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The Logistics Aspect in Research on the Reduction of Carbon Dioxide Emissions from Agricultural Biogas

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Abstract: The article addresses the progressive changes in the climate caused by increasing concentration of greenhouse gases in the atmosphere. In light of the applicable regulations, Poland should reduce the emissions with significant potential of creating the greenhouse effect. One way to achieve this is to increase the use of renewable energy sources, where biogas energy production is one of the most effective methods. Using the Life Cycle Assessment (LCA) method, the greenhouse gas emissions, expressed as CO_2 equivalent generated during the entire logistic process of its production, were calculated.

Keywords: biogas; agricultural biogas plants; emission reduction; supply chains; LCA; climate change

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1. Introduction

Due to a wide range of products and relatively cheap raw material sources, the agricultural biogas plant sector has an undisputed chance for rapid development [1]. An agricultural biogas plant is a "bio-power plant" used to produce biogas from organic substrates such as: natural fertilizers (slurry, manure, manure, liquid manure); plant biomass (e.g., maize, sugar beet, grass, rye silage); and by-products of the agri-food industry (e.g., stillage, potato pulp, whey, pulp, vegetable and fruit residues) [2]. Agriculture can provide substrates defined as "agricultural by-products and waste", which also include food waste [3]. Mixing different residues can improve the efficiency of biogas production, while ensuring production continuity as the seasons change [4]. The conversion of by-products and waste products into biogas is important for environmental protection, while generating energy [5].

Poland is one of the largest EU countries, with an average level of its forest cover and urbanization predominantly lowland and a small area of inland waters and wastelands [6]. Thus, most of the country's area is arable land. Compared to other European Union countries, Poland is the third largest agricultural area [7]. The area of Poland is over 31 million ha, with agricultural land in 2019 amounting to approximately 15 million ha, while the fallow land additionally amounted to 1 million ha [8]. According to the data [9], 1.9 million hectares of agricultural land are needed to produce 10 billion m^3 of methane.

Among the EU countries, Germany has the highest percentage of biogas energy production as a percentage of renewable energy sources and its share in the structure of obtaining energy from renewable sources is over 20%, compared to about 3% in Poland [10]. Poland's potential, for obtaining waste biomass, from the theoretical point of view, may be compared with German market, which is dynamically operating in the RES sector; unfortunately, in practice, Poland has only implemented limited improvements to harnessing potential biogas [11–13]. Meanwhile, 2030, with the prospect of reducing CO_2 emissions by 55% and emission prices of at least EUR 76/ton, is fast approaching [14]. In this context, there is an exploitable opportunity for biomass, in particular for biogas. Specialists from the Institute of Biosystems Engineering of the University of Life Sciences in Poznań estimated [15] that the use of nearly one hundred million tonnes of animal excrements, ad various types of straw and waste from the agri-food industry may result in the production of over 14 billion cubic meters of biogas, which gives a volume greater than all natural gas imports from Russia.

In 2018, the domestic greenhouse gas emissions (calculated in CO_2 equivalent) were dominated by carbon dioxide, whose share in total emissions was 81.8%, methane (CH_4) was 11.8%, and nitrous oxide (NO_2) was 5.4%. Worldwide agricultural activities emit 52% methane (CH_4) and 84% nitrous oxide (NO_2) [4]. In total, the agricultural sector emitted GHG in the amount of 33.1 thousand kt in CO_2 equivalent [4]. On a Polish scale, agriculture is, after the energy sector, the second largest producer of methane [16], i.e., the most aggressive gas in terms of its impact on the creation of the greenhouse effect (23 times more harmful than CO_2). The conducted research shows [17] that farms are responsible for about 16–27% of all anthropogenic emissions. Agricultural emissions take place at every stage of production, from seed preparation to harvesting and storage of finished products. The forecasts of the International Energy Agency (IEA) are that by 2030 the global CO_2 emission may increase by as much as 45% [18].

In 2021 in Poland, the number of installations included in the register of agricultural biogas producers kept by the National Agricultural Support Center was 103 [19]. At the end of April 2021, 490.144 million m^3 of biogas was produced, the total installed capacity was 120.397 MWe, and the total amount of electricity produced from agricultural biogas amounted to 646.284 GWh [20]. It is worth mentioning that the micro-installation sector is also developing in Poland. The quarterly report of energy producers in micro-installations shows that in August 2020 there were 22 such biogas plants. In micro-installations, the amount of electricity introduced to the electricity distribution network for the first half of 2020 was 539,787.858 kWh [21]. The planned installations can produce 4 billion m^3 of biomethane annually within 10 years, which would constitute 20% of the domestic demand. Biogas production is a combined system increasing the efficiency of using green natural resources, disposal of waste, while production of renewable energy delivers environmental benefits and increases Poland's energy security, and also fits in the new paradigm of sustainable development [22].

The concept of sustainable development also occurs in logistics in the context of the supply chain, in which the aim is to organize the flows that are implemented in such a way that they have the least impact on the condition of the natural environment, and thus on the quality of life of the society. M. Sołtysik [23–25] notes that many authors begin their considerations on the essence of logistics by showing the consequences of spatial dispersion of places: the origin of raw materials, the production of final products, as well as their consumption and consumption. As M. Christopher [24] writes, "the goal of logistics generally boils down to ensuring availability". This accessibility has a dimension not only in terms of time and space, but also in terms of economic efficiency (cost of access). The goal of logistics understood in this way is reflected in the well-known definition (rule) 7R presented in 1985 by R.D. Shapiro and J.L. Heskett, and also fits perfectly into the concept of generating energy from renewable sources, including biogas [26].

So, what is the purpose of logistics due to the specific requirements of biomass as a raw material? The final effect of the operation of logistics processes is to ensure a stable resource base for entities involved in the production of energy from biomass. In many cases, obtaining biomass is difficult due to being widely dispersed. In order to avoid the movement of large masses of biomass over long distances, which causes CO_2 emissions, it is reasonable to create local biomass markets and logistic systems that minimize the costs of obtaining, transporting and storing biomass. Local biogas plants could be such a solution. Factors that should be considered in the safe management of the biomass supply chain are, among others [27]:

- Type of biomass;
- Physical, chemical and mechanical properties of biomass;
- Raw material availability;
- Technical possibilities of transport;

- The possibility of pre-treatment before the conversion process;
- Location of energy production sites.

The use of biomass requires measures to be taken throughout the supply chain, including raw material extraction, production, distribution and use of biomass, including transport and storage. Taking as the criterion the source for energy production in renewable energy technology, we distinguish two groups of management in logistics:

- Complete supply chain management (CSCM) with solid and liquid biomass as an energy source;
- Partial supply chain management (PSCM) with solar energy, wind, geothermal energy, hydropower, etc. [28–30].

The complete supply chain (CSCM) covers the supply of raw materials and materials for energy production and maintenance as well as the energy production and distribution process itself. The goal of supply chain management is to increase efficiency while reducing operating costs, and above all to adapt energy production to the needs of customers [31].

Achieving the above assumptions should also be consistent with the aforementioned principles of sustainable development, which requires the integration of activities in three key areas: economic, environmental and social. In practice, the tools allowing for such a combined assessment are used to a limited extent. On the other hand, tools are commonly used, thanks to which it is possible to assess the scale of the effects arising in each of these three areas separately. Considering the directions of the energy development, which includes the promotion of energy from renewable sources, including biomass, more and more attention is paid to the aspect of reducing CO_2 emissions. The most popular tool supporting the process of emission analysis is the use of the Life Cycle Assessment (LCA) methodology, which allows for the identification and prioritization of environmental hazards occurring in the life cycle of products or processes, and consequently creates the basis for determining the methods of minimizing them.

Life Cycle Assessment is a relatively new method of environmental management [32]. It allows the identification of the most important environmental aspects and assessment of their impact on the environment throughout the life cycle of a given product (i.e., "from cradle to grave"), starting from obtaining raw materials through the production process, use and final waste management [33]. It can be concluded that an agricultural biogas plant is an installation that perfectly complies with the principles of sustainable development also in terms of the logistics process [34].

The increase in the share of renewable energy sources in the world fuel and energy balance contributes to the improvement of the efficiency of the use and saving of energy raw materials, improvement of the environment by reducing the emission of pollutants into the atmosphere, and thus contributing to counteracting negative climate warming. Theoretical analyses show that as a result of production 1 GJ of primary energy (from burning an appropriate amount of fuel), approximately 98 kg CO_2 is generated if coal is burned and 56 kg CO_2 if high-methane gas is burned. The amount of carbon dioxide emitted to produce 1 MWh of electricity is specified at about 350 kg/MWh for fossil fuels (hard coal) and 201.6 kg/MWh for high-methane gas, respectively [35]. Direct combustion of 1 m^3 of agricultural biogas results in the emission of 1.96 kg of CO_2. For comparison, 1 m^3 of landfill gas emits 9.2 kg of CO_2 [36]. The research carried out so far [37] has estimated the overall greenhouse gas reduction potential with the use of agricultural biogas technology up to 148%.

The aim of this study is to investigate for several substrates (edible plant—corn, agricultural waste—slurry) the level of carbon dioxide reduction in the life cycle of products during biogas production.

2. Materials and Methods

2.1. Purpose and Methodology of Research

The article describes in detail the LCA method used in the analysis and collected literature data on crops, which at a later stage were used to calculate the final greenhouse gas emissions expressed in carbon dioxide equivalent (CO_{2eq}).

The analysis of the reduction of carbon dioxide emissions resulting from the production of energy from agricultural biogas was performed based on the data for crops, taking into account the simulated operating parameters of plants producing agricultural biogas.

2.2. Description of General Assumptions

In the analysis, a model of a biogas plant was used, in which the technological process is based on methane fermentation taking place in mesophilic conditions, because in Poland this is the most used and the most effective process [38,39].

One of the substrates most used in biogas plants in Central and Eastern Europe is maize silage. In 2018, approx. 480 thousand tons of silage were used to produce biogas. A typical biogas plant with a capacity of 1 MW of electricity consumes 70–80 tons of maize substrate per day [40].

Apart from maize, the most frequently used substrate in Poland in biogas installations was slurry, of which approx. 760 thousand m^3 were used in 2018 [41]. Therefore, the analysis will cover technologies based on the use of the above-mentioned substrates. The assumption was that the produced biogas would be used in the process of high-efficiency cogeneration. The generated heat will be used to cover own needs, and above all, to heat the fermentation chamber. It was assumed that heat energy for own needs will constitute 25% of the total energy generated in the installation. The raw material will be transported by a truck powered by diesel fuel over a distance of 30 km.

The analyses were carried out for separate substrate variants, which are:

- Variant I—agricultural biogas production is based only on the use of maize silage.
- Variant II—agricultural biogas production based on a substrate mix consisting of a mixture of maize and cattle slurry in the ratio of 70:30 [42].

Variant II was used because it is a representative example for Polish conditions [43].

The construction of the computational model consisted of creating a sequence of logical dependencies between the sub-processes included in the analyzed processes. A graphical representation of such an activity is the product life cycle (Figure 1), where the stage of obtaining raw materials, processing them and obtaining energy, producing the product and its consumption, are interdependent processes according to the LCA approach. Obtaining electricity from each installation is treated in the simulation as a logistic process—it includes numerous data, such as obtaining raw materials, physical and chemical parameters of the raw material, physical and mechanical parameters of the installation (efficiency, lifetime, efficiency, etc.), supplementary processes and auxiliary [44].

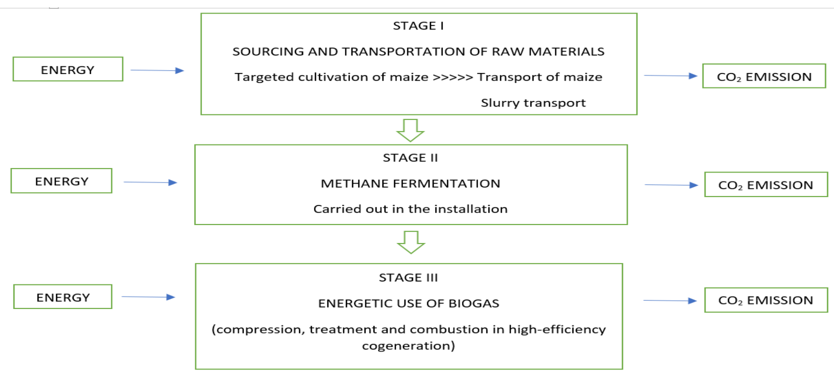

Figure 1. A simplified diagram of the life path of raw materials for energy production from biogas. Source: own elaboration.

3. Results

3.1. Calculation of CO_2 Emission Reduction for Variant I (Maize Silage)

At the beginning of the analysis, the potential amount of gross biogas yield was established. The adopted values necessary for calculations, based on the relevant literature data [35,45], were:

- Mass of the substrate—1 t.;
- Dry matter content—32.5%;
- Content of dry organic matter—90.8%.

It was assumed that the yield of maize is at the level of 60 [t/ha]. The biogas yield from one ton of maize forage was determined at 190 [m^3/t], which was converted into biogas yield per hectare of 60 [t/ha] × 190 [m_3/t] = 11,400 [m^3/ha]. The calorific value (CV) of biogas was determined at 25 MJ/m^3, which corresponds to 5.4 kWh. After processing the above data, the following energy value was obtained: 1026 kWh/m^3/t of silage. The amount of biogas losses because of various leaks in the biogas system was assumed to be about 2% (20.52 kWh/m^3 is irretrievably lost), the electrical efficiency is 35% and the thermal efficiency is 45% (the overall efficiency of cogeneration was assumed to be 80%). Therefore, from the installation adopted in the simulations, there will be 351.9 kWh of electricity and 452.25 kWh of heat. Further, 25% of heat energy in the amount of 90.45 kWh will be used for own needs, mainly to maintain a certain temperature.

3.1.1. Calculation of the Value for Stage I

Stage I, as illustrated in Figure 1, consists of unit processes such as cultivation, agrotechnical works and transport of raw materials. In order to calculate the amount of carbon dioxide emitted to the atmosphere due to energy consumption for growing the substrate in the form of maize, the amount of CO_{2eq} emitted due to agricultural works and industrial production of fertilizers used for cultivation was determined. When starting the calculation of the emissions during agricultural work, it was assumed that plowing, harrowing, fertilizing three times and sowing maize requires six times the use of a farm tractor per hectare. This entails, in order to obtain a yield of 60 t per ha, diesel consumption in the amount of 154 [kg/ha]. Therefore, to produce one MWh in biogas, it is needed to cultivate 0.0125 hectares and use 0.0125 [ha/MWh] × 154 [kg/ha] = 1.92 [kg ON/MWh] = 0.53 [g/MJ].

When starting the calculation of the amount of CO_2 emitted during the application of mineral fertilizers it was assumed that the recommended doses of artificial fertilizers for the cultivation of maize for silage are as follows: phosphorus—300 kg/ha, urea—150 kg/ha and ammonium nitrate 20–250 kg/ha [46–48]. Knowing the percentage of NPK in the fertilizer and the corn yield (60 t), the following demand for fertilizers was assumed:

- Synthetic nitrogen fertilizer: 169 kg N/ha/year;
- Calcium fertilizer: 780 kg CaO/ha/year;
- Potassium fertilizer: 90 kg K_2O/ha/year;
- Phosphorus fertilizer: 60 kg P_2O_5/ha/year.

One should also take into account the field emissions of N_2O, which I will take according to the calculation of the Biograce II = 6.07 gCO_{2eq}/MJ biogas calculator used, inter alia, in numerous Polish articles [49–52]. The corn grown in this way is then transported to a biogas plant. In order to determine the amount of CO_{2eq} emitted during the transport of maize, it was assumed that the distance of the maize green fodder harvesting site from the biogas plant was equal to 30 km. A truck with a load of about 20 tons and a semi-trailer consumes 40–45 L of diesel/100 km. The values quoted above show that 1 L of diesel fuel is 154 [kg/ha]/183 × [L/ha] = 0.84 kg of diesel.

Thus, it was assumed that the lorry consumes on average 42.5 L × 0.84 kg/L = 35.7 kg of diesel per 100 km and, respectively, for the discussed transport of diesel fuel:

$$Z \times Q/Ł = 10.71 \text{ [kg of diesel]} \times 0.96 \text{ [t/MWh]}/40 \text{ [t]} = 0.257 \text{ [kg of diesel/MWh]},$$

where: Z = L = 35.7 [kg] × 30 [km]/100 [km] = 10.71 [kg of diesel], it is the diesel consumption for transport by a lorry 40 [t] over a distance of 30 km. After summing up all the calculated indicators at stage I—i.e., transport, harvesting and cultivation of maize, the emission amounts to 13.62 g CO_{2eq}/MJ of biogas.

3.1.2. Calculation of the Value for Stage II

Stage II is direct methane fermentation. For the full calculation of the balance, biogas losses must be taken into account as 2% of the total energy of the produced gas. According to the calculations of the Biograce 4.0 calculator, these losses amount to 2.22 gCO_{2eq}/MJ of biogas.

Another component of the methane fermentation process are emissions resulting from the feeding of pumps and mixers in the fermentation chamber, as well as heating the fermentation chamber. For this purpose, in the further part of the assumptions for the analysis, it was assumed, regardless of the type of substrate used, that the energy inputs (electricity) amount to 0.0097 kWh/1 MJ of biogas for feeding the loading pump and mixers in the fermentation chamber, 0.011 kWh/1 MJ of biogas for purification of biogas. According to the Biograce calculator, these emissions are 0.32 gCO_{2eq}/MJ biogas.

3.1.3. Calculation of the Value for Stage III—The Energetic Use of Biogas

At this stage, according to further calculations of the tool, the emissions caused by the surplus of energy produced are 9.95 gCO_{2eq}/MJ biogas. Summing up the emissions from all stages of biogas production from maize silage gave the value of 27.2 gCO_{2eq}/MJ biogas. After converting this value to the second functional unit, which is already MJ of electric energy, this value was 86.2 g CO_{2eq}/MJ electric energy. The reference amount of carbon dioxide from fossil fuels is 186 gCO_{2eq}/MJ electric energy. The reduction in this analysis was 54%.

3.2. Calculation of CO_2 Emission Reduction for Variant II (Substrate Mix—70% Maize Silage and 30% Slurry)

In this variant, changes in the amount of CO_2 emissions will be visible only in the first stage of the entire life cycle. As already mentioned in the general assumptions and descriptions of individual variants, the slurry at stage I, i.e., obtaining the raw material, is considered as agricultural waste. The slurry used for the production of biogas, and thus disposed of, is considered to be zero-emission.

In order to calculate the overall balance of CO_2 emissions reduction, we can therefore conclude that the emissions at the stage of methane fermentation and energy use of biogas will be the same as in the case of variant I, i.e., biogas production from maize silage. Emissions will differ only at stage I—here you should reduce the emissions by the percentage of the slurry share. In this case, the emissions generated during the production of the raw material at stage I amounted to 9.56 gCO_{2eq}/MJ of biogas. Other emissions remain unchanged. Obtaining biogas from the substrate mix then generates 22.03 gCO_{2eq}/MJ biogas. After converting this value to the second functional unit, which is already MJ of electricity, this value was 69.8 gCO_{2eq}/MJ electric energy. The overall reduction of CO_2 emissions in this instance was 62%.

4. Discussion

Based on the conducted analysis and the obtained calculation results, it was found that the use of biogas production technology contributes significantly to the reduction in greenhouse gases, even though some stages of the process often cause significant emissions of these gases to the atmosphere.

The results show that the reduction in the level of emission reduction occurs with an increase in the share of substrate burdened with deliberate cultivation and numerous energy inputs—in the case under consideration it is maize from which we obtain silage. Such a statement is confirmed by the fact that when using silage as the only substrate for a biogas plant, almost half of the emissions generated are generated during the first stage, i.e., the process of obtaining the substrate (according to the calculations of 13.62 gCO_{2eq}/MJ biogas). Field emissions and emissions related to the use of nitrogen fertilizers account for the largest share in the energy and emission balance of the maize silage cultivation process at stage I.

The remaining greenhouse gas emissions from the technological process stage (stage II), i.e., the emissions from energy consumption from conventional raw materials needed to heat the digester, as well as emissions caused by surplus electricity (stage III), amounted to 13.58 gCO_{2eq}/MJ biogas. The overall emissivity of the biogas production process from maize silage was 27.2 gCO_{2eq}/MJ biogas, which translated into a 52% reduction in greenhouse gas emissions.

In the second considered case of the substrate mix (70% maize silage plus 30% slurry), the emission reduction was 10% more than in the case of using only maize silage. This is due to the fact that the slurry at the acquisition stage is a zero-emission substrate. It is agricultural waste, which, if not managed and properly utilized, would emit significant amounts of greenhouse gases into the atmosphere. The total greenhouse gas emissions expressed in CO_2 equivalent during the production of biogas from the substrate mix amounted to 22.03 gCO_{2eq}/MJ biogas. This results in a reduction of CO_2 emissions of 62% compared to CO_2 emissions from fossil fuels.

5. Conclusions

The results presented above show that the use of the substrate mix as a biogas input is more effective and economical in terms of CO_2 emissions in terms of climate and environmental protection.

The analysis shows that both when using maize silage and the substrate mix for biogas production, the reductions in greenhouse gas emissions expressed in CO_2 equivalent amount to over 50%. In the case of the substrate mix, the savings in emissions compared to the required threshold are large, amounting to 12%. The biogas installation has a positive effect on the environment, contributing to the reduction of the greenhouse effect, and should be used in Poland. In the case of a biogas plant based only on the cultivation of maize silage, the reduction of emissions is lower and amounts to 52%.

As a result of a series of studies and experiments, it was found that the methane fermentation process itself, assuming the tightness of the installation, proceeds without major emissions of greenhouse gases into the atmosphere. Stage I (described above) generates the greatest release of harmful gases into the atmosphere. Thus, the emphasis should be on limiting gas emissions in the preliminary stage during the deliberate cultivation of plants. In addition, reducing the transport distances of raw materials for the production of biofuels also affects the final result of reducing CO_2 emissions. Also, the use or exploration of less emitting crop fertilizers can bring benefits in the amount of CO_2 emissions reduction of up to 5%.

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References

1. Muradin, M.; Foltynowicz, Z. Potential for Producing Biogas from Agricultural Waste in Rural Plants in Poland. *Sustainability* **2014**, *6*, 5065–5074. [CrossRef]
2. Kowalczyk-Juśko, A.; Szymańska, M. Poferment Nawozem dla Rolnictwa (Digestate as Fertilizer for Agriculture). 2015. Available online: https://ksow.pl/files/Bazy/Biblioteka/files/Poferment_nawozem_dla_rolnictwa_01.pdf (accessed on 19 June 2022).
3. Powałka, M.; Klepacka, A.; Skudlarski, J.; Golisz, E. Aktualny stan sektora biogazu rolniczego w Polsce na tle krajów Unii Europejskiej. The current state of the agricultural biogas sector in Poland compared to the European Union countries). *Zesz. Nauk. Szk. Gł. Gospod. Wiej. Warszawie Probl. Rol. Świat.* **2013**, *13*, 203–212. [CrossRef]
4. Florkowski, W.; Us, A.; Klepacka, A. Food waste in rural households support for local biogas production in Lubelskie Voivodship (Poland). *Resour. Conserv. Recycl.* **2018**, *136*, 46–52. [CrossRef]
5. Ginalski, Z. Substraty dla Biogazowi Rolniczych (Substrates for Agricultural Biogas Plants). Available online: https://cdr.gov.pl/pol/OZE/substraty.pdf (accessed on 19 June 2022).
6. Rosińska-Bukowska, M.; Janiszewska, A.; Mordwa, S. *Potential of Poland. Introduction to Socio-Economic Geography of Poland for Foreigners*; Department of Spatial Economy and Spatial Planning: Warsaw, Poland, 2012.
7. Jasiulewicz, M. Possibility of liquid bio-fuels, electric and heat energy production from biomass in Polish agriculture. *Pol. J. Environ. Stud.* **2010**, *19*, 479–483.
8. Statistics Poland. *Agriculture in Poland in 2019*; Statistics Poland: Warsaw, Poland, 2020.
9. Romaniuk, W.; Łukaszuk, M.; Karbowy, A. Potencjalne możliwości rozwoju biogazowni w gospodarstwach rolnych w Polsce. (Potential possibilities for the development of biogas plants on farms in Poland). *Probl. Inż. Rol.* **2010**, *4*, 129–139.
10. Gradziuk, P. Potencjał i prognozy wykorzystania biogazu rolniczego w Polsce (Potential and forecasts for the use of agricultural biogas in Poland). *Rocz. Nauk. Stowarzyszenia Ekon. Rol. Agrobiz.* **2017**, *19*, 64–70.
11. Weiland, P.; Rieger, C.; Ehrmann, T. Evaluation of the newest biogas plants in Germany with respect to renewable energy production, green house, gas reduction and nutrient management. In *The Future of Biogas in Europe II*; European Biogas Workshop: Esbjerg, Denmark, 2003.
12. Pochwatka, P.; Pulka, J. *Biogaz Rolniczy-Nowe Otwarcie (Agricultural Biogas-New Opening)*; Technika: Vilnius, Lithuania, 2020; pp. 72–74.
13. Budzianowski, W.M.; Chasiak, I. The expansion of biogas power plants in Germany during the 2001–2010 decade: Main sustainable conclusions for Poland. *J. Power Technol.* **2011**, *91*, 102–113.
14. European Environment Agency. *Trends and Projections in Europe 2021*; European Environment Agency: Copenhagen, Denmark, 2021.
15. Gołasa, P.; Gradziuk, P.; Gradziuk, B.; Golonko, M.; Gromada, A.; Bieńkowska-Gołasa, W.; Siedlecka, A. Źródła emisji gazów cieplarnianych w rolnictwie, ze szczególnym uwzględnieniem emisji ze zużytej energii (Sources of greenhouse gas emissions in agriculture, with particular emphasis on emissions from the energy used). *Energies* **2021**, *14*, 3784. [CrossRef]
16. Piechota, G.; Igliński, B. Biomethane in Poland—Current Status, Potential, Perspective and Development. *Energies* **2021**, *14*, 1517. [CrossRef]
17. Sztekler, K.; Komorowski, M.; Wal-Agh, K. Modelowanie procesu ograniczania emisji CO_2 z układów energetycznych (Modeling the process of reducing CO_2 emissions from energy systems). *Energetyka* **2020**, *11*, 740–747.
18. International Energy Agency (IEA). Net Zero by 2050. A Global Roadmap for the Energy Sector. Available online: https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf (accessed on 19 June 2022).
19. Krajowy Ośrodek Bilansowania i Zarządzania Emisjami (KOBIZE). *Krajowy Raport Inwentaryzacyjny*; Krajowy Ośrodek Bilansowania i Zarządzania Emisjami (KOBIZE): Warszawa, Poland, 2016.
20. Budzianowski, W.M. Sustainable biogas energy in Poland: Prospects and challenges. *Renew. Sustain. Energy Rev.* **2012**, *16*, 342–349. [CrossRef]
21. IPCC. *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2012.
22. Pawlita-Posmyk, M.; Wzorek, M. Biogas production from the perspective of sustainable development. *Econ. Environ. Stud.* **2018**, *18*, 1043–1057. [CrossRef]
23. Sołtysik, M. *Zarządzanie Logistyczne, III Wydanie, Zmienione i Rozszerzone*; Wydawnictwo AE: Katowice, Poland, 2003; p. 11.
24. Beier, F.J.; Rutkowski, K. *Strategia Zarządzania Dystrybucją*; Placet: Warszawa, Poland, 1996.
25. Witkowski, J. *Strategia Logistyczna Przedsiębiorstw Przemysłowych*; Wyd. AE: Wrocław, Poland, 1995.
26. Oniszk-Popławska, A.; Matyka, M.; Dagny-Ryńska, E. Evaluation of a long-term potential for the development of agricultural biogas plants: A case study for the Lubelskie Province, Poland. *Renew. Sustain. Energy Rev.* **2014**, *36*, 329–349. [CrossRef]
27. Osiak, J.; Dwórznik, M. *System Storage, Distribution and Sale of Biomass*; Amicus Society: Warsaw, Poland, 2016.
28. Krupnik, D. Bezpieczeństwo zarządzania łańcuchem dostaw biomasy. *Ekon. Organ. Logistyki* **2019**, *4*, 41–53. [CrossRef]
29. Igliński, B.; Buczkowski, R.; Iglińska, A.; Cichosz, M.; Piechota, G.; Kujawski, W. Agricultural biogas plants in Poland: Investment proces, economic and environmental aspects, biogas potential. *Renew. Sustain. Energy Rev.* **2012**, *16*, 4890–4900. [CrossRef]
30. Murphy, J.D.; McKoegh, E. The benefits of integrated treatment of waste for the analysis production of energy. *Energy* **2006**, *31*, 294–310. [CrossRef]

31. Davis, T. Effective supply chain management. *Sloan Manag. Rev.* **1993**, *34*, 35–46.
32. Curran, M.A. *Life Cycle Assessment: Principles and Practice*; United States Environmental Protection Agency: Washington, DC, USA, 2006.
33. Aziz, N.I.H.A.; Hanafiah, M.M.; Gheewala, S.H.; Ismail, H. Bioenergy for a Cleaner Future: A Case Study of Sustainable Biogas Supply Chain in the Malaysian Energy Sector. *Sustainability* **2020**, *12*, 3213. [CrossRef]
34. Jürgensen, L.; Ehimen, E.A.; Born, J.; Holm-Nielsen, J.B. A combination anaerobic digestion scheme for biogas production from dairy effluent—CSTR and ABR, and biogas upgrading. *Biomass Bioenergy* **2018**, *111*, 241–247. [CrossRef]
35. Kwaśny, J.; Banach, M.; Kowalski, Z. Technologies of biogas production from various sources—A review. *Chem. Technol. Trans.* **2012**, *17*, 83–102.
36. Hennecke, A.M.; Faist, M.; Reinhardt, J.; Junquera, V.; Neeft, J.; Fehrenbach, H. Biofuel greenhouse gas calculations under the European Renewable Energy Directive-a comparison of the Biogracee tool vs. the tool of the Roundtable on Sustainable Biofuels. *Appl. Energy* **2013**, *102*, 55–62. [CrossRef]
37. Żmuda, K. Biomass Potential in the Production of Agricultural Biogas in Poland. In *Renewable Energy Sources as a New Challenge for Rural Areas in Poland*; Kucharska, B., Ed.; Foundation of Assistance Programme for Agriculture (FAPA): Opole, Poland, 2009; pp. 17–20.
38. Borowski, S.; Domański, J.; Weatherley, L. Anaerobic co-digestion of swine and poultry manure with municipal sewage sludge. *Waste Manag.* **2014**, *34*, 513–521. [CrossRef] [PubMed]
39. Fugol, M.; Szlachta, J. Feasibility of using maize silage and pig slurry for biogas production. *Agric. Eng.* **2010**, *119*, 169–174.
40. Kutera, J.; Hus, S. *Agricultural Treatment and Use of Sewage and Slurry*; Agricultural University in Wrocław: Warszawa, Poland, 1998.
41. Murphy, J.D.; McKeoghb, E.; Kiely, G. Technical/economic/environmental analysis of biogas utilization. *Appl. Energy* **2004**, *77*, 407–427. [CrossRef]
42. Gołembska, E. *Logistyka Jako Zarządzanie Łańcuchem Dostaw*; AE: Poznan, Poland, 1994.
43. Kowalczyk-Juśko, A.; Kościk, B.; Jóźwiakowski, K.; Marczuk, A.; Zarajczyk, J.; Kowalczuk, J.; Szmigielski, M.; Sagan, A. Effects of biochemical and thermochemical conversion of sorghum biomass to usable energy. *Przem. Chem.* **2015**, *94*, 1838–1840.
44. Księżak, J. Produkcja kukurydzy w różnych rejonach Polski (Maize production in various regions of Poland). *Wieś Jutra* **2009**, *3*, 16.
45. Król, A. Kiszonki—Cenny substrat do produkcji biogazu (Silage—A valuable substrate for biogas production). *Autobusy Technol. Eksploat. Syst. Transp.* **2011**, *10*, 249–254.
46. Romaniuk, W.; Domasiewicz, T. Substraty dla biogazowni rolniczych (Substrates for agricultural biogas plants). *Agrotech. Porad. Rolnika* **2014**, *11*, 74–75.
47. Oslaj, M. Biogas production from maize hybrids. *Biomass Bioenergy* **2010**, *34*, 1538–1545. [CrossRef]
48. Dołęga, W. *Ekologia w Wytwarzaniu (Ecology in Production)*; Energia Gigawat: Poznan, Poland, 2016.
49. Konieczna, A.; Borek, K.; Mazur, K.; Wardal, W. Emisje tlenku azotu (I) i ditlenku węgla z aplikacji nawozów nieorganicznych i naturalnych w wybranych technologiach upraw kukurydzy na kiszonkę (Emissions of nitrogen oxide (I) and carbon dioxide from the application of inorganic and natural fertilizers in selected technologies of maize cultivation for silage). *Przem. Chem.* **2019**, *1*, 901–906. [CrossRef]
50. Jarosz, Z.; Faber, A. Możliwości ograniczenia emisji rolniczych z uprawy pszenicy przeznaczonej na cele paliwowe (Possibilities to reduce emissions agricultural with growing wheat intended for fuel purposes). *Probl. Inż. Rol. Probl. Agric. Eng.* **2015**, *6*, 75–83.
51. Jarosz, Z.; Faber, A. Możliwości ograniczenia emisji rolniczych z uprawy kukurydzy przeznaczonej do produkcji bioetanolu (The p ossibility of agricultural emission limitations from corn cultivation on bioethanol). *Stow. Ekon. Rol. Agrobiz.* **2016**, *6*, 12–126.
52. Rogowska, D. *Ocena Wpływu Czynników Występujących na Etapie Uprawy na Emisję GHG w Cyklu Życia Bioetanolu (Assessment of the Influence of Factors Occurring at the Stage Crops for GHG Emissions in the Life Cycle of Bioethanol)*; Nafta-Gaz: Zug, Switzerland, 2017; pp. 119–125.