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Environmental Assessment of the Life Cycle of Electricity Generation from Biogas in Polish Conditions

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Abstract: Life cycle analysis allows for the assessment of the qualitative and quantitative relationship between selected areas of human activity and the consequences for the environment. One of the important areas is the production of electricity and heat, for which the main raw material in Poland is hard coal. An alternative may be to use biogas as a fuel for energy purposes. This article presents the assessment of environmental hazards caused by the production of energy from biogas. The analysis took into account the change of the substrate from maize silage, commonly used in Polish biogas plants, to waste from the domestic agri-food industry. The evaluation covered the acquisition of substrates, their transport to a biogas plant, generation of electricity from biogas, and management of the generated by-products. The analysis was done in terms of both the impact and sensitivity categories. It was found that the emission of pollutants related to the acquisition of the substrate plays a key role and the use of waste for the production of biogas used for energy production brings environmental benefits. The analysis has shown that replacing coal with biogas, regardless of the raw materials used in its production, results in a positive environmental effect, especially in the areas of human health and resources categories. The positive environmental effect of the production of electricity from biogas can be enhanced by switching raw materials from purpose-grown crops to waste from the agri-food industry and agriculture. An important factor influencing the environmental impact is the degree of heat utilization (the greater the percentage of heat utilization, the greater the environmental benefits) and management of all by-products.

Keywords: LCA; life cycle assessment; waste; biogas; GHG emission

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1. Introduction

Progressing climate change and its negative effects on the environment are already a matter of course. The last five years have been the warmest in the history of temperature measurements, and since 2019, the average global temperature has risen by 1.1 °C above pre-industrial levels [1]. The effects of global warming are undisputed and increasingly felt in all regions of the world. One of the main causes of global warming is anthropogenic emissions of greenhouse gases (GHG), mainly carbon dioxide (CO_2), caused by the burning of fossil fuels [2]. Together with the emissions of other greenhouse gases, such as methane, CO_2 emissions from the energy sector account for more than 75% of the total GHG emissions in the European Union countries [3]. This justifies the need to transform the energy system toward a climate-neutral economy, as well as to take urgent and intensive measures to reduce GHG emissions. The answer to Europe's climate problems is the concept of the European Green Deal, which assumes a reduction of GHG emissions by 55% in 2030 compared to the base year (1990), as well as achieving climate neutrality in 2050 [4]. Achieving the indicated climate goals will be a very big challenge for the Member States with a greater share of fossil fuels in the energy mix, and thus also higher greenhouse gas emissions. One of such countries is Poland, the power industry of which is largely based on the combustion of fossil fuels, primarily hard coal. The consequences of burning coal, in addition to CO_2 emissions, are high emissions of dust, nitrogen, and sulfur oxides, contributing to the intensification of the greenhouse effect in the atmosphere. Considering the above, other technical solutions for energy generation are sought, the use of which will reduce the negative impact of the use of fossil fuels [5,6].

Tangible environmental benefits can be obtained by using renewable energy sources (RES), which enable a radical reduction of fossil carbon dioxide emissions [7–9]. Among renewable energy sources, biofuels, especially the so-called advanced biofuels, have attracted increased attention. These fuels are produced from products unsuitable for the agri-food industry, i.e., by-products and waste materials [10]. In addition to environmental benefits, this approach fits in with the ideas of a circular economy [11].

One of the alternative fuels is biogas. This gas can be produced by microorganisms from different substrates (e.g., organic waste from agricultural, industrial, and food sources, as well as the biodegradable fraction of municipal wastes) during the methane fermentation process [12–14]. The use of biogas as an energy carrier brings various environmental benefits [15,16], such as waste management or the avoidance of methane emissions to the atmosphere. Moreover, it can contribute to a significant reduction in GHG emissions. In some cases, a negative CO_2 balance (known as negative emissions) is found throughout the life cycle resulting from avoided GHG emissions associated with the use of the alternative case concerning reference one [17–19]. The positive result of the emission (negative values) is mainly influenced by the use of waste for the production of biogas, the so-called WtE (waste to energy) process. However, as an energy carrier, biogas does not always have such a favorable environmental impact. The amount of the final emission in the entire life cycle of this gas is influenced by many factors, such as: the type of raw materials used, the fermentation method, the method of storing the digestate mixture and its management, or the method of managing the biogas itself [20,21].

One of the most frequently used methods allowing for the multidimensional assessment of GHG emissions is the life cycle assessment (LCA) analysis [22]. This method aims to identify and quantify the total environmental impacts/burdens of a product, process, or activity in terms of energy use, materials, and CO_2 emissions to the environment. LCA analysis covers all stages in the entire life cycle of a product, process, or activity, from obtaining materials/raw materials, through production, transport, and distribution, ending with operation and management after use [23]. Based on the analysis results, it is possible to select technical and technological solutions that are more environmentally friendly and contribute to its improvement. Due to its complexity and wide scope, LCA is often used to assess the environmental impact of various biofuels [24–26], processes of energy, bioproducts or energy carrier production [27–32]. This is evidenced by numerous examples of this type of analysis available in the literature, concerning the management of various wastes, e.g., food waste [33], plastics waste [34–36], municipal waste [37–39], sewage sludge and sewage [40–42]. Moreover, this kind of analysis can also be performed for the entire production systems, e.g., for biorefineries [43–47]. Numerous analyses have also been published for biogas. The work available in the literature relates to LCA in terms of:

- Selection of raw materials used in the methane fermentation process [48–52];
- Selection of the raw materials pretreatment methods [53–56];
- Selection of biogas production methods [57–60], including co-fermentation [61–64];
- Selection of upgrading methods from biogas to biomethane [65–69];
- The use of biomethane as a fuel for internal combustion engines [70–73];
- Method of digestate management [74–76];

As well as methods of managing the obtained biogas for energy purposes (e.g., in biogas plants, power plants and heating plants) [77–80]. In reference [81], the authors conducted research on the combined heat and power (CHP) life cycle from biogas from various agri-food raw materials. The system boundaries covered the extraction of raw material (slurry, whey, maize silage, and beet pulp), its transport, the methane fermentation process, energy production, as well as storage and use of the digestate as fertilizer. 1 MWh of energy was defined as the functional unit, with a ratio of electricity to heat of 1:1.4. It was found that compared to traditional fossil fuels, the co-production of electricity and heat from biogas produced from agricultural waste instead of target crops, leads to a reduction in environmental burden in various impact categories (the highest in the category of global warming potential—reduction by 50%). An unfavorable effect was found for the category of acidification and eutrophication potential (an increase of 25 and 12 times, respectively), due to the emission of ammonia during digestate storage and its application in the field. This impact can be reduced by recovering methane at all stages of the production of both biogas, electricity, and heat, and by improving the technique of using digestate on agricultural land.

Similar results were obtained in the study [82], where the reference system was electricity and natural gas from the national grid. Based on the analysis of five Italian biogas plants, it was found that the origin of the raw material and the method of storing the digestate have the greatest impact on the environment. Moreover, it was stated that the biogas plant may have a negative impact on the environment, e.g., due to the loss of methane at various stages of the process. Importantly, a crucial element in the LCA analysis is also the scale of the installation (a smaller environmental burden is caused by small biogas plants operating based on co-fermentation of waste raw materials than large biogas plants using maize silage). The obtained results of the LCA analysis also indicate clear environmental benefits related to the management of heat generated in a biogas plant, especially in the category of fossil fuels depletion, depletion of the ozone layer, global warming, and the formation of smog.

In the work [83] attention was drawn to the importance of the so-called avoided production processes. The use of this category contributes to the balancing of environmental burdens. In the case of a traditional agricultural biogas plant, the positive effects are related to the avoidance of conventional management of pig slurry, thus avoiding methane emissions during slurry storage and contamination of soil and groundwater during its storage or flushing from the field. The category of "avoided products" can also be applied to the avoided heat production from conventional energy sources owing to the heat produced from biogas.

In the work [84], the authors made a comparative analysis of 15 scientific publications, which presented LCA results for various biogas installations located in nine EU countries. Despite the different functional units, system boundaries, or analysis methods adopted in publications, it was possible to draw common conclusions. It has been studied that environmental benefits (especially in the categories of global warming potential and fossil resources depletion) can be reached due to the use of waste materials as a substrate. In the case of deliberately cultivated biomass, the process of obtaining it for biogas production becomes dominant in the entire biogas system. Regardless of the origin of the feedstock, it is essential to minimize methane losses during the methane fermentation process, digestate storage, and field application to further reduce negative environmental impacts.

The paper [85] presents an LCA analysis of biogas production and its use: (1) as an energy carrier in the gas network and (2) as a transport fuel. A significant reduction in GHG emissions was found for biogas as a fuel (from 524 to 477 kg CO_2 equivalent due to avoiding the use of conventional fuels). The solution concerning the use of biogas to generate electricity avoided about 300 kg of CO_2 equivalent.

Based on many reviews, it can be concluded that the researchers in LCA analyses make various assumptions regarding the scope of the analysis, methodology, etc., which makes the comparison of LCA results a challenge [86]. In addition, the assumptions made for the calculations, and thus the results obtained from these analyses, do not translate into the biogas market in other countries. This is due to, inter alia, different levels of development of the biogas market, different raw material characteristics, or different methods of biogas and by-products management.

The degree of biogas market development in Poland compared to other EU countries is relatively low. Currently, there are only 112 agricultural biogas producers in Poland (with total biogas production equal 532,224,626.000 m^3/year), so there is a lack of publications in the literature presenting the results of LCA analysis for national conditions. Considering the above, the subject of this publication is the environmental assessment of energy production from biogas through WtE processes, concerning Polish conditions. This assessment comprehensively covers all stages—both the production of gaseous fuel (obtaining raw material, the process of producing biogas) and the method of managing the gas product (applications in electricity generators). The results of life cycle assessments of biogas plants available in the literature indicate that they are primarily determined by the environmental load associated with the biogas production process itself, in which the emissions associated with substrate acquisition play a key role. These emissions depend on the type of feedstock, the way it is grown or the technology used to produce it, the types of energy carriers used, the local climatic conditions, and the farming practices in a given country. For the same feedstock, the emissions associated with its production can vary from country to country. In Poland, the conventional approach is to produce agricultural biogas by co-fermentation of maize silage and various agricultural waste (mainly slurry). The remainder of the process is used as fertilizer, while the obtained biogas is a carrier for the production of energy (electricity, and heat produced in cogeneration, but the heat in most cases is not fully used and constitutes an emission to air). For this reason, the paper presents the results of an LCA analysis of electricity generation from biogas under Polish conditions. Due to the gradual implementation of the circular economy model in Poland (the REDII Directive recommendations), it is reasonable to move away from the use of dedicated raw material crops toward the use of a wide variety of waste and residues. Therefore, the subject of the publication is to compare the environmental impact of two raw material models of biogas plant operation: a model based on the co-fermentation process of maize silage with waste from the agri-food industry and an alternative model based on the co-fermentation of only raw material that is a waste or residue from the agri-food industry in the Polish conditions. The authors' intention is to indicate the environmental benefits of using only waste materials for the methane fermentation process.

2. Materials and Methods

2.1. Goal and Scope

As part of the work, a simplified life cycle analysis of electricity generation from biogas through the WtE processes was carried out. The analyses were carried out under ISO 14040 [87] and ISO 14044 [88], using the SimaPro software and the BIOGRACE calculator. Several different methods are available in the SimaPro software. In the frame of this paper, the Eco-Indicator 99 for LCA analysis has been chosen. One of the advantages of Eco-Indicator 99 is a damage-oriented approach. Moreover, in the frame of this method a distinction is made between emissions to agricultural soil and industrial soil, which is very important, in that it takes into account the agricultural processes covered by the LCA analysis results presented in this study. It is also very important to pay attention to the uncertainties in the methods that is used to calculate the indicators. In the Eco-Indicator 99, two types are distinguished: uncertainties about the correctness of the models used and data uncertainties. When the decision-maker must compare a life cycle assessment of several different products using the Eco-Indicator 99, this method suggests considering the relative and absolute uncertainties. If we compare two similarly produced products, even small differences in results such as 10% to 20%, indicate that the materials differ (relative uncertainty). The Eco-Indicator 99 method is one of the first available in the SimaPro, but it is still valid and useful [89–92] and is based on constantly updated databases.

As part of the Eco-Indicator 99 method, 11 categories of the process impact on the environment were assessed: global warming, ozone depletion, acidification/eutrophication, ecotoxicity, photochemical smog, ionizing radiation, reduction of natural resources, land use, carcinogens, and substances affecting negatively on the respiratory system. The results were expressed in units assigned to each impact category and presented in two cases: characterization (in %) and normalization (in environmental impact points—Point) [93]. The characterization categories and the emissions are shown in Table 1.

Table 1. Impact categories available in the frame of the Eco-Indicator 99 method.

Impact Category	Input and Output Emission (LCI)
Global warming	Carbon dioxide—CO_2, nitrogen dioxide—NO_2, methane—CH_4, chlorofluorocarbon—CFC, hydrochlorofluorocarbon—HCFC
Ozone layer depletion	CFC, HCFC, halons
Acidification	Sulphur oxides—SO_x, nitrogen oxides—NO_x, ammonia—NH_4
Eutrophication	NO_x, NH_4, phosphates—PO_4^{3-}, nitrates—NO_3^-
Ecotoxicity	Heavy metals, particulate matter—PM
Ionizing radiation	Nuclides
Minerals and fossil fuels depletion	The amount of fossil fuels and minerals used
Land use	The area of land developed for crops as well as its conversion
Carcinogens	Polycyclic aromatic hydrocarbons—PAHs, heavy metals
Effects on the respiratory system	SO_x, NO_x, carbon monoxide—CO, PM

In the analyzed scope, concerning electricity generation from biogas, the most important categories of impacts were considered to be:

- Climate change;
- Ozone layer depletion;
- Acidification/eutrophication;
- Land use;
- Minerals and fossil fuels depletion.

The climate change impact category is characterized by an indicator defined on the basis of the greenhouse effect for the substance under consideration over the years. This indicates a strong, and sometimes direct relationship with the number of greenhouse gases emitted into the atmosphere, mainly carbon dioxide and methane.

Ozone depletion is described in terms of the ozone layer depletion (ODP) equivalent of the substance under consideration and its emissions. Stratospheric ozone is a direct barrier to ultraviolet radiation reaching the earth's surface. The increase in the intensity of ultraviolet radiation causes harmful effects on humans, animals, and plants. The emission of some greenhouse gases by industry and agriculture has a very large impact on the reduction of the ozone layer. Energy-consuming technologies in agriculture and the frequent use of agents supporting the growth of crops result in the depletion of the ozone layer. The effects of ozone depletion affect entire aquatic and terrestrial ecosystems, biochemical cycles, and indirectly, an increase in yields and a decrease in agricultural productivity.

Eutrophication is a process of enriching water reservoirs with nutrients (nutrients, biogens), increasing trophy, i.e., water fertility. This process also applies to watercourses. The main cause of eutrophication is the increasing load of biogenic elements, mainly nitrogen and phosphorus. A large amount of phosphorus is associated with the intensification of fertilization and an increase in erosion in the catchment area. On the other hand, the intensification of the nitrogen supply is related to, inter alia, increasing emission of nitrogen oxides to the atmosphere, and thus their high content in atmospheric precipitation. Fertilizing the land for cultivation also contributes to the so-called increase in nitrogen load. Heavy rainfall can easily leach nitrogen from the topsoil and fertilizer, and significant amounts of phosphorus may also be brought into the reservoir. The main source of these compounds in the natural environment is fertilizers used in agriculture. Considering the impact of production lines on eutrophication is therefore justified due to the use of fertilization of energy crops.

Acidification is caused by the excessive emission of mainly sulfur dioxide, nitrogen oxides, and ammonia. Since the combustion of fossil fuels contributes to high emissions, especially of sulfur compounds, it is proposed to include the acidification category in the environmental analysis. In addition, the use of fertilizers in agriculture is associated with ammonia emissions. An excess of acidic compounds has a negative impact, inter alia, on surface and groundwater, soil, flora and fauna.

The indicator of the reduction of mineral and fossil fuel resources is considered in the LCA method both on a global, regional, and local scale.

Land use should be understood as both using the land for cultivation and its conversion from one use to another. Population growth resulting in an increase in the demand for food brings an inevitable need for the development of agriculture and the mining industry to meet the nutritional and energy needs. This is largely related to the need to develop ever larger areas of the earth and to constantly transform it. The characterization index for the land use category is land use and the degree of land transformation expressed in surface area units. In the LCA surveys, the land use indicator is considered jointly at global, regional, and local levels.

The normalization categories included:

- Human health expressed in the unit of DALYs (disability adjusted life years i.e., the total amount of "healthy life" lost, from premature death to some degree of disability over a given period of time) used by the World Health Organization (WHO) and the World Bank in health statistics;
- Ecosystem quality: for acidification/eutrophication and land use, the damage dimension is determined by the fraction of species at risk of extinction (potentially disappeared fraction—PDF), and for ecotoxicity, the damage is expressed as [PAF $\times$ $m^2 \times year^{-1}$], which is the proportion of species present in the environment that are under toxic stress (potentially affected fraction of species—PAF);
- Reduction in natural resources expressed in [MJ/year].

In Poland, the main raw material for heat and electricity production is coal. The share of coal in the national energy mix is about 65%. The second major component at 25% is renewable energy sources, consisting of biomass co-firing, wind farms, and growing photovoltaics. For this reason, the production of heat and electricity in Poland, with such a significant share of fossil fuels, is a great burden on the environment. LCA analyses available in the literature for the national energy system, based on coal, indicate that the highest negative impact is characterized by the fossil fuel category. There is also a noticeable impact on the inorganic compounds and climate change categories due to significant dust and gas emissions into the air from coal combustion [94,95]. Example results of LCA analysis for a coal-fired CHP plant operating in Polish conditions are presented in Figure 1.

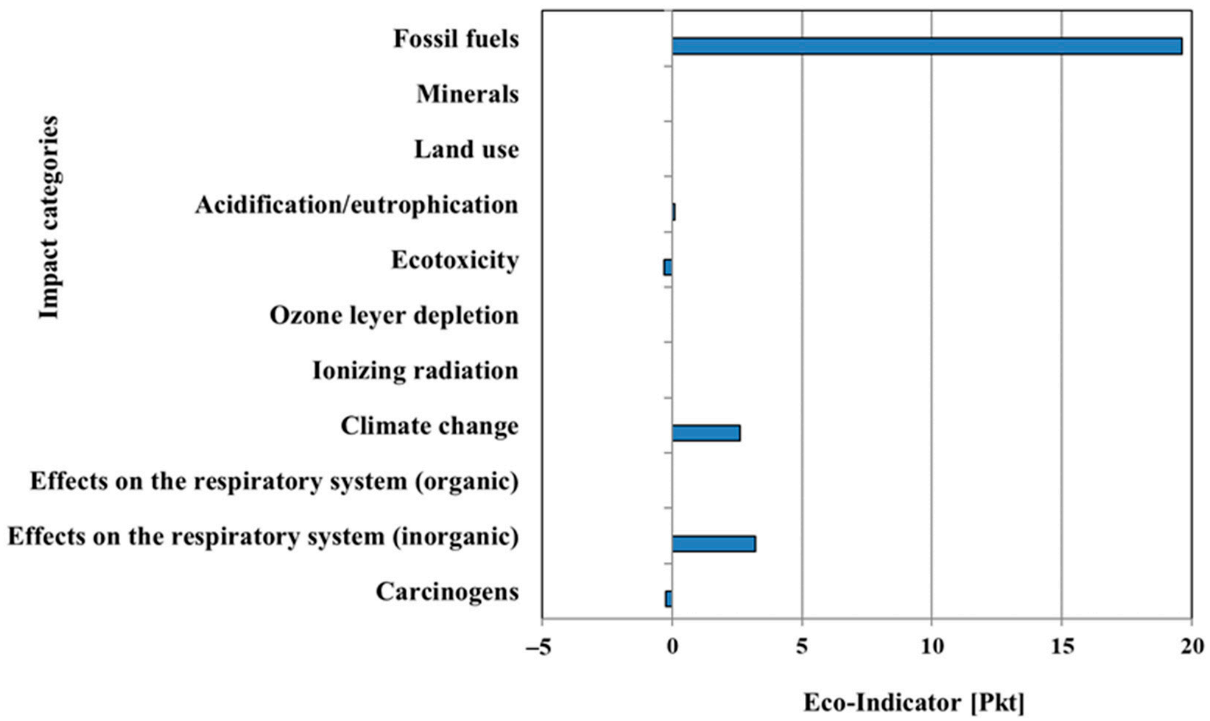

Figure 1. Results of LCA analysis for a coal-fired CHP plant operating in Poland (on the base of [94,95]).

Taking into account the degradation of the environment, the need for efficient management of the organic waste fraction, and the diversification of energy sources in the national energy mix, biogas plants, especially agricultural ones, are beginning to play an increasingly important role. Biogas plants can use different raw materials in the fermentation process, which can also generate different environmental loads. Therefore, one of the Polish biogas plants was analyzed, in which electricity and heat are produced in cogeneration processes. The biogas plant has an installed electric power of 1.2 MWe and thermal power of 1.3 MWt. Methane fermentation is carried out in mesophilic conditions, i.e., in the temperature range of 32–42 °C. The main substrates for the production of biogas are maize silage and residues from the agri-food industry (stillage, beet pulp, and pig slurry). The LCA analysis was carried out for two cases of electricity generation from a biogas produced from different kinds of substrates:

- **Case 1**—biogas obtained during the process of co-fermentation of waste materials (stillage, beet pulp, pig slurry);
- **Case 2**—biogas produced during the process of waste materials (stillage, beet pulp, pig slurry) and maize silage co-fermentation process.

Figure 2 shows the cases analyzed in this paper, while Table 2 describes the inventory assumptions for LCA. These assumptions were made based on data obtained from the biogas plant under consideration. This biogas plant operates under the assumptions presented in Case 2. For the analyzed plant, a change consisting of the complete elimination of maize silage and its replacement with waste was also considered (Case 1).

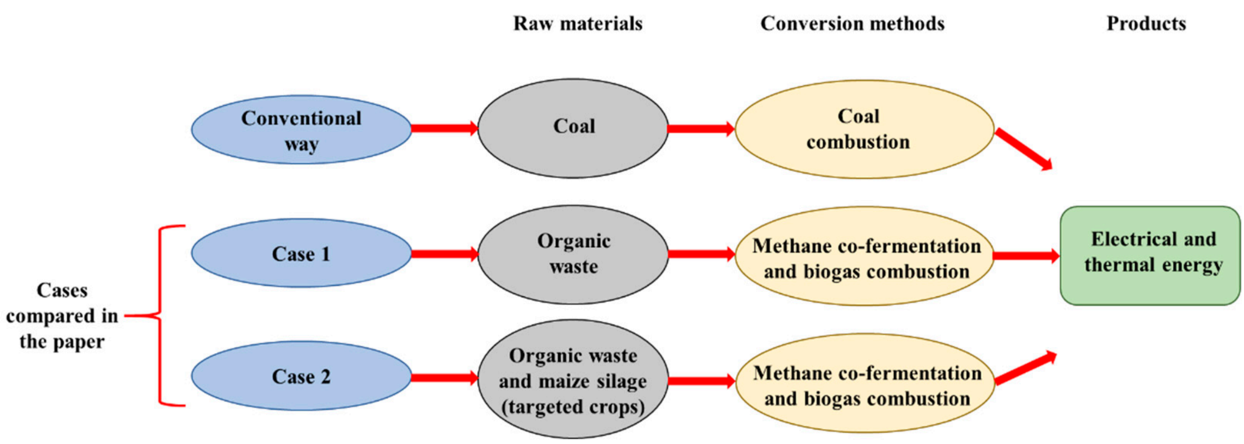

Figure 2. Cases analyzed in the frame of this paper.

Table 2. The inventory assumptions for life cycle assessment.

Kind of Input	Amount	Destination	Source of Data
Input from nature			
Water	1000 dm^3/MWh_e	Used in fermentation technology	Data from the biogas plant
Input data from technosphere (materials, fuels, electricity, heat, other)			
Maize silage Stillage Beet pulp	1.04 Mg/MWh_{el} 1.95 Mg/MWh_{el} 0.38 Mg/MWh_{el}	Substrate for fermentation	Data from the biogas plant
Diesel fuel	0.3 dm^3 0.0107 GJ/MWh_{el}	Fuel consumption related to the operation of machines and devices servicing the installation	Data from the biogas plant
Diesel fuel	2.57 dm^3 0.09165 GJ/MWh_{el}	Feedstock transport to the biogas plant	Own calculations
Transport distance	19 km—beet pulp, 95 km—stillage and 5 km—maize silage	n/a	Own calculations
Electricity	62.5 kWh/MWh_{el}	Electricity for own needed	Data from the biogas plant
Heat	87 kWh/MWh_{el}	Heat for own needed	Data from the biogas plant
SULFAX	0.98 kg	Biogas cleaning	Data from the biogas plant
Output data—main product			
Biogas (60% of methane)	400 Nm^3/MWh_{el}	Electricity and heat production	Data from the biogas plant
Electricity production from	2.5 kWh	-	Data from the biogas plant

Table 2. *Cont.*

Kind of Input	Amount	Destination	Source of Data
Output data—by-products, wastes, residues			
Digestate	2.8 Mg/MWh_{el}	Used as a fertilizers	Data from the biogas plant
Avoided production of ammonium nitrate (converted into total nitrogen)	48.55 kg/MWh_{el}	Avoided emission	Own calculations
Heat (treated as a waste to the air)	74% 0.80 MWh_c	Part of the heat is used to heat the hall and fermenters, while the rest is sent to a nearby garden farm	Data from the biogas plant and own calculations
Emission			
GHG emissions during the diesel fuel combustion by the machines operating the installation	CO_2: 783.39 kg/MWh_{el} CH_4: 0.06 kg/MWh_{el} N_2O: 0.03 kg/MWh_{el}	Emission to the air	Own calculations
GHG emissions to the air caused by feedstock transport	CO_2: 6705.45 kg/MWh_{el} CH_4: 0.550 kg/MWh_{el} N_2O: 0.275 kg/MWh_{el}	Emission to the air	Own calculations
GHG emissions to the air caused by cogeneration engine and in the flare	CO: 0.022232 kg/MWh_{el} SO_2: 0.036844 kg/MWh_{el} NO_2: 0.18132 kg/MWh_{el} CO_2: 791.986 kg/MWh_{el}	Emission to the air	Own calculations
GHG emissions connected by digestate storage	4.8 m^3 3.44 kg CH_4/MWh_{el}	Emission to the air	Own calculations
GHG emissions connected by digestate storage	3.2 m^3 6.24 kg CO_2/MWh_{el}	Emission to the air	Own calculations
Heat (as a waste)	24% 0.28 MWh_c	Emission to the air	Data from the biogas plant

For the purposes of this analysis, the following additional assumptions were made:

- In a biogas plant, depending on the substrate type, the produced biogas contains 58–65% v/v of methane; the mean methane concentration was assumed for the analyses at the level of 60% v/v;
- The production of biogas and electricity is a continuous process;
- Part of the electricity and heat generated in a biogas plant is allocated to the installation needs—the installation does not use energy from conventional sources;
- In the winter period (from September to April), 100% of thermal energy is used for the own needs and the needs of a horticultural farm operating nearby; in the summer period (May to August), about 30% of thermal energy is used for own needs, the rest is emitted to the environment; for the purposes of the analysis, it was assumed that 76% of generated heat energy is managed during the year;
- Digestate is not a waste—it is used as a soil-improving agent;

- The share of methane emissions from digestate is 2% v/v of the total greenhouse gas emissions from open lagoons; the literature data show that the share of methane emissions from open lagoons is 3–4% v/v [96], however, in the analyzed biogas plant, the fermentation process is carried out in two stages, which reduces the emission of this gas from the lagoons;
- Production of 1 MWh of electricity from biogas (biogas combustion in a cogeneration unit) results in unit emissions of: carbon monoxide—0.022 kg/MWh, carbon dioxide—791.986 kg/MW, sulfur dioxide—0.037 kg/MWh and nitrogen dioxide—0.181 kg/MWh.

For the analysis purposes, the following specific objectives were defined:

- Assessment of the potential environmental impact of maize cultivation and silage production;
- Assessment of the potential environmental impact of the technology used to generate electricity from biogas;
- Comparative analysis of the technology of generating electricity from biogas obtained in Case 1 and co-fermentation in Case 2.

The analysis lists two main stages:

- The raw material stage—the cultivation of maize for energy purposes;
- Technological stage covering the processes taking place in the biogas plant.

2.2. System Boundaries

For the raw material stage, the LCA analysis covered the cultivation of maize and the process of its ensilage. The remaining substrates are treated as waste or residue; therefore, in accordance with the RED2 Directive, their acquisition does not constitute an additional burden on the environment. For the raw material stage, the following sub-stages were analyzed (defined for this Life Cycle Assessment (Figure 3):

1. Establishing a plantation that includes the following unit processes:
    - Disking;
    - Winter ploughing.
2. Pre-sowing cultivation.
3. Sowing.
4. Cultivation of plantations, which includes the following unit processes:
    - Production of multi–component mineral fertilizers containing nitrogen—N, phosphorus—P and potassium—K (marked as NPK) and their application;
    - Foliar feeding;
    - Combating diseases and pests;
    - Water consumption related to the use of plant protection products.
5. A single-phase set consisting of the following unit processes:
    - Harvesting with a combine;
    - Field transport, including diesel oil production.
6. Transport of raw material from the field to the biogas plant with a truck tractor with a semi-trailer, including the production of diesel oil.

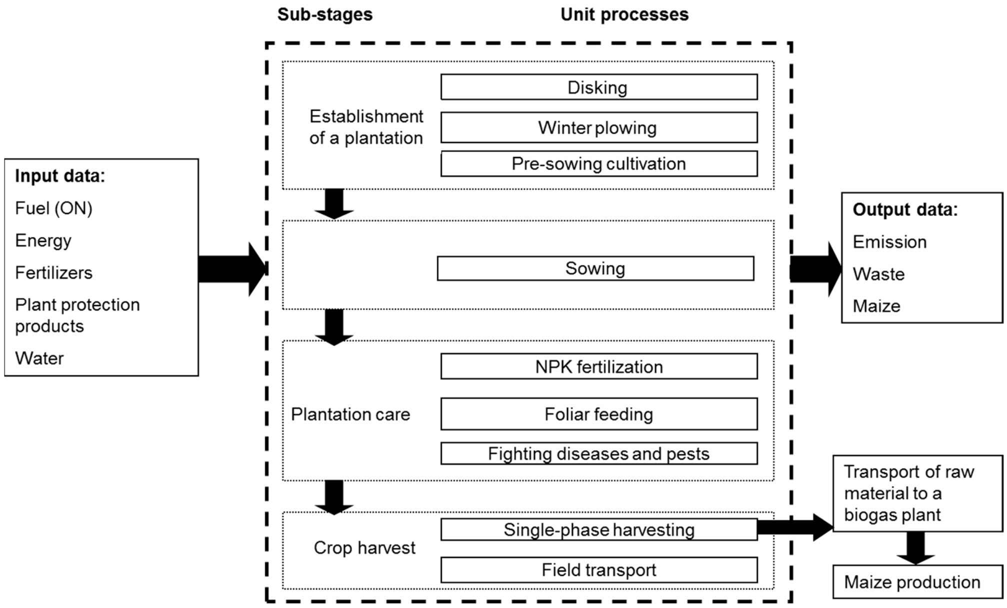

Figure 3. General flow chart covering the system boundaries and the unit processes of the maize growing and silage stage.

The following processes are outside the system boundaries:

- Production of plant protection products (no input data);
- Production of agricultural machinery (excluded from the system boundaries according to Directive 2018/2001.

For the technological stage, the following sub-stages were analyzed (Figure 4):

1. Transport of waste materials/residues to the installation and their storage (including production of diesel oil).
2. Substrates pretreatment (pickling, grinding, maceration, mixing).
3. Introducing the substrates into the fermentation chamber.
4. Methane fermentation.
5. Biogas storage.
6. Biogas purification.
7. Generation of electricity and heat.
8. Storage/management of digestate.

Procedures related to the use of digestate in the field were beyond the system boundaries. In addition, the analysis takes into account the so-called avoided emissions associated with the production of mineral fertilizers, for which the digestate from the biogas plant is a substitute. The use of digestate as a fertilizer is not simple and depends on many factors, mainly on the feed substance in the fermentation process and the quality of the digestate. If the digestate meets the national or European requirements for the quality of the digestate, it can be used in the field as a fertilizer. The quality requirements relate, inter alia, to the nutrients contained in the digestate (nitrogen, phosphorus, potassium content), as well as to chemical impurities (chromium, cadmium, lead, etc.,), biological (e.g., presence of intestinal parasites such as *Ascaris* sp., *Trichuris* sp.) and veterinary (e.g., *Enterobacteriaceae*).

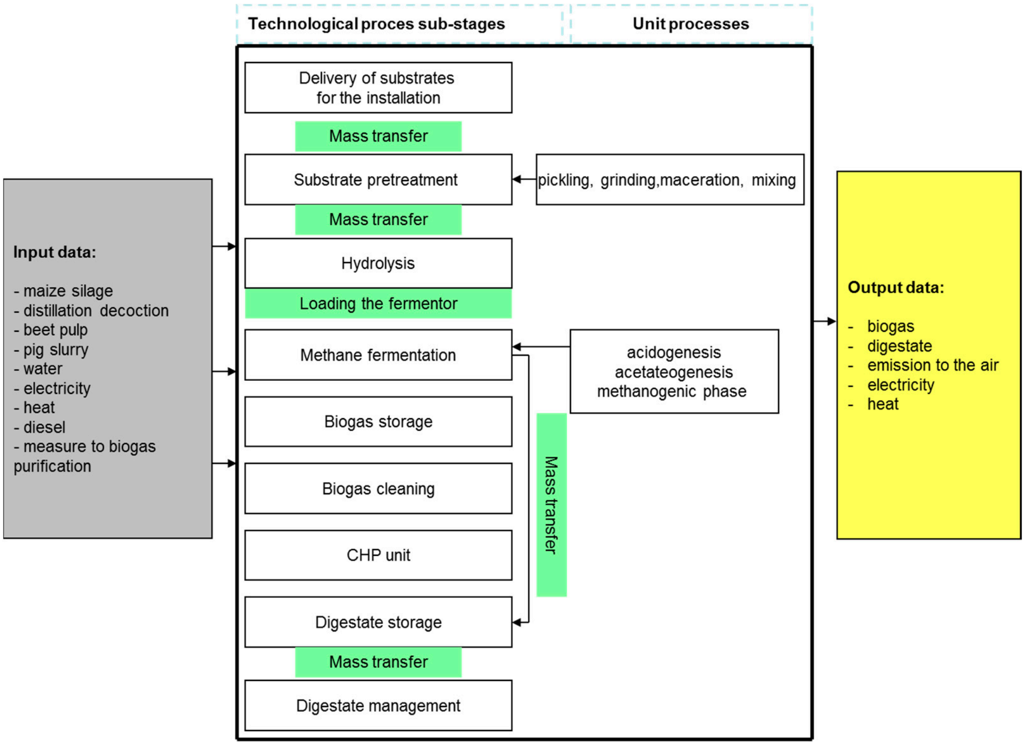

Figure 4. General scheme of sub-steps in the technological process of biogas production.

2.3. Functional Unit and Input Data for LCA

For the raw material stage, the functional unit in the form of 1 Mg of maize silage (1 Mg of silage) was adopted. For the technological stage, 1 MWh of electricity generated from biogas was assumed as the functional unit.

Data on the raw material stage (maize cultivation) were obtained from an agricultural advisory center appropriate for the location of the biogas plant, available literature on the subject, and own calculations.

For the pollutants emission caused by the production of nitrogen fertilizers, the values of the emission factor provided by [97] were taken into account. In Poland, the pollutant emission index related to the production of nitrogen fertilizers is lower than its average value for Europe and amounts to 3414.2 g CO_2 eq/kg N concerning mineral fertilizers (in the form of nitrate or urea).

The calculations also took into account the field emissions of nitrous oxide—N_2O, related to the use of nitrogen fertilizers and partially with a decomposition of leaves remaining on the plantation and crop residues in the case of cereals. Field emissions of nitrous oxide have a very strong influence on the overall greenhouse gas emissions from biomass cultivation. It should be emphasized that determining the value of this parameter is subject to very high uncertainty, which is emphasized both in the methodology of the BIOGRACE calculator and the methodology used in this analysis according to the Ecoinvent Center report [98] (in both cases it is based on the IPCC guidelines). For maize, the value of 2.332 kg/ha was adopted.

As part of the analysis for the technological stage, the input data for the biogas production process are real data and were obtained from the analyzed national biogas plant.

2.4. Sensitivity Analysis

A sensitivity analysis was performed, in which the impact of input data variability on the results of the analysis was assessed. The analysis was carried out in accordance with the ISO 14041 standard. The analysis included:

- Comparison of the life cycle of 1 MWh of electricity-generated from biogas obtained in **Case 1**, with 76% and 100% heat recovery;
- Comparison of the life cycle of 1 MWh of electricity-generated from biogas obtained in **Case 2**, with 76% and 100% heat recovery;
- Comparison of the life cycle of the production of 1 MWh of electricity from biogas in **Case 1** and **Case 2** with 100% heat recovery.

3. Results and Discussion

Figure 5 shows the results of a comparative analysis of generating 1 MWh of electricity from biogas obtained from raw materials in Case 1 and Case 2 in the life cycle.

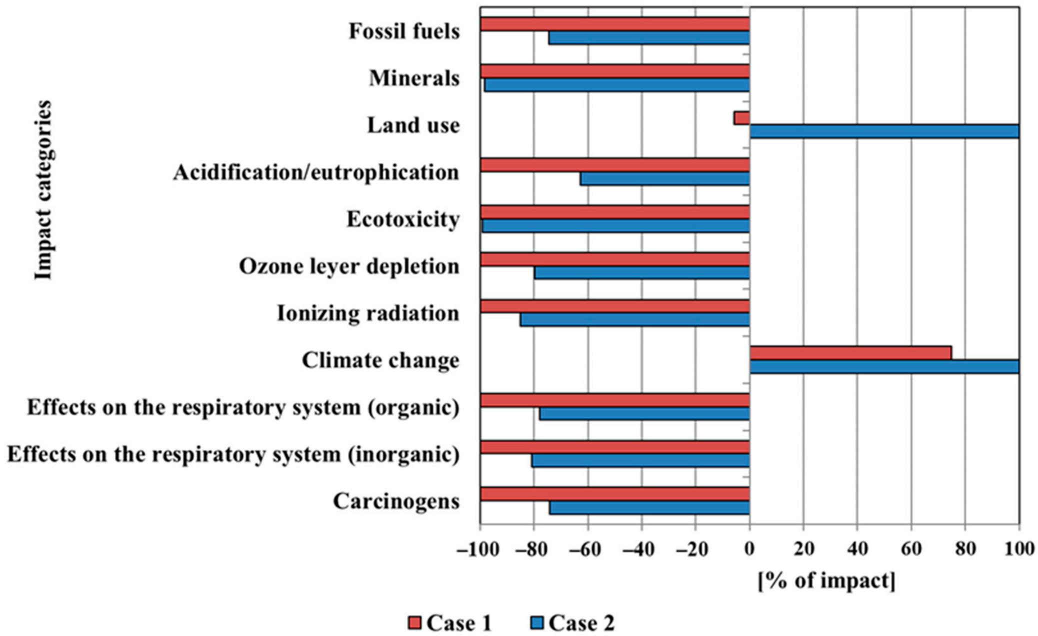

Figure 5. The results of a comparative analysis of generating 1 MWh of electricity from biogas obtained from raw materials in Case 1 and Case 2 in the life cycle for individual impact categories under the Eco–Indicator 99 method (characterization).

The categories that are most important from the point of view of the analyzed process include: climate change, ozone depletion, eutrophication/acidification, land use, depletion of mineral, and fossil fuel resources. Based on the LCA analysis, it was found that the greatest negative impact on the environment, regardless of the raw materials case used in the process, occurs in the category of climate change (75% for Case 1 and 100% for Case 2), which is particularly visible in Case 2. This result is related to the use of diesel fuel to power agricultural machinery at various stages of maize cultivation, from field work preparing the soil for cultivation, through planting, treatments related to fertilization, and application of plant protection products for harvesting as well as the transport of substrates (from the field, sugar factories and distilleries to biogas plants). The result was also influenced by emissions related to the production and use of mineral fertilizers and plant protection products. In Case 1, in which waste/residues are the raw material for the fermentation process, the high result in the discussed category is mainly influenced by the transport of waste, and thus the combustion of transport fuels.

A negative impact (at the level of 100%) was also found for Case 2 in the category of land use. This result is due to the need to allocate a large area of land for the cultivation of maize for silage. Comparing both cases of raw materials, it was found that in this impact category, the process of generating electricity from biogas for the production of which waste was used (Case 1) had a positive result (−6%), which resulted from the lack of the need to purposefully cultivate these raw materials (and thus no need to occupy the land for cultivation), and the fact that instead of a landfill, waste and residues are managed in a biogas plant. The management of waste instead of its storage results in an added value in the form of savings in land management, as well as the possibility of using them for purposes other than storage.

In the case of the other impact categories, both for the process of generating electricity from biogas obtained from waste materials and maize silage, the results indicated that both cases had no negative impact on the environment. The change in the type of raw material for the methane fermentation process practically did not affect the categories of minerals and ecotoxicity. The type of raw material, on the other hand, influenced the amount of positive environmental impact, in terms of impact such as:

- Ozone layer depletion, related to the emission of greenhouse gases generated during the combustion of diesel fuel-supplying agricultural machinery and vehicles used for transporting substrates, as well as the production and application of fertilizers and plant protection products;
- Eutrophication/acidification, related to the production and use of mineral fertilizers and plant protection products that end up in groundwater or are washed out of the soil by rainfall and end up in rivers, lakes, and seas;
- Fossil fuel depletion, related to the use of fuel to power agricultural machinery at various stages of raw material cultivation (maize) and its transport to biogas plants;
- Ionizing radiation—this is an indirect impact resulting from the use of averages for Europe taken from the Ecoinvent database available in the SimaPro software;
- Impact on the respiratory system, related to the reduced consumption of transport fuel during the operation of agricultural machinery as well as the production and application in the field of fertilizers and plant protection products;
- Carcinogenic, related to the reduced consumption of transport fuel during the operation of agricultural machinery as well as the production and application in the field of fertilizers and plant protection products.

In the above categories, the production of energy from biogas in Case 1 was environmentally more favorable than in Case 2. The values for these categories in Case 1 amounted to 100%, while in Case 2 they ranged from −74% (for the carcinogens category) to −85% (for the ionizing radiation category). This is caused, inter alia, by the use of waste in the process (avoided emissions related to the intentional cultivation of the raw material) as well as the use of digestate as a fertilizer (avoided emissions related to the deliberate production of mineral fertilizers, especially nitrogen fertilizers, the production of which is highly energy-absorbing, and also associated with significant emissions of GHG to the environment).

Figure 6 shows the results of the LCA analysis concerning the endpoints under the Eco–Indicator 99 method used, such as: human health, ecosystem quality, and natural resource depletion.

Based on the data presented, it can be concluded that for both the biogas electricity generation process in Case 1 and Case 2, the environmental impact at the respective endpoints is positive, especially in the areas of human health and resources. This is due to the use of waste in the process (avoided emissions related to the cultivation of special-purpose raw materials), replacement of energy generated from hard coal (in Poland the main energy carrier) with energy generated in a biogas plant, and the use of digestate as fertilizer (avoided emissions related to the deliberate production of nitrate ammonia). The positive impact is greater for the process in which waste is used as a raw material (−10 Pkt) compared to co-fermentation (−5 Pkt)—for the category of human health and −13 Pkt for Case 1 compared to −7 Pkt for Case 2 for the resources category. In the quality of ecosystems category, a particularly positive effect is observed for Case 2, in which waste is used as a raw material in the methane fermentation process −3 Pkt.

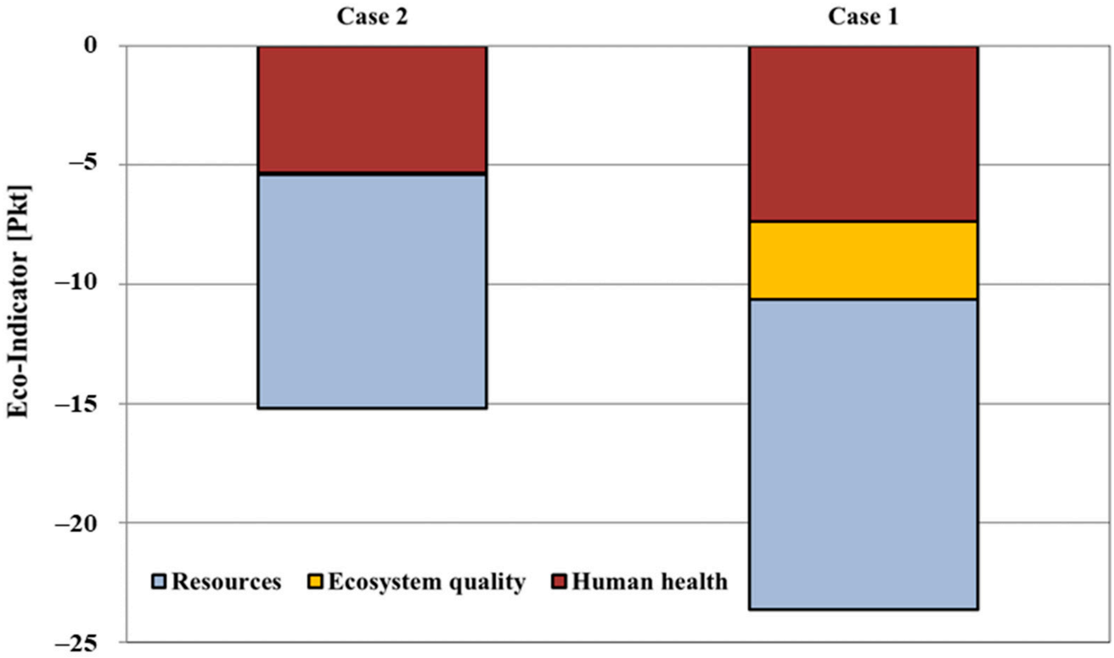

Figure 6. The results of comparative life cycle analysis for production of 1 MWh of electricity from biogas process in Case 1 and Case 2 for different impact categories according to Eco-Indicator 99 method (normalization).

Figures 7 and 8 show the results of the life cycle sensitivity analysis of 1 MWh of electricity from biogas obtained in Cases 1 and 2, with 76% and 100% utilization of thermal energy.

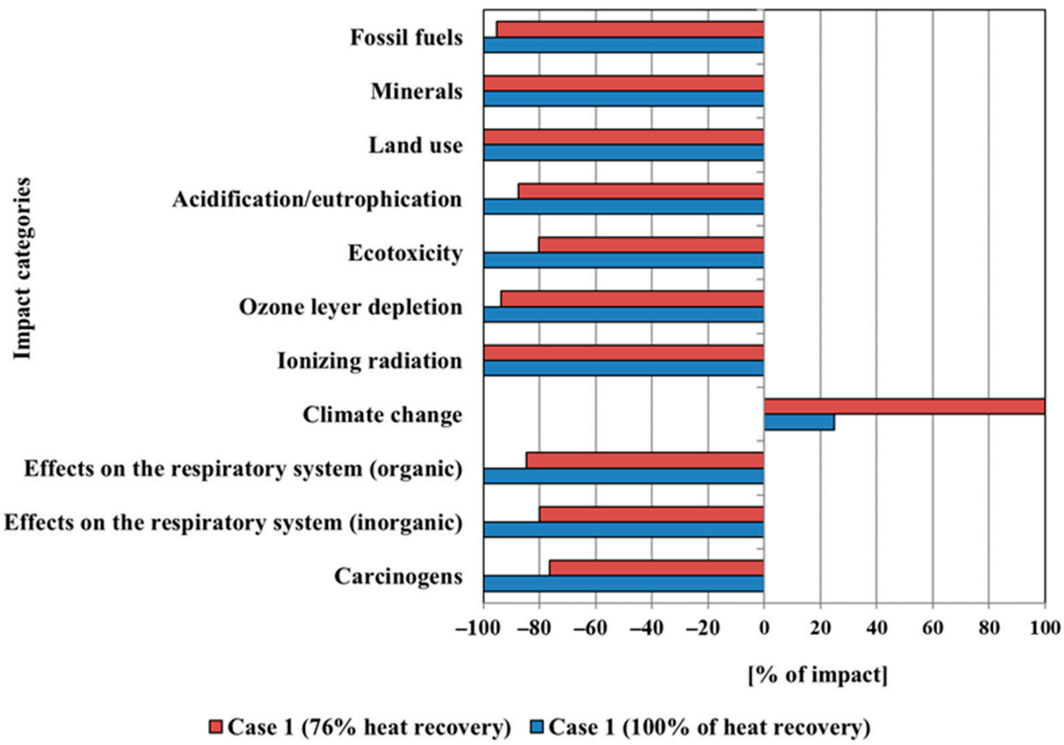

Figure 7. The comparative life cycle analysis results between 1 MWh of electricity generation from biogas obtained in Case 1 with 76% and 100% thermal energy utilization for individual impact categories under the Eco–Indicator 99 method (characterization).

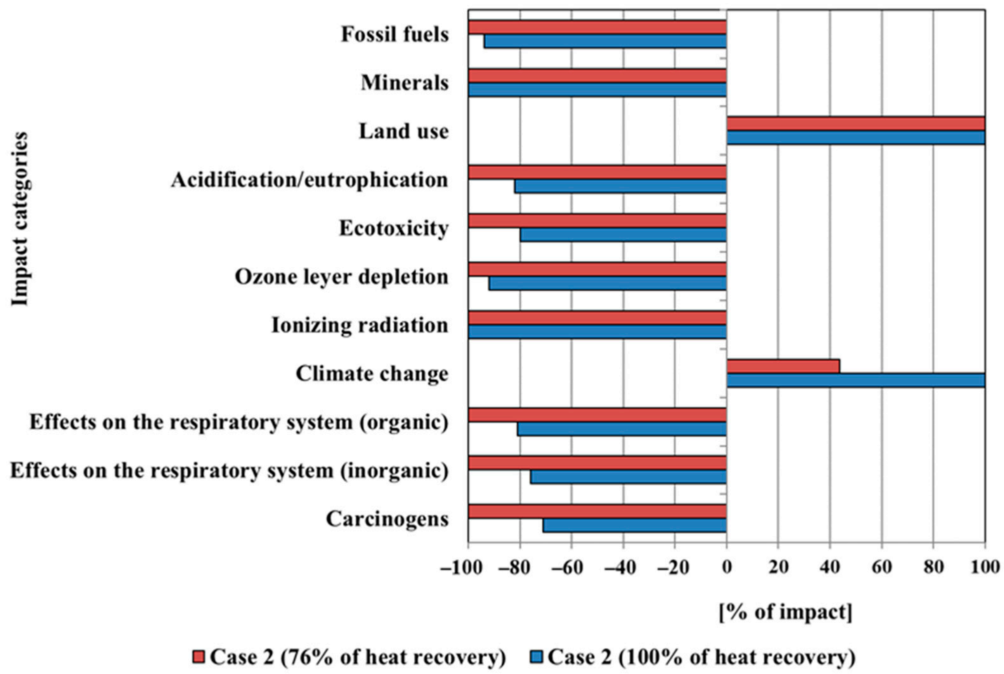

Figure 8. The comparative life cycle analysis results in the in 1 MWh of electricity from the biogas production process obtained in Case 2 with 76% and 100% thermal energy utilization for individual impact categories under the Eco–Indicator 99 method (characterization).

Figures 7 and 8 show that from the environmental point of view, the most favorable result is achieved by electricity from biogas, during the production of which the waste heat generated in the biogas plant was fully utilized. The heat was used for the own needs of the installation for heating fermentation chambers and buildings included in the biogas plant, and for the needs of a nearby farm running greenhouse cultivation of vegetables. The heat can also be used for drying purposes related to agriculture or the agri-food industry. The management of heat generated in a biogas plant in the cogeneration process makes it possible to replace the need to use district heat, which in Poland is produced from fossil resources such as natural gas or coal (mainly hard coal). The environmental effect of replacing district heating with heat produced in a biogas plant is particularly evident in the climate change category. The greater the percentage of heat utilization generated in a biogas plant, the greater the environmental benefits resulting from the reduction of emissions during the combustion of fossil energy carriers. The difference for the mentioned impact category between 76% of heat recovery and 100% is as high as 57%.

Increased use of heat also has a positive impact on ecotoxicity, acidification/eutrophication, and health categories. This is due to the avoidance of emissions of e.g., NO_x, SO_x, PM, or PAHs, which would be released into the atmosphere when this heat is produced from coal (in Poland, next to liquid fuels, the main energy resource). In the case of land use, mineral resources depletion, and ionizing radiation categories, the result for the analyzed process is the same as both 76% and 100% heat recovery, because the treatment of heat as waste and its emission to the air do not have a direct impact on the score in these categories.

Figure 9 shows a comparison of the results of the life cycle study of the production of 1 MWh of electricity from biogas obtained in Cases 1 and in Case 2 with 100% thermal energy management.

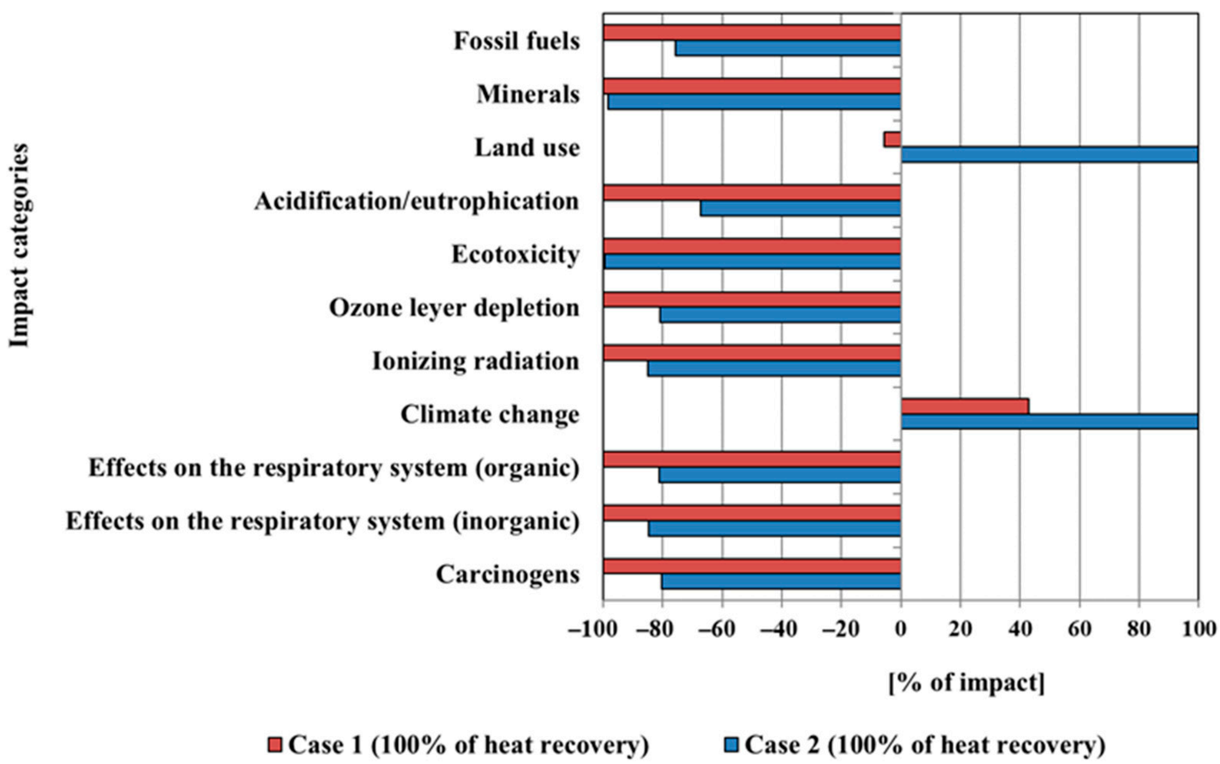

Figure 9. The results of the life cycle comparative analysis of 1 MWh of electricity-generating from biogas for Case 1 and Case 2 with 100% thermal energy utilization for individual impact categories under the Eco–Indicator 99 method (characterization).

As can be seen, the most favorable result in all impact categories was obtained for the process of generating electricity from biogas obtained only from waste raw materials. As it was mentioned above it is related primarily to the reduction of environmental burdens connected with the need to conduct targeted maize cultivation on silage (production and application of fertilizers and plant protection products, as well as combustion of fossil fuels during fieldwork). The categories of land use and climate change are the most sensitive to input variability. The differences between Cases 1 and 2 in the mentioned categories are respectively 106% (for the land use category) and 26% (for the climate change category).

4. Conclusions

It is well-known that the energy industry has a negative impact on the environment. The awareness of the society in this area is growing, which means that new solutions, more favorable for the environment are sought or the old ones are modified. These activities concern, for example the use of undeveloped waste, technological changes in processes, improvement of the efficiency of machines and devices, and better management of energy and by-products. The LCA analysis is a method enabling the assessment of the correlation between the introduced changes and their consequences on the environment. It allows for a qualitative and quantitative assessment of significant environmental threats. The results of such analysis are an important source of information in the decision-making process aimed at minimizing the negative impact of solutions on the environment.

In Poland, the main raw material for heat and electricity production is hard coal. An LCA analysis has shown that replacing coal with biogas, regardless of the raw materials used in the process, results in a positive environmental effect, especially in the areas of human health and resources categories. Electricity generation from biogas was found to have a positive environmental effect. Negative effects were found only in the categories of land use (using purpose-grown crops) and climate change (in both cases studied). These categories are at the same time the most sensitive to change in the raw materials studied.

The positive effect can be strengthened by changing the raw materials, from purpose-grown plants to waste from the agro-food industry and agriculture. Such a change eliminates the need for land use (and associated emissions; a change from 100% to −6%), reduces the negative effect on the climate change category (from 100% to 75%), and increases the positive effect in the other categories examined, especially in the acidification/eutrophication category, related to the production and use of mineral fertilizers and plant protection products that end up in groundwater or are washed out of the soil by rainfall and end up in rivers, lakes, and seas. This is caused, inter alia, by avoided emissions related to: the intentional cultivation of the raw material and the deliberate production of mineral fertilizers, through the use of the digestate as fertilizer.

In addition, the analysis carried out showed that an important factor influencing the environmental impact is the degree of heat utilization generated at the biogas plant. The greater the percentage of heat utilization, the greater the environmental benefits resulting from the reduction of emissions during the combustion of fossil energy carriers. Regardless of the feedstock, the most sensitive category to changes in heat utilization is climate change and health-related categories. Generally, the LCA analysis of the process of electricity production from biogas obtained only from waste raw materials and a mixture of waste raw materials and maize silage showed that the process in which only waste substrates were used was more environmentally beneficial. Raw materials such as silage, beet pulp, or pig slurry are wastes in other processes, therefore the only material and energy inputs and environmental consequences are related to their transport to the biogas plant. In the case of maize silage, the deliberate cultivation of maize and the related inputs present a significant additional burden on the environment. Thus, waste is a usable substrate and a valuable source of energy, which is particularly important in relation to the implementation of sustainable development. Moreover, it was very important for the environment to manage all possible by-products (e.g., digestate) generated during the process, as it allowed to avoid emissions related to the production and application of mineral fertilizers.

Generating electricity from locally sourced biogas to power the combustion engines of generators is a solution that provides tangible environmental benefits, not only in terms of protecting natural resources but also in terms of reducing emissions of substances harmful to health and greenhouse gases. These benefits relate to the life cycle of the facility, from obtaining feedstock for biogas fuel and ending with the generation of electricity. This is particularly important in Poland, where hard coal is the main raw material for generating electricity and heat. Thus, the use of biogas fuels to power internal combustion engines is an element of rationalizing the use of natural energy resources.

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