BIOGAS PRODUCTION FROM AGRICULTURAL RAW MATERIALS

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Abstract. Nowadays no one doubts the need for alternative energy sources; yet, their choice and conditions of use are quite complicated and difficult to understand. In Latvia, the experience in the use of biogas from agricultural raw materials to generate energy is quite small, and optimal resources and their mixtures are sought constantly. The research aim of the present paper is to identify the optimal type and quantity of substrate for a biogas facility for the conditions in Latvia by means of a simulation model. To achieve the aim, the following research tasks were set: to develop and describe a simulation model for the fermentation of a substrate for biogas production; and to identify an optimal substrate mixture for biogas production. It is necessary to examine several factors for the choice of a biogas substrate. If calculations are based on the energy potentials of substrates and their cost, an optimal substrate consists of a mixture of silage (22%) and manure (78%). The cheapest energy could be obtained if only manure is used; yet, the necessary electric capacity of the bioreactor would not be reached in this case. The optimisation model can be effectively used for identifying the optimal biogas substrate and its quantities and for calculations of alternative energy production.

Keywords: biogas, agricultural raw materials for energy, cost, energy potential.

JEL code: Q1; Q4

Introduction

The EU strategy Europe 2020 envisages increasing the output of energy from renewable energy sources until 2020 compared with the level of 1990. These targets set at the EU level are aligned with each Member State's national energy targets. Modern energy solutions are very complicated due to the diversity of production possibilities, the integrity of markets, and changes in the purchasing power of society. The association of energy production with other fields is especially explicitly seen in biogas production, which plays an increasing role in Latvia's economy. Biogas production affects not only the supply of and demand for energy but also, to a great extent, agriculture.

A complete assessment of biogas production cannot be presently made in Latvia, as this field is relatively new and little researched. There is a lack of statistical data, and credible information has to be obtained, which would allow examining the possibilities to use biogas in the energy sector. For this reason, the authors of the paper have developed a simulation model to assess biogas as a source of energy. The assessment was based on economic considerations. The research aim of the present paper is to identify the optimal type and quantity of substrate for a biogas facility for the conditions in Latvia by means of a simulation model. The model is approximated to the performance of the biogas facility on the research and training farm (RTF) "Vecauce" of Latvia University of Agriculture, which ensures that the data obtained fit practical performance results. This biogas facility is the first facility of this type in Latvia, which was established in 2008 and in which agricultural materials, including manure, are used as a

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substrate. To achieve the aim, the following research tasks were set: 1) to develop and describe a simulation model for the fermentation of a substrate for biogas production; and 2) to identify an optimal substrate mixture for biogas production.

A production model is actually a production function, which involves production of agricultural products (preparation of a substrate), biogas production, and cogeneration resulting in the generation and sale of electricity and thermal energy. The paper will contain calculations for the production model's first part focusing mainly on economic gains from the use of resources and the maximum output of biogas. The amounts of electricity and thermal energy and their sales will not be considered in this paper.

Research results and discussion

Replacement of energy resources in the context of economic considerations

For raising economic efficiency, alternatives in the supply of energy are constantly sought based on economic efficiency as the leading criterion. Every new economic cycle starts with the use of new types of energy or innovations in this field.

Marceti, whose research was based on the Fisher-Pry model of energy substitution, discovered a shift in the historical life cycles of primary energy sources from wood, coal, oil and natural gas to nuclear energy and, in the future, solar energy (Devezas T. et al., 2008). Kondratieff's long waves reflect the logarithmic movement of economic growth from the perspective of technological progress or innovation. The waves replace one another by significantly overlapping each other, which enables some regions to review their energy supply policies. Due to technological progress, new waves might emerge more frequently, which may be explained by the fact that there is no so efficient (from the public point of view) source of energy that would be able to take a similar position as once coal was. From this point of view, it is possible to explain the change of the type of energy as well. Georgescu-Roegen (1975), one of the founders of the energy theory of value, emphasises that economic efficiency, ease of use and capital intensity determine innovations in the choice of energy. This evolution highlights the decreasing role of factors of stock and the increasing role of factors of flow in energy supply, while at the same time stressing economic efficiency.

Along with technological progress, economic growth is ensured by a transition to a higher level of energy. It contradicts the energy theory of value that envisages the transition to a cheaper type of energy source. The price of energy as the leading determinant in the choice of alternatives is also contended by I.Matutinovic (2009), the Gfk Group, an expert of one of the largest research companies in the world. He points that in a foreseeable future, high prices will not be the leading determinant that will define the production/export level according to foreign demand; those will be domestic, not global, economic, or political decisions.

The cyclical use of energy sources may be viewed not only from the perspective of progress but also from the perspective of possibilities for the use of sources. There is no conformity of opinions regarding the period for which mineral reserves can meet demand, as the efficiencies of extraction and use constantly rise. Yet, to identify the need for alternative energy based on the amount of dominant energy reserves, the situation may be examined by using simulation models. The paper presents simulation results of the model for the biogas production, which assumes that biogas is produced from agricultural products.

Simulation model for the fermentation of a biogas substrate

Using the optimisation model, the authors analysed various agricultural substrates and the efficiency of their use for biogas production, focusing mainly on substrate production costs.

The values were initially calculated assuming that fertilisers are used for crops. Biogas energy production is based on examining the following technical indicators: content of substrate dry matter, biogas yield, potential capacity, optimal substrate mixture etc. The model for simulating biogas production assumes an electric capacity of 260 kW in cogeneration (the designed capacity of the biogas facility is 0.26 MW). The electricity generated is a product for sales.

Besides the characteristics of substrates, the volume of the biogas fermentor or bioreactor and the allowed content of dry matter that is needed to ensure optimal biochemical processes should be considered when choosing an optimal substrate mixture. In the particular case, the volume of the fermentor is 2000 m^3 (the effective fermentation volume is 1870 m^3) and the allowed content of dry matter is 17%.

The average period of keeping a substrate in the fermentor depends on the type of bioreactor and the substrate depletion period. For biogas facilities running mainly on livestock manure and/or livestock manure combined with industrial organic waste, it takes from 15 to 40 days, depending on the temperature mode in the fermentor. For biogas facilities using mainly energy crops as a substrate, it takes a longer period – from 60 to 100 days – in the mesophilic digestion process (30 - 42^o C) (Al Saedi et al., 2008).

In Denmark, the thermophilic process (43-55^o C) is mainly used at biogas facilities, as it significantly shortens the substrate depletion period; for instance, the substrate depletion period in the mesophilic process lasts for 25 days, while in the thermophilic process it takes only 12-15 days. The thermophilic process ensures a saving of volume up to 40% (Birkmose T. et al., 2007). Yet, a mesophilic fermentor is more stable and simple; it is less affected by changes in substrate mixtures (Frandsen T. et al., 2011). For simulations, the authors assume that the bioreactor operates in the mesophilic process (at approximately 38^o C) just like at the facility on the RTF "Vecauce".

Biogas is a gaseous fuel resulting from anaerobic fermentation; it consists of methane (CH_4), 50-70%, carbon dioxide (CO_2), 30-40%, and other components, for example, N_2O, O_2, NH_4, H_2S. Biogas can be obtained in a natural process in swamps, peat swamps, and waste deposit sites as well as from manure, sewage, fresh biomass, and biodegradable waste by using special fermenters. The energy value of biogas is usually within a range of 5-7 kWh m^{-3} depending on the content of methane in biogas, which is affected by the composition of nutrients in the fermented substrate, moisture, a type of waste and other factors.

The fermentation process takes place in the bioreactor, and the substrates needed for anaerobic fermentation may be very different. The substrates may differ by origin, methane yield, dry matter content etc. Yet, the common attributes are their ability to degrade biologically, energy is generated in this process and methane as a component of biogas is produced.

The energy obtained from a substrate may be calculated according to an equation:

$$Q_{en} = Q_{biogas} * K_{met} * Q_{met} \quad , \qquad (1)$$

where Q_{en} – total amount of energy, kWh;

Q_{biogas} – amount of biogas, m^3;

K_{met} – proportion of methane in biogas, m^3;

Q_{met} – lowest calorific value of methane, kWh m^{-3}.

The lowest calorific value of methane is assumed to be 10 kWh m^{-3}, and this choice is based on the recommendations of several scientists (Blumberga D. et al., 2009), while the amount of biogas obtained may be calculated by an equation:

$$Q_{biogas} = Q_{substr} * K_{biogas} \quad , \qquad (2)$$

where Q_{biogas} – amount of biogas, m^3;

Q_{substr} – amount of substrate, t;

K_{biogas} – biogas yield from fresh biomass, m^3.

The characteristics of various types of agricultural substrates – biogas yield, content of methane in substrates, and content of dry matter – differ, and the period needed for fermentation has to be also taken into consideration (Table 1). Accordingly, the unit cost among substrates is quite different.

Biogas yield from fresh biomass is a standard value that is based, in Table 1, on research conducted by German scientists, while in Latvia this indicator is lower. Laboratorial tests have been carried out both at the laboratories of the Faculty of Engineering, Latvia University of Agriculture, under the guidance of V.Dombrovskis and at laboratories in Germany on maize substrates grown under the guidance of professor Z.Gaile. The test results have been reported in numerous research papers (Dubrovskis V. et al., 2010; Dubrovskis V. et al., 2008;Bartusevics J., Gaile Z., 2010).

Table 1

Characteristics of biogas from agricultural substrates and the price of substrates

Type of substrate	Biogas yield, m^3, from fresh biomass	Proportion of methane in biogas, %	Content of dry matter in fresh biomass, %	Time needed for fermentation, days*	Substrate price, EUR t^{-1}
Winter wheat	596-616	52	87	80-100	161
Winter barley	596-616	52	87	80-100	195
Triticale	596-616	52	87	80-100	239
Barley	596-616	52	87	80-100	194
Oats	616	52	87	80-100	100
Silage (spring mixed crops, in trenches)	137-225	52-55	35	60-100	50
Haylage (in trenches)	137-225	52-55	35	60-100	26
Silage (grass)	137-225	52-55	35	60-100	43
Silage (maize)	187-218	49-59	35	60-100	29
Bran	200	52	87		336
Liquid manure (cattle)	20-30	55	7-10	15-40	3
Rapeseed granules	616	52	87	80-100	117
Milk (spoiled)	245	63	12	15-40	14

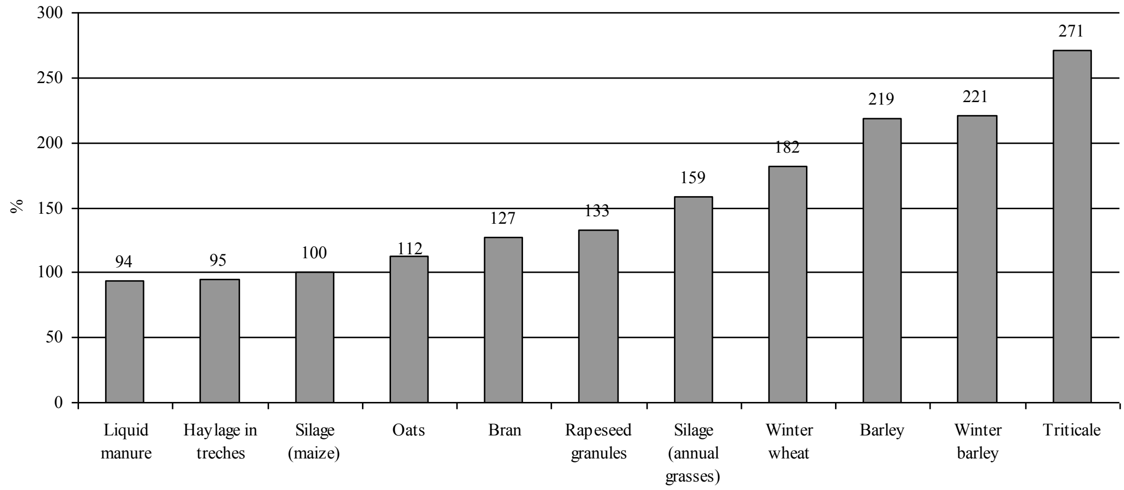
Note: * mesophilic digestion; substrate prices of 2010 for the RTF "Vecauce"

Source: authors' calculations based on Blumberga et al., 2009; Kalnins, 2009; Kalnins, 2007; Al Saedi et al., 2008

Table 1 presents information on the most popular types of substrates for biogas production in Latvia; prices are approximate to show the range of substrate prices. The prices range from 3 EUR t^{-1} for manure to even 336 EUR t^{-1} for bran. The methane content for these substrates is within a range of 49-63%, while the greatest differences are observed for the content of substrate dry matter, as it changes from

12% to 87%. Besides the mentioned bran, the most expensive substrates are grains – winter wheat, barley and triticale, the prices of which range from 161 to 239 EUR t^{-1}–, whereas the cheapest crop products are haylage and maize silage. According to Table 1, the biogas yield from these crops is quite different – from 20-30 m^3 for manure up to 616 m^3 for bran. Therefore, the choice of a biogas substrate is a complicated issue.

Figure 1 shows the efficiency of substrates chosen by the farm if the choice is based only on the biogas yield from various substrates and the cost. Yet, the choice is much more complicated, as a range of various indicators have to be taken into consideration, for instance, proportion of methane in fresh biomass, content of organic dry matter as well as a range of biochemical indicators, for example, content of sulphur in biogas or use of grain in the substrate (the key purposes of grain is food as well as feed for livestock). The use of grain may be justified by the insufficient volume of the bioreactor, which is a considerable precondition for the choice of a substrate.



Source: authors' calculations based on RTF Vecauce data, 2010

Fig.1**. Cost of energy from substrates for biogas production as a percentage of the cost of energy from maize**

It is important to compare the cost of production of a substrate and the potential of energy obtained from the particular raw material. Figure 1 assumes maize silage as a standard substrate and shows the total cost of one kWh of energy generated from a substrate expressed as a percentage. In the given case, the cost of maize silage is assumed to be 100%. It has to be noted that the costs and their ratios are calculated based on the economic performance indicators of the RTF "Vecauce"; thereby, as the prices change, the ratios may also change.

According to the scientific literature, the biogas yields from substrates used by the given farm are highest for milk (900 l of biogas from one kg of organic dry matter) and winter wheat (700 l of biogas from one kg of organic dry matter). Yet, if analysing these substrates in terms of their cost per unit of energy generated, the cost is high. The cost of winter wheat reaches 182% of the cost of maize silage or, for instance, to produce the necessary amount of energy by using barley for biogas production, two times more funds have to be spent as compared with maize silage. The cheapest energy can be generated from manure.

Determination of an optimal substrate mixture

The process of fermentation within a biogas facility is limited by various factors that have to be considered to obtain the recipe for the optimal composition of a substrate. The required conditions can be expressed as a system of conditions and calculated as an optimisation problem (3), thus, identifying the optimal amount of a substrate and its optimal mixture ratio.

$$\begin{cases} a_i x_1 + a_i x_2 + a_i x_3 + \ldots a_i x_n = b \\ \dfrac{e_i x_1 + e_i x_2 + e_i x_3 + \ldots e_i x_n}{x_1 + x_2 + x_3} = g \\ x_1 + x_2 + x_3 + \ldots x_n = X \end{cases} \quad (3)$$

where a – electricity yield from a type of substrate, kWh t^{-1} per day;
b – maximum capacity of a cogeneration plant, kWh per day;
e – dry content of substrate, %;
g – optimal content of dry matter in the fermentor, %;
x – optimal amount of a type of substrate, t per day;
X – maximum possible amount of substrate supply, t per day.

The electricity yield a_i and the dry content of substrate e_i depend on the type of substrate – i. This equation has to minimise the function's value or, in the given case, the cost of substrate mixture (4):

$$F = cx_1 + cx_2 + cx_3 + \ldots cx_n \quad (4)$$

where c – cost of a type of substrate, EUR t^{-1}.

In the optimisation problem, the authors set an energy limit, which is affected by the capacity of the cogeneration plant. Electricity production is considered a type of basic economic activity; thus, for instance, the value of minerals of the digestate, which is a by-product of fermentation process, plays no considerable role. Therefore, the maximum amount of electricity generated per day is calculated by the equation 5:

$$b = Q_{el.yield} * 24h, \quad (5)$$

where b – amount of electricity generated, kWh per day;
$Q_{el.yield}$ – nominal electric capacity of a cogeneration plant, kWh.

Electricity yield is derived from the indicators of the corresponding type of substrate and is calculated by the equation 6:

$$ax = Q_{biogas} * K_{met} * R_{met} * \dot{\eta}_{el} , \quad (6)$$

where ax – electricity yield, kWh;
Q_{biogas} – amount of biogas, m^3;
K_{met} – amount of methane in biogas, m^3;
R_{met} – lowest calorific value of methane, kWh m^{-3};
$\dot{\eta}_{el}$ – electric efficiency of the cogeneration plant.

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Based on the data on the biogas facility of the TRF "Vecauce", a calculation table may be created for the selected types of substrates (Table 2). The types of substrates were voluntarily selected with the purpose of providing the diversity of substrates and representing some group of substrates: liquid manure, grain, maize, and grass silages. It was assumed that the optimal fermentation period is 32 days. Since the unit of measure in the equation is m^3 – to switch to a single unit of measure in the calculations – it was assumed that a ton of silage is equal to 0.7 m^3 of substrate, while the ratio of weight to volume for liquid manure was assumed to be 1:1.

Table 2

Basic characteristics of the biogas substrates used for simulation

Indicator	**Type of substrate**			
	liquid manure	**grain (winter wheat)**	**maize silage**	**grass silage**
Electricity yield (ax), kWh t^{-1}	39.00	1085.00	350.00	254.00
Content of dry matter, %	7.00	87.00	33.00	35.00
Substrate price, EUR t^{-1}	3.00	160.78	29.27	42.94

Source: authors' calculations based on RTF Vecauce data, 2012

The cheapest substrate was liquid manure; yet, if taking into account only the allowable amount of liquid manure per day, which is derived from the optimal fermentation period, there is only one third acquired of the required capacity. In the present example, it means that the 55 tonnes of liquid manure required for processing would produce only 2145 kWh of electricity or 34% of the required capacity – 6240 kWh per day. Since the most important condition is not met, this alternative is not optimal. After analysing all the substrates in terms of energy generated and cost, one can find that the most optimal mixture is 12.7 tonnes (22%) of maize silage and 46.1 tonnes (78%) of liquid manure. Such a mixture allows reaching the required capacity, which fits the volume limit of the selected bioreactor; yet, it does not allow reaching the required average content of dry matter (17%). The total cost of such a substrate mixture amounts to EUR 502.64 per day or EUR 0.08 per kWh^{-1} of electricity.

Conclusions

1. The present optimisation model and its options can be successfully used for biogas facilities in Latvia to determine the optimal type of substrate and the optimal substrate mixture if the raw materials are substrates of agricultural origin. Given the economic considerations, it allows reaching the required electric capacity of a biogas facility.
2. For small biogas facilities with a bioreactor capacity of less than 0.3 MW, under the conditions of Latvia, an optimal substrate mixture is as follows: 78% manure and 22% maize silage. In this case, the average cost of the substrate mixture amounts to EUR 502.64 per day or EUR 0.08 per kWh^{-1} of electricity. It allows reaching the maximum electric capacity of the bioreactor.
3. The use of various cereals for biogas production is not recommendable not only due to ethical reasons, as it reduces the availability of food; but also because the economic calculations show that the energy generated from grain is from 2 to 3 times more expensive than the energy produced from other agricultural products.

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