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PRODUCTION, ECONOMIC AND ENVIRONMENTAL EFFECTS OF AGRICULTURAL BIOGAS PLANT IN KOSTKOWICE

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Abstract. This paper presents the economic and ecological effect of Kostkowice Agricultural biogas plant based on a four year study carried out on the prototype installation. Agricultural biogas plant is part of the nature of the research conducted for twenty years at the National Research Institute of Animal PIB Experimental Station. Prof. Mieczyslaw Czaja relates to various aspects of environmental protection. It describes the economic justification for the production of energy from waste biomass (manure, slurry, wastes from feeding table), by the characteristics of substrates and products. It was found that agricultural biogas plant in rural areas are an important link in energy security, mainly due to the very high availability. Ecological effect is presented as effect of the installation solutions for the reduction of pollution of water, soil and air. Reducing greenhouse gas emissions through the recycling of environmentally harmful by-products of animal production of electricity and thermal energy, which is a substitute for environmentally harmful fossil fuels. The advantage of substances digestate is odorless, which is important both in an effort to improve the work culture in agriculture and improving living conditions in rural communities and it is an indisputable argument for the use of biomass for energy purposes.

Keywords: biomass, renewable energy, biogas plant, ecological effect

INTRODUCTION

One of the requirements of modern agriculture is to address the increasing energy needs. In view of the steadily rising energy prices, especially from the perspective of small remote users, rational energy management must be put in place and alternative sources of energy need to be developed. The sustainable agriculture concept addresses the environmental needs and is conducive to rational energy management through a more efficient use of resources and by managing the industrial waste or byproducts of energy production. The consequences are a limited use of chemical fertilizers and plant protection products, and the reduced consumption of fossil fuels, which has a favorable environmental impact (including reduced GHG emissions). According to Roszkowski (2011), animal production accounts for 80% of the agricultural GHG emissions. While carbon emissions are offset by photosynthesis in the agriculture sector, methane and nitrogen oxides pose a serious problem. According to FAO, animal husbandry accounts for 35–40% of total methane (CH4) emissions. Digestive processes are the largest contributor to methane emissions, followed by the anaerobic decomposition of manure (10–15%). Animal production generates 64% of ammonia (NH3) emissions. While not a GHG, ammonia causes acid rain, eutrophication and environmental acidification. A method for the reduction of anthropogenic emissions

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from the agriculture sector is to limit the number of livestock or develop an emission reduction technology. According to the "Economic assessment of the policy options for the reduction of agricultural GHG emissions in the EU," a report by the General Direction in charge of Agriculture and Rural Development for the National Emission Ceilings Directive (Kuznowicz, 2015), the emissions are supposed to be decreased by 19% or 28% by 2030. This will mean reducing the number of beef cattle, dairy cattle and pigs by 42.4%. 24.1% and 12%, respectively. The restriction of animal production may result in increased prices of animals. Also, as pointed out by the agricultural communities and as confirmed by data of the Central Statistical Office, this will have an adverse effect on soil fertility.

From the economic perspective, energy price is the essential factor, affecting 300,000 commercial farms on a nationwide basis. Specific attention should be paid to seasonal demand for energy. These farms pay the energy bills based on tariff C (or higher) which includes the power compensation service. Therefore, energy costs are 20% higher and the energy quality gives rise to concerns, especially because of the underinvested transmission grid which results in reduced power and power cuts. The above aspect is an argument for the development of renewable energies in rural areas. According to research, around 30% of farmers are interested in installing renewable energy equipment in their farms (Lemans_raport_pl).

One of the alternative (and empirically proven) ways to reduce the emissions is the technology for livestock manure management that minimizes the environmental emissions of ammonia and methane. That technology was developed by the Professor Mieczysław Czaja Experimental Establishment of the National Research Institute of Animal Production in Gródziec Śląski which assesses multiple aspects of the environmental impact of the Kostkowice biogas plant launched in 2012.

This paper presents only the results of studies on the energy content of substrates and on the ability to use the biogas, heat and digestate to enhance the environment.

BIOMASS AS A SOURCE OF ENERGY IN AN AGRICULTURAL BIOGAS PLANT

Biomass, the biogas plant fuel, is the source of food for methane bacteria which release methane in complex biochemical processes. The biogas is combusted in a cogeneration plant where electric power and heat is produced. The digestate is a valuable organic fertilizer. As the technology deployed in biogas plants enables the use of all components of the production cycle, it has a favorable impact on the project's economic viability and protects the environment.

The purpose of this study was to discover the biomass properties of the substrate which, as a biological material, demonstrates diversified features, including those of relevance for biogas productions. The basic substrates in the production process are manure and slurry from cowsheds and piggeries located near the biogas plant. Table 1 shows the characteristics of selected substrates produced in the farms concerned and used in the Institute's agricultural biogas plant.

Biogas efficiency was calculated based on chemical analyses of substrates with the use of the Weende method, and on biogas efficiency coefficients based on the Baserga's method (Myczko et al., 2011; Podkówka and Podkówka, 2010; Węglarzy and Podkówka, 2010). Note the changes in efficiency of manure biogas depending on the storage period. This finding confirms that manure storage results in the emission of GHG ($CH4$) into the atmosphere, and that fresh manure used in the agricultural biogas plant has a positive impact on productivity. Therefore, the effects are positive both from the economic and environmental perspective.

The calculation of energy efficiency of the substrate components allows to select them so as to achieve the best environmental and economic performance of energy production processes. The important thing is the continuous monitoring of metabolic processes based on the defined FOS/TAC ratio (ratio of volatile organic acids to alkaline buffer capacity) as the load factor of the methane fermentation process.

ECONOMIC ANALYSIS OF ELECTRIC POWER PRODUCTION FROM BIOMASS

An important economic aspect is the cost of the substrate input loaded to the fermenter. According to the comparative analysis of results shown in Table 2, corn silage significantly raises the input cost with no impact on the quantity of biogas which is the primary product for electric power production. Therefore, the share of corn silage in input materials of the Kostkowice agricultural biogas plant has been decreasing over the years (Table 3), which has a considerable effect on the profitability.

Table 1. The characteristic of chosen substrates for biogas, electric and thermal energy production
Tabela 1. Charakterystyka wybranych substratów do produkcji biogazu, energii elektrycznej i cieplnej

Substrate Substrat	Dry matter Sucha masa (%)	Production – Produkcja			
		biogas m^3/Mg F.W.* biogazu m^3/Mg M.Ś.*	methan m^3/Mg F.W.* metanu m^3/Mg M.Ś.*	electric energy energii elektrycznej (kWh)	thermal energy energii cieplnej (kWh)
Corn silage Kiszonka z kukurydzy	32.80	201	107	338	411
Haylage Sianokiszonka	37.60	168	91	289	340
Pasture green weight Zielonka pastwiskowa	16.89	92	51	164	203
Swine slurry Gnojowica świńska	10.05	33.5	20	65	80
Cattle slurry Gnojowica bydlęca	8.50	22	12	39	41
Fresh solid manure Obornik świeży	19.42	130	71	221	270
Stored solid manure Obornik składowany	25.25	100	50	160	189

* F.M. fresh matter.
Source: own elaboration.
* M.Ś. świeża masa.
Źródło: opracowanie własne.

Table 2. The analysis of energy production depending on substrate type
Tabela 2. Analiza produkcji energii w zależności od rodzaju substratu

Specification Wyszczególnienie	Animal production wastes Odpady produkcji zwierzęcej	Corn silage Kiszonka z kukurydzy
Methane yield (m^3/Mg F.M.*) Wydajność metanu (m^3/Mg M.Ś.*)	41	123
Electric energy production (kWh/Mg F.M.*) Produkcja energii elektrycznej (kWh/Mg M.Ś.*)	131	394
Bath production cost (Mg/PLN) Koszt produkcji wsadu (Mg/zł)	25.00	250.00
Bath cost (PLN/kWh) Koszt wsadu (zł/kWh)	0.19	0.63

*F.M. – fresh matter.
Source: own elaboration.
*M.Ś. – świeżej masy.
Źródło: opracowanie własne.

Table 3. The electric energy production from biomass in Kostkowice agricultural biogas plant in 2012–2015
Tabela 3. Produkcja energii elektrycznej z biomasy w agrobiogazowni Kostkowice w latach 2012–2015

Specification Wyszczególnienie	2012	2013	2014	2015
Share of by-products in bath (%) Udział produktów ubocznych we wsadzie (%)	46.7	61.9	82.9	90.0
Electric energy production (MWh) Produkcja energii elektrycznej (MWh)	2 962	3 475	3 954	3 712
Income from energy sales (thous. PLN) Przychód ze sprzedaży energii (tys. zł)	1 327.79	1 355.51	1 248.23	1 035.28
Share of certificates in income (%) Udział świadectw w przychodzie (%)	63.1	45.7	50.8	53.5
Unit sales price (kWh/PLN) Cena jednostkowa sprzedaży (kWh/zł)	0.45	0.39	0.32	0.28

Source: own elaboration.
Źródło: opracowanie własne.

The unit cost of energy produced from fresh animal by-products is an economic argument for the production of energy based on waste biomass originating from animal production.

An important aspect of the cost efficiency of renewable energies is the unit cost of own energy production used for economic purposes. It does not include the transmission (distribution) component representing around 70% of the value of energy purchased through a power plant. Thus, the consumption of energy supplied from indigenous sources is a way to considerably reduce the costs of other energy-intensive economic activities (seed drying, milk cooling).

In the 2012–2015 period, the Kostkowice agricultural plant supplied over 14,000 MWh of green electric power to the national power grid. Almost 7,000 tons of coal would be required to produce the same amount of energy from conventional sources, assuming a boiler efficiency of 30%. What is interesting is the nearly 60% decrease in unit prices of electric power in 2015 compared to 2012. The reasons are both the decline in unit prices of energy delivered to the national grid and the consistent decrease in prices of participation certificates.

Note also that some valuable components (silage) of the substrate are being gradually replaced with waste from animal and vegetable production. In 2015, the share of silages was 90%, and will remain at that level as it ensures the best economic viability and technological safety.

ECONOMIC ANALYSIS OF HEAT PRODUCTION FROM BIOMASS

The essence of using biomass for energy production purposes (in addition to generating the main product, i.e. electric power, in an optimum way) is to manage the byproducts. Energy is produced primarily from animal byproducts, manure, liquid manure, slurry, left-overs and waste from African catfish farming.

The byproducts of the biogas plant are the cogeneration heat and digestate.

The heat generated in the process of electric power production from biomass is used to heat the fermenter and farming facilities, including piggeries and the housing for African catfish, a thermophilous fast-growing fish with an excellent feeding quotient (1.1). The waste heat from cogeneration is decisive for the profitability of African catfish production. What also matters is the environmental effect of heat management which debunks the myth, advanced by the opponents of the biogas plant, that the electric power production from biomass has an adverse environmental impact. The waste heat from cogeneration allows to save around 70,000 m^3 of gas per year. This is the quantity that would need to be used for farming purposes, and represents savings of PLN 180,000. Over four years, the operation of the biogas plant enabled savings of the order of some PLN 501,600, assuming that natural gas is used for

Table 4. The calculation of profitability o using heat from co-generation (2012–2015)
Tabela 4. Kalkulacja opłacalności wykorzystania ciepła kogeneracji (lata 2012–2015)

Specification Wyszczególnienie	Total production Produkcja całkowita	Energy using Wykorzystanie energii		
		fermenter fermentor	catfish house dom suma	piggeries chlewnie
Thermal energy (MWh) Energia cieplna (MWh)	14 322	615	1 096	922
Thermal energy (GJ) Energia cieplna (GJ)	51 558.8	2 214.0	3 945.6	3 319.2
Energy per carbon (Mg) Energia w przeliczeniu na węgiel (Mg)	1 909.6	82.0	146.1	122.9
Energy per gas (m^3) Energia w przeliczeniu na gaz ziemny (m^3)	1 432 188	61 499	109 599	25 611
Energy value per carbon (PLN/Mg) Wartość energii w przeliczeniu na węgiel (zł/Mg)	1 336 709.4	57 399.54	102 292.5	86 052.6
Energy value per gas (PLN/m^3) Wartość energii w przeliczeniu na gaz ziemny (zł/m^3)	3 652 080.8	156 823.7	279 477.8	65 308.3

1 GJ = 277.78 kWh, calorific value of coal = 27 GJ/Mg (80% of boiler efficiency), calorific value of gas = 0.36 GJ/m^3, price of 1 Mg of coal = 700 PLN, price of 1m^3 of gas = 2.55 PLN.
Source: own elaboration.
1 GJ = 277,78 kWh, wartość opałowa węgla = 27 GJ/Mg (80% sprawności kotła), wartość opałowa gazu ziemnego = 0,036 GJ/m^3, cena 1 Mg węgla = 700 PLN, cena 1 m^3 gazu ziemnego = 2,55 PLN.
Źródło: opracowanie własne.

heating and the heat generated in the Kostkowice agricultural biogas plant represents as little as 18% of the total consumption.

ECONOMIC ANALYSIS OF ORGANIC FERTILIZER (DIGESTATE) PRODUCTION FROM BIOMASS

The residue of the anaerobic digestion process taking place in the agricultural biogas plant are the methane bacteria biomass, undigested organic compounds and minerals. The chemical composition of the digestate depends on that of the input materials having undergone the anaerobic digestion process. In the case of fermentation of liquid substances such as liquid livestock faeces, liquid manure and slurry, the chemical composition of slurry undergoes significant changes, including:
- the removal of easily degradable carbon compounds,
- maintenance of non-decomposable carbon compounds such as lignin, fibrin etc.,
- decomposition of colloids, mucus etc.,
- transformation of nitrogen compounds into ammoniacal nitrogen (90%),
- destruction of pathogenic bacteria and viruses and parasites,
- increase in content of amino acids and vitamin B12,
- essential reduction of quantities of oxygen consuming substances,
- no significant quantitative or qualitative changes of other nutrients, such as P, K, Na, Ca, Mg, and microelements.

The high hydration level is an adverse feature of the digestate. Depending on the substrate, the water content of the digestate ranges from 90 to 97 percent. According to the analysis, the hydration level of the digestate from the Kostkowice agricultural biogas plant was 93,38% in the case of a coferment composed of bovine liquid manure, pig slurry, grass silage and corn silage.

Also, the carbon to nitrogen ratio changes during fermentation as the carbon is incorporated into methane.

Table 5. The comparison of fertilizing properties of digestate and liquid manure
Tabela 5. Porównanie właściwości nawozowych dygestatu i gnojowicy

Specification Wyszczególnienie	Years – Lata			
	2012	2013	2014	2015
Digestate – Dygestat				
Production (Mg) Produkcja (Mg)	10 539	14 227	14 573	12 329
Nitrogen production (kg) Produkcja azotu (kg)	33 724.8	49 794.5	48 090.9	41 918.6
Fertilizing area (ha) Powierzchnia nawożenia (ha)	198.4	292.9	282.9	246.6
Slurry – Gnojowica				
Production (Mg) Produkcja (Mg)	6950	12 084	12350	8527
Nitrogen production (kg) Produkcja azotu (kg)	23 630.0	45 919.2	41 990.0	30 697.2
Fertilizing area (ha) Powierzchnia nawożenia (ha)	139.0	270.1	247.0	180.6

Source: own elaboration.
Źródło: opracowanie własne.

During fermentation, the organic substance levels decrease while those of nitrogen and mineral compounds increase. This is due to loss of organic substance which results in improved fertilizing conditions because of the increased levels of ammoniacal nitrogen (N-NH4), reaching 90%. In raw slurry, that share is around 48.8%. The ammoniacal form is more easily absorbable by plants and is less prone to leaching into surface waters and ground waters.

In the 4-year period considered, the production volume of digestate was nearly 52,000 Mg. Also, 173.5 Mg of nitrogen fertilizers were produced, allowing to address the demand for fertilizers to cover the area of 1020 ha. The slurry used for fertilizing purposes would supply enough nitrogen to address the demand of an area of 837 ha.

The digestate was used as a fertilizer in compliance with the requirements provided for in applicable regulations that specify both the nitrogen quantity (up to 170 N/ha) and the spreading dates, taking into account the composition of soil, in a manner similar to mineral fertilization patterns applied in the control part of the crops.

The composition of soils is diversified, especially when it comes to phosphorus levels, ranging from 5.3 to 34.5 mg/100 g of soil. A study was conducted (Table 7) to assess the impact of fertilizing on the yields (or rather on the diversification of yields) of winter crops: rape, wheat and barley (grain yield per ha), of spring crops: maize (yields of green matter per ha) and grassland (yields of green matter per ha). Due to diversified soil composition, as mentioned above, the study was carried out in test stands located in areas with similar soil properties, usually within the same land plot which was divided into the experimental part (fertilized with the digestate) and the control part (where traditional fertilizers were used). In the case of rapeseed, the study was conducted in two adjacent land plots with a comparable mineral content in soil.

As plant yields depend on multiple factors, it is unclear whether any single one could be decisive. In the experimental model deployed, subjective factors that could affect the comparison were eliminated: the experimental and control areas were located within the same or neighboring land plots, and therefore the quality and nutritional content of soil was similar. The chemical

Table 6. The crop yield in 2012
Tabela 6. Plonowanie upraw w roku 2012

Crop name Nazwa uprawy	Fertilization type Rodzaj nawożenia	Area Powierzchnia (ha)	Yield Plon (dt/ha)
Rape Rzepak	control – kontrolne	3.5	29.32
	liquid digestate – dygestat płynny	3.6	30.20
Wheat Pszenica	control – kontrolne	6.3	48.70
	liquid digestate – dygestat płynny	10	52.10
Barley Jęczmień ozimy	control – kontrolne	10	40.70
	liquid digestate – dygestat płynny	9.3	46.22
Corn Kukurydza	control – kontrolne	15.6	421.00
	liquid digestate – dygestat płynny	9.3	511.00
	regular, liquid digestate – dygestat stały, płynny	14.7	492.00
Grassland in Kostkowice Użytki zielone Kostkowice	control – kontrolne	10.3	217.2
	liquid digestate – dygestat płynny	4.6	252.7
Grassland in Grodziec Użytki zielone Grodziec	control – kontrolne	6.9	225.7
	liquid digestate – dygestat płynny	4.0	312.7
Grassland in Jaworze Użytki zielone Jaworze	control – kontrolne	4.0	162.3
	liquid digestate – dygestat płynny	4.3	221.4

Source: own elaboration.
Źródło: opracowanie własne.

Table 7. The results of ecological effect calculations of green energy production in Kostkowice agricultural biogas plant
Tabela 7. Wyniki obliczeń efektu ekologicznego produkcji zielonej energii w agrobiogazowni Kostkowice

Reduction of emission of dust-gas pollutants Obniżenie emisji zanieczyszczeń pyłowo-gazowych	Years – Lata			
	2012	2013	2014	2015
CO_2 (kg)	1 914 448	2 246 022	2 555 402	2 399 444
SO_2 (kg)	19 423	22 787	25 926	24 344
NO_x (kg)	6 924	8 123	9 242	8 678
CO (kg)	10 518	12 340	14 040	13 183
Dusts (kg) Pyły (kg)	1 820	2 136	2 430	2 282
Benzo α-pyrene (kg) Benzo α-piren (kg)	0.9	1.0	1.2	1.1

analyses of the digestate allowed to use such quantities of specific elements that theoretically would be suitable to address the nutritional needs of plants.

However, the study did not extend to all factors that could affect the yields or their diversification. Methane fermentation is known to affect the neutralization, or inhibit the germination, of weeds. This could be the factor which, on top of the fertilizers included in the digestate, had a favorable impact on yields.

In the case of maize and grassland, liquid digestate used during the growing season was not only a fertilizer but also an important irrigation factor. This could be another reason why fertilization with digestate results in higher yields. To supplement this argument, it should be noted that this region has experienced low rainfall in the recent years. Therefore, each way of supplying humidity (despite dense, impermeable soils where the plants have been grown) could be beneficial in terms of higher yield. This irrigation method proved to be particularly efficient with respect to grassland and maize crops, and was applied in both cases.

THE ENVIRONMENTAL EFFECT OF THE KOSTKOWICE BIOGAS PLANT

Agricultural biogas plants are not only a considerable support for the energy system. The estimated technical availability of biogas facilities is 98%, ranking them among stable sources of renewable energy which may constitute an important part of energy security of local grids.

The second extremely important feature of biogas plants is the environmental security of biogas facilities This means that the air, waters and soils are protected. Table 7 shows the calculated indicator of environmental effects of the Kostkowice biogas plant in the four-year operating period.

The reduced emissions of gases with the worst environmental impact are an argument for the development of this branch of the energy industry. A similar effect could be achieved by using the energy for heating purposes, and would allow to double the favorable environmental impact. The use of heat from the Kostkowice biogas plant follows an upward trend as more and more facilities are connected to this environmentally-friendly source of energy.

Note also that the anaerobic digestion process enabled a significant reduction of odor of the digestate, the second by-product of the agricultural biogas plant. In the Kostkowice agricultural biogas plant, the digestate resulting from the fermentation of livestock faeces and bovine and porcine slurry, and the coferment in the form of a mixture of faeces and silage reduced the odor of the digestate by more than 80%, according to organoleptic assessment. While the residual odor of the digestate was perceptible at a distance of 10-20 cm, the odor of liquid substrates (livestock faeces) remains intensive even at a distance of several hundred meters (in the case of pig slurry).

Compared to raw slurry, the digestate demonstrates multiple advantages and environmental benefits, primarily including:

- a better use of nutrients by the plants,
- inhibiting the germination of weeds, and reducing or eliminating the use of herbicides,
- neutralization of pathogens,
- reducing the risk of contamination of ground water and surface water, mainly with nitrogen and phosphorus compounds and pathogens found in animal faeces.

CONCLUSIONS AND SUMMARY

For nearly 20 years, the Experimental Establishment of the National Research Institute of Animal Production in Gródziec has been conducting research to support the anticipated energy revolution. That term is increasingly mentioned not only in industry magazines but also in popular literature. Professor Benjamin Savacool (2016), a British scientist, believes that fossil fuels could be phased out within only a decade. The finite natural resources, climate change and continuous technology improvements are the reasons why innovation, such as renewable sources of energy, could become widely adopted much faster to provide us with a clean future. However, in addition to technological advancements and legislative changes, a change in the users' mindsets is necessary for such a revolution.

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EFEKTY PRODUKCYJNE, EKONOMICZNE I ŚRODOWISKOWE AGROBIOGAZOWNI W KOSTKOWICACH

Streszczenie. W pracy przedstawiono efekt ekonomiczny i ekologiczny funkcjonowania agrobiogazowni w Kostkowicach na podstawie czteroletnich badań wykonanych w tej prototypowej instalacji. Agrobiogazownia wpisuje się w charakter badań prowadzonych od dwudziestu lat w Instytucie Zootechniki PIB – Zakładzie Doświadczalnym im. Prof. Mieczysława Czai, które dotyczą różnych aspektów ochrony środowiska. Opisano ekonomiczne uzasadnienie dla produkcji energii z odpadowej biomasy (obornik, gnojowica, niedojady) poprzez charakterystykę substratów i produktów ubocznych. Stwierdzono, że agrobiogazownie w środowisku wiejskim są ważnym ogniwem bezpieczeństwa energetycznego, głównie z uwagi na bardzo wysoką dyspozycyjność. Efekt ekologiczny przedstawiono w postaci wpływu zastosowanych w instalacji rozwiązań na redukcję zanieczyszczeń wód, gleby i powietrza. Potwierdzono ograniczenie emisji gazów cieplarnianych przez przetwarzanie szkodliwych dla środowiska produktów ubocznych produkcji zwierzęcej, będących substytutem szkodliwych dla środowiska paliw kopalnych, w energię elektryczną i cieplną. Atutem substancji pofermentacyjnej (dygestatu) jest bezzapachowość, co ma znaczenie zarówno w dążeniu do podnoszenia kultury pracy w rolnictwie, jak i dla poprawy warunków życia w społecznościach wiejskich i jest bezspornym argumentem za wykorzystaniem biomasy dla celów energetycznych.

Słowa kluczowe: biomasa, energia odnawialna, biogazownia, efekt ekologiczny

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