energies

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Identification of Key Factors for the Development of Agricultural Biogas Plants in Poland

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Abstract: Agricultural biogas plants are a renewable source of energy and at the same time enable the disposal of biodegradable waste generated in agriculture and the food industry. In Poland, a program aimed at constructing agricultural biogas plants has been in operation since 2010 with the goal of producing 1.7 billion Nm^3 of biogas, which has not been achieved. Factors that could influence the development of this energy source were identified based on a register of agricultural biogas producers from the National Agriculture Support Center and data from the Energy Regulatory Office. These factors are technology, substrates, state energy policy, profitability, population density in the commune and the spatial arrangement of the commune resulting from spatial development plans. A pairwise comparison analysis using the DEMATEL method was conducted for these factors. It allowed us to conclude that they are population density and the lack of local spatial development plans in most rural areas. The situation may be improved by the obligation to develop such plans for the entire area of each commune and by locating biogas plants near livestock farms and agri-food processing plants. The selected DEMATEL method is mature and comprehensively verified. It enables research to be carried out in other contexts, taking into account the correlations between factors. It is a universal method, and after collecting expert opinions, research can be expanded. The obtained results of the analysis will allow for further research by collecting the opinions of experts such as biogas plant users, local communities, local government officials and other stakeholders. In addition, further analysis of key factors will be carried out using the DEMATEL method for several scenarios. The PESTEL method will be used to identify key factors.

Keywords: agricultural biogas plants; pairwise comparison; DEMATEL method

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Citation: Ginda, G.; Szyba, M. Identification of Key Factors for the Development of Agricultural Biogas Plants in Poland. *Energies* **2023**, *16*, 7779. https://doi.org/10.3390/en16237779

Academic Editor: Seung Gu Shin

Received: 12 October 2023
Revised: 22 November 2023
Accepted: 24 November 2023
Published: 26 November 2023

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1. Introduction

A growing population, technological progress and economic development result in a constant increase in the demand for electricity. Its extraction from fossil energy resources leads to atmospheric pollution by greenhouse gases (CO_2, CH_4, NH_3 and N_xO) and particulate matter (PM 2.5 and PM 10). Approximately half of these emissions arise during the combustion of fossil fuels in power plants and refineries [1]. The increase in these gases causes climate change resulting in rising sea levels, which threatens people living in coastal areas and island countries [2,3]. For this reason, energy production from renewable sources is being developed: flowing or dammed water, sun, wind and biomass. Renewable energy production also has environmental and spatial impacts. Windmills emit infrasound that is harmful to humans, cause stroboscopic effects and interfere with bird migration. Dams damming up river waters alter the environment. Agricultural biogas plants are a source of unpleasant odors. So they all require space for the plants themselves and protective zones, which excludes it from agricultural production, other economic activities and the construction of settlements [4,5]. Reconciling the needs of different groups of space users is a task of spatial planning at national, regional and municipal levels. Without finding places for Renewable Energy Source (RES) installations, it will not be possible for Poland to transition to a zero-emission economy, which is the goal adopted by the European Union (EU) [6].

The "Energy Policy of Poland until 2040" developed by the Ministry of Energy and the Environment, adopted on 2 February 2021, sets out three goals. These are "energy security, competitiveness of the economy and reducing the impact of the energy sector on the environment" [7]. The implementation of the last goal is closely related to the development of Renewable Energy Sources (RES). It is assumed that in 2030 RES should have at least a 23% share in gross final energy consumption. Increasing the share of RES is to, among other things, contribute to achieving the GHG emission reduction indicator by 30% in 2030 [7]. The sources of RES in the power industry are to be solar, wind, water, biomass and biogas energy. Due to limited hydropower resources and difficulties in controlling the supply of wind and solar energy, "(. . .) the use of biogas will be particularly useful in the combined production of electricity and heat. The advantage is the ability to store energy in biogas, which can be used for regulatory purposes. In terms of general economic use, biogas is an additional added value, as it enables the management of particularly onerous waste (e.g., animal waste, landfill gases)" [7]. The largest resources of organic waste (biomass) are found in the agricultural and food sector and in the municipal economy. These resources are farm waste (pig and cattle slurry, poultry manure), slaughterhouse waste, feed processing waste, fruit and vegetable waste and distillery waste, as well as biodegradable municipal waste from households (kitchen waste and green waste from home gardens) [8,9].

Biogas plants are the best way to manage organic waste generated in the agri-food and municipal sectors because they reduce the amount of greenhouse gases (GHG) emitted to the atmosphere as a result of burning fossil fuels. For this reason, they are part of the circular economy. This concept, emphasizing the recycling and reuse of waste and by-products, organizes agricultural production according to the principle resources–agricultural products–renewable energy sources in place of traditional and extensive production. Circular agriculture requires the introduction of changes consisting of reducing the consumption of resources and energy, maximizing their degree of use in production and consumption systems and reducing waste and pollutant emissions [10].

Energy production in agricultural biogas plants is popular in European countries with intensive animal husbandry and large cattle, pig and poultry farms. These countries are Germany, Switzerland, Austria [11], Italy and Denmark, [12–14]. The biogas produced is used to produce energy and heat in the cogeneration combustion process; it can also be dried and purified to the parameters of natural gas and introduced into the gas network or compressed and as CNG used as fuel for driving trucks [15–22]. The largest producer of biogas is Germany, where 10,431 biogas plants of all types operated in 2018. The second country in terms of the number of biogas plants is Italy with 2004 installations. In the remaining EU countries, there are less than a thousand biogas plants [23,24].

In 2020, there were 336 biogas plants of all types in Poland, including 120 agricultural biogas plants [25]. The number of launched agricultural biogas plants is small in relation to the assumptions adopted in 2010 in the document of the Council of Ministers entitled "Directions of development of agricultural biogas plants in Poland in 2010–2020" [26]. The document states that by the end of 2020, there will be one biogas plant on average in each commune. The program failed as there are around 2200 municipalities in Poland.

Such a state of development of agricultural biogas plants is caused by many factors whose impact and mutual relations have not been the subject of previous research. The method of pairwise comparison of multiple factors has so far been used for investment decision-making [27–40]. This study aims to fill this research gap by analyzing the current state and by using the pairwise comparison method to support the decision-making process on the location of agricultural biogas plants [41–47]. However, we are primarily interested in identifying the key factors determining decisions related to the location of agricultural biogas plants [48–52]. A literature review, meta-analysis of statistical data from the Central Statistical Office, data from the Energy Regulatory Office and data from biogas producers from the National Agricultural Support Center were used to identify key factors influencing the development of agricultural biogas plants in Poland. Knowledge about them can significantly shorten the investment cycle in voivodships where small farms dominate [53]. In order to identify the most important factors determining the choice of location for agricultural biogas plants, a descriptive approach has been used so far, which is not conducive to an objective assessment of the role and importance of factors of not only a quantitative but also a qualitative nature. In addition, they can significantly influence the final selection of the location of the biogas plant. Therefore, in order to eliminate this research gap, the paper presents the possibility of using the universal DEcision MAking Trial and Evaluation Laboratory (DEMATEL) methodology.

2. Research Object

Poland is a country where agriculture has a significant share of the country's economy. In 2022, agriculture generated approximately 2.5% of GDP (Gross Domestic Product). Agri-food production is based on the cultivation of cereals, mainly wheat (2.5 million ha and harvest of approximately 134.5 million dt), corn (1.8 million ha and harvest of approximately 389 million dt), barley (639 thousand ha and harvest of over 28 million dt), rye (over 662 thousand ha and harvest of almost 24 million dt) and oats (over 466 thousand ha and harvest of over 15 million dt). The breeding of fruit (mainly apples, strawberries) and vegetables (potatoes, carrots, cabbage) is also developed. Cereals, fruits and vegetables are grown as food for the inhabitants of Poland and as feed for farm animals. The breeding of pigs, cattle and poultry plays an important role. In 2022, approximately 6.5 million cattle, over 9.6 million pigs and almost 199 million poultry were kept on farms. Poland is one of the main producers of pork in Europe. Agriculture covers a significant part of Poland, constituting approximately 60% of the country's area. Land use in agricultural holdings accounted for 89.7%, which translates into approximately 16.7 million hectares in 2020. Many farms are managed by families, but the share of large farms managed by companies is increasing. Some of them are managed by the National Center for Support for Agriculture, owned by the state treasury [54].

In the course of agricultural activities, biodegradable waste of animal origin (slurry, manure, bird droppings) and plant origin (vegetables and fruit unsuitable for consumption and their remains, residues from grain threshing, mown greenery, etc.) are generated, which may become a raw material for energy production in agricultural biogas plants. Another type of bio-waste is generated by households and companies. In 2022, over 1.9 million tons of this waste fraction were collected, which is 14.3% in relation to all municipal waste collected in the same year. This waste could be successfully used as a raw material for the production of biogas, but the Act on Renewable Energy Sources states that biogas in agricultural biogas plants can only be produced from agri-food waste [55].

Biogas Plants in Poland

The object of this research are factors that influenced the location of agricultural biogas plants in Poland in 2010–2022. Data on the number of agricultural biogas plants, their capacity to produce biogas, the power of installed generators and their location in individual voivodships and communes were taken from the "register of agricultural biogas producers" kept by the National Agricultural Advisory Center (KOWR).

Poland is a country with a high potential for agricultural biogas production. In a document of the Council of Ministers, its potential was estimated at 1.7 billion Nm^3/year [26]. The register of agricultural biogas producers is kept by the National Agricultural Advisory Center. It shows that in 2011 (the first year of implementation of the agricultural biogas plant development program), 13 of them, with a production capacity of 52,870 thousand tons, were registered. Nm^3 (average 4,067,000 Nm^3) of biogas and electricity capacity was 11,826 (average 0.985 MW). Most of them were registered in the following voivodships: Zachodniopomorskie—five and Pomorskie—four. Most of them, i.e., eight registered biogas plants, belong to Goodvalley Agro S.A., which has large breeding farms in the above-mentioned voivodships. The number of agricultural biogas plants registered in 2010–2022 is shown in Figure 1. The largest number (15) of new biogas plants were registered in 2015, and the smallest one, namely only one, in 2018.

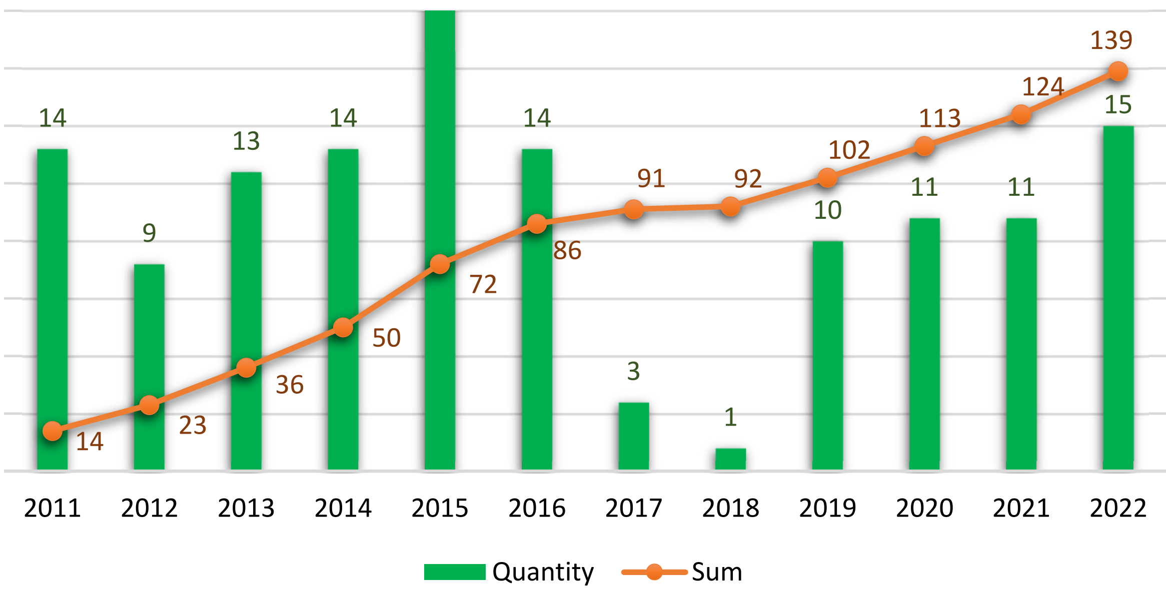

Figure 1. The number of biogas plants registered in individual years and their sum. Source: [56].

Table 1 contains basic information on agricultural biogas plants in 2020 and 2022. It shows that the average capacity of biogas production and the average power of installed power generators were similar to those in 2011. The biogas production capacity in 2022 was higher by 15.5 percentage points compared to 2020. In the same period, the installed capacity of power generators increased by 20 percentage points.

Table 1. Data of agricultural biogas plants in 2020 and 2022.

Item	Unit	2020	2022
Number of biogas plants	pieces	109	137
Total biogas capacity	[k Nm^3]	466,949	539,571
Average per installation		4284	3938
Total substrate consumption	Mg	4,409,054	4,912,454
Average per installation		40,450	35,857
Total installed electrical power	MW	117,980	141,670
Average per installation		0.983	1034
Electricity produced *	MWh	508,381	-
Average per installation		4664	-

* Quantity based on share certificates submitted to the Energy Regulatory Office. Source: [56].

The increase in the number of biogas plants was accompanied by an increase in the consumption of substrates. In 2022, it was 11.5 percentage points higher than the consumption in 2020. The full list of substrates used in agricultural biogas plants includes 34 items. As can be seen from Table 2, ten of them account for over 80% of the weight of all substrates used. This top ten includes nine wastes from farming and food processing. Corn silage is only fifth, with a share of about 11%. It can be concluded that the composition of used substrates is beneficial for the environment because waste is disposed of in a manner recognized as optimal in the EU [57].

Table 2. Amounts of the most important substrates used.

No.	Item	Substrates Mass [Mg]	
		2020	2021
1	Distillery decoction	759,774	932,499
2	Residues from fruits and vegetables	706,945	734,356
3	Slurry	759,774	805,940
4	Corn silage	491,870	550,560
5	Technological sludge from the agri-food industry	227,148	413,766
6	Food processing waste	344,329	402,309
7	Beet pulp	209,816	205,963
8	Expired food	117,184	146,142
9	Waste from the dairy industry	132,911	134,911
10	Manure	91,681	91,076
	Sum 1–10	3,749,750	4,326,446
	The sum of all substrates	4,409,054	4,912,454
	Sum 1–10/Sum of all substrates	85%	88%

Source: [56].

As shown in Table 1, the average power of power generators installed in Polish agrigas plants is about 1 MW. Table 3 contains information on the power of the installed power generators. The most numerous group consists of aggregates with a capacity of 0.751–1.000 MW. The second largest group consists of aggregates with a capacity of 0.251–0.500 MW. There are only a few generators with a capacity of less than 0.250 MW, and their number has not changed.

Table 3. Relationship between the number of biogas plants and population density in municipalities.

Power of Generator Sets MW	Number of Biogas Plants Per Day			
	31 December 2020		31 December 2022	
	Number	%	Number	%
<0.250	4	3.67	4	2.94
0.251–0.500	17	15.60	27	19.85
0.501–0.750	9	8.26	11	8.09
0.751–1.000	40	36.70	51	37.50
1.001–1.250	11	10.09	13	9.56
1.251–1.500	3	2.75	3	2.21
1.501–2.000	17	15.60	18	13.24
>2.001	8	7.34	9	6.62
Total	109	100.00	136	100.00

Source: [56].

The number of biogas plants in individual voivodships was also analyzed. The results are presented in Table 4. The highest number of biogas plants is found in voivodships with a population density below the national average, which may indicate large agricultural areas. The high population density in voivodships such as Mazovia, Lower Silesia, Łódź and Pomerania does not contradict the previous statement, as it is a result of the existence of large urban agglomerations in those regions. The voivodships in Table 4 are grouped according to the typology of the agricultural structure developed by Jadwiga Bożek and Bogusław Bożek [58]. In Group I, there are voivodships where the agricultural structure is the most fragmented. Farms with 1–5 hectares of agricultural land (AL) account for approximately 80%. Group II consists of voivodships where farms with 1–5 hectares of AL represent about 50%, and farms with 5–10 hectares of AL account for approximately 30%. In voivodships of Group III, the agricultural structure is the least fragmented, as farms with over 30 hectares of AL constitute over 30%. In Group IV voivodships, the percentage of small farms is similar to Group II, but the percentage of farms above 10 hectares of AL exceeds 25%. It appears that the number of agricultural biogas plants in a voivodship is higher when there is a greater proportion of large farms, as there are large livestock farms and large food processing plants generating waste.

Table 4. Number of agricultural biogas plants in individual voivodships.

Group	Voivodship	Population Density [people/km^2]	Number of Biogas Plants in the Year	
			2020	2022
I	Małopolskie	222	2	2
	Śląskie	371	2	2
	Podkarpackie	119	3	6
II	Łódzkie	137	5	8
	Mazowieckie	150	7	12
	Lubelskie	85	8	8
III	Podlaskie	59	8	11
	Wielkopolskie	117	12	17
	Kujawsko-pomorskie	116	6	6
	Pomorskie	126	11	12
	Warmińsko-mazurskie	60	16	16
	Zachodniopomorskie	75	14	15
IV	Lubuskie	73	3	8
	Dolnośląskie	146	10	10
	Opolskie	106	1	2
	Świętokrzyskie	107	1	1
	Poland	121	109	136

Source: [54,56].

Large resources of substrates produced by the Polish agri-food sector are used to a small extent for the production of agricultural biogas, which is associated with threats related to the operation of agrogas plants. In 2015, Igliński et al. [16] conducted a SWOT analysis, as a result of which they identified the most important threats as the following:

- Instability of prices of agricultural substrates;
- No guarantee of stable input supplies;
- Decline in prices of conventional fuels.

In the SWOT analysis conducted in 2019 by Iwaszczuk et al. [59], additional threats are listed:

- Drop in prices of "blue certificates";
- Decrease in prices for the disposal of agri-food waste;
- Closure of a large agri-food processing plant that supplied substrates to the biogas plant;
- Repeated natural disasters (droughts, floods, epidemics of infectious animal diseases).

The weaknesses in both analyses included resistance from the local community and the long investment process due to the lack of Local Spatial Development Plans (MPPZP) in most commune areas.

After analyzing the literature on the issue of agricultural biogas production, statistical data from the Central Statistical Office (GUS), the list of biogas producers from the National Center for Agricultural Support (KOWR) and interviews in towns where agrogas plants operate (Piekoszów, Liszkowo, Odrzechowa), the authors decided to examine key factors influencing the location of agricultural biogas plants. Based on the analysis of the number of agricultural biogas plants operating in Poland and their parameters, the authors considered the factors influencing their location [53,60,61]:

- Technology: knowledge of the process that affects its efficiency and safety related to operation, eliminating the inconveniences associated with substrate and digestate transport and storage—T;
- Substrates: availability, price, transport costs, regularity of supply—S;
- Policy: state energy policy creating an energy mix—O;
- Profitability: profitability of biogas plant operation, electricity selling price per MWh, price of ETS certificates for emitting 1 ton of CO_2, possibility of selling thermal energy—R;
- Population density in the municipality—G;
- Spatial layout of the municipality resulting from the local spatial development plan or historically shaped residential development—P.

To identify the influence of these factors on the development of agricultural biogas plants in Poland, the DEMATEL method was used, which allows for the assessment of the impact of the examined factors. The choice of this method was made based on the analysis of the availability of methods enabling the identification of key factors in the case of including imperfect information about them, which we deal with in the practice of making contemporary decisions. Ultimately, three such tools were identified, namely MicMac, Interpretative Structural Modeling (ISM) and DEMATEL [62–70]. The universal nature of these methods means that, despite their considerable age, they are still willingly used by researchers. DEMATEL stands out from them by having a much richer arsenal of ways of presenting and interpreting results.

3. Methods and Research

DEMATEL Method

Among many pairwise comparison methods, the DEMATEL method (DEcision MAking Trial and Evaluation Laboratory), developed by the Battelle Memorial Institute in Geneva, is a decision support tool that is still relatively underutilized in the national scientific literature. Typically, the potential of the DEMATEL method is employed, amongst others, for the identification and evaluation of strategic decisions in logistics and assessing factors influencing the quality of designed municipal infrastructure facilities. However, the application of the DEMATEL method can be broader, as it allows for addressing complex decision problems with imperfect information, i.e., incomplete or uncertain information. For this purpose, straightforward mathematical calculations are used to provide a graphical interpretation of the problem's solution [71].

The versatility of the DEMATEL method has led to its practical application in various fields related to management, innovation, marketing, education, environmental and civil engineering, information systems, finance, banking and insurance, public safety, energy, medicine, logistics and transportation. The decision-making trial and evaluation laboratory research methodology (DEMATEL) has become an effective method for analyzing direct and indirect relationships among factors within a given field in terms of their intensity and nature [72].

Analysis using the DEMATEL method consists of six steps [72]:

1. Defining quality characteristics and establishing a measurement scale for relationships;
2. Determining the matrix of direct relationships among factors $\mathbf{X}^*$;
3. Normalizing the matrix of direct relationships among factors in a way that ensures its convergence to the zero matrix in the process of raising it to successive natural powers:

$$\lim_{k \to \infty} \mathbf{X}^k = 0 \tag{1}$$

4. Determining the resulting structure of total (and intermediate) influence of the factors;
5. Constructing a cause-and-effect diagram, as shown in Figure 2;
6. Analyzing the resulting structures of influence as well as the significance and role of individual factors.

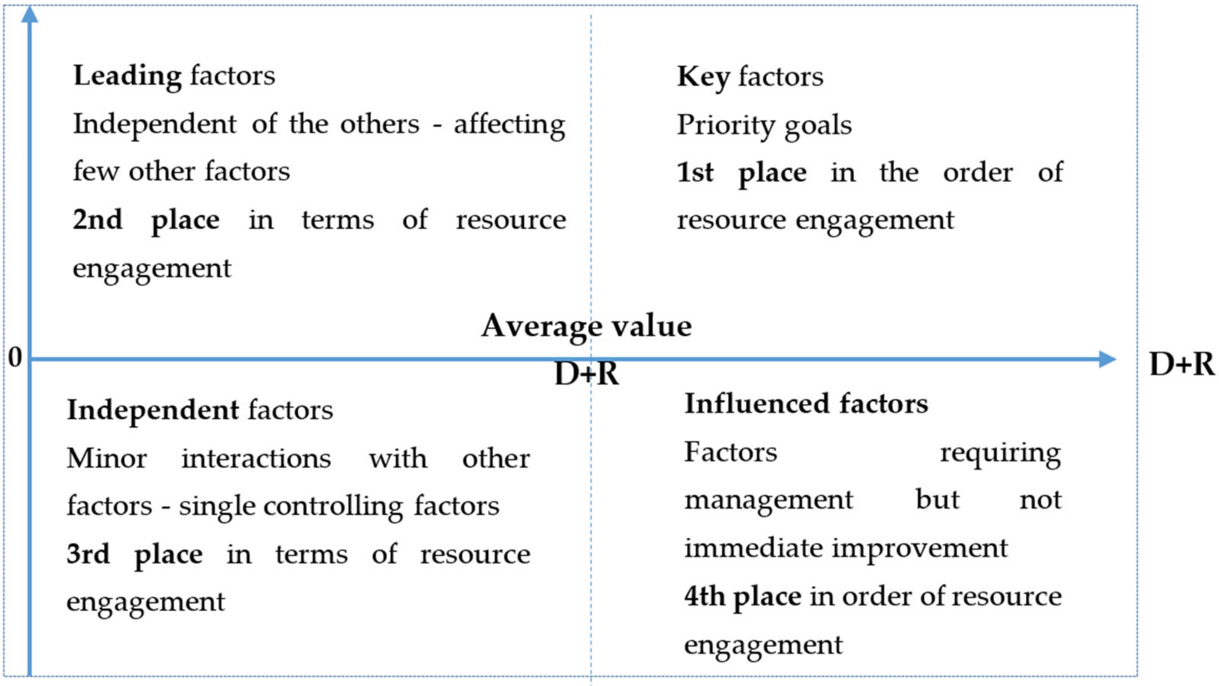

Figure 2. Classification of factors. Source: Own study based on [72].

The adopted structure of direct influence for selected factors is presented in Figure 3. A complete set of n^2 ratings of direct influence expresses the structure of their direct influence. It is worth noting that the determination of the structure of direct influence is based on the following assumptions:

- The possibility of bidirectional interactions between the i-th consecutive factor and j-th consecutive factor ($i, j = 1 \ldots n$) out of n factors is considered;
- The possibility of direct influence by an individual factor on itself is not allowed.

The strength of the direct influence of one of the compared factors on the other factors is usually expressed using the following scale:

- 0—no direct influence at all;
- 1—a slight influence;
- 2—significant influence;
- 3—very significant influence;
- 4—extreme influence.

4. Results

In the case of the considered set of factors—T, S, O, R, G and P—the assumed structure of direct influence is illustrated by a directed graph, i.e., a graph of direct influence. The assumed graph is presented in Figure 3. The absence of direct influence between factors corresponds to the absence of an arc connecting the vertices of the factors. However, the direct influence at the level of individual scale degrees is expressed by different styles of arc lines:

- The dotted linestyle corresponds to the assessment of direct influence at level 1;
- The dashed linestyle corresponds to level 2;
- The normal solid linestyle corresponds to level 3;
- The bold solid linestyle corresponds to level 4.

The structure of direct influence of factors expresses expert consensus in this regard. It is characterized by the following assumptions (compare Table 5):

1. Factor G strongly influences factors P, S and T but only weakly influences factor R;

2. Factor O strongly influences factors S and T but only weakly influences factors G and P;
3. Factor P strongly influences factors S and T;
4. Factor R only weakly influences factor S;
5. Factor S strongly influences factors O, R and T;
6. Factor T strongly influences factors O and R, moderately influences factor S and weakly influences factor P.

Table 5. Matrix of direct influence of factors X*.

Factors	G	O	P	R	S	T	Total
G	0	0	3	1	3	3	10
O	1	0	1	0	3	3	8
P	0	0	0	0	3	3	6
R	0	0	0	0	1	0	1
S	0	3	0	3	0	3	9
T	0	3	1	3	2	0	9
						λ=	10

The above assumptions are reflected in the graphical illustration of the direct influence structure, shown in Figure 3, as well as in the square matrix of direct influence $\mathbf{X}^* = [x_{ij}]_{6\times6}$ depicted in Table 5. The order of rows and columns of the matrix corresponds to the alphabetical order of factors, namely, G, O, P, R, S and T.

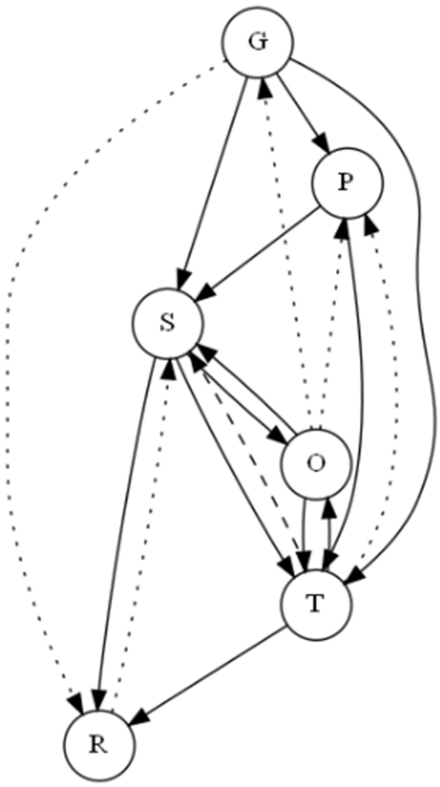

Figure 3. Structure of direct influence of factors.

In order to properly transform the matrix, a standard method was used, which involves normalizing it by dividing its contents by the maximum value of the row's sum of its elements λ:

$$\mathbf{X} = \frac{\mathbf{X}^*}{\lambda} \tag{2}$$

In the considered case, the value of λ is 10 (compare Table 5).

Based on this value, we ultimately obtain the structure of total influence, expressed by the total influence matrix T. It is worth noting that total influence can also be expressed as the sum of the following:

- Direct influence **X**;
- Indirect influence $\Delta\mathbf{T}$ (compare Table 6), resulting from the transmission of direct influence of factors, which, thanks to property (1), can be expressed by the formula

$$\Delta \boldsymbol{T} = \boldsymbol{X}^2(\boldsymbol{I} - \boldsymbol{X})^{-1} \tag{3}$$

Table 6. Matrix of indirect influence of factors $\Delta\mathbf{T}$.

Factors	G	O	P	R	S	T
G	0.0506	**0.5058**	0.1510	**0.5109**	**0.5338**	**0.5524**
O	0.0473	**0.4731**	0.1716	**0.4878**	**0.4765**	**0.5005**
P	0.0384	0.3841	0.1150	0.3880	0.3301	0.3503
R	0.0065	0.0650	0.0155	0.0657	0.0467	0.0701
S	0.0650	0.3504	0.1547	0.3569	**0.4670**	0.4011
T	0.0630	0.3299	0.1285	0.3362	0.4334	**0.4664**

According to Table 6, the highest-level indirect influence intensity was achieved in the case of the indirect influence of factor G on factor T, which amounts to 0.5524. Several other relationships of indirect influence can also be identified among the remaining pairs of factors, with intensities exceeding 80% of the maximum level of indirect influence, which is 0.4419. Such cases are highlighted in bold font in Table 6. The cases include the indirect influence of the following:

- Factor G on factors O, R, S and T;
- Factor O on factors R, S and T;
- Factors O, S and T on themselves due to feedback loops mediated by other factors.

The structure of total influence of factors is expressed, therefore, by the total influence matrix $\mathbf{T} = [t_{ij}]_{n \times n}$:

$$\mathbf{T} = \mathbf{X} + \Delta\mathbf{T} \tag{4}$$

Property (1) also allows to express the structure of total influence of factors in the following way:

$$\mathbf{T} = \mathbf{X}(\mathbf{I} - \mathbf{X})^{-1} \tag{5}$$

The structure of the total influence of the considered factors is illustrated in Table 7, where bold font is used to indicate several outstanding values of total influence. Note that the highest indirect influence value $t_{\max}$ is equal to 0.8524.

The structure of total influence **T** is shown in Figure 4 using a directed graph called a graph of total influence. It illustrates the typical occurrence of total influence feedback loops, which occur both between different factors and within themselves. These feedback loops are a natural consequence of indirect interactions between the factors.

To make the structure of total interactions between factors more readable, it can be reduced by removing the least significant, i.e., the weakest connections, using a typically arbitrarily chosen threshold level of total influence $\theta > 0$. This way, we obtain a reduced structure of total influence expressed by the matrix $\mathbf{T}_{\text{red}}$:

$$\mathbf{T}_{\text{red}} = \left[t_{ij} \geq \theta\right]_{n \times n} \tag{6}$$

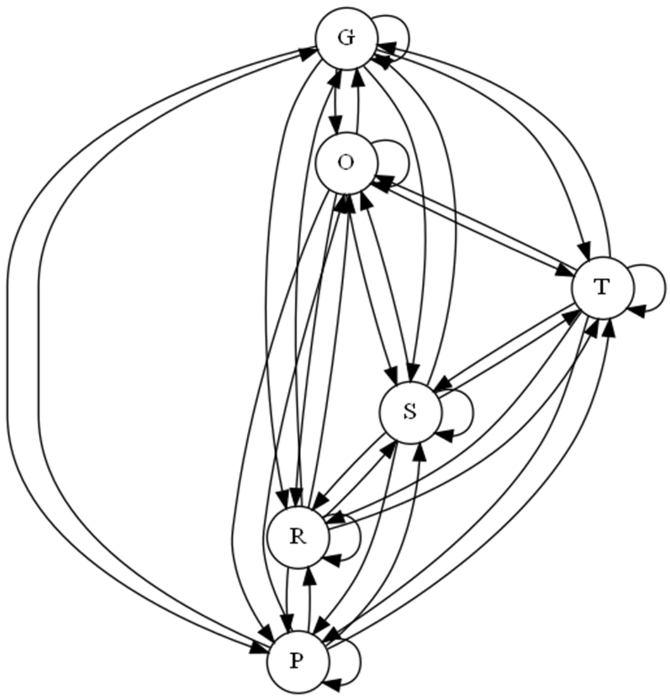

Figure 4. Graphical illustration of the structure of total influence of factors.

For example, by setting the threshold of total influence at 80% of $t_{\max}$, that is, θ = 0.6819, a reduced form of the structure of total influence is obtained. It is limited to several keymost intense relationships of total influence (compare Table 7):

- Factors G and O on factors S and T;
- Factors R and S on factor T.

Table 7. Matrix of total influence of factors T.

Factors	G	O	P	R	S	T	Total
G	0.0506	0.5058	0.4510	0.6109	**0.8338**	**0.8524**	3.3045
O	0.0473	0.4731	0.2716	0.4878	**0.7765**	**0.8005**	2.9568
P	0.0384	0.3841	0.1150	0.3880	0.6301	0.6503	2.2058
R	0.0065	0.0650	0.0155	0.0657	0.1467	**0.0701**	0.3695
S	0.0650	0.6504	0.1547	0.6569	0.4670	**0.7011**	2.6952
T	0.0630	0.6299	0.2285	0.6362	0.6334	0.4664	2.6575
Total	0.3708	2.7085	1.2362	2.8456	3.4874	3.5409	-

It is worth noting that isolating such a small group of relationships of total influence also significantly improves both further analysis of the structure of factor interactions and the preparation of key actions aimed at resolving the problem at hand.

Another way to clarify the structure of total influence is to transform it into a structure of net total influence, which determines the overall interactions within each pair of factors. It is expressed by the matrix of net total influence $\mathbf{T}_{nt}$:

$$\boldsymbol{T}_{nt} = \left[t_{ij} - t_{ji} > 0\right]_{n \times n} \tag{7}$$

The structure of net total influence, obtained for the considered factors, is illustrated in Table 8, and Figure 5 indicates the hierarchical nature of the structure of total influence of factors, with factor G as the fundamental cause and R as the primary effect, along with other factors of an intermediate nature.

Table 8. Total net impact matrix $\mathbf{T}_{nt}$.

Factor	G	O	P	R	S	T
G	0	0.5058	0.4510	0.6109	0.8338	0.8524
O	0	0	0	0.4878	0.7765	0.8005
P	0	0.3841	0	0.3880	0.6301	0.6503
R	0	0	0	0	0	0
S	0	0	0	0.6569	0	0.7011
T	0	0	0	0	0	0

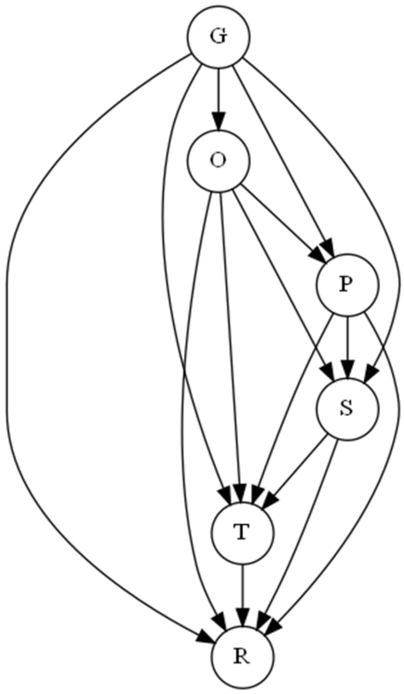

Figure 5. Graphical illustration of the structure of the total net impact of $\mathbf{T}_{\mathrm{nt}}$.

A comprehensive analysis of the significance and roles (causal relationships, effect relationships) of factors in the DEMATEL method requires determining a pair of indicators for each factor: the prominence position s^{+} and the relation s^{-}. These values are obtained based on the row's contents, which express the strength of total influence of factors and the column contents, which express the strength of total influence on factors in the matrix of total influence **T**. The first indicator expresses the degree of association of a given factor with other factors, and it is determined by the sum of the corresponding row's elements D and the sum of the corresponding column's elements R of the matrix of total influence **T**. On the other hand, the relation indicator expresses the causal and effect role of factors. It is described by the difference between D and R. The indicator values obtained for each factor are presented in Table 9.

Table 9. Position and relationship indicators and the role of factors.

Factor	D	R	Item	Relation	Relationship	Role
G	3.3045	0.3708	3.6753	2.9336	weak	P1
O	2.9568	2.7085	5.6653	0.2484	strong	N/P3
P	2.2058	1.2362	3.4420	0.9696	weak	P2
R	0.3695	2.8456	3.2151	−2.4760	weak	S1
S	2.6952	3.4874	6.1825	−0.7922	strong	S3
T	2.6575	3.5409	6.1984	−0.8834	strong	S2

The obtained values allow to construct a causal-effect diagram, as shown in Figure 6 (compare it with Figure 2). Once again, it clearly confirms the fundamental causal role of factor G and the fundamental effect role of factor R. Most of the remaining factors can be classified as relatively weak causes (P) or effects (S, T) due to their relatively low absolute relation indicator values. An exception is factor O, which, due to its low absolute relation indicator value, could even be considered a neutral factor. On the other hand, the prominence indicator values allow to clearly distinguish two groups of factors. The first group consists of factors R, P and G, which have low indicator values that testify to weak associations with other factors. The second group includes the remaining three factors, T, S and O, which are significantly more strongly interconnected with other factors.

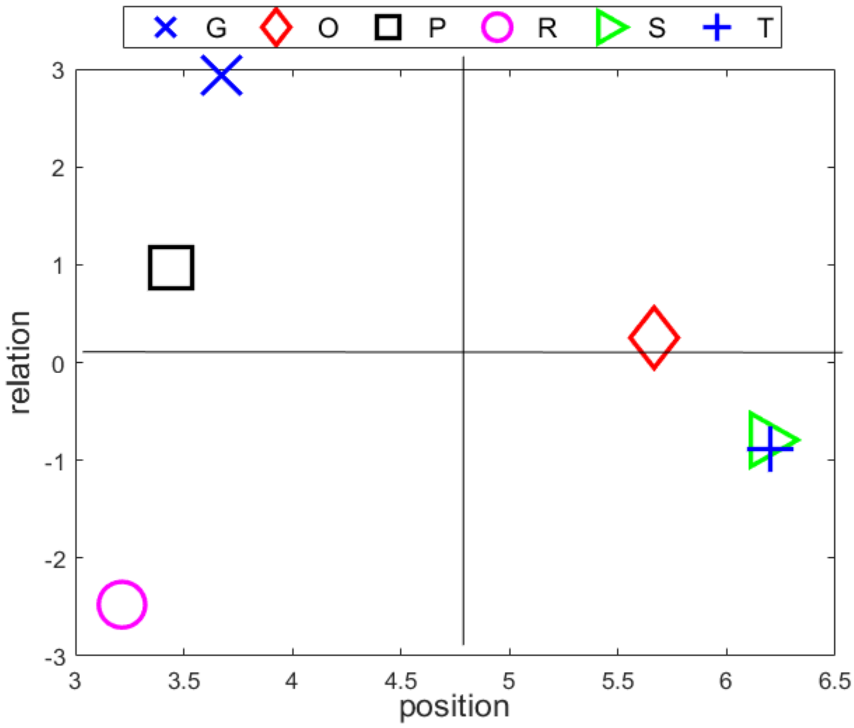

Figure 6. Cause and effect diagram for factors.

Factors can also be characterized in the context of the quadrant scheme shown in Figure 2. In this regard, only factor O could be classified as a pure key factor. However, it corresponds to a value of the relation indicator that is close to zero. Such a value indicates that this factor should be ultimately considered neutral. On the other hand, factors P and especially G should certainly be described as leading factors. The context of the scheme from Figure 6 also confirms the clearly secondary role of the only unrelated factor, R, and the dependent factors S and T.

5. Discussion

The analysis conducted indicates that the leading factor in the localization of agricultural biogas plants in Poland is population density in municipalities (G). This is confirmed by data presented in Table 4, which indicate that the highest number of agricultural biogas plants is found in municipalities with a population density below 50 persons/km^2. The transportation, unloading and storage of certain substrates are associated with odor emissions. Therefore, it is recommended that biogas installations are to be located at a distance of at least 300 m from residential buildings [8,73]. In municipalities with low population density, it is easy to find a location that meets this criterion and obtain the necessary permits for the construction and operation of biogas plants. Such municipalities have an agricultural character and, therefore, have an adequate amount of substrates required for large-scale biogas plants. According to Table 1, the average power generation capacity of biogas plants in 2020 was 4.284 million Nm^3, and in 2022 it was 3.938 million Nm^3. To produce such amounts of biogas, an average of 40.450 Mg of substrates was needed in 2020 and 35.857 Mg in 2022. These biogas plants were equipped with cogeneration units, with an average power of 0.983 MW in 2020 and 1.034 MW in 2022 (see Table 1). Nearly 75% of biogas plants had cogeneration units with a power capacity exceeding 0.5 MW (see Table 3).

A biogas plant that would be part of a farming or livestock operation would not pose such a problem because agricultural or livestock activities themselves generate odors. These odors are emitted by stored silage for cattle, animal manure in the form of dung and slurry or the mere presence of animals. Such biogas plants could be smaller, as evidenced by the situation in Switzerland and Austria [74]. In 2018, Switzerland had 60 biogas plants with a total capacity of 20 MW (average power of 0.33 MW). These plants operated exclusively on agricultural waste since the country has a ban on cultivating crops for energy purposes. On the other hand, Western Austria had 30 biogas plants with a total capacity of approximately 8 MW (average of 0.26 MW), while Eastern Austria had 115 biogas plants with a capacity of 55 MW (average of 0.30 MW). Augustyn et al. [21] conducted a simulation on the biogas production potential of a dairy farm with 20 cows. Based on their calculations, it was found that only from the cow manure and slurry of such a herd, approximately 60 MWh of electrical energy can be generated. In 2018, there were about 750,000 dairy farms in Poland with more than 20 cows [75]. This indicates a potential electricity production of approximately 1,872,730 MWh, which is more than four times the amount produced in 2020 (508,381 MWh, see Table 1) from all substrates.

In densely populated areas, modern biogas plants equipped with odor control systems should be constructed to eliminate the possibility of significant odor-related issues. One such technology is Central Anaerobic Digestion (CAD), developed in Denmark, which minimizes the odor nuisance of biogas plants [14,76]. Biogas plants using CAD technology, designed and built near residential areas, provide heat and electrical energy. Unlike traditional agricultural biogas plants, all processes in CAD plants take place in sealed installations [77].

The overarching goal of climate policy in the EU is to achieve climate neutrality by 2050 in a modern and resource-efficient way. In 2020, energy generated from renewable energy sources was to constitute 20% of the energy consumed by end users. This target has been increased to 30% in 2030, and it can be expected that these goals will increase in the following years [78]. Agricultural biogas is a renewable energy source that fits into a number of EU policies and activities, including the European Green Deal policy, the strategy to reduce methane emissions and the action plan for the circular economy. The management of agri-food waste in agricultural biogas plants will contribute to reducing uncontrolled methane emissions into the atmosphere from this sector. The development of the biogas sector in Poland should not only be based on cogeneration but also on biomethane plants [79]. Then, biomethane could be injected into the gas network, which would allow for better integration of the gas and electricity systems and a greater share of renewable energy in these sectors [80]. Experiments are being carried out based on the assumption that separate gas networks will be created to distribute partially purified agricultural biogas, free of H_2S and N_2, moisture and, to a large extent, CO_2, and a mixture of pre-purified agricultural biogas with high-methane natural gas [81,82]. Another way to use biogas is to produce biohydrogen. It can be obtained from biogas through steam reforming, which allows for obtaining biohydrogen without pollutants. Such biohydrogen can be used to generate electricity in fuel cells to power vehicles and generate energy for industry [83]. Combustion of biohydrogen in cells does not cause emissions of CO_2 and other greenhouse gases, although its production in steam reforming leaves a significant carbon footprint, depending on the production technology [84]. As of 2020, Europe dominated the biogas market and was the largest biogas producer, with approximately 18,943 biogas plants. According to the European Biogas Association (EBA), biogas production in Europe is expected to reach 98 billion cubic meters (bcm) of biomethane by 2050, a 4.800% increase in current production levels. It is expected that the plan to increase biogas production will attract investments in the construction of biogas plants, which will support the development of biogas plants in the near future [85].

The analysis shows that for the increase in biogas production required by the EU to occur in Poland, it is necessary to plan an area in each commune for the construction of an agricultural biogas plant and to introduce a requirement for each large animal farm to have a biogas plant with a biogas production capacity adequate for their number. There should be a similar requirement for food production plants.

6. Conclusions

Biogas plants are renewable energy installations that, due to their characteristics, can provide a stable source of energy in rural areas and contribute to improvements in the quality of the natural environment. The development of biogas plants in Poland should be based on effective management, utilizing modern decision support methods. Sound decisions would enable the growth of the biogas sector in Poland, which has been experiencing very slow development for over 13 years. The pace of decision-making regarding the construction of new biogas plants is too slow compared to the potential that rural areas in Poland possess.

The article presents a practical application of the DEMATEL method, which was used to determine the matrix of interdependencies among all pairs of factors (technology, substrates, policy, profitability, population density, spatial development plans). A total influence matrix T was derived, and a pair of indicators, called position and relation, were obtained for each factor. Factors with the greatest and smallest impact on the development of biogas plants in Poland were identified.

The analysis conducted on the development of the biogas plant market in Poland identified population density (G) as the main cause of weak biogas plant growth in the country. This result is not coincidental, as agricultural biogas plants have a strong impact on people living in their vicinity, mainly due to odors emitted from substrate storage tanks, anaerobic fermentation chambers and post-fermentation tanks. Other factors such as spatial development plans (P), substrates (S) and technology (T) have a weak influence on the situation. The exception is Poland's energy policy, which has a neutral impact on the biogas sector, despite incentives such as blue certificates, which have a higher value than green certificates for other renewable energy sources, and government support programs for the construction of agricultural biogas plants with a capacity of up to 50 kW [86].

Society should be made aware of the benefits of building agricultural biogas plants in their area. Biogas plants are renewable energy sources in which the cogeneration process produces electricity, which can be sold to an energy consumer, and heat energy, which can be sent to the local heating network. In addition to energy benefits, agricultural biogas plants fit the concept of a circular economy, providing long-term and sustainable benefits. Thanks to this, it is possible to dispose of waste generated on farms, and this waste becomes less burdensome to the environment and the local community. In order for the above-mentioned benefits to be implemented, a new program for the development of biogas plants and a program educating the local community in this area should be developed by the central authorities.

Future research may extend the presented research with regard to several specific topics. The use of the DEMATEL technique alone supports numerous directions for future research because the technique covers a lot more possibilities than those utilized in the paper. For example, it could also be applied to analyze diverse opinions of different stakeholders to make the identification of key factors more comprehensive. It could be especially useful for the reliable identification of necessary means for overcoming specific obstacles, e.g., local social and regulatory obstacles, that hinder biogas plant industry development. Another possible extension of the current research would deal with the determination of the actual importance of the key factors. For example, the combined application of DEMATEL with MCDA tools is capable of providing the necessary means in this regard while allowing for the inclusion of diverse possible scenarios that describe the state of conditions influencing the development of biogas plants.

Author Contributions: Conceptualization, M.S. and G.G.; methodology, M.S.; software, G.G.; validation, M.S. and G.G.; formal analysis, G.G.; investigation, M.S.; resources, M.S.; data curation, G.G.; writing—original draft preparation, M.S.; writing—review and editing, M.S. and G.G.; visualization, G.G.; supervision, M.S.; project administration, M.S.; funding acquisition, M.S. and G.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by AGH University of Krakow, Agreement No 16.16.200.396 B310.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses or interpretation of data; in the writing of the manuscript or in the decision to publish the results.

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