ENERGY BALANCES OF BIOGAS PRODUCTION FROM INDUSTRIAL WASTES AND ENERGY PLANTS

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Abstract. The energy balance of biogas production from industrial wastes and energy plants has been investigated during this research. Conversion efficiency of digestion of industrial wastes and energy plants to biogas by using different temperatures in the range from 52 to 57 ºC has been evaluated. The variation of digestion temperatures shows the difference in the total energy input from 1563 $MJ \cdot t^{-1}$ to 1666 $MJ \cdot t^{-1}$. Energy consumption for co-digestion of industrial wastes and energy plants in biogas plant was evaluated in theoretical research. The model results show that the rise of temperature (from 52 to 57 ºC) for anaerobic digestion reduces the efficiency of the biogas plant. Useful energy obtained after digestion at different temperatures varies in the range of 3822 $MJ \cdot t^{-1}$ to 6089 $MJ \cdot t^{-1}$. The energy conversion ratio ranged from 3.2 at 57 ºC to 4.9 at 52 ºC.

Keywords: energy balance, industrial waste, biomass, biogas, thermophilic process.

Introduction

Biogas is arguably a more versatile renewable energy source due to its determinate energy value and ease of storage. It can be used directly for heating and electricity generation, and as a substitute for fossil fuel applications. The potential utilization of the digestate as fertilizer can also reduce the dependence on energy intensive mineral fertilizers and further mitigate greenhouse gas (GHG) emissions [1]. The environmental impact of a biogas plant depends on integration into a close sustainable cycle [2; 3], when the digested substrate is used on the fields for fertilization of energy plants. Such biogas technologies contribute sustainable development of agriculture and rural society [4-6].

The energy balance summarizes entering and leaving energy flows of the process [2; 7]. The highest energy consumption factor in the anaerobic digestion process is the heating of the digester. The heat is needed for favorable conditions of microbes. Most studies have considered energy flows in crop or silage production, transportation and biogas production [8; 9]. Those studies showed the need of local data, because regional conditions affect crop cultivation, transportation and biogas production. Mass and energy balance was calculated for biogas production in Lithuanian conditions in this paper. The aim of this study was to analyse how the energy performance and inputs in biogas production are affected by the temperature influence using the thermophilic process.

Materials and Methods

Energy balance includes the whole technological processes from cultivation and harvest of energy plants through storage to the biogas plant and energy generation. The direct energy input in the form of electricity and fuel as well as the indirect energy input for the manufacturing of machines, equipment were considered. In order to compare the different temperature scenarios in energy balance, the technological process has been divided in two stages (Fig. 1).

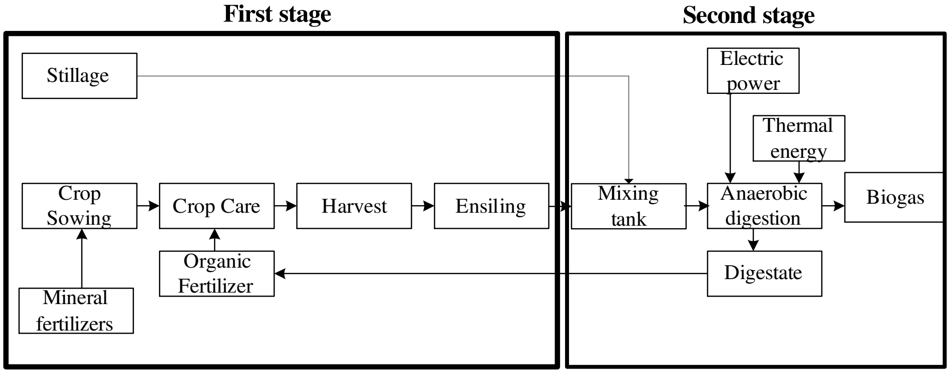

Fig. 1. **Technological scheme of biogas production from industrial wastes and energy plants**

The biomass production stage is based on soil cultivation and plant sowing, maintenance, plant cultivation and ensiling of biomass. On the second stage the biogas generation is based on technological processes as mixing of feedstock and substrate, pumping and digestate storage, digestate will not be recycled. All these processes require energy expressed as direct and indirect (embodied) energy input.

The total energy input E_{te} for the whole technological scheme of biogas production from industrial wastes and energy plants can be expressed combining all direct and indirect energy inputs by the following equation:

$$E_{te} = E_{di} + E_{indit}, \quad (1)$$

where E_{di} – all direct energy inputs $MJ \cdot t^{-1}$;
E_{indit} – all indirect energy inputs $MJ \cdot t^{-1}$.

The energy input for plant biomass cultivation and processing at the first stage E_{cult} can be expressed by the equation:

$$E_{cult} = \sum_{1}^{n} E_d + \sum_{1}^{n} E_{idei}, \quad (2)$$

where E_d and E_{indei} – direct and indirect energy input for biomass cultivation and processing, $MJ \cdot t^{-1}$.

The direct energy input for biomass cultivation and processing is related to technological operations and is calculated by summing the individual technological operations:

$$E_d = E_{da} + E_{pd} + E_s + E_{tr} + E_{dn} + E_{tran} + E_{sil} \quad (3)$$

where E_{da} – direct energy input for soil tillage, $MJ \cdot t^{-1}$;
E_{pd} – direct energy input for soil cultivation, $MJ \cdot t^{-1}$;
E_s – direct energy input for crop sowing, $MJ \cdot t^{-1}$;
E_{tr} – direct energy input for fertilization, $MJ \cdot t^{-1}$;
E_{dn} – direct energy input for yield harvesting, $MJ \cdot t^{-1}$;
E_{tran} – direct energy input for transportation, $MJ \cdot t^{-1}$;
E_{sil} – direct energy input for ensiling, $MJ \cdot t^{-1}$.

The direct energy input E_{dei} for anaerobic digestion (the second stage of technological scheme) of ethanol stillage and grass silage at the biogas plant consists, of electrical and thermal energy inputs:

$$E_{dei} = \sum_{1}^{n} E_{el} + \sum_{1}^{n} E_{th}, \quad (4)$$

where E_{el} – electrical energy consumption for technological equipment, $MJ \cdot t^{-1}$;
E_{th} – thermal energy input, $MJ \cdot t^{-1}$.

The direct energy input as electric power of the biogas plant consists of chopping, digester filling of fresh biomass, substrate and stillage pumping, mixing and other technological operations. The energy input expressed can be calculated by the following equation:

$$E_{el} = E_{doz} + E_{uz} + E_m + E_{sp} + E_{kp} + E_{slr} + E_d + E_{slp} + E_{ka} + E_{doz} + E_{sc} + E_{bv} + E_{ba} + E_{kv} + E_{ws}, \quad (5)$$

where E_{doz} – energy consumption for biomass mixing and measuring, $MJ \cdot t^{-1}$;
E_{uz} – energy consumption for filling the digester, $MJ \cdot t^{-1}$;
E_m – energy consumption for biomass mixing in digester, $MJ \cdot t^{-1}$;
E_{sp} – energy consumption for substrate pumping, $MJ \cdot t^{-1}$;
E_{ws} – energy consumption for stillage pumping, $MJ \cdot t^{-1}$;
E_{kp} – energy consumption for condensate pumping, $MJ \cdot t^{-1}$;
E_{slr} – energy consumption for pressure maintenance of gasholder, $MJ \cdot t^{-1}$;
E_d – energy consumption for biogas flare, $MJ \cdot t^{-1}$;
E_{slp} – energy consumption for biogas pressure elevation, $MJ \cdot t^{-1}$;

E_{ka} – energy consumption for cogeneration service, MJ·t^{-1};
E_{sc} – energy consumption for heating fluid circulation, MJ·t^{-1};
E_{bv} – energy consumption for biogas purification, MJ·t^{-1};
E_{ba} – energy consumption for biogas counting, MJ·t^{-1};
E_{kv} – energy consumption for biogas plant controlling system, MJ·t^{-1}.

Thermal energy is used for warming up the substrate and to compensate the heat losses to the surrounding environment through the walls of the digester. The thermal energy input for heating can be calculated by the following equation:

$$E_{th} = E_{thl} + E_{thb}, \tag{6}$$

where E_{thl} – energy loss, MJ·t^{-1};
E_{thb} – energy input to heat raw biomass, MJ·t^{-1}.

The starting temperature of the raw material before filling in the digester is calculated by determination of mixture wheat stillage temperature combining with grass silage temperature.

$$t_{ikr} = m_1 c_1 t_1 + m_2 c_2 t_2 , \tag{7}$$

where: m_1 – mass of wheat stillage
c_1–specific heat of wheat stillage
t_1– wheat stillage temperature from industrial plant
m_2– mass of grass silage
c_2–specific heat of grass silage
t_2– grass silage temperature (average temperature in Lithuania is 6.2 ºC)

Embodied energy of biogas plant constructions and equipment for biomass digestion is calculated by determination of the used materials embodied energy [7]:

$$E_{indb} = \frac{\gamma_{kgi} \cdot M_{kgi} \cdot (n_{ka} + n_{kt})}{t_d \cdot 100\%}, \tag{8}$$

where γ_{kgi} – embodied energy equivalent of material, MJ·t^{-1};
M_{kgi} – material mass, t;
n_{ka} – yearly depreciation rate, %;
n_{kt} – energy consumption for maintenance and repair, %;
t_d – days per year.

The energy output is expressed as the biogas yield and energy potential of biomass and determined by experimental investigations in the laboratory. Investigation of biogas production from industrial wastes and energy plants and process optimization were performed using periodic biomass loading and applying different temperatures from 52 ºC to 57 ºC. The experimental system was set up and monitored in the Energy and Biotechnology Engineering Institute located in the Aleksandas Stulginskis University in Lithuania. The seed material (inoculum) was taken from laboratory experiments on wastewater sludge with a starting temperature of 52 ºC. More detailed information about this experiment is presented in the article of the current edition [10].

To estimate the resource efficiency, the output/input ratio is computed. The energy ratio is calculated as the total energy output divided by the total energy input and can be defined as the net amount of energy one obtains when putting one unit of energy into the system:

$$\varepsilon = \frac{E_{fue}}{E_{te}}, \tag{9}$$

where E_{fue} – total conversion energy output, MJ·t^{-1};
E_{te} – total energy input, MJ·t^{-1}.

The energy potential of biomass is expressed as the biogas production intensity, biogas yield from digested mass unit (B_M); biogas yield from total solids (B_{TS}) and biogas yield from volatile solids

(B_{VS}). The methodology of energy potential determination is given in other works [5]. The statistical analysis was done using Stat software adapted in the Visual Basic for Application as macro program to run in the Excel [11].

Results and discussion

The energy input of a biogas plant treating industrial wastes and energy plants has been analysed at six different scenarios. The energy consumption is calculated for the biogas plant which treats 30000 tons of stillage and 10000 tons of cocksfoot grass during the year. Temperature of stillage and cocksfoot grass mixture was 49 ºC. This temperature was simulated regarding information from two biogas plants in Lithuania operating on stillage and average temperatures of grass silage found from the experimental farm.

The energy input in the form of fertilizer, fuel, machinery was included as the process energy used for the processing on the biogas plant. It was decided that the model used for this study is based on a biogas system where the industrial wastes and energy plants are used as the only feedstock with a hydraulic retention time of 120 days.

The results show that the highest total energy consumption that combines the whole cycle (soil cultivation, plant sowing, maintenance, plant cultivation, ensiling of biomass and technological processes in biogas plant) is 1665 MJ·t^{-1} at 57 ºC and the lowest – 1563 MJ·t^{-1} at 52 ºC (Fig. 2). The indirect energy input does not differ with constant 1002 MJ·t^{-1} among the scenarios although the direct energy input varies from 561 MJ·t^{-1} to 664 MJ·t^{-1} depending on the temperature range (Table 1).

The heat and electricity consumption were based on the measured data and electric power production capacity. It was calculated that the electricity consumption in the biogas plant was 9 % of the produced electricity. The heat requirement was calculated to be 7.1-12.3 % of the produced heat, depending on temperature range.

The main component of the energy input is due to warming up the biomass to the termophilic temperature that ranges from 52 to 57 ºC temperature and varies from 58 MJ·t^{-1} to 156 MJ·t^{-1} and energy losses from the reactor walls vary from 51 MJ·t^{-1} to 57 MJ·t^{-1}. The results show that differences in the required temperature of the digester can increase the direct energy input in the biogas systems significantly. The embodied energy of the construction input is 208 MJ·t^{-1}, soil cultivation energy input is 225 MJ·t^{-1}, plant sowing, maintenance and plant cultivation is 794 MJ·t^{-1}, ensiling of biomass 30 MJ·t^{-1}. All these energy inputs from embodied energy to ensiling of biomass were constant for all scenarios.

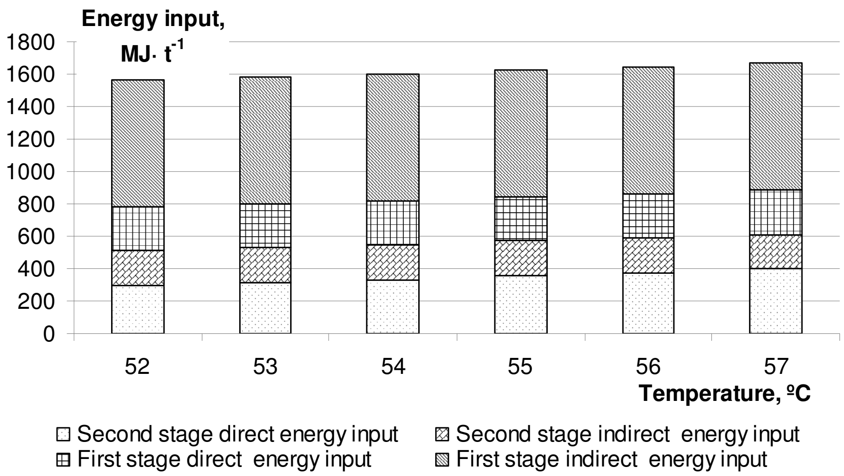

Fig. 2. **Total energy input at biogas plant**

The experimental research showed the maximum biogas yield at 52 ºC with the yield averaging 674 l kg^{-1}·VS^{-1}. Increase of the temperature up to 57 ºC showed that the biogas yield decreases to 512 l kg^{-1}·VS^{-1} by 24.1 %. At each 1 ºC temperature shift from 54 ºC to 57 ºC, there was a rapid initial drop in the biogas yield rate. The biogas yield decreased in average 6.0 % every time the temperature was increased by 1 ºC.

The methane (CH_4) concentration in the produced biogas depends on the digester temperature and it was in the range of 55.7-59.6 %. The lowest methane concentration was produced when the digester was operating at 55 ºC and varied from 55.7 % to 56.1 % while the highest methane concentration was achieved at 52 ºC digester temperature and varied from 59.3 % to 59.6 %.

The energy potential from industrial wastes and grass silage was obtained experimentally (by biogas yield and methane concentration). The results are expressed as difference between the energy input and energy potential (Fig. 3). The final useful energy depending on the temperature varies in the range of 3822 $MJ \cdot t^{-1}$ at 57 ºC to 6089 $MJ \cdot t^{-1}$at 52 ºC.

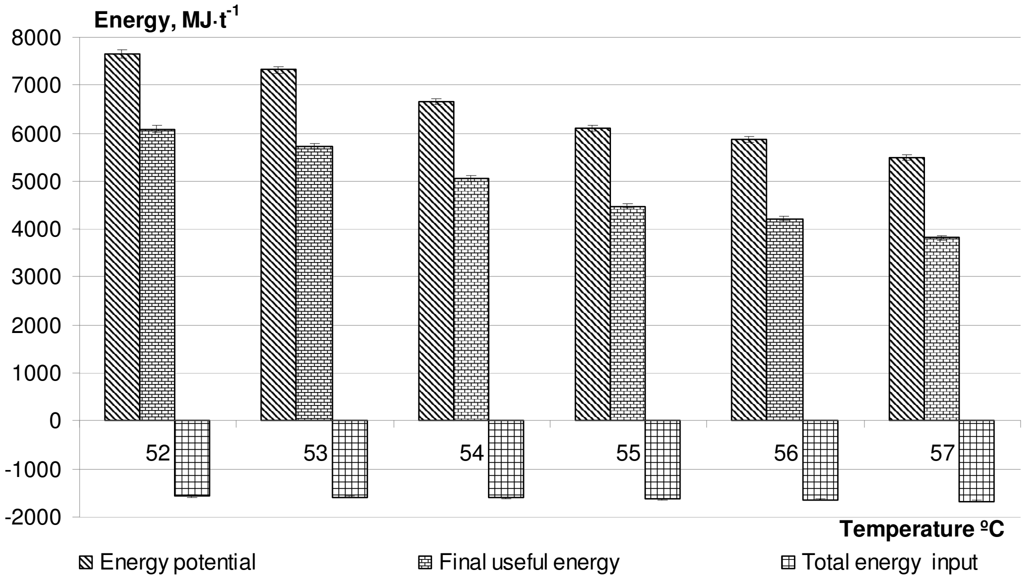

Fig. 3. **Energy balances of biogas production using different temperatures**

The energy ratio differs among temperatures, generally being lower at higher temperatures due to a higher energy demand and lower energy potential (Fig. 4).

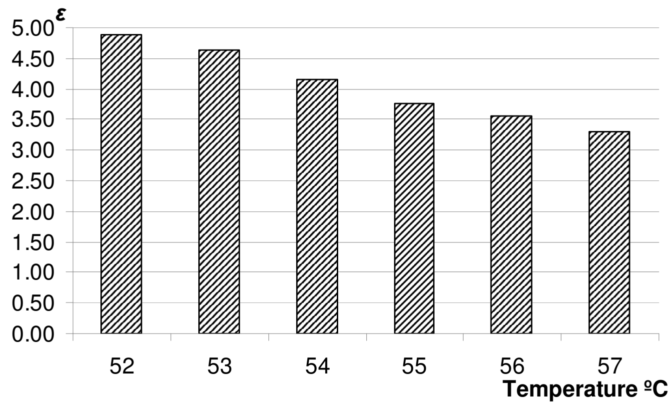

Fig. 4. **Energy conversion ratio at different temperatures**

The energy conversion ratio was the highest when the reactor was operating at 52 ºC with the ratio of 4.9 and the lowest was 57 ºC with the ratio of 3.2.

Conclusions

1. The total energy input ranged from 1563 $MJ \cdot t^{-1}$ at 52 ºC to 1666 $MJ \cdot t^{-1}$ at 57 ºC. The direct energy input was the highest 664 $MJ \cdot t^{-1}$ at 57^{o}C and the lowest 561 $MJ \cdot t^{-1}$ at 52 ºC, while the indirect energy input was constant (1002 $MJ \cdot t^{-1}$).
2. The useful energy using different temperatures varies in the range of 3822 $MJ \cdot t^{-1}$ to 6089 $MJ \cdot t^{-1}$. The highest useful energy was obtained at 52 ºC and the lowest – at 57 ºC.

3. The results show that the direct and indirect energy input required in the scenarios typically corresponds to 20-30 % of the energy content in the biogas produced, depending on the used temperatures.

References

1. Berglund M., Borjesson P. Assessment of energy performance in the life-cycle of biogas production / Biomass and Bioenergy Vol. 30, 2006. pp. 254-266.
2. Murphy J., Power N. How can we improve the energy balance of ethanol production from wheat? / Elsevier Ltd Vol 87, 2008. pp. 1799-1806.
3. Helbig S., Küstermann B., Hülsbergen K.-J. Energy balance of different organic biogas farming systems / 16th IFOAM Organic World Congress, Modena, Italy, June 16-20, 2008. 4 p.
4. Navickas K., Venslauskas K. Energy balance of biogas production from perennial grasses / Enginnering for rural development Vol 10, 2011. pp. 382-386.
5. Navickas K., Venslauskas K., Nekrošius A., Župerka V., Kulikauskas T. Influence of different biomass treatment technologies on efficiency of biogas production / Engineering for rural development: 11th international scientific conference: proceedings, May 24-25, vol. 11. 2012. pp. 586-590.
6. Kryzeviciene A., Navickas K., Venslauskas K., Zuperka V. Energy potential for reed canary grass as energy crops in organic agriculture in Lithuania / Grassland science in Europe. Vol 12, 2007. pp. 587-590.
7. Mikkola H. and Ahokas J. Indirect energy input of agricultural machinery in energy analysis / Renewable Energy, Vol. 35, Issue 1, 2010. pp. 23-28.
8. Navickas K., Venslauskas K., Zuperka V. Potential and possibilities of biogas production from agricultural raw materials in Lithuania / Rural development 2009. Proceedings of Fourth international scientific conference Vol. 4, Book 2. 2009. pp. 365-369.
9. Nielsen A., Paavola T. Manure and energy crops for biogas production / TemaNord, 2008 Copenhagen. pp. 38-50.
10. Navickas K., Venslauskas K., Petrauskas A., Župerka V. Influence of temperature variation on biogas yield from industrial wastes and energy plants / Engineering for rural development: 12th international scientific conference: proceedings, May 23-24, vol. 12. 2013.
11. Tarakanovas P., Raudonius S. The program package for processing statistical data. – Akademija, Kauno r., 2003.56 p.