sustainability

MDPI

Article

Biogas Power Plants in Poland—Structure, Capacity, and Spatial Distribution

Daniela Szymańska *,† **and Aleksandra Lewandowska** †

Received: 13 July 2015; Accepted: 15 December 2015; Published: 21 December 2015
Academic Editor: Marc A. Rosen

Department of Urban Studies and Regional Development, Faculty of Earth Sciences, Nicolaus Copernicus University, Lwowska 1, 87-100 Toruń, Poland; dani@umk.pl
* Correspondence: dani@umk.pl; Tel.: +48-56-611-2606; Fax: +48-56-611-2605
† These authors contributed equally to this work.

Abstract: This paper presents the analysis and evaluation of biogas power plant capacity in Poland based on the generic structure and energy production. These issues are also presented from the point of view of the obtained energy and biogas energy production in Poland against selected European Union countries. The paper also indicates a significant diversity in the spatial distribution of biogas plants in Poland. It also discusses the importance of biogas plants as one of the elements of bottom-up development of the second tier administrative units. There are 231 biogas power plants in Poland (as of 2013), which are based on biogas from landfill sites, biogas from wastewater treatment plants, and agricultural biogas. The generic structure of biogas power plants in Poland is dominated by power plants based on biogas from landfill. Despite the fact that Poland has large resources of agricultural substrate, there are very few biogas power plants based on agricultural biogas. There are no biogas power plants in almost 60% of *poviats* in Poland, despite the fact that every *poviat* in Poland has enough of this substrate at its disposal. This article contributes innovative elements to existing knowledge on biogas power plants in Poland, thanks to its comprehensive treatment of the problem of biogas power plants in Poland and because it urges local authorities and local communities to behave more ecologically, as well as promoting endogenous factors of the economic development of a given region.

Keywords: renewable energy sources; biogas; biogas plants; biomass; Poland

1. Introduction

The modern world is facing a huge energy crisis associated with the depletion of conventional energy resources. Therefore, obtaining energy from alternative sources is arousing more and more interest, expressed by both scientists and businesses. One of those sources is biogas, which in the future—together with wind and solar energy—may become an important renewable energy source (RES). What is more, energy production from biogas is beneficial to the diversification of the socio-economic development of regions and may be one of the elements of their endogenous development [1–5].

Biogas power plants have a huge potential which can positively influence the socio-economic development and improve the environment of a given area. It should also be emphasized that biogas can be an opportunity for the development of underdeveloped and developing regions and countries [6–11].

The particular importance of biogas is connected with its wide application, as it is used for energy production, direct and indirect heat production and as fuel. The issue of electricity generation from biogas and indirect heat production via cogeneration (Combined Heat and Power—CHP) for

heating purposes, formed in special units as a byproduct in the production and transmission of electricity to the grid, was pointed out by, *inter alia*, Murphy, Mc Keoghb, and Kiely [12], Pöschl, Ward and Owende [13], Havukainen *et al.* [14]. As mentioned above, biogas is also used for direct heat production and for commercial purposes in the heating of industrial buildings, public buildings, and housing [15,16]. Recently, the great importance of biogas (purified to natural gas quality) as fuel for public and individual transport has also been highlighted [17,18].

Another advantage of biogas is its universal source, *i.e.*, waste found in all corners of our planet. Biogas is an endogenous resource of the area, and therefore can be produced virtually everywhere, especially in urban areas. As emphasised by Taleghani and Kia [19], and Jingura and Matengaifa [20], the technology of obtaining gas is relatively simple.

Biogas production can be treated as a kind of innovative activity in local development because its production depends on the quality of human resources and their openness to environmentally friendly behavior, the amount of substrate produced by urban and rural populations (including municipal waste, food production, and farming waste), as well as the possibilities of growing energy crops for biogas in a given area [21,22]. Good practices in the implementation of environmentally friendly solutions are provided by the local authorities and residents of Vienna. In 2007, the composting plant Biogas Wien opened there, where heat is produced in fermentation processes to warm the Viennese households [23].

Such varied sources of biogas make biogas power plants suited to both urban and rural areas. In the latter, biogas production, especially agricultural biogas, may exceed its consumption. Therefore, it is possible to sell it, thereby generating additional profits, so important and needed for those often-underinvested areas [6,7]. In Poland, development of biogas power plants is at an early stage [4], but due to the relatively high possibility of obtaining substrate (landfill waste, waste water, and agricultural waste), there are opportunities for the further development of this fuel and energy sector.

Generally, there are two groups of factors affecting the development of biogas plants—exogenous and endogenous [4]. The exogenous factors include political and legal conditions [24,25] and external financial support for the development of the RES sector [26–29]. The second group of factors include, the availability of substrates and appropriate technologies [3,30–32], as well as the support and openness of the local government and community and their openness to this type of investment [7,33–35].

It follows from the above that the issues taken up by the authors are extremely important and multifaceted. The aim of the study is to analyze and evaluate the capacity of biogas plants in Poland based on the generic structure of biogas power plants and their energy production volume and to show the position of Poland in terms of the amount of the obtained energy and electricity production from biogas compared to other European countries. One of the aims of the paper is to show the regional variation in the distribution of biogas plants in Poland and to indicate that their development can be one of the elements of bottom-up development of a *poviat*. Moreover, the study attempts to define the strengths and weaknesses, as well as the opportunities and threats of developing biogas power plants in Poland in the context of exogenous and endogenous conditions.

Additionally, the study undertakes an attempt to answer a number of questions:

- What is the structure of biogas plants in Poland and what is their energy production volume in gigawatt-hours (GWh), as well as the total capacity of biogas plants in Poland in megawatts (MW)?
- Is the distribution of biogas plants in Poland concentrated, or are they are dispersed (due to the prevalence of biogas obrained in all areas—especially urban)?
- Is there a relationship between the nature of the area and the generic structure of biogas plants in Poland (*i.e.*, whether agricultural areas are dominated by biogas plants based on agricultural substrates, and in urban areas biogas plants at landfill sites)?
- Are biogas plants and the use of their power correlated with the level of the socio-economic development of the area?

Until now the majority of publications on biogas in Poland analyzed only one kind of biogas power plant. In the literature one can find many papers dealing with the development of biogas from landfill sites [36,37], biogas from wastewater treatment plants [38,39], and the production of agricultural biogas in Poland [4,40]. There are also works on biogas in Poland which deal with the subject of the regional market in biogas production in Poland [41–43], the cultivation of biofuels in Poland [21], and the most available biogas technologies in Poland [44]. However, there are no papers dealing comprehensively with biogas power plants in Poland which are based on all types of substrate or discussing the variation in the spatial distribution of different types of biogas power plants. This article is an attempt to fill this gap and to contribute innovative elements to existing knowledge on biogas power plants in Poland, both with respect to a comprehensive treatment of the problem of biogas power plants in Poland and encouraging ecological behavior of local authorities and local communities, as well as promoting endogenous factors of the economic development of a given region. Moreover, there are case studies of biogas power plants located in a large town, in a village on the outskirts of a town and in a typical agricultural area in the countryside. In the first case, *i.e.*, a large town (Krakow—758,992 inhabitants), a biogas power plant based on substrate from landfill and from wastewater treatment plants is described. In the second, a biogas power station in the suburban village of Machnacz near the town of Włocławek (114,885 inhabitants) is presented, which is based on substrate from waste from the town. The third example is a typical agricultural biogas power station in Boleszyn (515 inhabitants, a village in the *gmina* of Grodziczno, *nowomiejski poviat*, Warmińsko-Mazurskie *voivodeship*).

2. Methodology, Materials, and Source Data

The study is based on the primary data for the period 2003–2013, mainly from the Energy Regulatory Office (*Urząd Regulacji Energetyki*—URE [45]). It contains the number of biogas plants, their maximum installed capacity in MW, generic structure, and location by *poviat* (urban and rural). Some data were also taken from the Local Data Bank of the Central Statistical Office (*Bank Danych Lokalnych Głównego Urzędu Statystycznego*—BDL GUS [46]); these were related to the socio-economic characteristics of the individual first-tier administrative units—*voivodeships*—and the second-tier administrative units—*poviats*. In addition, the data source is a series of publications issued by the Central Statistical Office, titled "Energy from renewable sources" [47,48].

The study was based on the generally accepted methods for data quantification, processing, and presentation. For this purpose the authors used Statistica 9.0, IBM SPSS Statistics 22.0, and MapInfo Professional 12.0 software. In order to capture certain interdependences between the location of biogas plants and socio-economic characteristics, the correlation coefficients at the assumed significance level of 0.05%, and determination coefficients were calculated and a regression analysis was conducted for selected cases. The primary and secondary data, therefore, meet the criteria of credibility, methodological accuracy, reliability, and timeliness.

From the methodological point of view we should also define the expressions used in the paper: installed capacity of a biogas power plant, energy production from biogas, energy obtained from biogas, primary energy, derived energy, transformation input, and final consumption.

Installed capacity of a biogas power plant is the sum of the active power generators installed in this power plant measured in megawatts (MW or derived units).

Production of energy from biogas (yield) is the amount of electricity (in GWh or derived units) produced in the process of energy transformation (only for carriers of derived energy).

Energy obtained from biogas is the amount of energy (TJ or derived units) obtained from natural resources (this refers only to primary energy carriers). Primary energy is the sum of the energy contained in primary energy carriers obtained directly from renewable and non-renewable resources, while derived energy is the sum of the energy obtained from derived energy carriers, which are obtained in the process of energy transformation.

Transformation input is the sum of consumption of individual energy carriers used as raw material, *i.e.*, to be processed into other energy carriers in technological processes considered as energy transformations, excluding the use of energy carriers intended to support the process itself.

Final consumption is the use of energy by consumers (industry, services, households) to meet their technological, production, and living needs, and it does not include processing into other carriers [48].

3. Results and Discussion

3.1. Obtaining and Producing Energy from Biogas in Poland

Since the dawn of mankind people have produced side components, starting with food scraps, and then in more recent centuries remnants of worn-out home and office furniture and other municipal waste. The possibilities of their use were limited to feeding animals, fertilizing soil or burning for heating purposes. Only the technical and technological development of the twentieth century made it possible to process side-products of human activity for energy and heating purposes. The first documented use of biogas in Poland (generated from waste water treatment) for heating purposes was recorded in 1928 in Poznań [49]. Since then, there has been a considerable development of biogas plants in Poland, but this sector is still relatively small.

Today, the leaders in the production of energy from biogas in the EU are Germany, the United Kingdom, and Italy, which in 2012 together generated approx. 77% of the total EU biogas production [50]. In the other 25 European Union countries (EU membership as of 2012) (including Poland), so far this kind of energy has made up an insignificant percentage of energy production, but the number of biogas plants is growing due to the need to diversify energy sources.

It should be noted that the European Union (28 European Union States—2012) is increasing the proportion of energy from biogas in obtaining energy from renewable resources; it amounts to 6.8% (2012). Particular emphasis should be given to the distinctive position of Germany, whose share of energy from biogas, both in obtaining and producing energy from renewable sources, is over 19% (2012). There are numerous reasons why the biogas market is so well developed in Germany. They are institutional and legal (the act on renewable energy sources, *Erneuerbare Energien Gesetz*, promotes RES, tax relief for investors [51]), as well as technological (innovational technological solutions allowing production of biogas from various sources at the same time, such as from plants and animal waste [52]) and also organizational and economic—creating the climate for the formation of associations of small farmers producing biogas.

A significant share of energy from biogas within the total energy from renewable sources is also recorded in the Czech Republic (11.5% in obtaining energy, 18.2% in producing energy—2012) in which, as in Germany, agricultural biogas production is dominant (mainly produced from biofuel plants [53]) (*cf*. Figure 1 and Table 1). In the European Union there are countries where the share of obtaining and producing energy from biogas in the overall obtaining and producing energy from RES is very small, in the region of half a percent—Estonia, Finland, and Sweden (*cf*. Figure 1 and Table 1). If compared with selected European Union countries, the position of Poland is insignificant, because the share of energy from biogas in obtaining energy from renewable sources is approximately 2% (2012). Overall, if measured in terajoules (TJ), energy obtained from renewable sources in Poland in 2012 amounted to 356,070.0 TJ; it consisted of the energy produced from solid biofuels (82.1%), liquid biofuels (8.0%), biogas (2.0%), renewable municipal waste (0.4%), solar energy (0.1%), water energy (2.1%), wind energy (4.8%,) geothermal energy (0.2%), and heat pumps, *i.e.*, heat energy from the environment (0.3%) [47].

An important issue from the point of view of obtaining and producing energy from biogas is that with the increasing pro-ecological attitude a growing number of wastewater treatment plants and landfills with sustainable waste management are being opened, both in urban and rural areas. Waste management of agricultural production is also becoming more and more common (animal and

plant slurry, liquid manure, *etc.*). It is likely that in the long term these conditions will contribute to the growth in the participation of energy from biogas in the total energy from renewable sources.

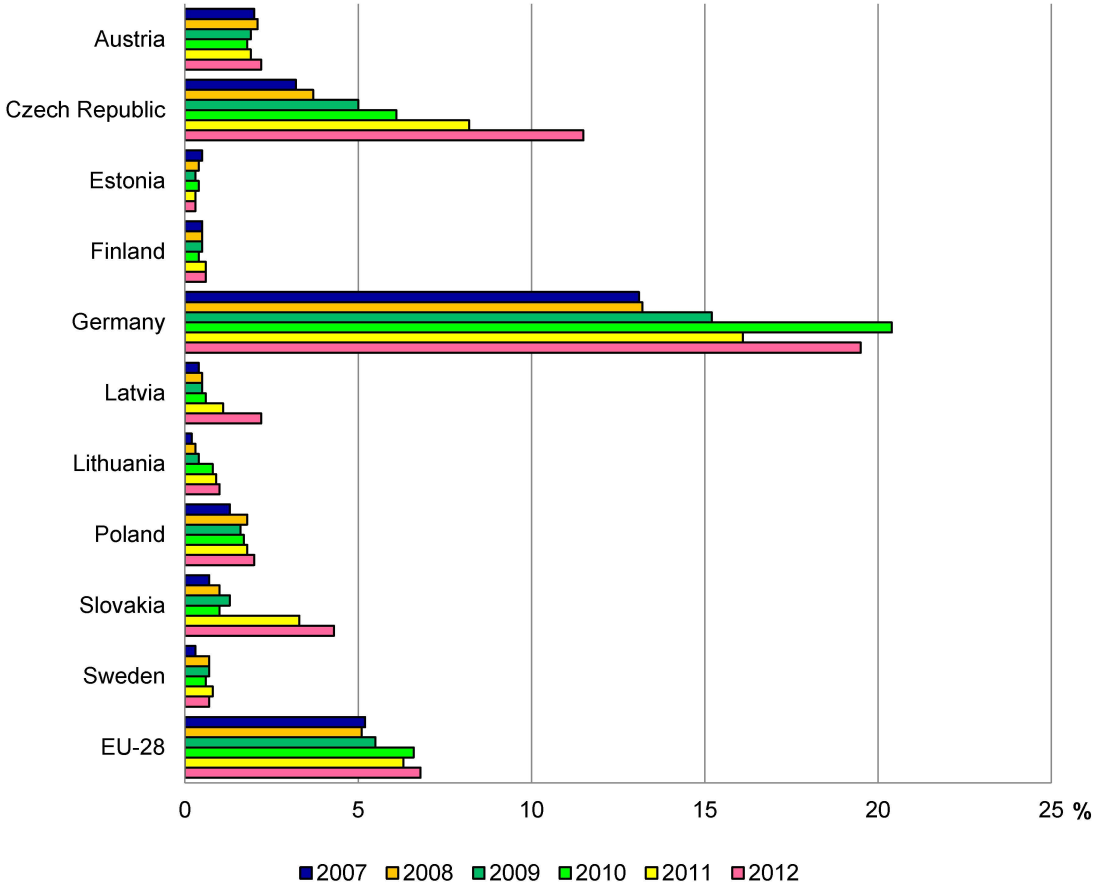

Figure 1. Energy obtained from biogas as % in the overall energy obtained from RES in selected EU countries.

Table 1. Producing energy from biogas as % in the overall producing of renewable energy in the European Union [48].

Country	2007	2008	2009	2010	2011	2012
Austria	1.2	1.3	1.3	1.4	1.5	1.2
Czech Republic	6.3	7.2	9.5	10.8	12.8	18.2
Estonia	9.0	4.6	1.3	1.0	1.3	1.1
Finland	0.1	0.1	0.1	0.4	0.6	0.5
Germany	9.5	14.0	15.9	16.7	17.2	19.1
Latvia	1.3	1.2	1.3	1.6	3.4	5.4
Lithuania	1.0	1.5	2.2	3.4	3.2	3.6
Poland	3.6	3.8	3.7	3.7	3.4	3.3
Slovakia	0.2	0.3	0.4	0.6	2.3	3.5
Sweden	0.1	0.0	0.0	0.0	0.0	0.0
EU-28	3.7 *	4.4	4.7	4.7	5.6	6.1

* Data for EU-27.

It is worth mentioning that in obtaining energy from renewable sources in general (EU-28), a clear increase is being noted, because in 2003 the proportion of renewable energy obtained was 11.1% of primary energy in general, and in 2012 it was 22.3%. Against this background Poland looks less

favorably because in 2012 the share of the obtained renewable energy was 11.7% of the primary energy in general (in 2003 it was 5.2%).

3.2. Structure and Size of the Energy Obtained and Produced from Biogas in Poland

The analysis of the structure and size of the obtained and produced energy from biogas in Poland was based on all 231 biogas power plants (2013). Out of them 102 power plants produced biogas from landfills (44%), 85 from wastewater treatment plants (36%), while 42 worked on agricultural substrate (agricultural biogas power plants), and two were mixed biogas plants (substrate for obtaining biogas came from various sources, *i.e.*, from agricultural sources, as well as from landfills and wastewater treatment plants).

Considering the amount of energy obtained from biogas it should be stressed that in 2013 it was 7593 TJ (7033 TJ in 2012) and such was the size of its annual domestic consumption. A total of 44.1% of the biogas obtained came from wastewater treatment plants, 28.4% from landfills, while 27.5% of it was from other sources (agricultural biogas obtained in the process of anaerobic fermentation of biomass from energy crops, residues from crop production and animal manure, as well as biogas obtained by the anaerobic fermentation of biomass from waste in meat works, breweries, and other food industries) [48].

It should be emphasized that the highest growth rate in terms of the energy obtained from biogas was recorded in the case of the remaining biogas sources (agricultural), amounting to 24 TJ in 2003, and to 2084 TJ in 2013 and, thus, it showed an over 85-fold increase in energy obtained from this source (8683%) (*cf.* Figure 2 and Table 2). A much smaller increase was noted with respect to obtaining biogas from wastewater treatment plants (approx. four-fold), and landfills (approx. three-fold). This enormous growth rate in obtaining agricultural biogas (*i.e.*, remaining biogas) is connected, *inter alia*, with the financial support from the European Union, which is allocated for investments in the renewable energy sources (e.g., the funds from the Regional Operational Programme 2007–2013). The Regional Operational Program takes into account, *inter alia*, the tasks aimed at the development of infrastructure for environmental protection, including increasing the use of renewable energy sources. Financial support for renewable energy sources accounted for approx. 1.4% of the funds of this programme [54]. Part of the funds for renewable energy sources was directed to the development of infrastructure for obtaining and producing biogas.

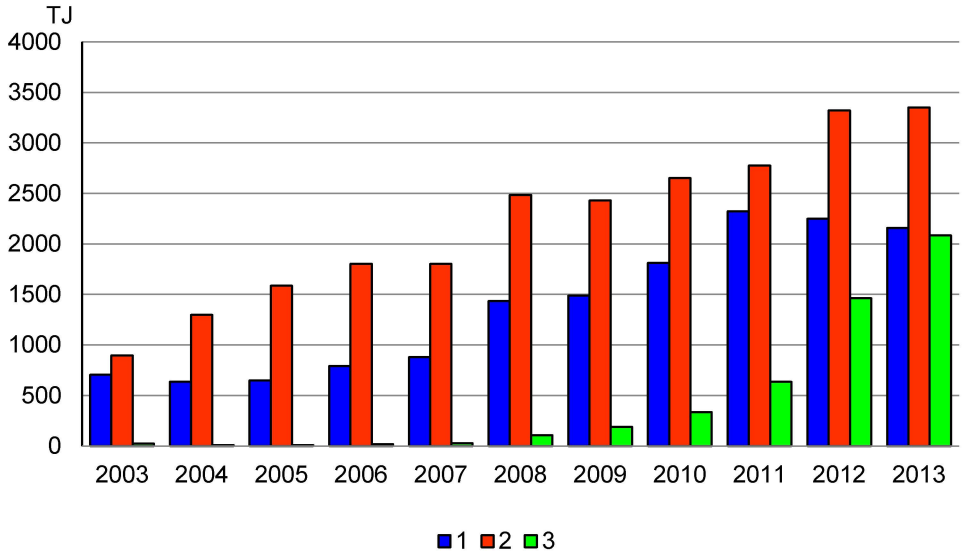

Figure 2. Energy obtained from biogas according to the structure of biogas plants in Poland. Explanation: 1—biogas from landfills; 2—biogas from wastewater treatment plants; 3—biogas from other sources (agricultural).

Table 2. Energy obtained from biogas and its production according to the structure of biogas power plants in Poland.

Structure of Biogas Power Plants	Year											A
	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	
Energy obtained (TJ)												
Biogas from landfills	704	636	649	791	879	1433	1487	1811	2323	2249	2157	306
Biogas from wastewater treatment plants	896	1297	1586	1803	1802	2486	2429	2652	2775	3321	3352	374
Biogas from other sources (agricultural)	24	8	8	19	27	107	188	334	634	1463	2084	8683
Total	1624	1941	2243	2613	2708	4026	4104	4797	5732	7033	7593	468
Energy produced (GWh)												
Biogas from landfills	53	63	75	92	114	148	175	220	234	237	241	455
Biogas from wastewater treatment plants	2	18	35	67	80	95	123	132	150	194	233	11,650
Biogas from other sources (agricultural)	1	1	1	2	2	8	22	46	68	135	216	21,600
Total	56	82	111	160	195	252	319	398	451	565	690	1196

Explanation: A—growth rate between 2003 and 2013 (2003—10%).

Generally, in the years 2003–2013 energy obtained from biogas increased over four-fold from 1627 TJ in 2003 to 7593 TJ in 2012 (*cf.* Figure 2 and Table 2).

Another element of the analysis of biogas power plants in Poland is to show the size of electricity production in these plants in GWh. It should be noted that in the years 2003–2013 an almost twelve-fold increase in the production of energy from biogas was recorded; it grew from 56 GWh in 2003 to 670 GWh in 2013. In the structure of energy production from biogas the share of production from each of the three types of power plants is almost the same and amounts to 35% for the production of energy from landfill, 34% from wastewater treatment plants, and 31% from agricultural biogas (remaining biogas) (*cf.* Figure 3 and Table 2). However, in the latter case, there was an over twenty-fold increase in energy production: from 1 GWh in 2003 to 216 GWh in 2013. The increase in the production of energy from biogas from wastewater treatment plants was tenfold, and biogas from landfills almost fivefold (*cf.* Figure 3 and Table 2).

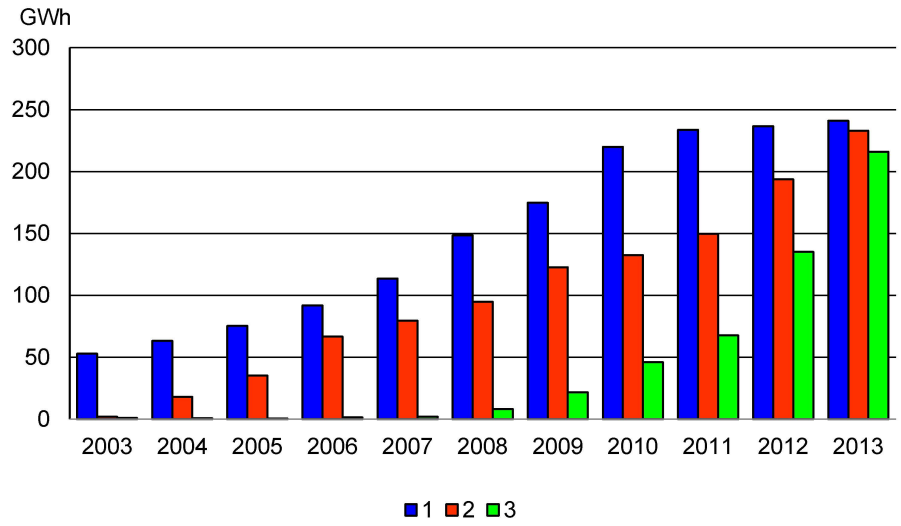

Figure 3. Energy production from biogas according to the structure of biogas power plants in Poland. Explanation: 1—biogas from landfills; 2—biogas from wastewater treatment plants; 3—biogas from other sources (agricultural).

Thus, it can be concluded that the amount of the energy obtained from biogas does not always translate into the amount of energy produced from biogas. This is because energy production depends largely on the type of substrate and the technology of its gasification. These factors influence the content of methane in the biogas, which is higher when the calorific value of biogas is higher, which translates into a higher energy production.

In addition to the energy obtained and produced from biogas, an interesting issue is the consumption structure of the energy from biogas. In 2013, 76.7% of consumption accounted for energy transformation input, while 23.3% accounted for final consumption. As much as 55% of the final consumption was generated by trade and services, 29% by agriculture and forestry, 11% by the food and tobacco industries, and 5% by the paper and printing industry.

3.3. Biogas Power Plants, Their Capacity, and Spatial Distribution

In this chapter, the authors analyze biogas power plants from the point of view of their capacity and spatial distribution. Referring to this issue it should be noted that from year to year the total capacity of power plants and thermal plants in Poland is increasing: it was 38.1 GW in 2012, 38.6 GW in 2013, and 39.1 GW in 2014. Moreover, the total capacity of power stations using energy from renewable sources is increasing: in 2012 it amounted to 4 GW (10.5% of total installed capacity), in 2013 it was 5 GW (13%), and in 2014 it reached 6 GW, of which 3.8 GW was from wind power plants, 1 GW from biomass, 0.98 GW from hydroelectric power plants, 0.19 GW from biogas power plants, and 0.03 GW from solar panels (*cf.* Figure 4).

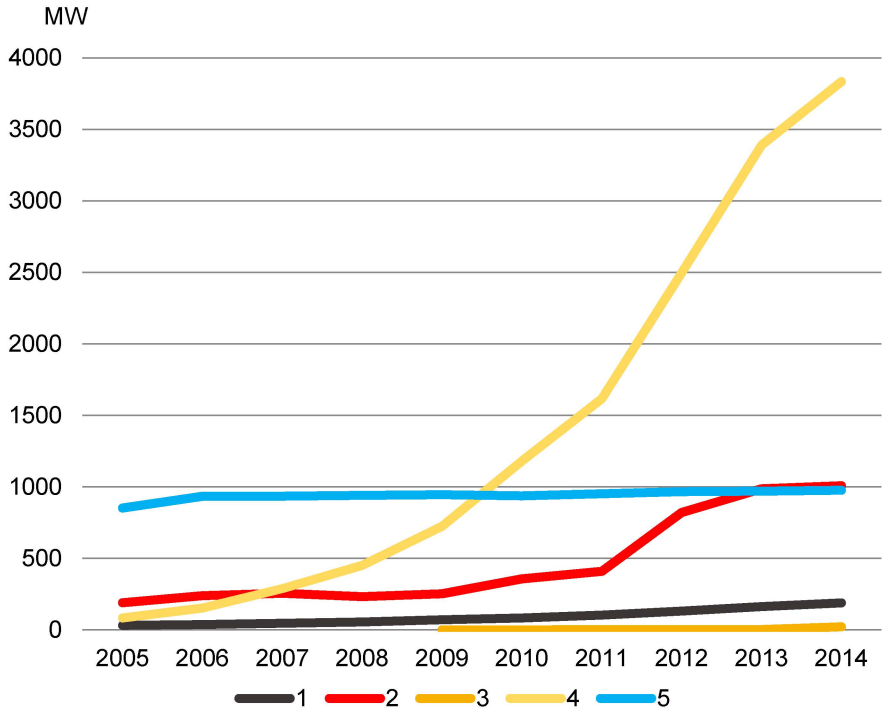

Figure 4. Installed capacity of RES in Poland [45]. Explanation: 1—biogas power plants; 2—biomass power plants; 3—power plants generating electricity from solar radiation; 4—wind farms; 5—hydropower plants.

It follows that the capacity of biogas power plants in Poland has been of minor importance so far. The combined share of installed capacity of biogas power plants represents 0.5% of the total installed capacity of power plants and thermal plants in Poland (39.1 GW of total installed power, 0.19 GW installed capacity of biogas power plants). The capacity of power plants producing biogas from landfills constituted 39%, those based on wastewater treatment plants made up 30%, those based on

agricultural biogas made up 30%, and 1% were the power plants producing mixed biogas (the latter type of biogas plants, that is two power plants, were not included in the further analysis due to their insignificant participation in the overall structure).

Considering the capacity of biogas power plants in Poland it should be emphasized that it depends, besides other factors, on the population of the *voivodeship*. The larger the population, the more biogas plants, and their greater installed capacity. For example, the most populous *voivodeships*, Mazowieckie and Śląskie, whose share in the population of the country is respectively 14% and 12%, have an installed capacity of, respectively, 16 MW and 20 MW; it stems from the number of biogas plants (respectively 32 and 29) (*cf*. Table 3).

Table 3. Generic structure of biogas plants and their installed capacity by sources in *voivodeships* in Poland (as of 31 December 2013).

Voivodeships	**A**	**I**		**II**		**III**		**Total**	
		1	**2**	**1**	**2**	**1**	**2**	**1**	**2**
Dolnośląskie	8	9	7	8	3	3	3	20	14
Kujawsko-pomorskie	5	8	4	4	4	3	6	15	13
Lubelskie	6	1	1	4	1	5	6	10	8
Lubuskie	3	1	1	2	1	3	2	6	3
Łódzkie	7	5	5	3	3	2	2	10	11
Małopolskie	9	6	3	7	4	0	0	13	7
Mazowieckie	14	23	12	8	3	1	2	32	16
Opolskie	3	1	0	2	1	1	2	4	3
Podkarpackie	6	3	2	8	3	0	0	11	4
Podlaskie	3	1	1	4	4	0	0	5	4
Pomorskie	6	5	4	4	4	8	9	17	18
Śląskie	12	15	13	13	7	1	1	29	20
Świętokrzyskie	3	1	0	2	1	1	1	4	2
Warmińsko-mazurskie	4	3	2	5	2	4	5	12	9
Wielkopolskie	9	10	6	7	6	4	4	21	16
Zachodniopomorskie	4	10	4	4	1	6	7	20	12
Poland	100	102	63	85	48	42	49	229 *	160

* Excluding two mixed biogas plants. Explanation: A—percentage of the national population in individual *voivodeships*; I—power plants based on biogas from landfills; II—power plants based on biogas from wastewater treatment plants; III—power plants based on agricultural biogas; 1—number of power plants; 2—installed capacity (MW).

As previously mentioned, the study shows that the structure of biogas power plants in Poland is dominated by power plants based on biogas from landfills; there are 102 such plants, which account for 44% of the total. Another large group are power plants based on biogas from wastewater treatment plants; there are 85 such plants, which constitute 37%. There are 42 plants based on agricultural biogas (18%) and two are mixed (1%).

In terms of the generic structure of biogas plants there are large regional differences in individual *voivodeships*. In some *voivodeships* (5 out of 16) the generic structure of the operating power plants is dominated by those based on biogas from landfills, which account for half of the total number of biogas plants in these *voivodeships*: Mazowieckie (23 out of 32 operating power plants are based on biogas from landfills), Kujawsko-Pomorskie (8/15), Śląskie (15/29), Zachodniopomorskie (10/20), and Łódzkie (5/10) (*cf*. Table 3). These *voivodeships* show a high level of urbanization, as well as large populations and well-developed networks of catering and restaurant services, and numerous hyper- and supermarket facilities. The population and the above-mentioned activities generate large amounts of waste. There are also *voivodeships* where the generic structure of biogas plants is dominated by agricultural biogas plants, namely Lubelskie (5/10) and Lubuskie (3/6), which reflects, among other things, the structure and size of farms (dominance of large farms), as well as the size of livestock production and crop cultivation. Treating the installed capacity of biogas plants in a *voivodeship* as 100%,

the largest proportion of installed capacity of plants using agricultural biogas is recorded in Lubelskie, Lubuskie, Opolskie, and Zachodniopomorskie *voivodeships* (URE data show there are also *voivodeships* in which agricultural biogas plants do not exist at all—Małopolskie, Podlaskie, and Podkarpackie).

It is worth emphasizing that, generally, agricultural biogas plants have a higher installed capacity, 1.2 MW on average, while the average installed capacity of biogas plants at landfill sites and at wastewater treatment plants is 0.6 MW. Installed capacity of agricultural biogas plants in individual *poviats* is, to some extent, correlated with the surface area of agricultural land (in ha). This is evidenced by the value of Pearson's linear correlation index $r = 0.31$ ($\alpha = 0.05$). There is also a correlation observed between the installed capacity of agricultural biogas plants and the participation of investment in agriculture, forestry, hunting, and fishing in the general investments in a *poviat* ($r = 0.48$; $\alpha = 0.05$). Moreover, the size of the installed capacity of agricultural biogas power plants is affected by the size of the share of investments in sector I (agriculture, forestry, hunting, and fishing) in the total investments in the *poviat*. This is evidenced by the good fit of the linear regression model $r^2 = 0.297$ with the significance level of the model of less than 0.001 (*cf.* Figure 5I). This correlation is also confirmed by the value of Pearson's correlation index $r = 0.48$ ($\alpha = 0.05$).

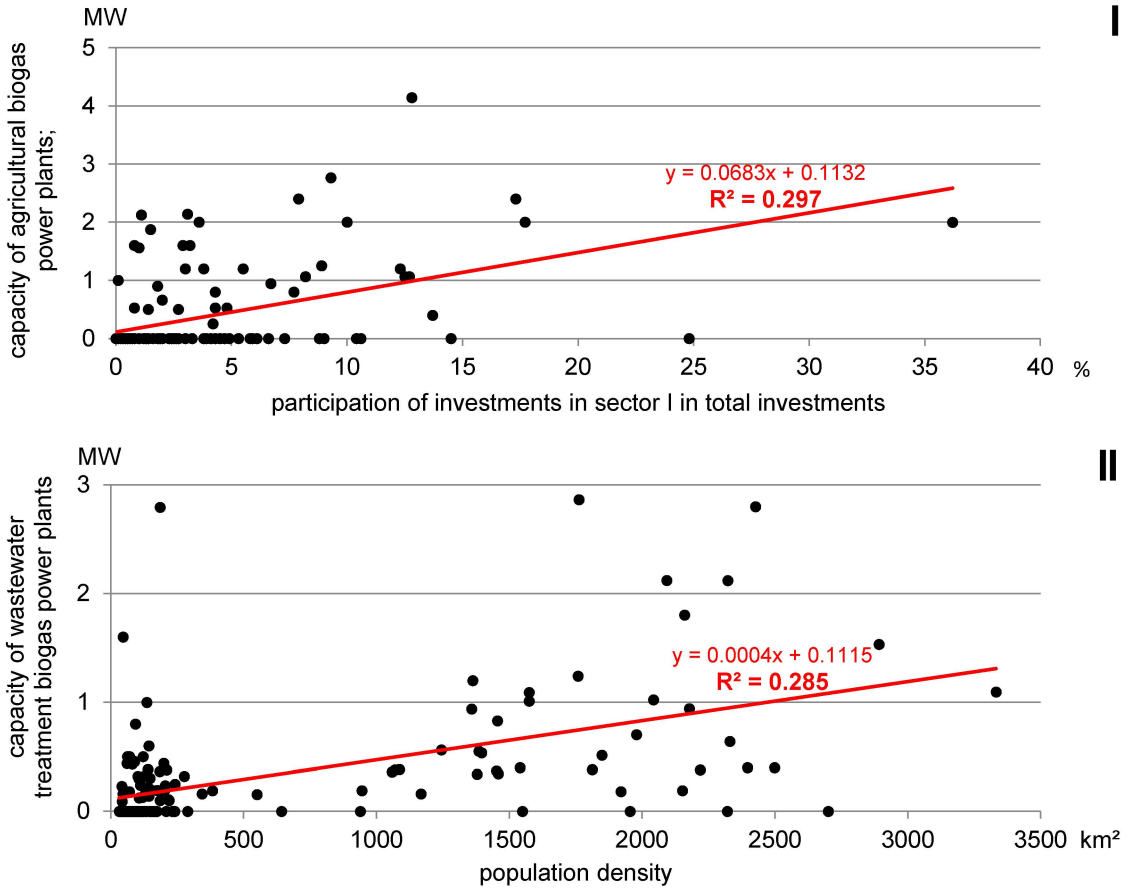

Figure 5. Graph showing regression analysis between the installed capacity of agricultural biogas power plants and the share of investments in sector I in the total investments in the *poviat* (**I**) and between the installed capacity of biogas power plants based on biogas from wastewater treatment plants and the population density (**II**).

In turn, with regard to biogas power plants based on biogas from wastewater treatment plants, it has been observed that the size of the installed capacity of a given biogas power plant depends to a great extent on the density of the urban population of a given *poviat* and the level of urbanization (percentage share of the urban population in the total population living in the *poviat*). In the former case

the Pearson correlation index is $r = 0.54$ ($\alpha = 0.05$), the determination index is $r^2 = 0.285$ (*cf*. Figure 5II), and in the latter one $r = 0.41$ ($\alpha = 0.05$). Additionally, a high correlation is recorded between the installed capacity of the power plants based on biogas from wastewater treatment plants and the amount of treated municipal wastewater per 100 km^2, where $r = 0.60$ ($\alpha = 0.05$).

The research shows that the overall average installed capacity of biogas power plants in Poland is 0.7 MW, and there is a considerable regional variation in terms of the size of their installed capacity. As already mentioned, the total installed capacity of all biogas power plants in Poland was 162 MW in 2013 (2014—189 MW). The highest installed capacity of biogas plants (from 15 MW to 20 MW) is recorded in Śląskie, Pomorskie, Wielkopolskie and Mazowieckie *voivodeships*. The lowest, below 5 MW, is recorded in Podlaskie, Podkarpackie, Świętokrzyskie, Lubelskie and Lubuskie *voivodeships* (*cf*. Figure 6 and Table 3).

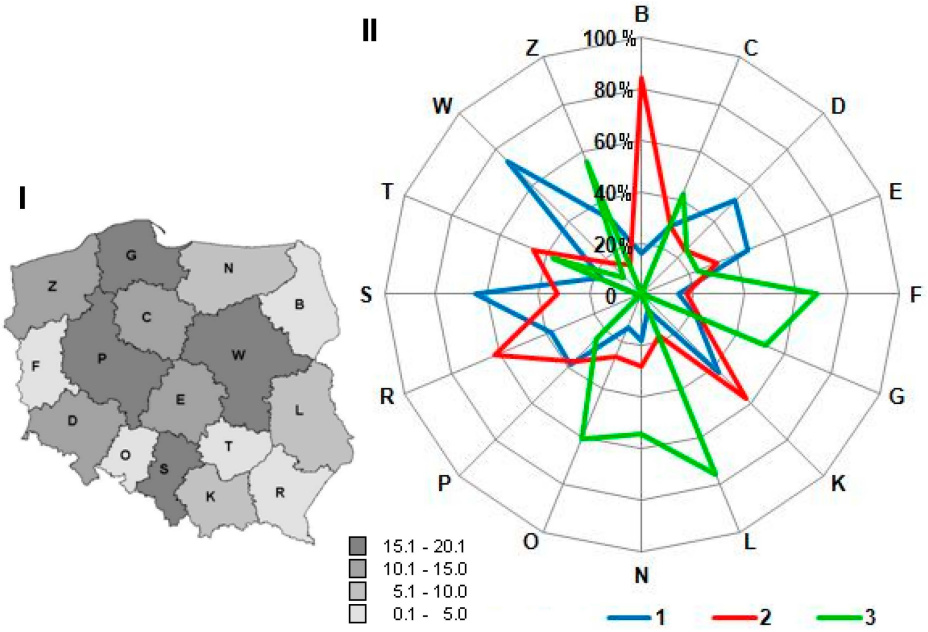

Figure 6. Structure of installed capacity of biogas plants by biogas sources in *voivodeships* in Poland (as of 31 December 2013). Explanation: I—capacity of biogas installations (MW); II—percentage structure; 1—biogas from landfills; 2—biogas from wastewater treatment plants; 3—agricultural biogas. *Voivodeships*: B—Podlaskie; C—Kujawsko-Pomorskie; D—Dolnośląskie; E—Łódzkie; F—Lubuskie; G—Pomorskie; K—Małopolskie; L—Lubelskie; N—Warmińsko-Mazurskie; O—Opolskie; P—Wielkopolskie; R—Podkarpackie; S—Śląskie; T—Świętokrzyskie; W—Mazowieckie; Z—Zachodniopomorskie.

It should be noted that the power station based on biogas from landfills operating in Siemianowice Śląskie in Śląskie *voivodeship* has the highest installed capacity in Poland—3.45 MW. It belongs to the group ENER-G Poland, which owns 13 power plants of this type in Poland. The largest capacity amongst power plants based on biogas from wastewater treatment plants is in a biogas plant in Gdańsk. Its installed capacity is 2.864 MW and its energy is used to power the installation for the thermal treatment of wastewater sludge in the Gdańsk Wastewater Treatment Plant Wschód, while in the future the surplus will be sold to the national grid. In turn, the generated heat is used for technological and living needs of the above-mentioned Wastewater Treatment Plant. Considering the installed capacity of agricultural biogas plants, one should note that the highest installed capacity of 2.4 MW is observed in the biogas plant in Potęgowo in Pomorskie *voivodeship* (as of 2012). By 2012, the largest installed capacity of agricultural biogas plants was in Koczała (Pomorskie *voivodeship*) and Liszkowo (Kujawsko-Pomorskie), each with an installed capacity of 2.126 MW.

For a more detailed discussion of the structure and size of the installed capacity of biogas plants in Poland, further analysis of the above-mentioned issues is based here on *poviats* (*cf.* Figure 7, Tables 4 and 5). In Poland there are 380 *poviats*, including 66 urban *poviats* (*i.e.*, towns with *poviat* rights) and 314 rural *poviats*. Biogas power plants are found only in 40.5% of all the *poviats*, *i.e.*, in 154 *poviats*—in 113 rural *poviats* (representing 36% of all the rural *poviats*) and in 41 urban *poviats* (which represent 62% of all the urban *poviats*) (*cf.* Figure 7 and Table 5). In 19 of the urban *poviats* biogas power plants are based on biogas from wastewater treatment plants, in four such *poviats* power plants are based on biogas from landfills, and in 18 *poviats* there are two types of biogas plants (*i.e.*, at wastewater treatment plants and at landfills). In total, in the above-mentioned urban *poviats* there are 66 biogas plants with a total installed capacity of 51 MW (*cf.* Table 4). However, in rural districts there are 165 biogas plants, of which 76 are based on biogas from landfills, 45 on biogas from wastewater treatment plants, 42 on agricultural biogas, and two are mixed biogas plants. Generally, in these *poviats* the total installed capacity of biogas plants is 112 MW (*cf.* Table 4).

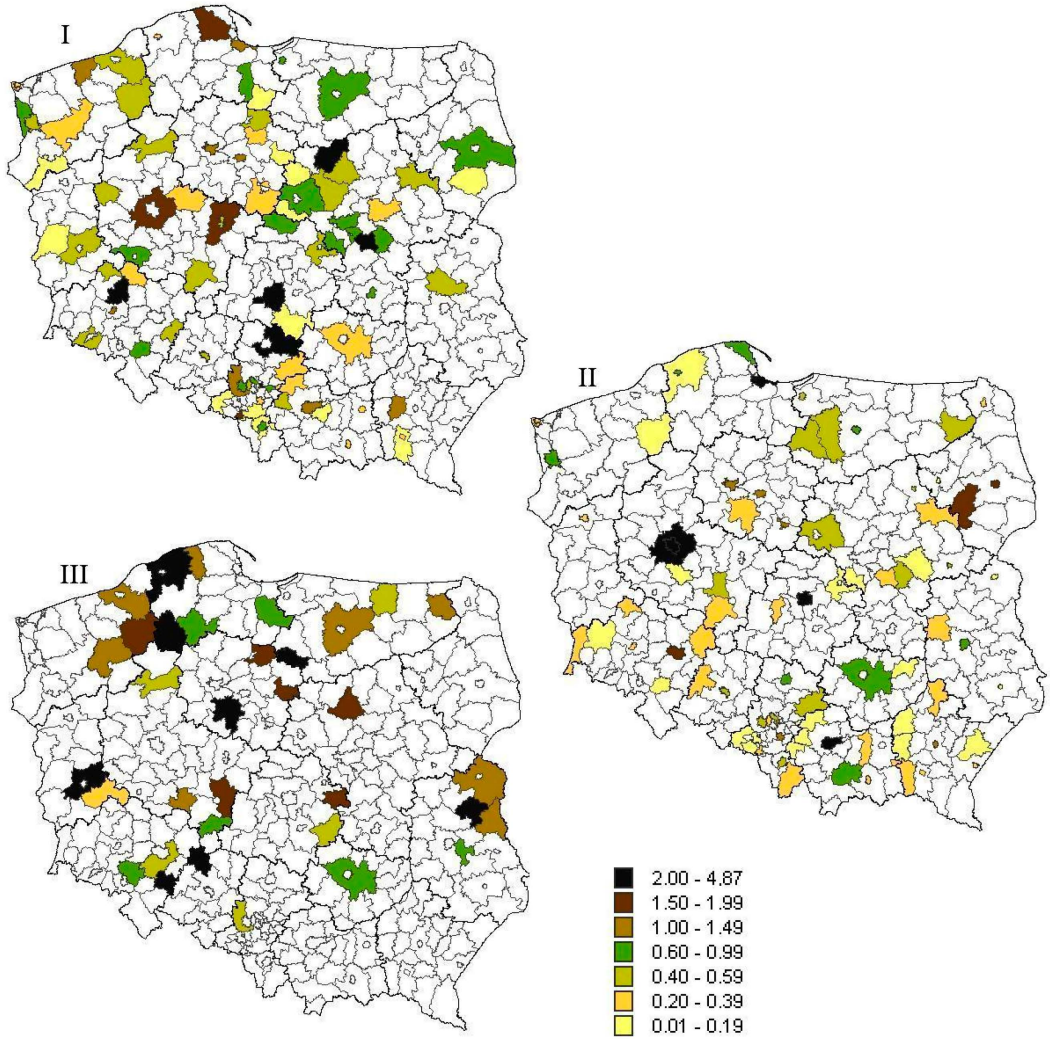

Figure 7. Total installed capacity of biogas plants in Poland in *poviats* by plant type (MW). Explanation: I—power plants based on biogas from landfills; II—power plants based on biogas from wastewater treatment plants; III—power plants based on agricultural biogas.

Table 4. Number of biogas plants and their installed capacity (MW) by *poviat* in Poland (as of 31 December 2013).

Structure of Biogas Power Plants	Rural *Poviats*			Urban *Poviats*			Poland		
	A	B	C	A	B	C	A	B	C
I	76	43	38	26	20	37	102	63	39
II	45	17	15	40	31	57	85	48	29
III	42	49	44	0	0	0	42	49	30
IV	2	3	3	0	0	0	2	3	2
Total	165	112	100	66	51	100	231	163	100

Explanation: I—power plants based on biogas from landfills; II—power plants based on biogas from wastewater treatment plants; III—power plants based on agricultural biogas; IV—power plants based on mixed biogas; A—number of power plants; B—installed capacity (MW); C—percentage of installed capacity.

Table 5. Total installed capacity of biogas plants in Poland in *poviats* by plant type (as of 31 December 2013).

Capacity (MW)	I			II			III			Total		
	1	2	3	1	2	3	1	2	3	1	2	3
2.00–4.87	8	6	17.97	7	5	12.70	15	9	21.98	30	19	52.65
1.50–1.99	6	4	6.96	3	3	4.94	6	6	10.23	15	13	22.13
1.00–1.49	10	8	9.64	6	6	6.66	9	8	9.24	25	22	25.54
0.60–0.99	26	19	13.80	9	8	6.45	6	6	5.11	41	32	25.36
0.40–0.59	22	19	8.53	16	14	6.57	5	5	2.48	43	39	17.58
0.20–0.39	17	16	5.01	23	23	7.34	1	1	0.25	41	39	12.60
0.10–0.29	13	13	1.29	21	21	3.07	0	0	0.00	34	34	4.36
Total	102	85	63.20	85	80	47.70	42	35	49.30	229	198 *	160.22

* The number of power plants is greater than the number of the analysed *poviats* in which there are biogas plants, because some *poviats* have two or more biogas plants. Explanation: I—power plants based on biogas from landfills; II—power plants based on biogas from wastewater treatment plants; III—power plants based on agricultural biogas; 1—number of biogas plants; 2—number of *poviats*; 3—total installed capacity (MW).

The issue described above, that is the development of biogas power plants and the production of energy from biogas, should be seen in the context of its strengths and weaknesses, as well as opportunities and threats regarding their development. Conditions for the development of biogas power plants in Poland are of a social and economic nature as well as an institutional and legal nature.

The social and economic weaknesses in the development of biogas power plants in Poland undoubtedly include the insufficient financial assistance from the state for carrying out investments [55], alongside the comparatively high investment costs of building biogas power plants [56], which prolongs the investment process. Another barrier to investing in biogas power plants is the hostility and resistance of the local community to this type of activity, which arises due to the lack of ecological education in Poland and from fear that living standards will fall as a result of unpleasant odors from the substrates supplied to the biogas power plant.

In turn, an institutional and legal weakness in creating biogas power plants is the fact that there is no clear national energy policy, which discourages the main electricity producers in Poland from buying energy from biogas, while at the same time encouraging them to produce energy from coal for political reasons, as every attempt to reduce the amount of energy from coal is met with great opposition from the mining community (especially at election time).

Strong sides in the development of biogas energy in Poland include the fact that Poland has a great potential as regards biomass, partly as a result of its large population (38.5 million inhabitants generating a large amount of waste and sewage) and partly because of its agricultural potential (expedient cultivation, e.g., maize, grass, clover, and a wide range of agricultural waste, including troublesome liquid manure). Moreover, investments in biogas power plants can contribute to increased income for farmers and also to increased employment, particularly in agricultural areas which are currently suffering high unemployment.

One threat for the development of biogas in Poland is instability in the price of agricultural substrates and also instability in the Polish energy policy resulting from new visions of state development based on political conditions.

Speeding up the development of biogas power plants in Poland should rely on removing institutional and legal barriers and on choosing the appropriate economic instruments which should contribute to the creation of support systems in the fields of research and scholarship, technology, and the service market connected with biogas installations [57].

Opportunities for the development of biogas in Poland include the experience of Western countries, which can be used as a model, for example in order to expand the use of biogas as a motor fuel. By way of example, the agricultural power plant in Linköping (Sweden) supplies fuel for the city buses, taxis, and private motorists [58]. In turn, in Bristol in Great Britain, the buses run on biogas (biomethane) produced from human sewage and food waste. The "poo bus" uses biomethane from wastewater treatment plants in Bristol [59]. Without doubt such solutions can be implemented in Poland as the substrates mentioned above are renewable resources.

Great potential in the creation and development of biogas power plants lies in local authorities and local communities. Therefore, below we present numerous examples of cooperation between local authorities and local communities in promoting pro-environmental attitudes conducive to the development of new biogas plants. As a case study, we use biogas power plants located in a large town, in a suburban village near a large town and in a typical agricultural area in the countryside.

As a first example, let us discuss three biogas power plants in a large town, *i.e.*, Krakow. One of them (Barycz) is based on substrate from the municipal waste collection centre, while the other two (Kujawy and Płaszów) are based on substrate from wastewater treatment plants. On the reclaimed, inactive part of the municipal waste site of Barycz is an installation to utilise gas from the waste dump in order to use it as energy. Energy is also obtained from municipal sewage. The wastewater treatment plant Kujawy utilizes biogas produced by sewage in fermentation chambers. Gas generators produce electricity with a capacity of 0.5 MW and heat with a capacity of 0.85 MW. In the modernized wastewater treatment plant Płaszów electricity and heat are produced from sewage biogas with a capacity of 2.0 MW and 3.0 MW, respectively [60].

In turn, the biogas plant in Machnacz (a village in the *gmina* of Brześć Kujawski, Włocławski *poviat*, Kujawsko-Pomorskie *voivodeship*) is an example biogas power plants located in a suburban village near a large town—Włocławek. It is owned by the Public Utilities Company SANIKO in Włocławek. The electricity produced at the landfill in Machnacz is used for the company's needs, *i.e.*, to power the machinery, while the surplus is sold to the local power grid (*cf.* Figure 8). Thermal energy, meanwhile, is used to heat the company's buildings, and the surplus is used to heat plastic tunnels in which ornamental plants are grown for the local market.

Another example is the agricultural biogas plant located in a typical rural area, *i.e.*, in Boleszyn, a village in the *gmina* of Grodziczno, *nowomiejski poviat*, Warmińsko-Mazurskie *voivodeship*. The plant, which was established in 2012, was beneficial for both farmers and the non-agricultural local community. Thanks to processing manure, a byproduct of pig rearing, this waste product is no longer burdensome for the residents. The agricultural biogas plant in Boleszyn provides local residents with thermal energy to heat water and houses. The investment cost 22 million PLN, of which over 11.5 million PLN [61] came from funds provided by the Operational Program Infrastructure and the Environment.

Of particular importance for the development of biogas power plants in every country is a healthy climate of cooperation between local authorities and the local community as well as with economic entities.

Here are some of the many examples of good cooperation between local authorities and residents. The result of cooperation between *gminas* (third tier administrative units) is the biogas plant, opened in 2010, based on a landfill in Trzebania (a village in the *gmina* of Osieczna, leszczyński *poviat*, Wielkopolskie *voivodeship*). The Trzebania landfill receives waste from 19 surrounding *gminas*, which

participated in the project of constructing a plant to obtain biogas from waste. Thanks to the cooperation of these 19 *gminas*, small local dumps were closed and reclaimed, and the electricity produced is used for local needs, while the rest is sold to the national grid; the obtained thermal energy heats the water and all the rooms of the Waste Management Plant in Trzebania. The investment cost almost 25 million euros, of which 18.6 million euros was obtained from the European Cohesion Fund, while the remaining 6.4 million euros was a direct contribution by the local authorities [62].

Figure 8. Biogas plant at a landfill in Machnacz (a village in the *gmina* of Brześć Kujawski, Kujawsko-Pomorskie *voivodeship*).

Another example of good cooperation between *gminas* in obtaining biogas is a power plant at the wastewater treatment plant at Zielona Łąka (*gmina* Pleszew, pleszewski *poviat*, *Wielkopolskie voivodeship*) run by the Municipal Company in Pleszewo. In 2012 the company obtained a concession for generation of electricity. The benefit of obtaining it is mainly the reduction in the consumption of traditional energy resources by the above-mentioned treatment plant, because the produced biogas is used for their own needs, *i.e.*, energy and heating needs.

4. Conclusions

The study shows that there is a slight progress in the development of biogas plants in Poland. However, compared with other European countries this segment is still relatively small. Both the energy obtained and produced from biogas plays a minor role in the Polish energy sector, because installed capacity of biogas plants amounts to 0.5% of the total installed capacity of power plants in Poland (39.1 GW of the total installed capacity, 0.19 GW installed capacity of biogas power plants). A positive trend, however, is that from year to year the production of energy from biogas is increasing; in the period 2003–2013 an almost twelve-fold increase was recorded.

The study showed that the generic structure of biogas plants in Poland is dominated by the power plants based on biogas from landfills, while the number of biogas plants based on agricultural

substrate is lower, although the agricultural area in Poland is huge (60% of the total area of Poland) and, therefore, one would expect more agricultural biogas plants.

The study shows that in 226 (*i.e.*, 59.5%) *poviats* in Poland there are no biogas power plants. All *poviats* (380) have wastewater treatment plants (3264 wastewater treatment plants in 2013), while the number of biogas plants using biogas from such facilities is 85. In 2013 there were 431 active landfills in Poland (as well as 2791 illegal dumping sites), which is more than the number of *poviats*, while the number of operating biogas plants based on biogas from landfills was 102. Therefore, there is a sufficient amount of the substrate for new biogas plants. The costs of such installations are high, but biogas plants can be financially supported from the EU subsidies. The issue is, therefore, not the expense, but the relationships of local authorities, initiatives of local communities, as well as carrying out public tasks under the Local Government Act (*poviat* tasks include environmental and nature protection).

It should, therefore, be noted that not all local communities (*poviats*) and local authorities follow the rules of pro-ecological behavior because, as shown above, local substrate resources to operate biogas plants are huge. Not all landfills, wastewater, and agricultural waste are used for energy purposes. The construction and development of biogas plants should be considered as one of the factors of pro-ecological behavior of local communities (*poviats*), residents, and local authorities and as an indispensable element of endogenous development of the area.

It follows from the above that the development of biogas power plants in Poland is at the initial stage, though with respect to the relatively large potential for obtaining substrate (municipal waste, sewage, and agricultural waste), there are chances for the further development of this fuel and energy sector. It is particularly important because of the need to realize the main aims of the Polish energy policy by 2020. Encouraging energy to be obtained from biogas could contribute to the diversification of energy sources and, consequently, would ensure energy security, increased efficiency, and competitiveness of energy markets and reduce the negative impact of energy on the environment by reducing greenhouse gas emissions and increasing the use of renewable sources of energy.

Acknowledgments: This work was supported by grant 1907-G from the Nicolaus Copernicus University in Toruń.

Author Contributions: All the authors have cooperated in the design, development, and preparation of this work. All authors have read and approved the final manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Biernat, K.; Działak, P.; Gis, W.; Żółtowski, A. *Biogas in Poland—Actual Condition and Perspective of Development. 4. Rostocker Bioenergieforum—Zukunftstechnologien für Bioenergie*; Institut für Umweltingenieurwesen, Band 27: Rostock, Germany, 2010.
2. Szymańska, D.; Chodkowska-Miszczuk, J. Endogenous resources utilization of rural areas in shaping sustainable development in Poland. *Renew. Sustain. Energy Rev.* **2011**, *15*, 1497–1501. Available online: http//dx.doi.org/10.1016/j.rser.2010.11.019 (accessed on 17 September 2015). [CrossRef]
3. Yang, Y.; Zhang, P.; Li, G. Regional differentiation of biogas industrial development in China. *Renew. Sustain. Energy Rev.* **2012**, *16*, 6686–6693. [CrossRef]
4. Chodkowska-Miszczuk, J.; Szymańska, D. Agricultural biogas plants—A Chance for diversification of agriculture in Poland. *Renew. Sustain. Energy Rev.* **2013**, *20*, 514–518. Available online: http//dx.doi.org/10.1016/j.rser.2012.12.013 (accessed on 19 September 2015). [CrossRef]
5. Murandi, M.; Foltynowicz, Z. Potential for Producing Biogas from Agricultural Waste in Rural Plants in Poland. *Sustainability* **2014**, *6*, 5065–5074.
6. Ramachandra, T.V. Geographical information system approach for regional biogas potential assessment. *Res. J. Environ. Sci.* **2008**, *2*, 170–184.
7. Mwirigi, J.W.; Makenzi, P.M.; Ochola, W.O. Socio-economic constraints to adoption and sustainability of biogas technology by farmers in Nakuru Districts, Kenya. *Energy Sustain. Dev.* **2009**, *13*, 106–115. [CrossRef]

8. Bond, T.; Templeton, M. History and future of domestic biogas plants in the developing world. *Energy Sustain. Dev.* **2011**, *15*, 347–354. [CrossRef]
9. Surendra, K.C.; Takara, D.; Hashimoto, A.G.; Khanal, S.K. Biogas as a sustainable energy source for developing countries: Opportunities and challenges. *Renew. Sustain. Energy Rev.* **2014**, *31*, 846–859. [CrossRef]
10. Temilola, T.O.; Odesola, I.F.; Oyewola, M.O. Energy production from biogas: A conceptual review for use in Nigeria. *Renew. Sustain. Energy Rev.* **2014**, *32*, 770–776.
11. Lombard, A.; Ferreira, S.L.A. The spatial distribution of renewable energy infrastructure in three particular provinces of South Africa. *Bull. Geogr. Socio-Econ. Ser.* **2015**, *30*, 71–86. Available online: http//dx.doi.org/10.1515/bog-2015-0036 (accessed on 27 September 2015). [CrossRef]
12. Murphy, J.D.; McKeoghb, E.; Kiely, G. Technical/economic/environmental analysis of biogas utilization. *Appl. Energy* **2004**, *77*, 407–427. [CrossRef]
13. Pöschla, M.; Warda, S.; Owende, P. Evaluation of energy efficiency of various biogas production and utilization pathways. *Appl. Energy* **2010**, *87*, 3305–3321. [CrossRef]
14. Havukainen, J.; Uusitalo, V.; Niskanen, A.; Kapustina, V.; Horttanainen, M. Evaluation of methods for estimating energy performance of biogas production. *Renew. Energy* **2014**, *66*, 232–240. [CrossRef]
15. Dudek, J. Wykorzystaniem biogazu ze składowisk odpadów komunalnych do celów energetycznych. *Polityka Energ.* **2008**, *11*, 25–32. (In Polish)
16. Lund, H.; Moller, B.; Mathiesen, B.V.; Dyrelund, A. The role of district heating in future renewable energy system. *Energy* **2010**, *35*, 1381–1390. [CrossRef]
17. Murphy, J.D.; McCarthy, K. The optimal production of biogas for use as a transport fuel in Ireland. *Renew. Energy* **2005**, *30*, 2111–2127. [CrossRef]
18. Patterson, T.; Esteves, S.; Dinsdale, R.; Guwy, A. An evaluation of the policy and techno-economic factors affecting the potential for biogas upgrading for transport fuel use in the UK. *Energy Policy* **2011**, *39*, 1806–1816. [CrossRef]
19. Taleghani, G.; Kia, A.S. Technical-economical analysis of the Saveh biogas power plant. *Renew. Energy* **2005**, *30*, 441–446. [CrossRef]
20. Jingura, R.M.; Matengaifa, R. Optimization of biogas production by anaerobic digestion for sustainable energy development in Zimbabwe. *Renew. Sustain. Energy Rev.* **2009**, *13*, 1116–1120. [CrossRef]
21. Chodkowska-Miszczuk, J.; Szymańska, D. Update of the review: Cultivation of energy crops in Poland against socio-demographic factors. *Renew. Sustain.Energy Rev.* **2011**, *15*, 4242–4247. Available online: http//dx.doi.org/10.1016/j.rser.2011.07.126 (accessed on 19 September 2015). [CrossRef]
22. Gis, W.; Żółtowski, A.; Grzelak, P. Potential of biogas production in Poland. *Proc. Inst. Veh.* **2013**, *1*, 13–20.
23. Szymańska, D. *Geografia Osadnictwa*; PWN: Warszawa, Poland, 2013. (In Polish)
24. Prasertsan, S.; Sajjakulnuki, B. Biomass and biogas energy in Thailand: Potential, opportunity and barriers. *Renew. Energy* **2006**, *31*, 599–610. [CrossRef]
25. Lantz, M.; Svensson, M.; Björnsson, L.; Börjesson, P. The prospects for an expansion of biogas systems in Sweden—Incentives, barriers and potentials. *Energy Policy* **2007**, *35*, 1830–1843. [CrossRef]
26. Raven, R.P.J.M.; Gregersen, K.H. Biogas plants in Denmark: Successes and setbacks. *Renew. Sustain. Energy Rev.* **2007**, *11*, 116–132. [CrossRef]
27. Haas, R.; Panzer, C.; Resch, G.; Ragwitz, M.; Reece, G.; Held, A. A historical review of promotion strategies for electricity from renewable energy sources in EU countries. *Renew. Sustain. Energy Rev.* **2011**, *15*, 1003–1034. [CrossRef]
28. Klessmann, C.; Held, A.; Rathmann, M.; Ragwitz, M. Status and perspectives of renewable energy policy and deployment in the European Union-What is needed to reach the 2020 targets? *Energy Policy* **2011**, *33*, 7637–7657. [CrossRef]
29. Kitzing, L.; Mitchell, C.; Morthorst, P.E. Renewable energy policies in Europe: Converging or diverging? *Energy Policy* **2012**, *51*, 192–201. [CrossRef]
30. Geels, F.W.; Raven, R.P.J.M. Socio-cognitive evolution and co-evolution in competing technical trajectories: Biogas development in Denmark (1970–2002). *Int. J. Sustain. Dev. World Ecol.* **2007**, *14*, 63–77. [CrossRef]
31. Weiland, P. Biogas production: Current state and perspectives. *Appl. Microbiol. Biotechnol.* **2010**, *85*, 849–860. [CrossRef] [PubMed]

32. Sliz-Szkliniarz, B.; Vogt, J. A GIS-based approach for evaluating the potential of biogas production from livestock manure and crops at a regional scale: A case study for the Kujawsko-Pomorskie Voivodeship. *Renew. Sustain. Energy Rev.* **2012**, *16*, 752–763. [CrossRef]
33. Devine-Wright, P. Reconsidering public acceptance of renewable energy technologies: A critical review. In *Taking Climate Change Seriously: A Low Carbon Future for the Electricity Sector*; Jamasb, T., Grubb, M., Pollitt, M., Eds.; Cambridge University Press: Cambridge, UK, 2008; pp. 443–461.
34. Ministerstwo Gospodarki. *Przewodnik dla Inwestorów Zainteresowanych Budową Biogazowi*; Ministerstwo Gospodarki: Warszawa, Poland, 2011. (In Polish)
35. Ribeiro, F.; Ferreira, P.; Araújo, M. The inclusion of social aspects in power planning. *Renew. Sustain. Energy Rev.* **2011**, *15*, 4361–4369. [CrossRef]
36. Ciupryk, M.; Gaj, K. Possibilities and benefits of landfill biogas utilization. *Ochr. Powietrza i Probl. Odpad.* **2004**, *38*, 28–32.
37. Dudek, J.; Klimek, P. Experience connected with energy usage of landfill gas. *Polityka Energ.* **2008**, *11*, 25–32.
38. Cupiał, K.; Dużyński, A.; Grzelka, J. Energetic biogas utilization in WARTA S.A. sewage treatment plant in Częstochowa. *Instal* **2005**, *249*, 23–28.
39. Kołtyś, S.; Szymanek, M.; Dreszer, K.A. Assessment of the technology involving biogas production from municipal wastes on the example of "Hajdów" sewage treatment plant. *Inż. Rol.* **2009**, *13*, 155–161.
40. Igliński, B.; Buczkowski, R.; Iglińska, A.; Cichosz, M.; Piechota, G.; Kujawski, W. Agricultural biogas plants in Poland: Investment process, economical and environmental aspects, biogas potential. *Renew. Sustain. Energy Rev.* **2012**, *16*, 4890–4900. [CrossRef]
41. Igliński, B.; Kujawski, W.; Buczkowski, R.; Cichosz, M. Renewable energy in the Kujawsko-Pomorskie Voivodeship (Poland). *Renew. Sustain. Energy Rev.* **2010**, *14*, 1336–1341. [CrossRef]
42. Igliński, B.; Buczkowski, R.; Cichosz, M.; Piechota, G.; Kujawski, W.; Plaskacz, M. Renewable energy production in the Zachodniopomorskie Voivodeship (Poland). *Renew. Sustain. Energy Rev.* **2013**, *27*, 768–777. [CrossRef]
43. Oniszk-Popławska, A.; Matyka, M.; Dagny-Ryńska, E. Evaluation of a long-term potential for the development of agricultural biogas plants: A case study for the Lubelskie Province, Poland. *Renew. Sustain. Energy Rev.* **2014**, *36*, 329–349. [CrossRef]
44. Budzianowski, W.M. Sustainable biogas energy in Poland: Prospects and challenges. *Renew. Sustain. Energy Rev.* **2012**, *16*, 342–349. [CrossRef]
45. Urząd Regulacji Energetyki—URE (Energy Regulatory Office). Available online: http://www.ure.gov.pl (accessed on 12 April 2015).
46. Bank Danych Lokalnych Głównego Urzędu Statystycznego—BDL GUS (Local Data Banks of the Central Statistical Office). Available online: http://stat.gov.pl/bdl/ (accessed on 17 April 2015).
47. Główny Urząd Statystyczny. *Energia ze Źródeł Odnawialnych w 2012 Roku*; Główny Urząd Statystyczny: Warszawa, Poland, 2013. (In Polish)
48. Główny Urząd Statystyczny. *Energia ze Źródeł Odnawialnych w 2013 Roku*; Główny Urząd Statystyczny: Warszawa, Poland, 2014. (In Polish)
49. Pieras, M. Rosnące Zapotrzebowanie na Energię—Wykorzystanie Biogazu. 2008. Available online: http://www.mojeopinie.pl/rosnace_zapotrzebowanie_na_energie_wykorzystanie_biogazu,3,1225795298 (accessed on 16 April 2015). (In Polish)
50. Eurostat. Available online: http://epp.eurostat.ec.europa.eu/tgm/refreshTableAction.do;jsessionid=9ea7d07d30e871b993f58d8648279c62e9697333df5d.e34OaN8PchaTby0Lc3aNchuNa3yQe0?tab=table&plugin=1&pcode=ten00081&language=en (accessed on 17 April 2015).
51. Möller, L. Expanding biogas production in Germany and Hungary. Good prospects for small scale farms? In *Structural Change in Europe's Rural Regions—Farm Livelihoods Between Subsistence Orientation, Modernization and Non-Farm Diversification*; Buchenrieder, G., Möllers, J., Eds.; Volume 49 of IAMO Studies Series (IAAE 2009 Minisymposium); IAMO: Halle, Germany, 2009; pp. 113–133.
52. Budzianowski, W.M.; Chasiak, I. The expansion of biogas power plants in Germany during the 2001–2010 decade: Main sustainable conclusions for Poland. *J. Power Technol.* **2011**, *91*, 102–113.
53. Lewandowski, I.M.; van Hooijdonk, A.; Weger, J.; Havlickova, K.; van Dam, J.; Faaij, A.P.C. The potential biomass for energy production in the Czech Republic. *Biomass Bioenergy* **2006**, *30*, 405–421. [CrossRef]

54. Portal Funduszy Europejskich. Available online: http://www.funduszeeuropejskie.gov.pl/strony/o-funduszach/ (accessed on 20 April 2015). (In Polish)
55. Igliński, B.; Buczkowski, R.; Cichosz, M. Agricultural Biogas Plants in Poland—Current Status, Potential, Swot Analysis. *Rynek Energii* **2015**, *118*, 93–101. (In Polish)
56. Lewandowski, W.M. *Proekologiczne Źródła Energii Odnawialnej*; Wydawnictwa Naukowo-Techniczne: Warszawa, Poland, 2002. (In Polish)
57. Pilarska, A.; Pilarski, K.; Myszura, M.; Boniecki, P. Perspectives and problems of agricultural biogas plants development in Poland. *Tech. Rol. Ogrod. Leśn.* **2013**, *4*, 2–4. (In Polish)
58. Martin, M. *The "biogasification" of Linköping. A Large Technical Systems Perspective*; Environmental Technology and Management, Linköping Univesity: Linköping, Sweden, 2009.
59. Szymańska, D.; Korolko, M. *Inteligentne Miasta: Idea, Koncepcje i Wdrożenia*; Wydawnictwo Naukowe Uniwersytetu Mikołaja Kopernika: Toruń, Poland, 2015. (In Polish)
60. Energia Biogazów. Available online: https://www.bip.krakow.pl/?sub_dok_id=26123 (accessed on 20 October 2015). (In Polish)
61. Biogazownia rolnicza w Boleszynie. Available online: http://biogazownie.fwie.pl/index.php?option=com_content&view=article&id=42:biogazownia-rolnicza-w-boleszynie&catid=15&Itemid=111 (accessed on 23 October 2015). (In Polish)
62. Biogazownia na składowisku odpadów w Trzebani. Available online: http://biogazownie.fwie.pl/index.php?option=com_content&view=articlelinebreak &id=41:biogazownia-na-skladowisku-odpadow-w-trzebani&catid=15&Itemid=111 (accessed on 20 October 2015). (In Polish)