. The income will be equal to the value of electricity produced, i.e. about $512,071 US dollars. In option WII, due to the cost of maize silage, this income should be reduced by the costs of obtaining silage, i.e. by approximately $262,800 US dollars which gives over $249,000 US dollars of income. The last variant, however, due to the use of the substrate for which there is a possibility of charging fees for its utilization, in addition to income from the sale of electricity allows generating another income of $704,900 US dollars (in total over $1,216,978 US dollars. This means that, with the adopted assumptions and quite simplified calculation, this option is the most profitable.

### 4. Conclusions

On the base of research made in this paper, the followed conclusions were made:

1. Maize silage was characterized by the highest methane and biogas yield from the analyzed substrate group. However this is the most expensive substrate.
2. Maize silage fermentation in the Polish condition is least profitable due to the approximately 50% income reduction by the costs of obtaining silage.
3. Due to the price received for treating waste materials, refood fermentation is the most economically feasible option because of additional income for its utilization.
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