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# Potential of biogas production from animal manure in Poland

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**Abstract:** The substrates to biogas production in anaerobic digestion, except plant materials, can also be animal feces and manure. It should be highlighted that Poland is one of leaders in the European Union in animal breeding. However, there is no precise data in the literature on the potential of biogas production from animal feces in this country. The aim of the paper was to analyze the biogas production potential from manure in Poland. The aim of work included anaerobic digestion research following materials: cow manure, pig manure, poultry manure and sheep manure. In the next step, based on the obtained results of the biogas yield, energy potential calculations were made. The methane yield for the investigated feedstock materials in the batch culture technology was performed following the internal procedures developed based on the adapted standards, i.e. DIN 38 414-S8 and VDI 4630. Animal wastes were obtained from the Agricultural Experimental Stations of Poznan University of Life Sciences (Poznan, Poland). On a base of achieved results it was concluded that tested substrates have a high energy potential (approx. 28.52 GWh of electricity). The largest potential for electricity production was found in chicken manure (about 13.86 GWh) and cow manure (about 12.35 GWh). It was also shown which regions of Poland have the best chance for development of agriculture biogas plants (Wielkopolskie and Mazowieckie voivodships) and where the potential is the least (Lubuskie and Opolskie voivodeships).

## Introduction

The electricity and heat production in the EU, especially in Poland, largely depends on the use of conventional energy systems based on hard and brown coal (Widera et al. 2016). However, it should be remembered that these methods have an adverse effect on the environment, caused by large amounts of pollution emitted during combustion (Dzikuć and Piwowar 2016, Urban and Dzikuć 2013). The use of modern environmentally friendly technologies, e.g. energy production from different sources such as water, sun, wind, biomass or the use of composting processes can be the solutions that would allow to limit the progress of those unfavorable conditions (Bugała et al. 2018, Czekała et al. 2018, Helbe et al. 2014, Malińska et al. 2014) Fortunately, the activities undertaken by countries associated within the EU are bringing aid. One of them was the Directive 2009/28/EC in 2009 and the energy policy of the European Union by 2050. These documents assume, inter alia, an increase in the consumption of renewable energy in the national energy systems of member states.

Poland as an EU Member State, under the Directive, has declared to increase the share of renewable energy in the final gross energy consumption to the level of 15% in 2020. However, observing the downward trend in the use of RES between 2015 and 2016, one can assume that these targets may not be met (Fig. 1), which also involves high penalties imposed on the country by the EU. Nevertheless, it should be remembered that biomass combustion together with coal is also considered as green energy (Hoffmann et al. 2012). However, this solution is not beneficial for the environment, although the opinions of researchers on the following are divided (Priyanto et al. 2016, Zhou et al. 2016). One should bear in mind that the organic matter after the process of direct co-combustion with coal can no longer be used as an organic fertilizer, which leads to deterioration of soil quality in Poland and the interruption of closed carbon dioxide circulation in nature.

The main producers of electricity and heat in Poland are coal power plants, which were constructed mostly before 1990. However, it should be added that only a few have undergone a thorough modernization, similarly like in the case of the power grid system. This situation may cause shortages in energy supplies in large areas of the country. The solution to this problem may be the use of renewable energy sources that allow for stable production of electricity and heat. The following measure will improve the country's energy security as a result of the decentralization of energy sources. Biogas plants are an example of such installations (Ciotola et al. 2011, Wiśniewski et al. 2015) that enable the production of biogas, whose main component is methane, as a result of the anaerobic digestion process (AD) (Dach et al. 2016). This fuel can be injected into the gas network after proper treatment or incinerated in a cogeneration engine in order to produce heat and/or cold energy (Kalinichenko and Havrysh 2019, Sgroi et al. 2015). Moreover, due to the ability to quickly launch a CHP unit, energy production in biogas installations can take place in the hours of greatest demand during the day. As a result, they may constitute a safety buffer for conventional energy, where the commissioning time of the installation is several hours.

AD is a complex biotechnology process that consists of four main phases: hydrolysis, acidogenesis, acetogenesis and methanogenesis (Bułkowska et al. 2015, Sawatdeenarunat et al. 2015, Zhang et al. 2016). During this process, as a result of transformation of organic matter, biogas is formed consisting mainly of methane (approx. 65%), carbon dioxide (approx. 35%) and trace amounts of other gases: ammonia, hydrogen sulphide, nitrogen and oxygen (Kozłowski et al. 2018, Wu et al. 2016). The content of methane and other biogas components is primarily influenced by compounds found in the feed medium (Dach et al. 2016). The second important aspect of the use of the AD process is the production of high quality organic fertilizer (digestion pulp), which allows for reducing the use of mineral fertilizers (Holm-Nielsen et al. 2009).

### *Production of livestock in Poland*

It should be emphasized that Poland is one of the EU countries with the greatest potential for biogas production. This is mainly due to the large area of agricultural areas (approx. 14.5 mln ha) and well-developed cattle, pig and poultry breeding (Statistics Poland 2018). Each of these sectors generates large amounts of bioproducts. These materials can be a good quality substrate in the methane fermentation process (Bocenetti et al. 2014, Wiater and Horysz 2017). In addition, the following way of their management allows to limit the uncontrolled decomposition and the emission of carbon dioxide and methane to the natural environment (Czekała et al. 2017). Therefore, it contributes to the reduction of global warming (Baral et al. 2018). Table 1 presents data on the number of cattle, swine and poultry in Poland in different years.

According to data collected by Statistics Poland in 2016, the population of cattle, swine, poultry and sheep in Poland was 5,970.2, 11,106.7, 135,814.0, and 244.2 thousand respectively. In recent years, an increase in cattle and poultry farming has been particularly noticeable. It should be noted that currently Poland is a leader in the production of poultry in Europe. In the case of pigs, a clear decrease in the number of farmed animals was observed after 2010. It resulted directly from the crisis in the sector of animal production and the drastic decline in the purchase prices of livestock. The Russian embargo imposed on Poland had an additional influence (Czekała et al. 2016). Table 2 shows the number of farm animals broken down by voivodeship.

The most developed voivodeships in Poland, in terms of animal production, include: Mazowieckie and Wielkopolskie. They are characterized by high cattle (more than 1,000 thousand of heads) and poultry production (29,194.8 and 28,387.9 thousand of heads respectively). In addition, the largest number of pigs in the whole country was recorded in the Wielkopolskie voivodship – 3,959.3 thousand pigs. This is mainly due to the

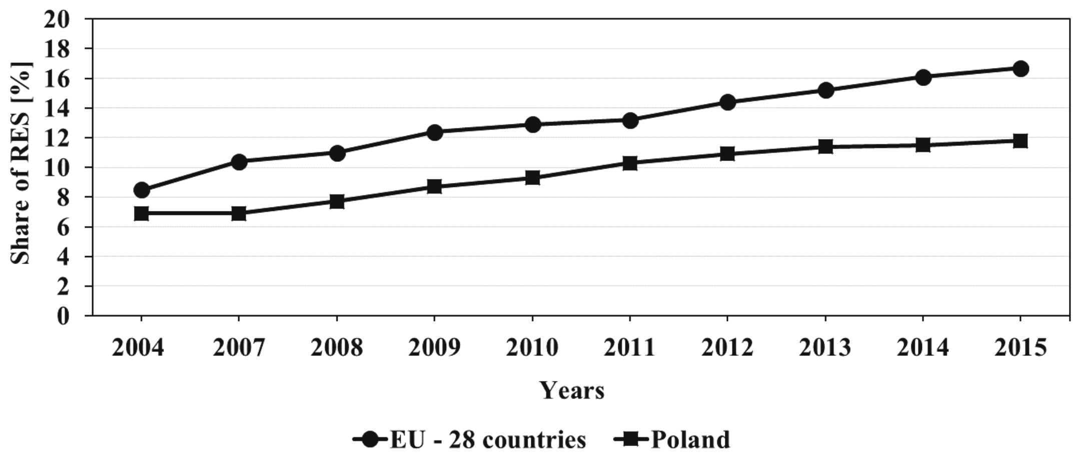


**Fig. 1.** Cumulated share of RES in energy production in Poland and EU (2004–2016).
Source: adapted from Eurostat (2017)

**Table 1.** Livestock and poultry population in Poland in 2010–2016 (in thousand heads) (Statistics Poland 2017)

| Specification | 2010 | 2013 | 2014 | 2015 | 2016 |
|---|---|---|---|---|---|
| Cattle Stocks | 5,561.7 | 5,589.5 | 5,660.3 | 5,762.4 | 5,970.2 |
| Pig Stocks | 14,775.7 | 10,994.4 | 11,265.6 | 10,590.2 | 11,106.7 |
| Poultry | 130,959.0 | 117,054.0 | 120,975.0 | 139,588.0 | 135,814.0 |
| Sheep | 213.7 | 223.1 | 201.3 | 221.2 | 244.2 |

largest number of large-scale farms. The highest number of sheep in Poland is observed in the Małopolskie voivodship. This is due to geographical conditions (mountainous areas with high gradient, and a large number of small farms) and local traditions (manufacture of regional products from sheep's wool).

### *Biogas market in Poland*

Three types of biogas installations are distinguished in Poland: agricultural biogas plants (using waste from the agri-food industry), biogas plants operating at sewage treatment plants or landfills (using sewage sludge or landfill gas for biogas production) and biogas plants producing energy from mixed substrates. According to the data of the Energy Regulatory Office (2018), there are currently 109 biogas installations at the sewage treatment plants, 101 installations using landfill biogas and 96 agricultural biogas plants (Table 3).

It should be noted, however, that the number of 96 biogas plants (Fig. 2) does not reflect the high production potential

**Table 2.** Farm animals by voivodship in December 2016 (Statistics Poland 2017)

| Voivodeship | Cattle | | Pigs | | Sheep | Poultry |
|---|---|---|---|---|---|---|
| | Altogether | In it cows | Altogether | In it sows | | |
| dolnośląskie | 102.5 | 40.4 | 196.0 | 28.5 | 12.2 | 4,614.4 |
| kujawsko-pomorskie | 492.6 | 155.5 | 1,197.4 | 107.5 | 10.5 | 8,981.0 |
| lubelskie | 371.8 | 136.7 | 550.2 | 43.6 | 14.9 | 4,922.6 |
| lubuskie | 73.0 | 27.5 | 153.2 | 11.0 | 4.9 | 4,017.4 |
| łódzkie | 473.2 | 183.1 | 1,119.8 | 70.2 | 13.0 | 10,933.0 |
| małopolskie | 178.1 | 86.7 | 168.7 | 19.6 | 78.5 | 4,028.6 |
| mazowieckie | 1,098.5 | 481.7 | 934.4 | 64.5 | 6.5 | 29,194.8 |
| opolskie | 122.9 | 41.8 | 391.0 | 33.3 | 2.1 | 2,653.9 |
| podkarpackie | 84.4 | 47.2 | 166.8 | 16.1 | 18.7 | 4,568.1 |
| podlaskie | 959.8 | 436.3 | 320.6 | 24.8 | 19.8 | 7,834.7 |
| pomorskie | 209.4 | 66.4 | 746.3 | 66.8 | 14.0 | 4,782.5 |
| śląskie | 122.7 | 44.8 | 243.6 | 21.9 | 12.6 | 6,527.4 |
| świętokrzyskie | 166.5 | 56.7 | 209.5 | 23.0 | 4.7 | 5,082.6 |
| warmińsko-mazurskie | 419.1 | 186.9 | 466.9 | 43.7 | 10.2 | 3,785.9 |
| wielkopolskie | 1,003.3 | 274.3 | 3,959.3 | 257.3 | 17.0 | 28,387.9 |
| zachodniopomorskie | 92.5 | 37.5 | 283.0 | 27.1 | 4.7 | 5,499.3 |

**Table 3.** Biogas plants in Poland (Regulatory Energy Office 2018)

| Voivodeship | Biogas from sewage treatment plants | Biogas from agricultural biogas plants | Biogas from landfill site | Biogas from mixing systems | Sum |
|---|---|---|---|---|---|
| dolnośląskie | 10 | 9 | 9 | 1 | 29 |
| kujawsko-pomorskie | 5 | 6 | 7 | 0 | 18 |
| lubelskie | 4 | 7 | 2 | 1 | 14 |
| lubuskie | 2 | 4 | 3 | 0 | 9 |
| łódzkie | 4 | 4 | 4 | 0 | 12 |
| małopolskie | 10 | 2 | 6 | 0 | 18 |
| mazowieckie | 14 | 5 | 20 | 0 | 39 |
| opolskie | 3 | 1 | 3 | 0 | 7 |
| podkarpackie | 11 | 3 | 3 | 0 | 17 |
| podlaskie | 5 | 9 | 1 | 0 | 15 |
| pomorskie | 5 | 9 | 6 | 0 | 20 |
| śląskie | 17 | 3 | 15 | 0 | 35 |
| świętokrzyskie | 2 | 1 | 1 | 0 | 4 |
| warmińsko-mazurskie | 6 | 10 | 3 | 0 | 19 |
| wielkopolskie | 7 | 10 | 10 | 0 | 27 |
| zachodniopomorskie | 4 | 13 | 8 | 0 | 25 |
| Sum | 109 | 96 | 101 | 2 | 308 |

that can be compared to the potential of biogas production in Germany (over 7 thousand installations) (Piwowar et al. 2016). The possibility of developing the biogas sector in Poland results from the large area of agricultural land and a well-developed agro-food and animal sector (Czekała 2018). The management of waste from livestock production for biogas purposes, in particular manure and slurry, allows for the production of renewable energy that is sustainable over time while reducing the uncontrolled decomposition of organic matter and the emission of carbon dioxide and methane to the environment (Gomez 2013). Thanks to the reduction in emission of the two most dangerous gases into the atmosphere it would be possible to limit the effect of global warming (Baral et al. 2018). It should also be emphasized that in Poland, slurry is the most commonly used substrate for biogas purposes. In 2016, 774,997 Mg of this material was used, which constituted 24% of all substrates used for the fermentation process (KOWR 2018). However, despite the large interest of society and the government in biogas plants, there is currently no detailed study regarding the potential of biogas production from animal manure in Poland. It is also important that potential of waste material in each EU region will vary significantly, due to the different technique of its production. Moreover, the development of the renewable energy sector and changes occurring in it requires supplementing the current state of knowledge on the situation of the biogas market, including that in Poland. Such calculations can also be used in other regions of Europe and the world.

Therefore, the aim of this work was to analyze the potential of biogas production from manure waste produced in Poland. The scope of work included carrying out BMP tests on biogas and biomethane performance of cattle manure (CM), swine manure (SWM), poultry manure (PM) and sheep manure (SHM). The next step was to calculate the energy production potential for individual regions of the country.


**Fig. 2.** Agricultural biogas plants in Poland in 2018. Source: developed by authors

## Materials and methods

### *Materials*

The selected feedstock materials including cow manure, pig manure, poultry manure and sheep manure were tested. Animal waste was obtained from the Agricultural Experimental Stations of Poznan University of Life Sciences (Poznan, Poland). These materials were sampled in a representative manner, and then stored under controlled conditions (at temperature of at 4°C, in a designated room). For laboratory tests the mesophilic inoculum was used. The inoculum was a liquid fraction of fermentation pulp after separation of dry matter obtained from an agricultural biogas plant in Międzyrzec Podlaski, Poland. The inoculum collected from the reservoir was stored under anaerobic conditions at room temperature.

### *Analysis of basic physicochemical parameters*

The analyzes of basic physicochemical parameters of the selected feedstock materials and the inoculum were conducted according to the Polish standards on: dry matter (PN-75 C-04616/01), dry organic matter (PN-Z-15011-3), and pH (PN 90 C-04540/01). These parameters allowed for the selection of the appropriate proportions of fermentation mixtures and subsequent calculation of the biogas efficiency which was calculated on Mg of FM, DM and VS of the substrate. In addition, $N_{tot}$, $C_{org}$, C/N ratio analysis was carried out in accordance with the Flash 2000 – Thermo Fisher Scientific device methodology.

### *BMP test*

The methane efficiency for the investigated feedstock materials in the batch culture technology was performed following the internal procedures developed based on the adapted standards, i.e. DIN 38 414-S8 (1985) and VDI 4630 (2006). These standards are commonly used in Europe. Detailed methodology of the performed research was presented by Cieślik et al. (2016) Gizińska-Górna et al. (2016) and Dach et al. (2014). VDI 4630 is a standardized norm related to fermentation of organic materials characterization of the substrate, sampling, collection of material data, and fermentation tests. Its main assumptions say about conditions that must be met to properly check the biogas efficiency of the substrates. Moreover, it characterizes the type of inoculum that should be used. It should come from the fermenter working on sewage sludge or from the biogas plant with similar profile of biogasified materials in comparison with the tested substrate. The content of organic dry matter in inoculum should be ranged between 1.5 and 2%.

The fermentation set-up consisted of 21 biofermenters. Each individual biofermenter (made from glass) had a volume of 1.8 $dm^3$. The process was carried out under mesophilic conditions at 39°C±1°C. The produced biogas in each fermenter chamber was transported via teflon pipe to the gas storage. These reservoirs were made from plexiglass as an inverted cylinder immersed in water. Between the water and gas areas, there was a liquid barrier preventing the dissolution of $CO_2$ in water.

The volume of biogas produced was read at equal 24-hour intervals. The tested gases were methane, carbon dioxide, ammonia, hydrogen sulfide and oxygen as a control; the results were recorded with accuracy of 0.01 $dm^3$. Measurements were made using Geotech's GA5000 certified gas analyzer (certificates ATEX II 2G Ex ib IIA T1 Gb (Ta = -10°C to +50°C), Atest, CSA certificates and UKAS ISO 17025 calibration. The ranges of gases detected by the analyzer were: 0÷100% $CH_4$, 0÷100% $CO_2$, 0÷25% $O_2$, 0÷10 000 ppm $H_2S$ and 0÷1 000 ppm $NH_3$.

### Calculation of manure and biogas potentials

The biogas potential was first calculated for each Polish region and the type of animal husbandry (cattle, pigs, poultry and sheep), based on actual animal populations (Statistics Poland 2017). The detailed amount of manure has been estimated for each livestock and poultry species and different age groups by multiplying the animal population by the amount of manure produced per head and year. The total amount of manure produced was calculated as the sum of material produced by all types of animals (eq. 1).

$$M = \sum_{t=1}^{n} M^t = \sum_{t=1}^{n} \sum_{a=1}^{k} P_a^t \cdot M_a^t \quad (1)$$

where:
$M$ – the total manure production [Mg FM·year$^{-1}$],
$M^t$ – the manure production of animal type t [Mg FM·head$^{-1}$·year$^{-1}$],
$P_a^t$ – the animal population of animal type t and age group a [heads],
$M_a^t$ – the manure production of animal type t and age group a [Mg FM·head$^{-1}$·year$^{-1}$].

The theoretical methane potential from manure was calculated as the sum of the biogas amount produced by for each livestock and poultry type considering the biogas and methane yields for each feedstock type (eq. 2). However, the actual methane potential is less than the theoretical potential due to the lower manure collection capacity and anaerobic batch conversion in the biogas plant.

$$B = \sum_{t=1}^{n} \sum_{a=1}^{k} M_a^t \cdot Y_a^t \cdot A_a^t \quad (2)$$

where:
$B$ – the actual methane potential [Nm$^3$CH$_4$·year$^{-1}$],
$M_a^t$ – the manure production of animal type t and age group a [Mg FM·head$^{-1}$·year$^{-1}$],
$Y_a^t$ – the methane yield of manure [m$^3$·FM$^{-1}$],
$A_a^t$ – the availability factor for the amount of manure that can be collected, depending on livestock, farming system and technical limitations for collection [-] = 0.95 (Wrzeszcz, 2010).

The expected potential of biogas from manure, expressed as biomethane equivalent, was obtained taking into account the lower calorific value and efficiency of CHP (eq. 3).

$$E^r = B_a \, LHV_{CH_4} \cdot (\eta e + \eta h) \quad (3)$$

where:
$E^r$ – the expected biogas potential [MJ·year$^{-1}$],
$B_a$ – the actual methane potential [Nm$^3$CH$_4$·year$^{-1}$],
$LHV_{CH_4}$ – the Low Heating Value for methane ($CH_4$) (35.9 MJ·m$^{-3}$ or about 9.97 kWh·m$^{-3}$),
$\eta e$ – electrical efficiency of cogeneration unit (for the purposes of these calculations, the efficiency of 40% was assumed for the unit offered by PAKTOMA, a Polish manufacturer of modern co-generation units for biogas plants),
$\eta h$ – heat efficiency of cogeneration unit (for the purposes of these calculations, the efficiency of 43% was assumed for the unit offered by PAKTOMA).

The biogas plant power was calculated based on the quotient of produced energy and cogeneration unit working time (eq. 4):

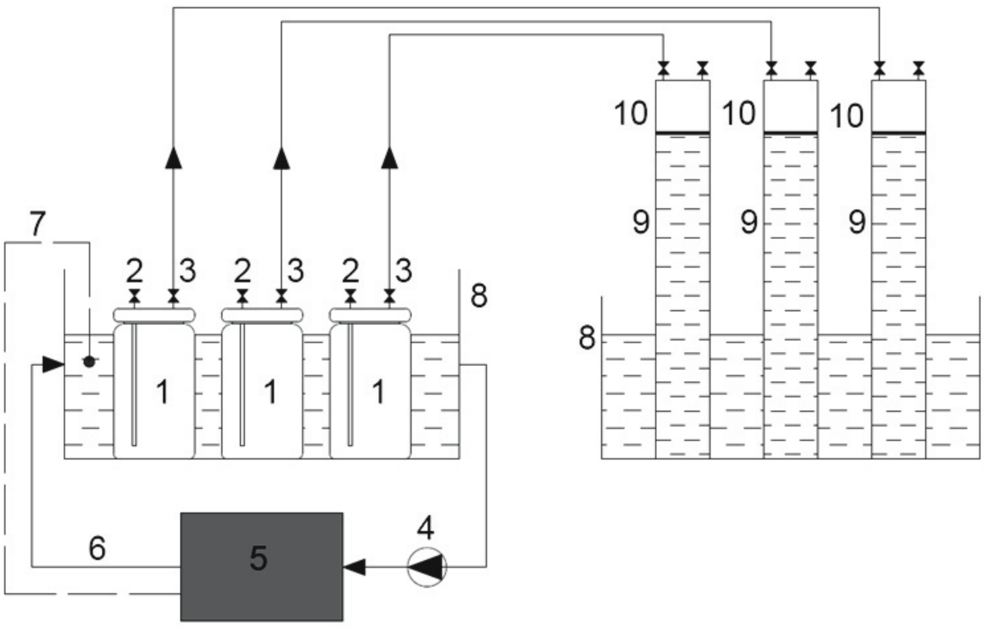


**Fig. 3.** Scheme of the AD reactors in BMP test (1. Biofermenter with the input of 1.8 dm$^3$ of capacity, 2. Sampling tube, 3. Tube for biogas flow, 4. Water pump, 5. Water heater with a temperature in the range of 20–70°C, 6. Isolated hot liquid tube, 7. Temperature sensor, 8. Reservoir, 9. Biogas container made of poly (methyl methacrylate), 10. Liquid barrier).
Source: developed by authors

$$P_e = \frac{E_e}{t_{CHP}} \quad (4)$$

where:

$P_e$ – biogas plant power [MW],

$E_e$ – amount of energy produced per year [MWh],

$t_{CHP}$ – cogeneration unit working time [h·year$^{-1}$] (for these calculations 8200 h·year$^{-1}$).

## Results and discussion

### *Characteristic of substrates*

The first step of the research was preparation of basic physical and chemical parameters, which are necessary to calculate energetic potential of the substrate. The parameters were: pH, total solids and volatile solids content. The results of analyzes of these parameters for microbial inoculum and substrate are presented in Table 4.

The content of dry matter in CM, PM, SHM and SWM amounted 16.89% FM, 38.02% FM, 28.89% FM and 16.62% FM respectively. The biogas during the fermentation process is produced from decomposed organic matter, decreased by the amount consumed by the fermentation bacteria. Consequently, the comparison of energy potential was possible after determining the content of dry matter of every substrate. The tested substrates were characterized by high volatile total solids content, which amounted to 14.47% FM, 32.77% FM, 25.12% FM and 14.71% FM. The most preferred C/N ratio was observed for CM. For this substrate, this parameter is optimal for conducting the methane fermentation process (Mao et al. 2015, Yein and Brune 2007). In the case of PM and SHM, it is necessary to select the appropriate co-substrates that allow the parameter to be adjusted or the technology to reduce the nitrogen content (Pokój et al. 2014).

### *Biogas yield of substrates*

The fermentation process of the analyzed substrates proceeded correctly. No inhibition or longer time of inactivity in biogas production was observed. Figure 3 shows the graph of cumulated methane production calculated on VS.

PM had a better biogas yield reaching a total production of 333 Nm$^3$·Mg$^{-1}$ VS of methane in 18 d which corresponds to 97.94 Nm$^3$ methane in calculation of 1 Mg FM. The fermentation time for other materials was accordingly: 22 d (CM), 24 d (SHM) and 29 d (SWM). However, it is worth to remember, that hydraulic retention time carried on an industrial scale, may not be less than 15–16 days (Lindmark et al. 2014, Deublein and Steinhauser 2008). Table 5 presents the biogas and methane yields of substrates.

The highest efficiency of biogas and methane production from 1 Mg fresh matter had PM. Significantly lower efficiency

**Table 4.** Physical and chemical parameters of substrates (cattle manure – CM, poultry manure – PM, sheep manure – SHM, swine manure – SWM)

| Parameters | Inoculum | CM | PM | SHM | SWM |
|---|---|---|---|---|---|
| pH | 7.41 | 8.10 | 5.09 | 7.90 | 7.80 |
| TS [% FM] | 2.88 ± 0.027 | 16.89 ± 0.644 | 38.02 ± 0.490 | 28.89 ± 0.776 | 16.62 ± 0.305 |
| VS [% FM] | 2.04 ± 1.537 | 14.77 ± 0.099 | 32.77 ± 0.091 | 25.12 ± 0.597 | 14.71 ± 1.099 |
| Total N [% TS] | – | 1.77 | 4.33 | 1.33 | 2.15 |
| Total organic C [% TS] | – | 35.69 | 42.82 | 10.44 | 38.40 |
| C/N ratio | – | 20.11 | 9.88 | 7.82 | 17.86 |

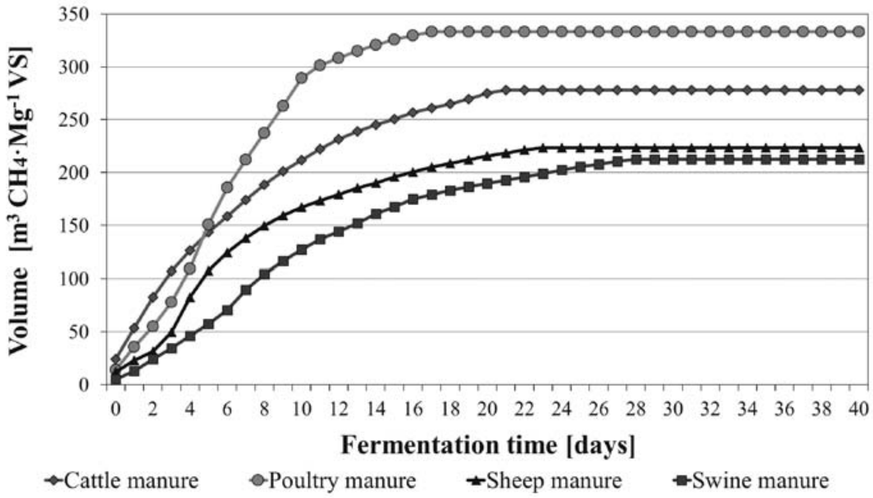


**Fig. 4.** BMP assay curves showing cumulated methane production (Nm$^3$CH$_4$·Mg$^{-1}$ VS) from 4 different substrates (CM, PM, SHM and SWM). Source: developed by authors

of biogas produced from agri waste is due to differential content of dry matter in tested substrates. Therefore, it is necessary to compare the energy potential of the substrates with each other, calculated on Mg of VS. In this case, the highest efficiency of biogas and methane production was obtained also from PM (595.58 $m^3 \cdot Mg^{-1}$ VS) and from CM (477.27 $m^3 \cdot Mg^{-1}$ VS).

### *Potential of biogas production from manure*

It is worth of underline that biogas yields from anaerobic digestion vary depending on the type of manure used (species, breed, age, body weight, feed, etc.). Additional influence is due to its specific chemical and physical composition and, in particular, to the difference of organic matter, carbohydrate and fat content.

This is the result of different specifics of maintaining animal husbandry in Poland and Western Europe (for example, higher water consumption when washing stands). The data from the subsection *Biogas yield of substrates* was used to analyze the potential included in Table 5.

The Livestock Unit (LSU) is a reference unit, which facilitates the comparison of livestock from various species and ages established on the basis of the nutritional or feed requirement. It is based on the grazing equivalent of one adult dairy cow using the correlations showed in Table 6.

Table 7 presents the estimates of manure production in Poland as well as the potential for biogas and methane production. An important fact is that, in the years 2002–2006, this potential was already estimated at approx. 80 million Mg (Igras and Kopiński 2007). Similar calculations were carried out by Scarlat et al. (2018) who determined the amounts of produced manure at 91.3 million Mg for the region of Poland. On the basis of calculations carried out in this work as well as public information on the farm animals population in Poland, the amount of manure produced at approx. 107.08 million Mg was estimated.

**Table 5.** Biogas yield from different type of manure used in calculation

| Substrate | Methane percent [%] | Fresh matter | | Volatile solids | |
|---|---|---|---|---|---|
| | | Biogas yield [$Nm^3 \cdot Mg^{-1}$ FM] | Standard deviation | Biogas yield [$Nm^3 \cdot Mg^{-1}$ VS] | Standard deviation |
| CM | 58.30 | 71.83 | ± 3.75 | 477.27 | ± 25.04 |
| PM | 55.75 | 175.67 | ± 4.32 | 595.58 | ± 14.56 |
| SHM | 59.89 | 91.70 | ± 3.11 | 373.10 | ± 12.58 |
| SWM | 58.92 | 51.72 | ± 0.44 | 360.29 | ± 10.62 |

**Table 6.** Estimated manure and biogas potential from various livestock types and age groups

| Specification | Livestock Unit | Manure | Manure | Methane yield | Methane yield | Electricity yield |
|---|---|---|---|---|---|---|
| | LSU | $kg \cdot head^{-1} \cdot day^{-1}$ | $Mg \cdot head^{-1} \cdot year^{-1}$ | $Nm^3 \cdot head^{-1} \cdot year^{-1}$ | $MJ \cdot head^{-1} \cdot year^{-1}$ | $kWh \cdot head^{-1} \cdot year^{-1}$ |
| Dairy cows | 1.0 | 53 | 19.3 | 808.2 | 29,015.2 | 8,057.978 |
| Other cows | 0.8 | 25 | 9.1 | 381.1 | 13,680.7 | 3,799.358 |
| Other pigs | 0.3 | 4.5 | 1.6 | 48.8 | 1,750.3 | 486.0904 |
| Sows | 0.5 | 11 | 4 | 121.9 | 4,375.8 | 1,215.226 |
| Sheep | 0.1 | 1.5 | 0.5 | 27.5 | 985.8 | 273.7845 |
| Other poultry | 0.03 | 0.3 | 0.11 | 10.8 | 386.8 | 107.4116 |

**Table 7.** Theoretic biogas and methane production potential in Poland

| Specification | Manure | Biogas potential | Methane potential |
|---|---|---|---|
| | Produced [million Mg] | Theoretic [million $m^3$] | Theoretic [million $m^3$] |
| Dairy cows | 42.23 | 3,033.68 | 1,768.65 |
| Other cows | 31.70 | 2,276.95 | 1,327.47 |
| Other pigs | 15.58 | 805.63 | 474.65 |
| Sows | 3.26 | 168.81 | 99.46 |
| Sheep | 0.12 | 10.64 | 6.37 |
| Poultry | 14.19 | 2,493.24 | 1,390.03 |
| Total | 107.08 | 8,788.94 | 5,066.64 |

However, in the absence of detailed data on the animal breeding system on farms and the production of agricultural waste, it is impossible to accurately estimate the amount of manure produced. According to data from Scarlat et al. (2018) 58.6 million Mg of manure is being collected and managed, which is only about 54.7% of produced manure. However, data from Poland Statistics (2018) show that about 52 million Mg of this material is used in Polish agriculture. The KOWR (2018) data in 2017 show that only 86,656 t of manure was used for biogas purposes. Even taking into account the 802,278.438 t of manure used for biogas production, only about 0.75% of the total production of animal waste is used for energy purposes. Some of the material is used for fertilizing purposes, however, a large part of it is often decomposed on fields under uncontrolled conditions.

In the case of collecting all available manure, the total biogas potential of this fertilizer can amount to approx. 5 billion $m^3CH_4$. Such volume will meet approximately 34% of domestic demand. In addition, taking into account the fact that about 3.7 billion $m^3$ of natural gas (about 25% of the total) is mined in Poland, the total use of manure for energy purposes would reduce gas imports to Poland by about 45.66%. Table 8 presents the potential of total energy production from animal wastes, as well as the total power of the installation and the amount of electricity possible to produce.

According to the Energy Regulatory Office (2017), at the end of 2016, the power installed in the national power grids amounted to 41,396 MW. However, the average annual demand for power amounted to 22,483 MW, with a maximum demand of 25,545 MW. The use of animal manure for energy production would allow for the construction of installations with a capacity of approx. 3,478 MW. The use of biogas plants should also be considered in terms of power plants operating in the period of the highest daily demand for electricity. This solution would help maintain the stability of energy supplies while diversifying them at the same time. In addition, throughout 2016, electricity production amounted to 162,626 GWh, while its national consumption – 164,625 GWh (Energy Regulatory Office 2017). However, taking into account the continuous increase in energy demand, the use of manure alone will allow for the production of approximately 28,520 GWh of electricity, which will satisfy the country's energy needs and reduce its imports, which amounts to approximately 5,000 GWh per year.

The largest potential for the production of electricity from animal manure was found for the Wielkopolskie (5,593.5 GWh), Mazowieckie (5,535.7 GWh) and Podlaskie voivodships (2,959.4 GWh). However, it should be noted that these are not voivodships where currently the largest number of agricultural biogas plants operate. This may be due to the inability to connect this type of installation to power grids. The lowest potential of electricity possible to be produced was determined for three voivodeships: Lubuskie (591.69 GWh), Opolskie (597.6 GWh) and Podkarpackie (701.6 GWh).

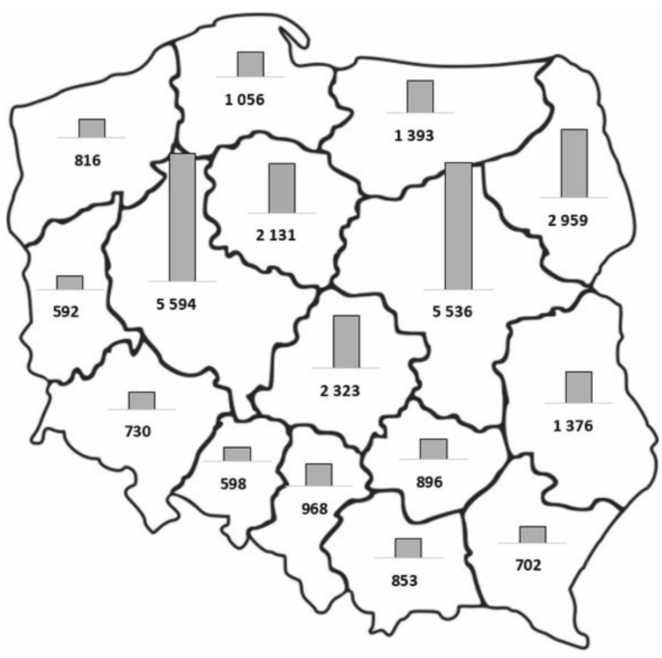

**Fig. 5.** Potential of energy production in different region of Poland (in GWh). Source: developed by authors

## Conclusions

The purpose of this work was to determine the energy production potential from animal manure. It was estimated that about 112 million Mg of manure is produced in Poland. The investigated animal manures can be used as the feedstock materials for biogas plants in Poland demonstrating that the biogas efficiency can range from 360 ± 10.6 $Nm^3 \cdot Mg^{-1}VS$ (for swine manure) to 595 ± 14.6 $Nm^3 \cdot Mg^{-1}VS$ (for poultry manure). Additionally, the management of biodegradable waste through methane fermentation can prevent the occurrence of negative

**Table 8.** Energy and electricity potential of biogas and biogas plant capacities

| Specification | Primary Energy | Plant capacity | Electricity |
|---|---|---|---|
| | [TJ] | [MW] | [GWh] |
| Dairy cows | 52,700.57 | 860.17 | 7,053.39 |
| Other cows | 39,554.73 | 645.61 | 5,293.96 |
| Other pigs | 14,143.23 | 230.84 | 1,892.92 |
| Sows | 2,963.47 | 48.37 | 396.63 |
| Sheep | 189.90 | 3.10 | 25.42 |
| Poultry | 41,418.75 | 1,690.07 | 13,858.61 |
| Total | 150,970.65 | 3,478.16 | 28,520.92 |

influence of uncontrolled decomposition of organic matter in environmental (reduction of methane and carbon dioxide emissions). The calculations carried out in this work show that in Poland, it is possible to produce about 150,970 TJ of energy (including approx. 28,520 GWh electricity). The presented methodology can be used for the determination of biogas potential for any feedstock material, and prediction of methane potential for different regions in Europe.

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## Potencjał produkcji biogazu z odchodów zwierzęcych w Polsce

**Streszczenie:** Substratami do produkcji biogazu w procesie fermentacji beztlenowej, obok materiałów roślinnych, mogą być odchody zwierzęce. Należy podkreślić, że Polska jest jednym z liderów w Unii Europejskiej w zakresie hodowli zwierząt. Jednak, w aktualnej literaturze nie ma dokładnych danych na temat potencjału produkcji biogazu z odchodów zwierzęcych w tym kraju. Celem pracy była analiza potencjału produkcji biogazu z obornika w Polsce. Zakres prac obejmował przeprowadzenie badań fermentacji beztlenowej następujących materiałów: obornika bydlęcego, obornika trzody chlewnej, obornika drobiowego i obornika owczego. W kolejnym etapie, w oparciu o uzyskane wyniki wydajności biogazu, dokonano obliczeń potencjału energetycznego. Badania wydajności metanowej dla badanych materiałów wsadowych w technologii okresowej zostały przeprowadzone zgodnie z procedurami wewnętrznymi opracowanymi w oparciu o zaadaptowane normy, tj. DIN 38 414-S8 i VDI 4630. Materiały do badań pobrane zostały z Zakładów Doświadczalnych Uniwersytetu Przyrodniczego w Poznaniu. Na podstawie uzyskanych wyników stwierdzono, że badane podłoża mają duży potencjał energetyczny (około 28,52 GWh energii elektrycznej). Największy potencjał produkcji energii stwierdzono dla obornika kurzego (ok. 13,86 GWh) oraz bydlęcego (ok. 12,35 GWh). Wykazano również, które regiony Polski mają największe szanse na rozwój biogazowni rolniczych (województwo wielkopolskie i mazowieckie), a w których potencjał produkcji jest najmniejszy (województwo lubuskie i opolskie).