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Development of biogas and biorafinery systems in Polish rural communities

Grzegorz WAŁOWSKI

Institute of Technology and Life Sciences, Falenty, Department of Renewable Energy, Poznań Branch, ul. Biskupińska 67,
60-463 Poznań, Poland

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Abstract

The article reviews selected systems and technological variants of biogas production. Biogas installations and methods of biogas production were characterized in terms of control and measurement. The required technical and technological criteria for biogas production and treatment were indicated. The conditions of biorefining in the context of the generation of new products were analysed. Based on the amount of manure produced in pig production, the potential of biogas production in Poland was indicated based on the visualization of the biogas production potential by poviats in Poland. The substrate in the form of slurry, manure and other agricultural waste for the production of agricultural biogas in Poland was analysed quantitatively. The economic aspects in the agricultural biogas plant sector were revealed, indicating the operation of the economies of scale for this industry sector.

An example of a pilot biogas production for anaerobic digestion using pig slurry is presented. The paper presents preliminary results of experimental studies on the course of changes in the biogas volume flow for the average daily production of agricultural biogas and the qualitative composition of agricultural biogas produced from pig slurry. The results of the measurements show a clear influence of the hydrodynamic mixing system of the substrate for the evaluation of the biogas flow through the adhesive bed in the context of agricultural biogas production in the range (1–14) $m^3\ d^{-1}$.

Key words: *agricultural biogas, biorafination, fermentation process, pig slurry*

INTRODUCTION

Biomass is a result of the photosynthesis process in which a concentrated substance (such as wood) is formed from extremely dispersed substrates: carbon dioxide from the atmosphere, water from the soil and light from the Sun.

In the past biomass $(CH_2O)_n$ has undergone deoxidation processes producing hard or brown coal $(CH_2)_n$ or natural gas $(CH_4)_n$.

By definition, in the broad sense "biomass" is any organic plant or animal substance and any similar substance derived from the processing of raw materials of plant or animal origin, including domestic and municipal waste water and landfill gas [CZECZKO 2012]. In Poland and worldwide, among all renewable energy sources, biomass is of greatest interest. This results from the following:

- producing a unit of energy from biomass requires several times less investment than other types of renewable energy;
- biomass, depending on its chemical composition, can be used for direct combustion, used for biogas production or converted to liquid engine fuels (biodiesel or bioethanol);
- there is an overproduction of food products in economically developed countries and it is justified to use part of agricultural lands to produce biomass for non-food purposes. The creation of a new direction for agricultural production results in new jobs in agriculture and its environment, stabilises the market for agricultural products, increases agricultural incomes, which stimulates the development of local industry and rural areas;
- protection of the environment by reducing nitrogen oxide emissions and a closed CO_2 cycle.

Methane fermentation is a biological process in which methane dissolves organic matter in anaerobic conditions, and the final product of this process is biogas with CH_4 content of 50–75% and CO_2 of 25–50% [KLIMIUK *et al.* 2012; WAŁOWSKI *et al.* 2016]. Methane fermentation can be divided into four stages [WAŁOWSKI *et al.* 2016]:

- hydrolysis, in which enzymes produced by hydrolytic bacteria break down proteins, lipids and carbohydrates into amino acids, long chain fatty acids and sugars;
- acidification in which acetic acid-forming compounds from hydrolysis produced volatile fatty acids (butyric, acetic and propionic acids) and carbon dioxide, hydrogen and ethanol;
- acetogenesis, where acetic acid, hydrogen and carbon dioxide are formed with the formation of acidic bacteria;
- methanogenesis, in which acetic acid and hydrogen produce the final product, biogas.

During methane fermentation in a typical agricultural biogas plant substrates, such as rapeseed straw, hay, maize straw, or ligno-cellulose substrates, are slightly decomposed. This is because these substrates consist of lignin that surrounds cellulose and hemicellulose. This structure greatly limits their ability to biodegrade. Cellulose and hemicellulose are readily degraded by anaerobic bacteria and can be converted to methane [Klimiuk *et al.* 2012]. As lignin is not digested by anaerobic bacteria in the anaerobic digestion process, solutions are being sought to develop methods of efficient pre-treatment of biomass fragmentation, thereby contributing to the ease of hydrolysis in the fermentation process. This is a technical problem, and therefore methods are sought that will lead to the release of cellulose and hemicellulose to achieve higher yields and quality of biogas produced [Wałowski *et al.* 2016].

There are many options [Oniszk-Popławska, Matyka 2012] for anaerobic digestion, but the most important is the choice of the fermentation mode [Jędrczak 2001]: Dranco, Valorga, Kompogas.

The biogas plant can be equipped with one or more fermentation chambers, depending on the technology used. The chambers may be concrete or steel, equipped with a heating system, must be adequately insulated to allow access to the interior in case of failure or maintenance or repair work. The chambers are most often built on the surface of the ground, and are less likely to be partially submerged. It is also possible to completely recess chambers in the ground, which allows for better thermal insulation, but hinders access to its interior and auxiliary devices [Kowalczyk-Juśko 2013].

The current state of knowledge about the operation of agricultural biogas plants concerns relatively large installations with power from 250 kW to 3 MW and relatively uncomplicated technology of biomass production (Tab. 1) mainly on arable land.

Numerous scientific reports (Bień [2007], Głodek [2010], den Boer and Szpadt [2013], Sikora [2012], Grosser *et al.* [2013], Olesienkiewicz [2015], Pilarska *et al.* [2014], Sikora and Tomal [2016]) refer to standard trials of anaerobic digestion of substrates and residues from post-production residues and by-products generated within farms and in rural areas. Publications in this field provide insights into the biogas efficiency of the different biomass used for biogas [Czekała *et al.* 2017; Czekała, Kaniewski 2015; Karłowski *et al.* 2011; Romaniuk *et al.* 2012]. Only the publication available contains the results of studies on the preparation of specific fermentation mixtures from available substrates and co-substrates with already known biogas yield [Myczko *et al.* 2011]. Such research is conducted at the Institute of Technology and Life Sciences in Falenty, Poznań Branch [Kołodziejczyk *et al.* 2011; Myczko *et al.* 2011; Wałowski 2017]. Few studies investigate interactions of inhibitors and studies on the optimization of fermentation mixtures, hard substrates that either can inhibit the fermentation process (eg. legume seeds) or cause excessive hydrogen sulphide in the biogas (eg. distillery) or are a source of odour emissions (eg. onion waste) [Wałowski *et al.* 2016].

Table 1. Variants of technological construction of agricultural biogas plant

Fermentation	Temperature (ºC)	Dry mass	Stages of fermentation	Loading mode	Use of biogas
Mesophil (standard solution)	35	below 16% wet fermentation	single stage	continuous	co-generation
In intermediate conditions	35–55	–	–	discontinuous	injection to the gas network
Termophil	55	above 16% wet fermentation	chapter phase of the process	quassi-continuous	gas boiler

Source: own elaboration acc. to Oniszk-Popławska and Matyka [2012].

The concept of biorefining has been developed in connection with the use of new bio-conversion technologies and previously known refining (purification) techniques, which have made it possible to obtain completely new products, from the same raw materials of biological origin [Olba-Zięty 2019].

A biorefinery is a facility that integrates biomass conversion processes and equipment for its processing into a single plant producing chemicals, fuels and energy, similar to an oil refinery plant [Harasym 2011]. Nowadays, biorefining is not limited to the production of biofuels, but it is considered as a rationally designed technological sequence that will make maximum use of the possibilities for processing renewable raw materials [Harasym 2011]. Depending on the raw material used, we can divide the biorefineries into three types of generation.

The first-generation biorefinery is based on raw materials used in the production of human food and animal feed, such as wheat, rape, maize, sugar cane, sugar beet and others. The conversion process produces first-generation biofuels. Bioethanol is produced from biomass rich in carbohydrates during ethanol fermentation. The main raw materials for the production of bioethanol in Poland are maize grains, agricultural distillates, molasses, potatoes and, in small quantities, cereal grains [Golisz, Wójcik 2013]. On the other hand, biodiesel is obtained from oil-rich biomass through their transesterification [Izdebski *et al.* 2014]. The most commonly used raw material for the production of methyl esters was rapeseed oil.

Despite the interest and the research and pilot works carried out for many years, conversion technologies to the second-generation bioethanol do not enable the economically viable production.

In third-generation biorefineries, algae are a potential substrate, and in this case the carbon source is not only CO_2 from the atmosphere but also CO_2 directly from exhaust gases, for example, and microalgae grown on waste water enable a significant reduction in fresh water consumption and further purify the environment. Third-generation biofuel production technologies are relatively new and research into their development is still carried out to maximise efficiency and economic viability. Biomethane, bioethanol and biodiesel, including valuable bio-products such as pigments, antioxidants, pharmaceuticals can be produced from algae [LEDAKOWICZ 2018]. In addition, fuels obtained from algae biomass are free of sulphur compounds, so they are not toxic and are highly biodegradable.

Nowadays, the bioeconomy fulfils its tasks through, inter alia, biogas plants and first-generation biorefineries. There are successful, cost-effective systems and plants in the market that produce many products involving the correct cascade use of biomass raw materials. Second- and third-generation biorefineries show the direction of a sustainable future, but these concepts still need research [OLBA-ZIĘTY 2019].

The most optimal way of large-scale sustainable use of biomass in the EU-backed vision of “BioEconomy” is biorefining [HARASYM 2015]. Biorefining is currently a sustainable synergistic processing of biomass in the form of energy or fuel production and into products. In biorefineries producing energy or fuels, the main objective is to produce huge quantities or low value energy or fuels from biomass. The full infrastructure of the chain of values exists, but their profitability is still in doubt, requiring significant financial support from the government or the regulated energy market in order to guarantee the implementation in the large-scale market. In biorefineries aimed at producing products (chemicals, materials), the main objective is to produce smaller quantities of relatively more valuable bio-value-added products from biomass; primary (agricultural) and secondary (post-process residues are used to produce energy – electricity/heat – for own or external use). A limited number of product biorefineries are currently in operation, mainly due to the fact that some key technologies are still in the research, pilot or demonstration phase. However, their potential is enormous and it is generally believed that there will be a shift in focus towards the optimal sustainable use of biomass from promoting mainly energy (fuel) applications to chemical or material applications and, depending on the raw materials used, even towards biorefineries using biomass in parallel for both food and non-food applications. The current energy and fuel infrastructure and experience in implementing full biomass value chains will be used as starting points for the transition between the recommended solutions. However, also in the long term, bioenergy (biofuels) will be produced in significant quantities from both primary (agricultural), secondary (post-process) and tertiary (post-consumer) waste and will thus become the driving force for the future “BioEconomy” [HARASYM 2015].

The intensive livestock production is a source of slurry, liquid manure or manure that is difficult to dispose of and pollutes the environment [KUPRYŚ-CARUK 2017]. The technology of waste utilization by methane fermentation is an excellent way to neutralize the waste with simultaneous energy generation [MARSZAŁEK *et al.* 2011]. Livestock farming is responsible for nearly one fifth of global greenhouse gas emissions. Methane emissions from cow breeding are more than 18 times higher than from fattening pigs [DACH *et al.* 2013]. According to Podkówka [PODKÓWKA 2016] the manure monofermentation is still not very effective, as this raw material contains only about 8% of dry matter and 75% of dry organic matter in dry matter. The carbon/nitrogen (C:N) ratio in cattle slurry is too low and equals to 6.8:1 [PODKÓWKA 2016].

This problem was taken up by the Institute of Technology and Life Sciences in Falenty, specifically the Renewable Energy Department in Poznań – a monosubstrate reactor for methane slurry fermentation was developed for this purpose [WAŁOWSKI *et al.* 2019]. The design and construction of the monosubstrate model of a flow biogas reactor was carried out on the basis of the invention [MYCZKO *et al.* 2012]. A biogas plant [Umowa 2019] was implemented on the farm in Ocieszyn as part of the project BIOGAS&EE financed by the National Centre for Research and Development implemented in the BIOSTRATEG 1 programme.

Biogas plants also use slurry as a co-substrate with biomass with high biogas potential [EL-MASHAD, ZHANG 2010; FUGOL, SZLACHTA 2010]. Slurry is one of the so-called diluting substrates that dilute the biogas feedstock, and inoculating substrates, by inoculating the feedstock with microflora, initiates methane fermentation [BUDIYONO *et al.* 2010].

MATERIALS AND METHODS

SLURRY, MANURE AND OTHER AGRICULTURAL PRODUCTION WASTES

In Poland in the 1960s there was a rapid development of litter-free industrial cattle and pig farms [KWIECIŃSKA 2013]. Large industrial farms (large industrial, large-scale) are defined as facilities requiring an integrated permit, and the basic criterion determining the size of a farm is its livestock density. In case of poultry, a large industrial farm is considered to be a farm with a livestock number of more than 40,000 animals, and for pigs it is 2,000 pigs (fattening pigs) weighing more than 30 kg and/or 750 sows [Directive 2010/75/EU]. In 2008 the Helsinki Commission HELCOM [HELCOM 2020] recognised large industrial farms as point sources of agricultural pollutions. However, cattle farms with a livestock number of 400 AU (animal units) are also recognised as industrial farms. In Poland there are registered 752 large industrial farms, including 606 poultry farms and 126 pigs farms [GUNGOR, KARTHIKEYAN 2005].

Industrial farms are characterised by a high concentration of individuals, homogeneous feeding of individual groups of animals, rhythmic production and even annual supply of products of equal quality. Unfortunately, these effects are achieved at the cost of worsening living conditions for animals and increased energy consumption. The most unfavourable, from the point of view of environmental protection, is the use of the litter-free breeding system, which involves the formation of huge amounts of slurry [Kutera 1994].

Compared to manure (generated during bedding animal breeding) and slurry (slurry permeate), it generates a number of problems, mainly related to its storage, transport and further use. The main environmental hazards resulting from the large-scale animal husbandry and related slurry production are as follows [Kwiecińska 2013]:

- water pollution, soil overfertilisation and outflow from fields to groundwaters and surface waters;
- eutrophication, overfertilisation of inland and sea waters (algal blooms, reduction of biodiversity and modification of aquatic ecosystems, loss of benthic fauna and the lack of oxygen);
- microbiological contamination, pathogenic microorganisms contained in slurry pose a serious health risk (the most important is as follows: *Staphylococcus sp.*, faecal streptococci, *Escherichia coli*, rubella, tuberculosis mycobacteria, pathogenic streptococci, foot-and-mouth disease virus, fungi and larvae and eggs of parasitic worms (tapeworms);
- indirect and secondary impact on the formation of acid rain (emission of nitrogen oxides and sulphur oxides) and increase of the greenhouse effect (emission of greenhouse gases damaging the ozone layer) [Skorupski, Kozłowska 2021].

Generally, slurry is assumed to be a liquid product produced during the litter-free animal husbandry; it is a mixture of animal faeces, both solid and liquid in natural proportions, that additionally contains process water used to rinse slurry and coming from leakages of animal watering equipment [Hus 1995; Kutera 1994]. Depending on animal species, there is cattle, pig and poultry slurry, and this latter type is discharged from dry farms as so-called litter. Slurry is also divided with respect to the content of admixtures (e.g. slurry, sewage from farms or from outside facilities). In this case, it is divided into complete slurry (without any admixtures) and incomplete slurry (mixed with at least one of the aforesaid admixtures) is distinguished [Skorupski, Kozłowska 2021].

According to Zbytek and Talarczyk [2008] slurry is a liquid product formed during litter-free animal husbandry. It is a mixture of animal faeces, both solid and liquid, in natural proportions, with the addition of process water used for its rinsing and from leaks from animal feeding equipment and feed residues.

The main components of slurry are faeces and urine. Faeces are waste products of digestion:

- feed residues: undigested and digested or non-absorbed parts, raw fibre, ligneous parts, cellulose, hair, parts of plants with varying degrees of decomposition and mineral materials and water;
- body secretions from the digestive tract; secretions, minerals and intestinal epithelium;
- bacteria and their metabolic products.

Urine is an aqueous solution of inorganic and organic nitrogen compounds from the metabolism of protein and non-protein substances and vitamins, hormones and enzymes [Kutera 1994]. The amount and composition of slurry is significantly influenced by species, age, efficiency, animal feeding method, slurry drainage and storage method, water consumption on farms, and weather conditions [Kwiecińska 2013]. Therefore, during the year 7.5–21.0 m^3 of slurry is obtained from one cattle production site and 1.2–6.0 m^3 of slurry from one pig production site [Jochimsen 2006; Maćkowiak 2003]. The daily production of slurry of different species and directions of animals is shown in Figure 1.

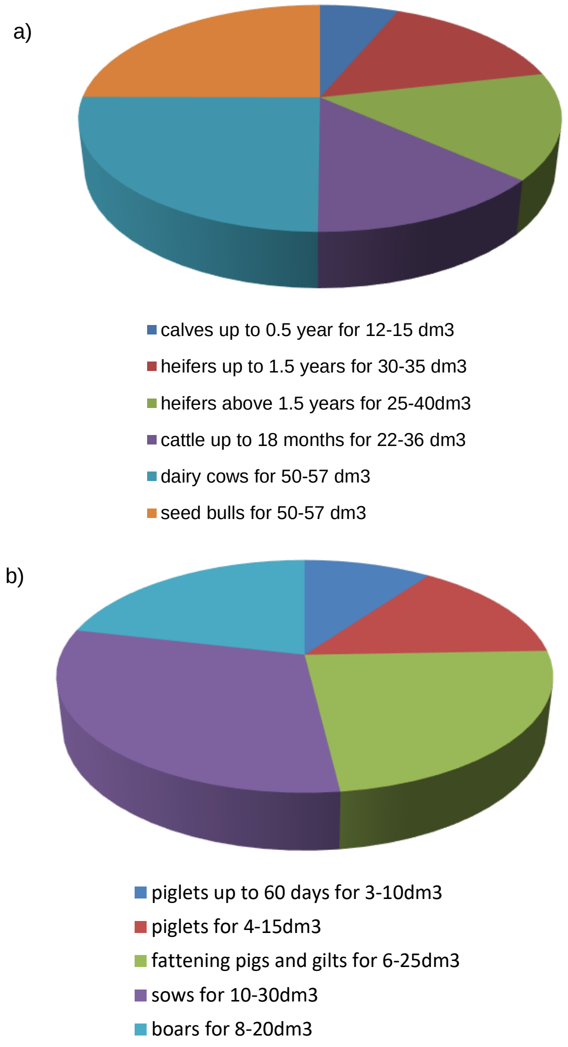

Fig. 1. Daily slurry production, average amount of slurry from: a) cattle, b) pig farms, according Buraczewski [1991]; source: own study

The estimated amount of excreted faeces and urine from one large livestock unit (LSU) is 45 kg per day [Podkówka 2016]. The standard water consumption for maintaining the hygiene of livestock housing should not exceed 10 dm^3 per day. In total, about 55 kg of slurry is obtained per day, which gives 20 m^3 of slurry per 1 year from one large livestock unit [Marszałek *et al.* 2011]. In practice, 1 Mg of slurry is assumed to have a volume of 1 m^3 [Jochimsen 2006; Maćkowiak 2003].

The content of dry matter in cattle slurry ranges 6.5–10.5% and that of pigs 3.8–7.5%. The amount of dry matter in slurry depends on the amount of water used. Due to the amount of water in manure, slurry is divided into dense (over 8% of dry matter) and thin (less than 8% of dry matter). There is also diluted slurry, in which process water exceeds 20% of the volume of manure and the dry matter content is less than 8% [Kwiecińska 2013].

Approximately 70–80% of dry matter contains organic compounds such as cellulose, lignin, hemicellulose, penthose and starch. The main source of nitrogen in slurry is urea [Dębska 2004]. Nitrogen in slurry is found in organic and mineral combinations. Organic compounds include: proteins, amino acids, urea, hippuric acid and others. On average, 50% of the nitrogen has a water-soluble form, and 40% is ammonium nitrogen, easily accessible to plants. The C:N ratio in cattle slurry is 6.8 on average [Flizikowski, Bieliński 2000]. Slurry contains macro- and microelements which are necessary in the process of biochemical changes in the digester chamber. In a year, an average quantity of slurry obtained from one livestock unit is as follows: P – 28.8 kg, K – 41.1 kg, Ca – 35.3 kg, Na – 11.0 kg, Mg – 10.0 kg. Pig slurry is more abundant in phosphorus than cattle slurry. The slurry reaction is stable and is about 7.2 for cattle slurry and about 7.0 for pigs and is a basic reaction.

Slurry is the basic substrate for biogas production in Poland – Table 2.

Table 2. Raw materials used for agricultural biogas production in Poland in 2011–2013

Substrate	Total amount of substrate consumed in each year (Mg)		
	2011	2012	2013
Slurry	265,960	349,173	455,583
Distillery stock	30,465	146,607	254,877
Maize silage	108,876	241,590	287,470
Residues of vegetables and fruit	10,984	86,109	268,599
Beetroot pulp	6,922	37,081	101,660
Manure	11,640	23,502	30,778

Source: ARR [2014].

This is due to the fact that the first biogas plants in Poland were built by the company [Brodziak 2020] and were located close to breeding farms. This was due to the availability of slurry, which, on the one hand, was feedstock for the biogas plant and, on the other, had to be disposed of. However, between 2011 and 2013, its share in the quantitative structure of raw material consumption decreased by 57–29% [Piwowar 2014]. Currently, biogas plants are often built next to agri-food processing plants (distilleries, dairies or fruit and vegetable processing plants) and meat processing plants (especially slaughterhouses) and use by-products generated there. For example, the construction of a biogas plant in Mełno has made the stillage the second largest number of substrates used in biogas plant digesters. The Strzelin facility, on the other hand, placed beet pulp in the fifth place in the ranking [Podkówka 2015].

EXPERIMENTS – EXAMPLE OF A PROTOTYPE INSTALLATION FOR THE PRODUCTION OF AGRICULTURAL BIOGAS

A pilot biogas production using pig slurry was implemented [Umowa 2019] on a farm with 1100 DanBred fatteners [DanBred 2020] kept in a grate system Photo 1.

Photo 1. Examples of DanBred fatteners kept in a grate system on the farm (phot. *G. Wałowski*)

The way of feeding pigs basically determines the production of the substrate (pig manure) – Table 3. The applied nutrition in the form of “Superconcentrate 600 plus” is a feed mixture composed of post-extraction meal: soybean meal, rapeseed meal, calcium carbonate, phosphate, herbal mixture, supplementary for fattening pigs over 30 kg with the addition of phytobiotic and acidifier – content of analytical ingredients in 1 kg [Neorol 2020].

Table 3. Summary of substrate production (pig slurry) necessary for the fermentation process

Porker quantity	Substrate volume (m^3)	Cycle time (days)
3500	1400	365
1	0.4	90
1	$0.4 \cdot 10^{-3}$	1

Source: own study

In the Institute of Technology and Life Sciences, Poznań Branch , a pilot plant was developed, schematic diagram – Figure 2.

The way of the substrate pre-treatment, the production and purifying treatment of the raw biogas and the co-generation is characterized with that the operational tank *1a* filled in with liquid substrate from the central biomass tank *0a*, the whole is agitated and fed to the top of the fermenter *2* via a stub pipe. The fermenter filling is carried out in an automatic way through the process monitoring and control system. The filling process is carried out after prior draining of the post-fermentation biomass and is effected in stages two or three times a day, totally for a fermenter of 15 m^3 in capacity, i.e. 1.5 $m^3 \cdot day^{-1}$. A hydrostatic probe is used to control the substrate level in the fermenter. Once in 24 hours a portion of the post-fermentation residue is routed to the post-fermentation residue tank *6* and it is replaced with the same volume of fresh biomass. The fermenter is filled with biomass from the top, which provides directional movement/migration of the fermentation fraction through the entire system. The biomass vertical circulation and the

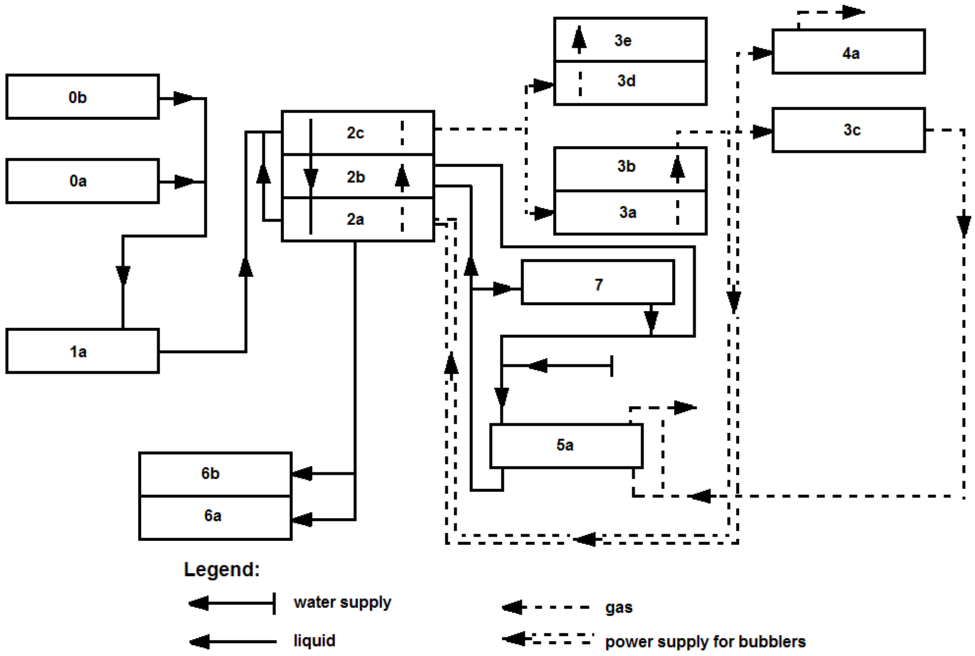

Fig. 2. Prototype installation of biogas production – block diagram of the test stand; *0a* = biomass tank, *0b* = disintegrator, *1a* = operating tank, *2a* = bubbler, *2b* = heating spiral, *2c* = upper part of the fermenter with biogas produced, *3a* = dehydrator, *3b* = desulfurization unit, *3c* = cogenerator, *3d* = internal biogas tank, *3e* = external biogas tank, *4a* = gas flare, *5a* = heat exchanger, *6a* = digestate solid tank, *6b* = digestate mobile tank, *7* = cooler; source: own study

circulation system of fresh just-generated gas are used to agitate the fermenter content. The fermenter content agitation, in order to average its composition, is effected by barbotage, using a bubbler *2a*. This is effected in such a way that a portion of biogas is taken from the gas space of the fermenter via blower and routed through a check valve to the bottom part of the fermenter through the system of bubblers (barbotage unit). The gas flows out of the bubblers in the form of bubbles and, while migrating upwards, agitates the suspension. A portion of the fermenting mass is transported by means of an external system from the bottom part of the fermenter to the pipeline, feeding the fresh/raw substrate to the fermenter. Packing for the fermentation bacteria flora is housed inside the fermenter. The fermenter is heated by means of a pipe in the form of a heating coil *2b*, with warm water which is taken from heat exchanger *5a* situated at the co-generator *3c*. The measurement of the biogas temperature in the fermenter and the fermenting biomass temperature is effected by means of sensors. As the biogas pressure increase is excessive, the biogas is released through the safety valve. The biogas obtained in the fermenter is routed to the biogas purifying treatment system, made up of two desulfurization units *3b*, with the equipment for the bed regeneration. The biogas flows alternately to one of the desulfurization units, in which it is purified/treated to remove sulphur compounds. At this time the bed of the other desulfurization unit is regenerated. In order to remove the excessive humidity from biogas, a biogas dehydrating unit *3a* is installed upstream the desulfurization unit. The biogas overpressure in the fermenter results in overcoming the resistance, estimated to be 2–3 kPa, of the flow through the dehydrating unit and desulfurization unit. The desulfurized biogas is stored in a vessel/tank *3d* under overpressure; the vessel is equipped with a ligud safety device protecting the gas vessel from exceeding the permissible overpressure. The control and measurement system monitors the non-treated gas and the chemical composition of treated gas; the system mainly communicates the concentration of hydrogen sulphide in the gas. The treated gas is routed through the blower to the co-generator *3c* for conversion into electric energy (power) and heating energy.

There is a heat exchanger *5a*, at the co-generator made up of a fuel (combustion) engine and a power generator, heated with the exhaust gases. The water heated in the heat exchanger is routed, among other things, to the heating coil *2b*, situated at the internal wall of the fermenter. The fermenter heating system is to keep the required temperature of the substrate. The heating medium, which is water at the temperature of 65°C, flows between heat exchanger *5a*, situated at the co-generator, and heating coil *2b*, until the preset temperature of the biomass is attained within the range 35–40°C. The excessive heat also flows through cooler *7*. In the event of a failure or switching off the co-generator, the pressure sensor will signal pressure increase and send a control signal to an automatic element controlling the three-way valve and then the gas feeds the gas flare *4a*. If there is no flame in the flare or if it decays, the biogas feed to the flare will be cut off automatically.

Experimental research on the implemented installation concerned a measuring system for the assessment of the quantity and quality of biogas under the conditions of the biogas production process [WAŁOWSKI 2019].

The research was carried out in the field of biogas flow rate measurement resulting from the reference pressure in the fermenter. An independent assessment of the amount of biogas and the pressure drop on the skeletal deposit was carried out.

The basis for the assessment of hydrodynamics of gas flow through the adhesive bed is the flow characteristic that results from the pressure forcing this flow. In each case, the determination of this characteristic consists in determining the impact of the biogas stream on the value of this overpressure, equivalent to a pressure drop – this is tantamount to determining the total resistance of biogas flow through the adhesive bed.

RESULTS AND DISCUSSION

POTENTIAL AND ECONOMY ASPECTS

Based on the information catalog [MAREK 2019] on the amount of animal excrements produced in pig production, the potential of biogas production in Poland in 2018 should be indicated, with the territorial division of Poland. Based on the information on the number of pigs in the country, broken down into poviats, the amount of animal manure and the potential amount of biogas that could be produced were calculated. The data on the number of pigs were obtained from the Agency for Restructuring and Modernization of Agriculture (Pol. Agencja Restrukturyzacji i Modernizacji Rolnictwa). On their basis, the average amount of animal faeces produced from different animal housing systems was calculated. Data on indicators for maintenance systems were obtained from the General Agricultural Census of the Central Statistical Office (GUS). Based on this information, an estimated amount of slurry L_G (in m^3) was calculated:

$$L_G = \sum(xDJP)_n \left(\frac{S_{BS}}{S_S+S_{BS}}\right)_n G_n \tag{1}$$

and the estimated weight L_o (Mg) of the manure:

$$L_O = \sum(x_n DJP)_n \left(1-\frac{S_{BS}}{S_S+S_{BS}}\right)_n O_n \tag{2}$$

where: n = type of animals pigs; x = livestock of n-animals in the commune, pieces; DJP = a large livestock unit equivalent to one 500 kg cow; S_{BS} = number of positions in the grate animal keeping system for the voivodeship, pieces; S_S = number of positions in the litter animal keeping system for the voivodeship, pieces; G = average amount of slurry per year per unit of nth type of animals (m^3·(DJP·year)$^{-1}$); O = average amount of manure per year per conversion unit of nth type of animals (Mg·(DJP·year)$^{-1}$).

This is how it is presented in Figure 3 estimated potential of biogas production from manure obtained from pig rearing and from liquid manure for poviats in Poland.

Any previous foreign and domestic experience shows that the sector of agricultural biogas plants is governed by the principles of economies of scale, i.e. unit capital expenditure increases or decreases with the change in the plant capacity. It is currently difficult to indicate the technical and economic criteria [CURKOWSKI *et al.* 2011] of the division into micro-gas plants below 100 kW$_{el}$ of electric power capacity, small biogas plants 100–500 kW$_{el}$, medium 500–1,000 kW$_{el}$ and large plants above 1,000 kW$_{el}$, as there is no larger statistical sample of the investments conducted in Poland. It is also unclear to what extent a single biogas plant has a scale effect that is determined by elements of individual investment assessment, such as the need to expand the necessary infrastructure, etc. The distribution of risk elements in large and small facilities also varies, affecting the investor's core business.

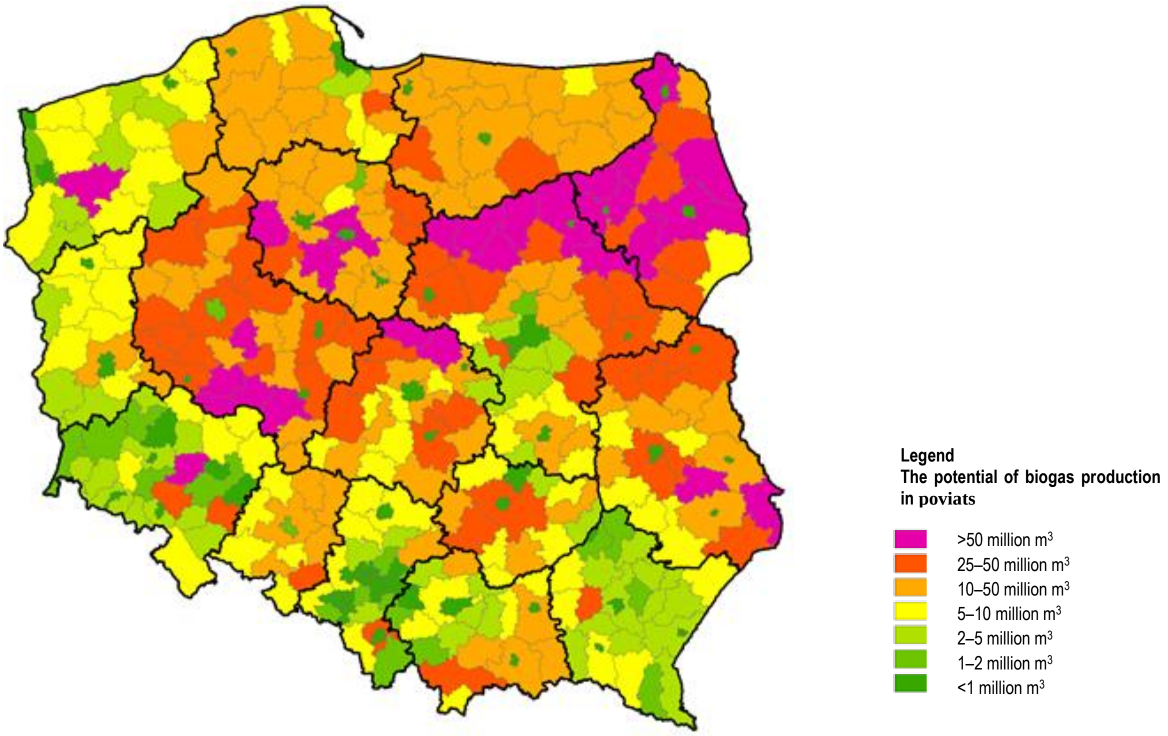

Fig. 3. Visualization of the biogas production potential by poviats in Poland; the spatial model based on data from the Institute of Technology and Life Sciences; source: DECEWICZ [2020]

CURKOWSKI *et al.* [2011] claim that economic aspects can be taken into account for costs as unit capital expenditures and operating costs that depend on the size of the scale of investment.

In case of micro- and small biogas plants there is no sufficiently reliable information on the market in Poland – an example is the biogas plant located in Studzionka [CURKOWSKI *et al.* 2011]. In view of the pilot nature of the facility, the adopted economic method of construction and the absence of wider operational experience, it is impossible to even roughly estimate costs of such investments. It is not possible to directly convert unit expenditures from large to small biogas plants as there is a whole group of expenditure categories, such as connection fees, purchase of technology, control and measurement equipment, which are rather fixed and less dependent on the installed capacity. While analogous connection conditions are applied at a given point, unit costs of connection to the system decrease with an increase in the size of the plant, in German conditions, for biogas plants with a capacity of 100–500 kW_{el}, they accounted for up to 8% of the total capital expenditures, while for plants with a higher capacity they equalled up to 3% [FNR 2005].

For micro and small biogas plants below 500 kW_{el}, therefore, capital expenditure per kW_{el} of the installed capacity is given as a reference for German biogas plants. It should be noted that it is not possible to directly translate information from the German market with the very extensive supplier and service market directly into the Polish market. Since the market for agricultural biogas equipment and services is at its early stages of development, it is estimated that for the same size of small biogas plant, expenditures may even be several times higher than for a large one. The economies of scale also apply to small biogas plants – unit expenditures decrease as the size of the plant changes – the larger the plant, the lower unit capital expenditures – Table 4.

Table 4. Unit capital expenditures per 1 kW_{el} of installed capacity for German biogas plants

Biogas plant capacity (kW_{el})	Digestion tank volume (m^3)	Capital expenditure ($EUR \cdot kW_{el}^{-1}$)
500	3 000	2 200
330	2 400	2 300
220	3 300	2 950
150	150	3 050
75	480	3 800
55	420	4 950

Source: own study based on FNR [2005].

The general breakdown of individual expenditure categories into subcomponents depends on the equipment in the process line of the biogas plant, but some significant and recurring expenditure categories can be noticed. In each of the analysed biogas plants, the largest share is held by two basic elements: the construction of digestion tanks and purchase of cogeneration units. These elements account for about 20% of capital expenditures each [CURKOWSKI *et al.* 2011]. The expenditure structure of a biogas plant is shown in Table 5.

Table 5. Structure of investment categories for a biogas plant based on maize silage and slurry with a capacity of 0.86 MW_{el}

Category of capital expenditure	Average share (%)
Digestion tank	16
Cogeneration	17
Storage and pre-treatment of substrates	12
Construction and assembly works	13
Storage of digested pulp	6
Power and measurement systems	8
Heating system	3
Means of transport	2
Water/sewage/gas systems	7
Others	16

Source: own study based on CURKOWSKI *et al.* [2011].

On the other hand, the percentage share of each category depends on the selection of technological options. Examples of the selection of technological options that may significantly shift the percentage share of individual expenditures in the capital expenditure are as follows [CURKOWSKI *et al.* 2011]:

- due to the lack of sufficient land area (additional few hectares), instead of lagoons the investor decides to construct a reinforced concrete tank to store the digested pulp (this solution is several times more expensive);
- the biogas plant will process hazardous waste requiring thermal and pressure treatment at a temperature of 133°C, which will increase capital expenditures;
- the construction of a facility and sterilization equipment may increase construction costs of the biogas plant by up to 20%, and waste such as slaughterhouse waste has a high potential for biogas production, hence its use will significantly increase the profitability of the project;
- the investor will sell the heat to an end user located a few kilometres from the biogas plant, which will result in a significant increase in capital expenditure on the expansion of heating pipelines.

The experience of the company [BRODZIAK 2020], a pioneer in the Polish market, shows that agricultural biogas plants can be constructed at unit expenditures of 8–12 mln $PLN \cdot MW_{el}^{-1}$ of the installed capacity. Other developers who implement foreign technologies in Poland – mainly German ones – estimate that capital expenditures on the construction of 1 MW_{el} of the installed capacity equals to 18–21 mln $PLN \cdot MW_{el}^{-1}$. These expenditures assume no foreign exchange risk and are calculated at an exchange rate below 4 PLN per 1 EUR. Since most of the components of the biogas plant's process line are purchased abroad, it is likely that the change in exchange rates will also affect the level of capital expenditures denominated in PLN. It is necessary to bear in mind that the net capital expenditures as set forth in this analysis do not include VAT [CURKOWSKI *et al.* 2011].

The percentage share of individual components of capital expenditures is shown in Table 6.

The results of economic analyses do not clearly link unit operating costs and the plant size. Therefore, the structure and estimated costs have been presented, including unit costs without attempting to separate them, i.e. categorisation for particular ranges of capacity of biogas plants.

Operating costs include all data on expenditures on the purchase of goods and services which are not of an investment nature because they are calculated for an annual accounting period in typical operating conditions. These include, among others, direct production costs (consumption

Table 6. Percentage share of expenditures on essential components of biogas, averaged data for German biogas plants for 55–500 kW_{el}

Component	Average share (%)	Biogas plants with capacity and volume					
		55 kW_{el}, 420 m^3	75 kW_{el}, 480 m^3	150 kW_{el}, 150 m^3	220 kW_{el}, 3300 m^3	330 kW_{el}, 2400 m^3	500 kW_{el}, 3000 m^3
Digestion tank	33.5	38	34	26	48	28	26
Co-generation	33.6	26	29	38	32	42	34
Pre-treatment and preparation of substrates	6.3	8	7	8	6	4	3
Additional equipment	17.5	16	22	18	4,8	16	27
Planning and permit costs	9.1	9.1	9.1	9.1	9.1	9.1	9.1

Source: own study based on CURKOWSKI *et al.* [2011].

of materials and equipment, costs of services and staff), administrative expenses, expenses related to the purchase of goods, including substrates. In addition to operating costs, there are also financial costs that relate, among others, to the loan repayment. According to German data, total annual operating costs range from 14.8% excluding the cost of purchasing substrates, to 22.6–40.4% including the cost of purchasing substrates – capital expenditures. In most biogas plants, annual operating costs equal to 20–25% of the total capital expenditures. The share of purchasing energy crops as substrates is of great importance, and for 62% of biogas plants, energy crops account for over 20% of annual operating costs [FNR 2005]. For example, maize silage costs about PLN 100 per Mg, whereas 1 Mg of slurry costs up to PLN 50. Another issue is the cost of transporting substrates from the place of waste production or crops to the biogas plant. If the biogas plant operator pays for the transport of substrates, those transport costs can also be incurred by the supplier; costs of fuel and costs of purchasing and maintaining the car fleet must be also included.

An operating cost structure for the biogas plant with a capacity of 0.86 MW_{el} based on maize silage and slurry, without depreciation, is shown in Table 7.

Individual categories of operating costs also depend on the selected technological option for the investment, for:

- there are no costs of lease in case of the purchase of land for the investment;
- as a result of the application of appropriate technologies, e.g. dry fermentation, there is no need to dilute the substrate mixture, hence no costs of purchasing process water occur;
- as there is no need to hygienise hazardous waste (classes II and III) or to treat digest, there are no operation costs of facilities required for this purpose;
- a lack of an appropriate system for desulphurisation of biogas makes the cogeneration system highly defective and requires frequent oil changes, which entails additional costs.

Table 7. Operating cost structure for the biogas plant with a capacity of 0.86 MW_{el} based on maize silage and slurry

Parameter	Average share (%)
Total cost of purchasing and storing substrates	48
Cost of transporting digested pulp to meadows/fields	23
Other, including:	29
– purchase of electric power, transformer station	8
– cost of oil for generator	3
– purchase of spare parts	3
– taxes (land, buildings)	2
– remuneration, employee insurance	6
– property insurance, third-party liability insurance, legal services	3
– site security	0.1
– cost of occupational health and safety and training	1
– other costs, administrative costs	5

Source: own study based on CURKOWSKI *et al.* [2011].

Biogas investments generate their own revenues from the sale of goods such as electricity, heat and digested pulp for fertilizer purposes. At the stage of preliminary economic analyses, these revenues are determined by multiplying the forecast quantities produced by their unit prices. Examples of unit prices for revenues from the sale of products and certificates of origin – these are average market data but are not guaranteed prices, each time they are negotiated with the buyer – are shown in Table 8.

Business models involving the sale of purified biogas, i.e. biomethane, to the grid are not yet tested in Poland and are sufficiently widespread abroad to propose solutions and reference costs for domestic investors. However, with the

Table 8. Revenue categories of biogas plants

Category	Unit revenues	Notices
Sale of electric power	197.21 $\text{PLN}\cdot\text{MWh}^{-1}$	average sale price of electricity in the competitive market for 2009 [URE 2010a].
Sale of green CO	275.73 $\text{PLN}\cdot\text{MWh}^{-1}$	average price of PMOZE_A_TGE [TGE 2010], negotiations with DSO
Sale of yellow CO	124.61 $\text{PLN}\cdot\text{MWh}^{-1}$	average price of PMGM with TGE [TGE 2010], negotiations with DSO
Sale of violet CO	59.16 $\text{PLN}\cdot\text{MWh}^{-1}$	expected price on the basis of the substitution fee information provided by the ERO, negotiations with DSO
Sale of brown CO	unknown	negotiations with PGNiG
Sale of heat	34.9 $\text{PLN}\cdot\text{GJ}^{-1}$*	reference price – average price of heat from RES [URE 2010b]
Fee for acceptance of waste for disposal	120 $\text{PLN}\cdot\text{Mg}^{-1}$	negotiations
Fertiliser (pouring into own fields)	50 $\text{PLN}\cdot\text{Mg}^{-1}$	average price of slurry from the market
Sale as fertiliser/transfer fee	20 $\text{PLN}\cdot\text{Mg}^{-1}$	negotiations ·

* The official heat price indicated is only a reference price; in practice, a local biogas plant operator fails to obtain (negotiate) prices in the district heating market and lower heat sales prices have been adopted for further analysis.

Explanations: CO = certificates of origin, DSO = distribution system operator, ERO = energy regulatory office.

Source: own study based on CURKOWSKI *et al.* [2011].

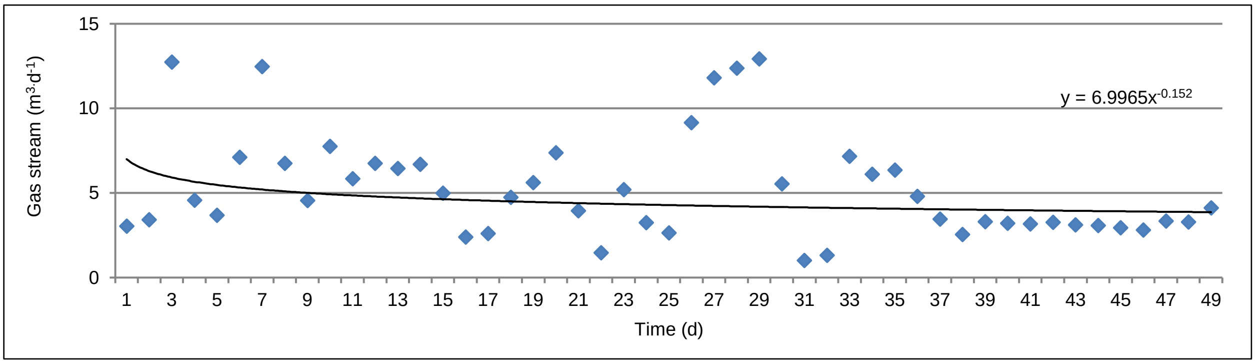

Fig. 3. Changes in the parameters of the mesophilic fermentation technology from a polydisperse substrate for the average daily production of agricultural biogas – time dependence of the gas stream; source: own study

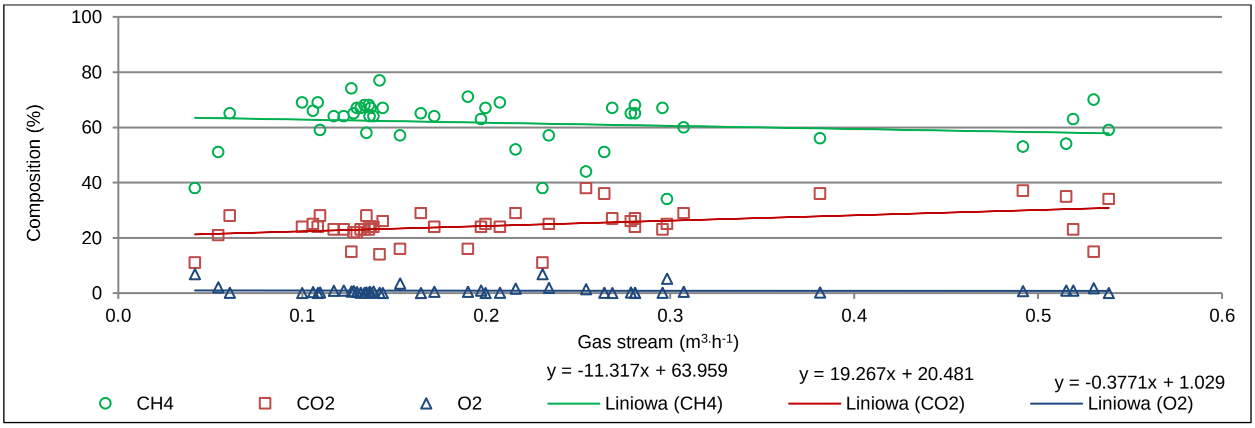

Fig. 4. Composition of agricultural biogas produced from a polydisperse substrate (pig slurry) – composition of CH_4, CO_2, O_2 depending on the gas stream source: own study

expected development of regulations, the first commercial projects of this type will also appear in Poland. The construction of a plant for upgrading biogas to natural gas parameters involves considerable expenditure. Total capital expenditures and annual operating costs primarily depend on the size of the system and the type of technology used. The capital expenditures depend on the size of the plant, location, access to substrates and functions to be performed by the biogas plant, and thus on the degree of technology advancement [KOSEWSKA, KAMIŃSKI 2008].

TEST RESULTS

The basis for the assessment of biogas production is the course of changes for the average daily gas stream. When interpreting Figure 3, it should be indicated that after the 10th day, the biogas production stabilized, which lasted 4 days. Then, on the 17th, 22nd, 25th, 31st and 32nd days, there was a minimal biogas production (inhibition phenomenon) caused by failures of the mechanical agitator, whose role was to stabilize the polydisperse substrate (pig slurry). The breakdown of the agitator in the operating tank led to the use of an innovative solution for hydrodynamic feeding of the polydisperse substrate. This led to stable biogas production starting from the 39th day.

The polydisperse substrate from which agricultural biogas is produced depends on the feed of the porker. This translates into the quality of agricultural biogas (Fig. 4), in which CH_4 reaches even 80% with very low release of H_2S. Within 24 hours, under the conditions of a minimum exchange of 1.5 m^3 of polydisperse substrate per 15 m^3 of fermentor volume – in order to maintain the biogas production process – acidity increases, i.e. H_2S begins to be released. It was observed that for optimal biogas production, mixing in the range of 1.5–2.0 m^3 of polydisperse substrate should be used, i.e. after 37 days, the technological parameters stabilized (Fig. 3) – on natural pig manure.

CONCLUSIONS

The paper presents the amount of animal excrements produced in pig production, at the same time indicating the potential of biogas production in Poland based on the visualization of the biogas production potential in poviats in Poland. Quantitative analysis of the substrate in the form of slurry, manure and other agricultural waste for the production of agricultural biogas in Poland was analysed. The economic aspects in the sector of agricultural biogas plants were revealed, indicating the operation of the principles of economics of scale for this sector.

An example of a pilot biogas production for anaerobic digestion using pig slurry is presented. The paper presents the preliminary results of experimental studies on the course of changes in the biogas volume flow for the average daily production of agricultural biogas and the qualitative composition of agricultural biogas produced from pig slurry. The results of the measurements show a clear influence of the hydrodynamic mixing system of the substrate for the evaluation of the biogas flow through the adhesive bed in the context of agricultural biogas production.

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