INTRODUCTION

Energetic potential of animal biomass

Poland has considerable agro-biomass potential that could pave the way toward sustainable development and achieve the country renewable energy targets by substituting the excessive use of fossil fuels, particularly coal and lignite [Czekała 2018; Zyadin et al., 2018]. The biomass potential in the northern part of Europe among the 9 analyzed countries, such: Denmark, Germany, Estonia, Finland, Latvia, Lithuania, Poland, Sweden and Norway showed that Germany and Poland have the largest technical potential of agricultural biomass, manure and slurry. Sweden has the largest number of pellet production plants, but the highest production was found in Germany, which is the leading biogas producer among the analyzed countries (92% of all biogas plants) [Stolarski et al., 2020]. Biomass is defined as the biodegradable part of products, waste or biological products from agriculture (including plant and animal substances) [Kupryaniuk et al. 2020; Marks et al. 2020], forestry [Czekała et al., 2018a] and industries, including fisheries and aquaculture [Bücker et al., 2020], as well as the biodegradable part of industrial and urban waste [Directive (EU) 2015/1513].

Database System for Estimating the Biogas Potential of Cattle and Swine Feces in Poland

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ABSTRACT

Animal biomass is an important substrate in the anaerobic digestion process. The implementation of a waste technology for energy production, such as the production of biogas from animal waste, has been recognized in many countries as one of the best ways to achieve the Sustainable Energy Development Goals. Without a systematic review of resources and accurate estimation of available sources in terms of the amount of potential electricity, it is impossible to manage biomass rationally. The main aim of the article was to present a new tool for assessing the biomass of animal origin and estimating its potential energy through a computer database, which will be widely available in the end of 2020 to show results from the calculation using the database. This tool is configured to enter the data on the developed and undeveloped biomass resources in production of farm animals in rural areas in Poland. Calculations from the database show the biogas potential of swine and cattle manure and slurry in Poland, which is approximately 5.04 billion m³, with a 60% share of methane in biogas. It is the value of approximately 3.03 billion m³ of methane. It is worth underlining that slurry and manure are not high-energy substrates; therefore, it is necessary to introduce more energetic substrate streams to improve the biogas plant efficiency.

Keywords: biogas plant; energetic optimization; substrates; manure; slurry; database

INTRODUCTION

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Poland has considerable agro-biomass potential that could pave the way toward sustainable development and achieve the country renewable energy targets by substituting the excessive use of fossil fuels, particularly coal and lignite [Czekała 2018; Zyadin et al., 2018]. The biomass potential in the northern part of Europe among the 9 analyzed countries, such: Denmark, Germany, Estonia, Finland, Latvia, Lithuania, Poland, Sweden and Norway showed that Germany and Poland have the largest technical potential of agricultural biomass, manure and slurry. Sweden has the largest number of pellet production plants, but the highest production was found in Germany, which is the leading biogas producer among the analyzed countries (92% of all biogas plants) [Stolarski et al., 2020]. Biomass is defined as the biodegradable part of products, waste or biological products from agriculture (including plant and animal substances) [Kupryaniuk et al. 2020; Marks et al. 2020], forestry [Czekała et al., 2018a] and industries, including fisheries and aquaculture [Bücker et al., 2020], as well as the biodegradable part of industrial and urban waste [Directive (EU) 2015/1513].
The biomass of animal origin is important as a valuable substrate in the anaerobic digestion process [Czekala et al., 2020]. It should be highlighted that Poland is one of leaders in the European Union in animal breeding [Kozłowski et al., 2019a]. Animal biomass consists mainly of solid and liquid animal waste (manure, slurry), food processing waste and the biomass derived from meat production [Zbytek et al., 2017]. Since 2004, Poland has been at the forefront of the countries generating the largest amount of industrial wastes in the entire European Union [Szymańska et al., 2020]. After proper food processing, waste can be used as raw materials for the production of technical fats, agricultural biogas [Czekala et al. 2018b], biodiesel, building material fillers, fertilizers, as well as for the synthesis of lipolytic enzymes, as feed additives (even for food products). High amounts of organic matter and protein in slaughterhouse wastes make them a viable choice for anaerobic digestion and biogas production [Latifi et al., 2019; Orlando and Borja, 2020]. The implementation of waste to energy technology such as biogas production from animal waste has been considered as one of the best means to achieve sustainable energy development goals in many developing countries [Munawar et al., 2019]. As an example, it is estimated that 9597.4 Mm³/year of biogas could potentially be generated from animal waste in Indonesia.

Energetic potential of animal biomass

In the circular bio-economy, effective biomass valorization through the strategic use of resources is essential in terms of generating valuable products, sustainable development, and maximizing the ecological and socio-economic benefits [Bogacka et al., 2017]. In EU legislation biomass is defined as the biodegradable fraction of products, waste, and residues of biological origin from agriculture (including vegetal and animal substances), forestry and related industries including fisheries and aquaculture, as well as the biodegradable fraction of industrial and municipal waste [Directive (EU) 2009/28/EC] or specified biomass as organic, non-fossil material of biological origin that can be used for heat production or electricity generation. It includes wood and wood waste, agricultural crops, biogas, municipal solid waste, biofuels [Eurostat Glossary 2020]. Nowadays, biomass is processed for energy purposes or to produce biofuels [Czekala et al., 2017]. Biofuels are liquid or gaseous transport fuels such as biodiesel and bioethanol which are made from biomass [Directive (EU) 2018/2001].

The biomass for energy purposes can be used in the following forms:
- organic waste: animal feces, meat processing residues;
- liquid biofuels, bioethanol from frying oils;
- biogas from slurry [Lewandowski, 2001].

Among animal biomass, the biomass from meat processing e.g. slaughter of animals, meat boning, cutting, and production of processed meats is the most difficult to manage. Modern infrastructure and advanced technologies, slaughterhouses and meat plants are still classified as the companies that generate waste, and thus significantly contribute to environmental degradation [Mroczek et al., 2019]. The largest amounts of animal excrement that need to be managed are slurry and manure [Esteves Mano et al., 2019]. In the case of biogas produced from animal wastes and by-products from agriculture, horticulture, housekeeping and food industry, the benefits are not limited to the energy balance. The biogas generation ensures also better use of the by-products, in general inconvenient for the environment (odor, contamination of waters) [Grzybek et al., 2015].

Construction of small and cheap agricultural biogas plants, is one of the best directions for disseminating the biowaste valorization technology [Dach et al., 2014; Pochwatka et al., 2020]. Its use in the production of biogas is an environmentally beneficial way not only to reduce this impact, but also to produce energy [Kozłowski et al., 2019b]. Although manure has a low energy value and a low biogas conversion efficiency, it is indicated for use in a co-fermentation process with other biogas substrates. The efficiency of biogas production is influenced by the mixing process and the addition of slaughter residues; the 1% addition of swine placenta increased the production of biogas and methane by 20% [Soares et al., 2020].

Systems for planning the energetic value of animal biomass

A systematic review of comprehensive solution tools to overcome the biomass supply chain (BSC) planning challenges is critical for both academic research and industry [Zahraee et al., 2020]. The combination of market incentives
and policy mandates scenario, the production of biomass-based ethanol and electricity increases considerably and could potentially cause substantial changes in the land use practices [Liu et al., 2014]. Radial Basis Function (RBF), as an innovative model dedicated to different silages, is useful tool to estimate the energy value without the necessity of expensive, long-term analysis [Kowalczyk-Juśko et al., 2020a]. The model used basic silage parameters such as: kind of silage, pH, dry matter, organic dry matter, conductivity and fermentation time. The output data in the database sheet contained the cumulative methane production.

A completely different method of estimating biomass originated from Colombia – a four step methodology for estimating the energetic value of biomass. These steps are: using a simple accounting framework, using a solid selection of the probability density function, using probabilistic propagation of uncertainty, and using sensitivity analysis to identify key variables [Salazar-Gonzales et al., 2016].

In Poland, local biomass resources from animal production are estimated by determining the theoretical potential [Siejka et al., 2008]. The theoretical potential of biomass from animal production is determined based on collective summaries concerning the amount of manure obtained from a given type of farm animals, hosted on different systems [Konieczny et al., 2015; Kowalczyk-Juśko et al., 2020b].

The paper aimed to show how to easily and precisely estimate the available sources of agricultural biomass of animal origin in terms of the amount of electricity. Besides, the obtained data were subjected to spatial visualization to indicate the regions of Poland, where the possibility of launching a biogas installation and electricity production is the most profitable. The work combines the scientific and practical aspects which in the future may facilitate the decision-making process regarding the location of a new biogas plant and at the same time avoid investment risks. The article also aimed to show the advantages of estimating the energy potential of the biomass of animal origin, which is a database system developed under the Program: Technology and nature projects for innovative and effective and a low-carbon economy in rural areas.

MATERIAL AND METHODS

Without prior assessment, biomass cannot be effectively managed. Livestock manure management (both solid and liquid fractions) under biorefinery approach seems an inevitable solution for the future sustainable development to meet the circular bioeconomy requirements [Khoshnevisan et al., 2021].

In the years 2016–2020 the Institute of Technology and Life Sciences carried out the program entitled “Technology and nature projects for innovative and effective and a low-carbon economy in rural areas” supported by Polish Ministry of Agriculture and Rural Development [PROGRAM 2016–2020]. The main purpose of the task which is presented in this manuscript is assessment of renewable energy resources in rural areas, in particular biomass, and rationalization of their use. The main product of this task is a computer database, which will be widely available in 2021. The database is configured to enter the data on the resources of developed and undeveloped biomass in the production of farm animals in rural communes in Poland. The database has a tab which concerns animal biomass – feces, but it is planned to be expanded by two tabs: plant production and waste from agri-food processing intended for biogas production.

Data collection

The statistical data are obtained annually from the Agency for Restructuring and Modernization of Agriculture. The data concern livestock production in rural areas divided into communes/counties/voivodships. The obtained data concerns the number of farm animals: swine and cattle, in each voivodeship of Poland.

The system was based on two kinds of mathematical models. Therefore, the calculations can be divided into two stages. In the first stage, the first model was used. This stage involves three steps. The aim of using the model was to calculate the amount of waste generated from keeping a specific group of animals on farms. Livestock can be kept in two systems: bedding and no litter systems. Depending on the type of housing system, the farm produces manure or liquid manure (slurry). The diagram (Figure 1) shows how to use one of the models to calculate the amount of animal excrement based on the number of animals kept in the farms in different regions of Poland.
I. Averaging number of animals depending on the age group (converted into LSU)

II. Swine and cattle maintenance system (indicators for provinces based on the data of the 2010 Agricultural Census)

III. Unit amount of animal excrements (average values of data from the literature)

Fig. 1. Model to calculate the amount of animal feces - divided into three steps

The next step was to define the animal keeping system (indicators for provinces based on the data of the General Agricultural Census of the Central Statistical Office). The indicators are shown in Table 1.

In the last step of this stage when indicators are assigned, the amount of excrement is calculated using the first mathematical model: for slurry and for manure. The calculations are based on the literature data.

Descriptive of system functioning (algorithms)

Algorithm for estimating the amount of manure (1).

\[ L_o = \sum (x_n \cdot \text{LSU})_n \cdot W_{O_n} \cdot O_n \quad [Mg] \] (1)

Algorithm for estimating the amount of slurry (2).

\[ L_G = \sum (x_n \cdot \text{LSU})_n \cdot W_{G_n} \cdot G_n \quad [m^3] \] (2)

where: 
- \( n \) – type of animals (cattle, swine);
- \( x \) – livestock of the nth type of animals in the commune [pcs.];
- LSU – Livestock Unit is an index of animals per unit [Regulation of the Council of Ministers of June 5th, 2018];
- \( W_G \) – coefficient of the system of keeping animals in the stands with slatted floor;
- \( W_o \) – coefficient of the animal keeping system in the stands with a solid floor;
- \( G \) – average amount of slurry per year per unit of nth type of animals \([m^3/\text{LSU \cdot a}]\);
- \( O \) – average amount of manure per year per unit of nth type of animals \([Mg/\text{LSU \cdot a}]\).

The \( W_G \) is calculated from mathematical formula (3).

Tab. 1. Animal keeping system indicators based on: Agricultural Census of the Central Statistical Office [GUS Agricultural Census 2010]

| Specification  | Animal keeping system in barns | Animal keeping system in piggeries |
|---------------|-------------------------------|-----------------------------------|
|                | Stands with a slatted floor | Stands with a solid floor | Stands with a slatted floor | Stands with a solid floor |
| Dolnośląskie  | 0.334                         | 0.666                           | 0.334                         | 0.666                           |
| Kujawsko-pomorskie | 0.204                         | 0.796                           | 0.204                         | 0.796                           |
| Lubelskie      | 0.108                         | 0.892                           | 0.108                         | 0.892                           |
| Lubuskie       | 0.176                         | 0.824                           | 0.176                         | 0.824                           |
| Łódzkie        | 0.198                         | 0.802                           | 0.198                         | 0.802                           |
| Małopolskie    | 0.118                         | 0.882                           | 0.118                         | 0.882                           |
| Mazowieckie    | 0.149                         | 0.851                           | 0.149                         | 0.851                           |
| Opolskie       | 0.130                         | 0.870                           | 0.130                         | 0.870                           |
| Podkarpackie   | 0.147                         | 0.853                           | 0.147                         | 0.853                           |
| Podlaskie      | 0.770                         | 0.230                           | 0.770                         | 0.230                           |
| Pomorskie      | 0.462                         | 0.535                           | 0.462                         | 0.535                           |
| Śląskie        | 0.304                         | 0.696                           | 0.304                         | 0.696                           |
| Świętokrzyskie | 0.127                         | 0.873                           | 0.127                         | 0.873                           |
| Warmińsko-mazurskie | 0.365 | 0.635 | 0.365 | 0.635 |
| Wielkopolskie  | 0.343                         | 0.657                           | 0.343                         | 0.657                           |
| Zachodniopolmskie | 0.312                         | 0.688                           | 0.312                         | 0.688                           |
\[ W_G = \left( \frac{S_{BS}}{S_S + S_{BS}} \right) [-] \quad (3) \]

where: \( S_{BS} \) – number of stands in the slatted floor animal keeping system for the province;
\( S_S \) – number of stands in the littered floor animal keeping system for the voivodeship.

The \( W_G \) is calculated from a mathematical formula (4).
\[ W_G = \left( 1 - \frac{S_{BS}}{S_S + S_{BS}} \right) [-] \quad (4) \]

In the second step, in order to estimate the amount of biogas from animal manure on the example of a monosubstrate biogas plant, the following data were used:

- the amount of animal excrements (results from the estimation of the amount of manure and slurry);
- the amount of biogas (based on the literature data) [Myczko et al. 2011].

RESULTS AND DISCUSSION

The calculations were based on the assumption that the swine manure biogas efficiency was 45 m³ per Mg of fresh mass, while the swine slurry efficiency was 25 m³ per Mg. In the case of cattle, the values for manure were 60 m³, and for slurry – 28 m³. On the basis of the information on the availability of a given substrate, the total biogas production was calculated for individual voivodeships. The results are shown below.

Swine manure and slurry produced mass and potential of biogas production

The mass of swine manure and slurry calculated on the livestock unit (LSU) number basis has shown a large difference between analyzed voivodeships (Table 2.).

The total amount of yearly swine manure production reaches over 15 million Mg, and this is almost twice more than the slurry production (7.75 million). This situation is abnormal in Western Europe, where the slurry production largely overtakes the generation of manure. However, it is typical in the Eastern European position. The slurry systems are significantly cheaper during their exploitation, comparing to the manure systems, because they need a much lower engagement of human work. Moreover, because working time is quite expensive in Western Europe, as well as the accessibility of workers in Western European agronomy is very limited, the farmers commonly invest in slurry systems in their animal buildings. There is a completely different situation than in Eastern Europe, where human work is a few times cheaper and is much more expensive in the phase of an investment than manure management.

The potential of biogas production from swine manure and slurry in Polish voivodeships has been presented on the map (Figure 2).

Cattle manure and slurry produced mass and potential of biogas production

The availability of manure and cattle slurry exceeds the production potential of swine several times. The total production of cattle manure and slurry exceeds 76 million Mg per year. The leading voivodeships – Mazowieckie, Wielkopolskie, and Podlaskie (Table 3) are characterized by a total production of over 40 million Mg (which is over 50% in relation to the entire territory of Poland). In Poland, the biogas potential of the entire stream of these substrates has been estimated at over 4.1 billion m³.

The potential of biogas production from cattle manure and slurry in Polish voivodeships has been presented on the map (Figure 3).

Considering the calculations above, it should be stated that the biogas potential of manure and slurry from swine and cattle in Poland is about 5.04 billion m³, which, assuming a 60% share of methane in biogas, gives the value of about 3.03 billion m³ of methane. The consumption of natural gas in Poland in 2018 was 19.7 billion m³. On the other hand, the gas imports to Poland amounted to 13.5 billion m³ [PGNiG, 2020]. This means that the biogas management of the said substrates is able to cover over 15.3% of the Polish demand for gas and, at the same time, 22.4% of the total import of this fuel. However, taking into account the availability of other waste streams from the agri-food sector and referring it to the potential obtained, for example, in Germany, it seems correct to say that the use of the available waste biomass could ensure the energy independence of Poland – which would become independent of gas imports from abroad.
Tab. 2. Calculation of swine manure and slurry mass and biogas yield

| Voivodeship          | Swine manure mass (Mg) | Swine slurry volume (m³)* | Amount of biogas from manure (m³) | Amount of biogas from slurry (m³) |
|----------------------|------------------------|---------------------------|-----------------------------------|----------------------------------|
| Dolnośląskie         | 233 440                | 156 094                   | 10 504 819                        | 3 902 357                        |
| Kujawsko-Pomorskie   | 1 702 268              | 581 679                   | 76 602 039                        | 14 541 984                       |
| Lubelskie            | 851 002                | 424 865                   | 38 295 095                        | 10 621 626                       |
| Lubuskie             | 372 810                | 106 173                   | 16 776 471                        | 2 654 314                        |
| Łódzkie              | 1 781 908              | 586 563                   | 80 185 866                        | 14 664 082                       |
| Małopolskie          | 243 478                | 43 432                    | 10 956 488                        | 1 085 803                        |
| Mazowieckie          | 2 147 774              | 501 400                   | 96 649 821                        | 12 534 990                       |
| Opolskie             | 675 551                | 134 592                   | 30 399 777                        | 3 364 811                        |
| Podkarpackie         | 288 617                | 66 318                    | 12 987 780                        | 1 657 942                        |
| Podlaskie            | 130 878                | 584 208                   | 5 889 500                         | 14 605 202                       |
| Pomorskie            | 586 349                | 671 359                   | 26 385 702                        | 16 783 966                       |
| Śląskie              | 329 375                | 191 820                   | 14 821 871                        | 4 795 497                        |
| Świętokrzyskie       | 471 353                | 91 427                    | 21 210 871                        | 2 285 674                        |
| Warmińsko-Mazurskie  | 723 488                | 554 484                   | 32 556 966                        | 13 862 109                       |
| Wielkopolskie        | 3 796 751              | 2 642 893                 | 170 853 782                       | 66 072 323                       |
| Zachodniopomorskie   | 677 393                | 409 587                   | 30 482 691                        | 10 239 664                       |
| **TOTAL:**           | **15 012 435**         | **7 746 894**             | **675 559 540**                   | **193 672 343**                  |

* It was assumed that 1 m³ of animal slurry has a weight 1 Mg

Fig. 2. The potential of biogas production from swine manure and slurry in Poland
**Tab. 3. Calculation of biogas yield from cattle manure and slurry**

| Voivodeship        | Cattle manure mass (Mg) | Cattle slurry volume (m³)* | Amount of biogas from manure (m³) | Amount of biogas from slurry (m³) |
|--------------------|--------------------------|----------------------------|-----------------------------------|----------------------------------|
| Dolnośląskie       | 1 219 450                | 69 513                     | 73 166 972                        | 1 946 372                        |
| Kujawsko-Pomorskie | 5 426 350                | 315 911                    | 325 581 029                       | 8 845 510                        |
| Lubelskie          | 4 059 764                | 345 512                    | 243 585 861                       | 9 674 332                        |
| Lubuskie           | 1 021 850                | 16 548                     | 61 311 007                        | 463 349                          |
| Łódzkie            | 4 857 030                | 679 805                    | 291 421 828                       | 19 034 550                       |
| Małopolskie        | 1 804 330                | 334 287                    | 108 259 810                       | 9 360 048                        |
| Mazowieckie        | 12 256 535               | 2 838 759                  | 735 392 102                       | 79 485 260                       |
| Opolskie           | 1 335 638                | 152 755                    | 80 138 301                        | 4 277 136                        |
| Podkarpackie       | 945 002                  | 124 616                    | 56 700 107                        | 3 489 237                        |
| Podlaskie          | 10 081 290               | 3 339 454                  | 604 877 417                       | 93 504 702                       |
| Pomorskie          | 2 295 210                | 317 512                    | 137 712 580                       | 8 890 349                        |
| Śląskie            | 96 974                   | 1 890 988                  | 5 818 424                         | 52 947 655                       |
| Świętokrzyskie      | 1 762 034                | 123 652                    | 105 722 033                       | 3 462 242                        |
| Warminsko-Mazurskie| 4 235 675                | 1 892 576                  | 254 140 520                       | 52 992 125                       |
| Wielkopolskie      | 10 725 376               | 768 520                    | 643 522 585                       | 21 518 563                       |
| Zachodniopomorskie | 1 194 621                | 136 627                    | 71 677 262                        | 3 825 554                        |
| TOTAL:             | 63 317 129               | 13 347 035                 | 3 799 027 837                     | 373 716 986                      |

* It was assumed that 1 m³ of animal slurry has a weight 1 Mg

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**Fig. 3.** The potential of biogas production from cattle manure and slurry in Poland
CONCLUSIONS

Due to the extensive agriculture, Poland is characterized by a large availability of organic waste streams that can be utilized for energy. Unfortunately, due to the lack of stable support for the development of this renewable energy sector in Poland in previous years, as of today, only 116 agricultural biogas plants are active (as of October 30, 2020). The annual capacity of these installations for the production of agricultural biogas is approximately 473 million m$^3$. It is only 9.4% the calculated potential of available manure and slurry.

Another major problem of Polish agriculture is its fragmentation. This state of affairs makes the investment process related to a biogas plant’s construction and operation difficult.

Additionally, it should be remembered that manure and slurry, despite their high availability, are not very energetic substrates. For this reason, the installations fed only with these substrates would have to be characterized by large volumes, which increases the investment cost and worsens the economic balance of the project. On the other hand, the legal regulations forcing farmers to store these substrates in winter, force the investments related to the construction of tanks necessary for their storage. This enables the development of two types of installations – either very simple and cheap, owing to which the economic balance of such a project will be positive, or more advanced installations, focused on maximizing the production per cubic meter of the fermentation tank. However, it is then necessary to introduce more energetic substrate streams to improve the efficiency of the installation. In this variant, the slurry is mainly used as a diluent for substrates with a higher dry matter content, characterized by higher energy, while the manure is processed by the installation, making it possible to use its energy potential, improving its fertilizing properties [Czekała et al., 2020] and allows its lawful storage in the winter when it cannot be applied to the fields.

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