ENERGY BALANCE OF BIOGAS PRODUCTION FROM PERENNIAL GRASSES

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Abstract. The energy balance of biogas production from perennial grass silage has been investigated in this paper. The anaerobic digestion process parameters and grass species have influence on biogas yield such as organic load. The model of technological process of biomass preparation and its digestion to biogas has been performed. The variation of digester organic load (1.0; 1.5 and 2.0 $kg_{VS}\cdot m^{-3}\cdot d^{-1}$ shows the difference in total (direct and indirect) energy input from 490 $MJ\cdot t^{-1}$ biomass at 2.0 $kg_{VS}\cdot m^{-3}\cdot d^{-1}$ up to 570 $MJ\cdot t^{-1}$ biomass at 1.0 $kg_{VS}\cdot m^{-3}\cdot d^{-1}$. The laboratory experiments of biogas production from grass silage show the highest biogas yield (115 $l\cdot kg^{-1}$ biomass) at 1.0 $kg_{VS}\cdot m^{-3}\cdot d^{-1}$. By increasing the organic load up to 2.0 $kg_{VS}\cdot m^{-3}\cdot d^{-1}$ the biogas yield decreases down to 93 $l\cdot kg^{-1}$ from biomass. The methane (CH_4) concentration in the obtained biogas had a little dependence on digester organic load and was in the range of 58-60 %. Such biogas has a sufficient methane concentration and is suitable for cogeneration.

Keywords: biogas, energy balance, perennial grass.

Introduction

The global demand for energy and more specifically clean energy is growing rapidly. The high cost of fossil fuels and intensive environmental pollution of carbon dioxide (CO_2) leads to search for alternative energy sources [1]. Energy production from renewable energy sources is one of the most prominent of the European Community energy policy priorities [2]. Biogas production from energy plants contributes to sustainable development of economics, agriculture and rural society [3]. It also increases security of energy production and supply, competitivety and sustainability and in addition provides possibilities of new income for farmers. Production of methane rich biogas through anaerobic digestion of energy crops has expanded extensively throughout Europe [4]. Large areas of agricultural land are cultivated predominantly for energy production in biogas plants [5]. Annual crop cultures need significant energy for plants, to cultivate and fertilize for their growth. Some studies [6; 7] show the advantages of perennial grasses usage for biogas production in Lithuania.

There have been made some researches on energy balance of biomass crops. Gerin et al has made the net balance of CO_2 emission and renewable energy production for maize and grass energy crops produced in several agricultural systems relevant for Southern Belgium and the surrounding areas [8]. They focused mainly on the fossil CO_2 and energy balances of maize and grass energy crops. Navickas et al analysed the comparison of energy input between different technologies of biomass preparation and different kinds of grasses [9]. The energy balance for wet oxidation pretreatment of perennial crops miscanthus and willow have been analysed in paper prepared by Uellendahl et al [10].The energy balance and cost-benefit analysis for perennial energy crops performed in [10] study implies the whole chain of plant cultivation, harvesting and conversion to biogas. Bohn et al explains the energy balance of a pilot scale reactor to be expected to adequately reflect the conditions present in a full-scale reactor [11]. Others focus mainly on the evaluation of the energy balance in various biogas systems [12]. The energy balance is analysed from a life-cycle and the analysis is based on the published data. Dubrovskis et al shows the energy calculation methodology for maize [13]. The energy output obtainable in the anaerobic digestion process from the energy crops area has been calculated by the yield of biomass harvested, biodegradation ratio of organic matter during anaerobic digestion process and lower heat value of biogas. This research includes all technological processes and direct energy inputs as well as indirect.

Materials and Methods

Energy balance of biogas production from various perennial grasses has been done by identifying the total energy input for crop cultivation and anaerobic digestion to biogas. Direct and indirect energy input depends on various grass species, agro technologies and the biogas plant technology process. Biogas production from perennial grasses includes soil tillage, crop planting, yield harvesting, ensiling, anaerobic digestion, substrate spreading and biogas utilization (Fig. 1).

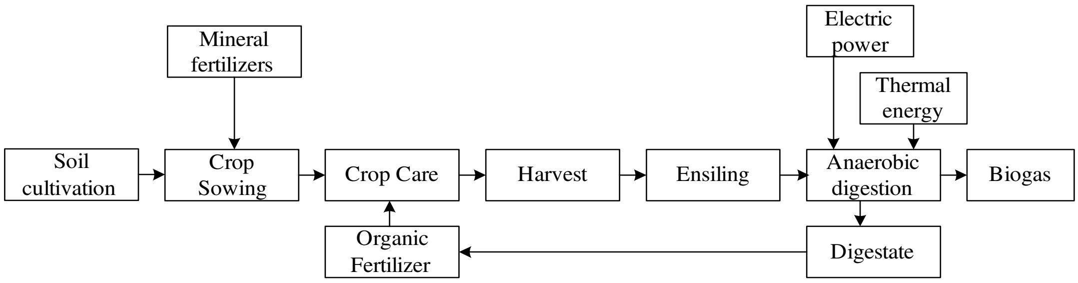

Fig. 1. **Technological scheme of biogas production from perennial grasses**

The technological process of biogas production from perennial grass can be divided into two technological steps – biomass production and biogas generation. The first stage includes soil tillage and cultivation, crop sowing, maintenance, harvesting and ensiling. The plant biomass energy input for cultivation and processing can be expressed by the equation:

$$E_{cult} = \sum_{1}^{n} E_d + \sum_{1}^{n} E_{ind} \, , \tag{1}$$

where E_d and E_{ind} – direct and indirect energy input for biomass cultivation and processing, MJ·ha^{-1}.

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

$$E_d = E_{da} + E_{pd} + E_s + E_{tr} + E_{dn} + E_{tran} + E_{sil} \tag{2}$$

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

Indirect energy input for biomass cultivation and processing is separated into intensity of agricultural machinery and embodied energy of fertilisers, pesticides and seeds. The total indirect energy input is calculated by this equation:

$$E_{indc} = \sum_{1}^{n} E_{zuu} + \sum_{1}^{n} E_{tras} \, , \tag{3}$$

where E_{zuu} – agricultural machinery intensity, MJ·ha^{-1};
E_{tras} – embodied energy of used materials for cultivation, MJ·ha^{-1}.

Direct energy input for anaerobic digestion of grass silage at biogas plant consists of fuel, electrical and thermal energy:

$$E_{bd} = \sum_{1}^{n} E_{fuel} + \sum_{1}^{n} E_{el} + \sum_{1}^{n} E_{th} \, , \tag{4}$$

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

Fuel is used for transportation and loading of grass silage at the biogas plant. The direct energy input as electric power of the biogas plant consists of chopping, digester filling of fresh biomass, substrate pumping, mixing and other technological operations. The energy input expressed as MJ·t^{-1} can be calculated by the following equation:

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

where E_{doz} – energy consumption of biomass mixing and measuring, $MJ \cdot t^{-1}$;
E_{uz} – energy consumption of filling the digester, $MJ \cdot t^{-1}$;
E_m – energy consumption of biomass mixing in digester, $MJ \cdot t^{-1}$;
E_{sp} – energy consumption of substrate pumping, $MJ \cdot t^{-1}$;
E_{kp} – energy consumption of condensate pumping, $MJ \cdot t^{-1}$;
E_{slr} – energy consumption of pressure maintenance of gasholder, $MJ \cdot t^{-1}$;
E_d – energy consumption of biogas flare, $MJ \cdot t^{-1}$;
E_{slp} – energy consumption of biogas pressure elevation, $MJ \cdot t^{-1}$;
E_{ka} – energy consumption of cogenerator service, $MJ \cdot t^{-1}$;
E_{sc} – energy consumption of heating fluid circulation, $MJ \cdot t^{-1}$;
E_{bv} – energy consumption of biogas purification, $MJ \cdot t^{-1}$;
E_{ba} – energy consumption of biogas counting, $MJ \cdot t^{-1}$;
E_{kv} – energy consumption of biogas plant controling system, $MJ \cdot t^{-1}$.

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, $MJ \cdot t^{-1}$;
E_{thb} – energy input to heat raw biomass, $MJ \cdot t^{-1}$.

Digesters mainly are constructed from steel with a layer of mineral heat insulation. The anaerobic digester volume depends on the organic load of biomass. Digesting the same mass of raw biomass the digester volume increases at lower organic load and decreases – at higher organic loads. Therefore, the digester height to the diameter ratio of 0.74 has been used.

The embodied energy of biogas plant constructions and equipment for biomass digestion is calculated by determination of the used materials embodied energy [14; 15]:

$$E_{indb} = \frac{\gamma_{kgi} \cdot M_{kgi} \cdot (n_{ka} + n_{kt})}{t_d \cdot 100\%}, \tag{7}$$

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

The human energy input for maintenance of the technological process at biogas plant is calculated by the equation:

$$E_{indh} = \gamma_d \cdot n_z \cdot t_z, \tag{8}$$

where γ_{kgi} – energetic equivalent of human work, $MJ \cdot h^{-1}$;
n_z – necessary number of people for maintenance of biogas plant, pc.;
t_z – work hours per day in biogas plant, h.

The energy output is expressed as the biogas yield and energy potential of biomass and determined by experimental investigations in the laboratory. The experiments have been done in the biogas laboratory in the Lithuanian University of Agriculture. Laboratory anaerobic digesters of 20 litters have been used and biomass digested at mesophilic conditions (38±0.5 ºC). The concentration of methane and hydrogen sulphide gases was measured by the biogas analyser Schmack SSM 6000. The energy potential of biomass is expressed as the biogas production intensity, biogas yield from digested mass unit (BM); biogas yield from total solids (BTS) and biogas yield from volatile solids (BVS). The methodology of energy potential determination is given in other works [16].

Investigation of biogas production from perennial grasses (reed canary grass (*Phalaris arundinacea*), tall fescue grass (*Festuca arundinacea*), cocksfoot grass (*Dactylis glomerata*)) and process optimization was performed using periodic biomass loading and applying different rates of organic load 1.0, 1.5 and 2.0 kg·m^{-3}·d^{-1}.

Results and discussion

The energy input of biogas plant treating grass silage has been analysed at the organic loads of 1.0, 1.5 and 2.0 kg·m^{-3}·d^{-1}. The energy consumption is calculated for the biogas plant which treats 5500 tons of perennial grass silage during the year. Technological operations are such as grass silage mixing, dosing, filling the reactor, substrate mixing in the digester, pumping of substrate and condensate, gasholder maintenance, biogas pressure elevation, cogeneration, fluid circulation of heating system, purification of biogas, biogas plant supervision and management. The quantity of the equipment, electrical power and duration of usage was taken into account while estimation of the energy consumption has been performed.

The results show that the highest total energy consumption at the biogas plant kg$_{VS}$ 569.8 MJ·t^{-1}, arises at a 1.0 kg·m^{-3}·d^{-1} organic load, and the lowest kg$_{VS}$ 491.5 MJ·t^{-1} at 2.0 kg·m^{-3}·d^{-1} organic load (Fig. 2). Average energy consumption of fuel kg$_{VS}$ 2.0 % (9.9 MJ·t^{-1}), electricity – 28.8 % (142.2 MJ·t^{-1}), heat energy kg$_{VS}$ 43.3 % (214.0 MJ·t^{-1}), energy intensity of machinery and equipment kg$_{VS}$ 25.9 % (127.8 MJ·t^{-1}), human labour - 0.1% (0.7 MJ·t^{-1}) of total energy input in the biogas plant.

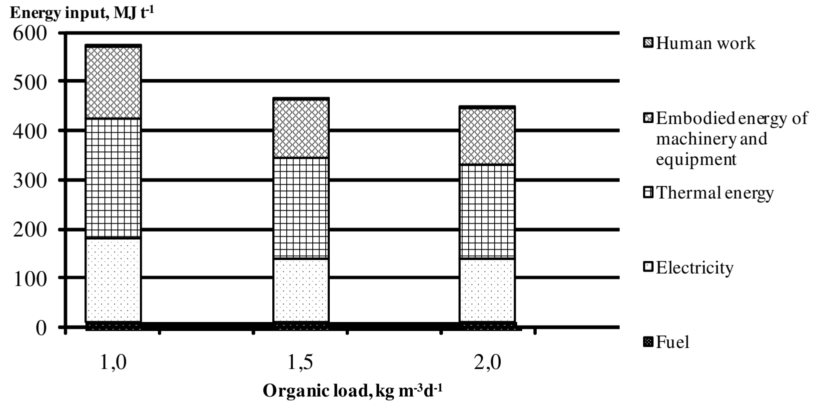

Fig. 2. **Total energy input at biogas plant**

Higher total energy input at the biogas plant is due to the longer retention time of biomass as it results in bigger volume of the digester and higher energy input is needed for mixing of biomass at 1.0 kg·m^{-3}·d^{-1} organic load.

The share of direct thermal energy was highest of the balance of energy input for all species of perennial grasses (Fig. 3).

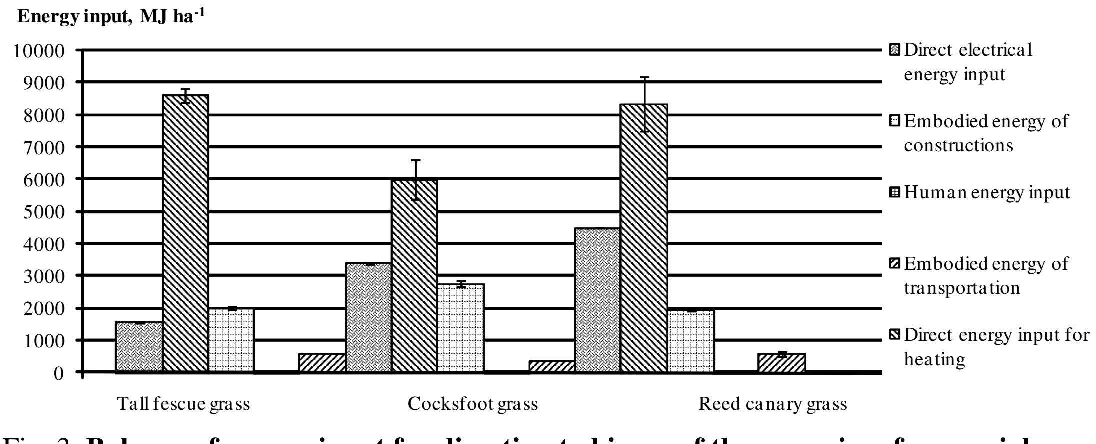

Fig. 3. **Balance of energy input for digestion to biogas of three species of perennial grass**

The heat requirements reach 5993 MJ·ha^{-1} for cocksfoot grass and 8332 MJ·ha^{-1} for tall fescue. The main component of energy input is due to warming up the biomass to the mesophilic temperature (38 ºC). The embodied energy of constructions is nearly constant for all cases of grass – 1989-2763 MJ·ha^{-1}.

The energy input on cultivation stage of various types of perennial grasses is shown in Fig. 4. The lowest part was used for human work, which accounts for only 22 - 49 MJ·ha^{-1}. Significantly higher proportion is given for the embodied energy of machinery - 6737 - 12838 MJ·ha^{-1}.

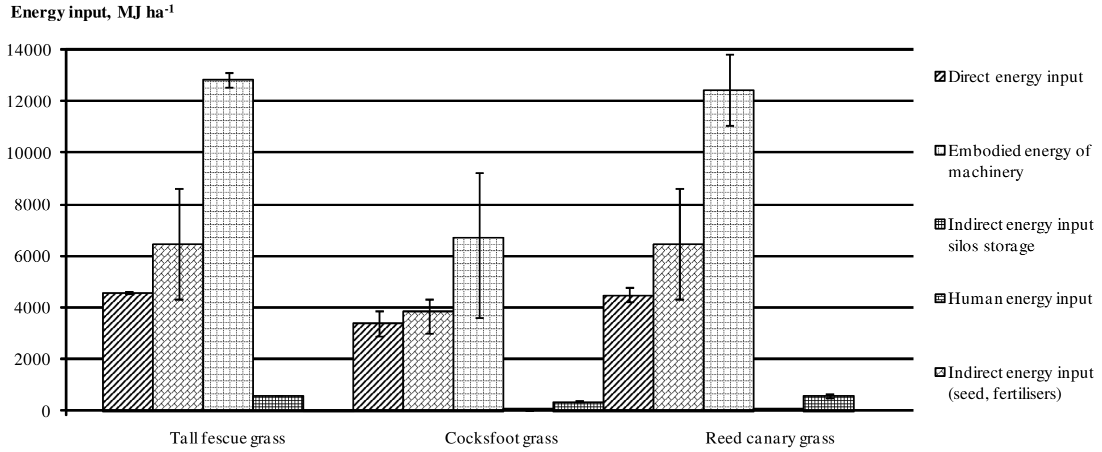

Fig. 4. **Energy input on cultivation stage of various types of grasses**

The use of mineral fertilizers for grass cultivation causes significant increase of indirect energy input. It is because of high energy input for fertiliser production (48 MJ·kg^{-1}) [12].

The experimental research made with tall fescue (*Festuca arundinacea*) silage shows the maximum biogas yield at 1.0 kg·m^{-3}·d^{-1} organic load. The biogas yield was 115 litters from 1 kg of biomass. Increasing the organic load up to 1.5 kg·m^{-3}·d^{-1} the biogas yield decreases to 108-109 l·kg^{-1}. The lowest yield of biogas (from 93.0 to 95.0 l·kg^{-1}) was obtained using 2.0 kg m^{-3}·d^{-1} organic load. The methane (CH_4) concentration in the produced biogas had minor dependence on the digester organic load and was in the range of 58-60 %. Such biogas has a sufficient methane concentration and is suitable for using at co-generation stations.

The study with reed canary grass (*Phalaris arundinacea)* silage shows that the maximum biogas yields at 1.0 kg·m^{-3}·d^{-1} organic load - 136 l·kg^{-1}. At the organic load of 1.5 kg·m^{-3}·d^{-1} ^{the} biogas yield decreased down to 120 - 122 l·kg^{-1}. Lower biogas yield was obtained by increasing the load up to 2.0 kg·m^{-3}·d^{-1}. The biogas yield dropped to 110 l·kg^{-1}. The methane concentration of biogas was quite stable 58 - 62 %. Such biogas energy value has the range from 5.8 to 6.2 kWh·m^{-3}.

Analysing experimentally the obtained energy potential from biomass and theoretically evaluating the total energy input from cultivation to conversion to biogas the result is expressed as the difference between the energy input and energy potential (Fig. 5).

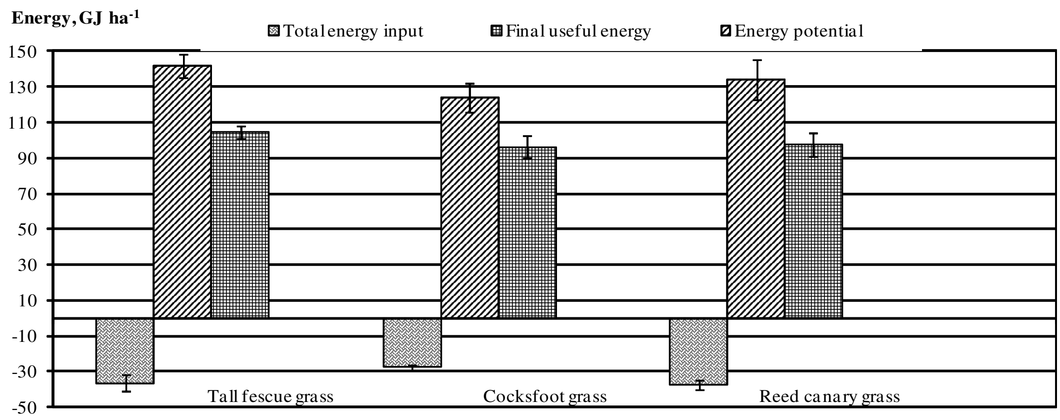

Fig. 5. **Energy balance of biogas production from perennial grasses**

The final useful energy for three species of perennial grass varies in the range of 96.2 - 104.3 GJ ha^{-1}. The use of mineral fertilizers can increase the total energy input, but it results in higher biomass energy potential as well. On the other hand, less biomass yield leads to lower energy input for transportation and anaerobic digestion. Therefore, the energy ratio for three types of grass varies from 71.6 to 77.5 %.

Conclusions

1. The energy input of cultivation of perennial grasses depends on the agro technology, embodied energy of the used equipment and fertilizer usage rate and varies between 14.4 and 24.5 $GJ \cdot ha^{-1}$.
2. The energy input on the biogas plant depends on volumetric organic loads and was the highest at 1.0 $kg \cdot m^{-3} \cdot d^{-1}$ organic load rate (569.8 $MJ \cdot t^{-1}$ and the lowest (491.5 $MJ \cdot t^{-1}$) at 2.0 $kg \cdot m^{-3} \cdot d^{-1}$ organic load.
3. The useful energy for three species of perennial grass varies in the range of 96.2-104.3 $GJ \cdot ha^{-1}$.

Acknowledgement

This work has been supported by the Lithuanian state science and studies foundation in the framework of the project "Plant biomass energy value enhancement by biotechnology methods (Biomass for Biogas)".

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