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THE USE OF BIOGAS FROM THE ANAEROBIC DIGESTION OF SEWAGE SLUDGE TO IMPROVE THE ENERGY BALANCE OF WASTEWATER TREATMENT PLANTS

A rational way to treat and disposal sewage sludge is to use it as a substrate for biogas production in the anaerobic digestion process, doing so can lead to an improvement in the energy efficiency of the entire wastewater treatment plant, and even enable it to become energy self-sufficient. The article analyses the amount of energy consumption in wastewater treatment plants, the course of the biogas production process and examples of wastewater treatment plants that are close to becoming, or have managed to become, "ecologically sustainable" facilities thanks to the production of green energy.

Keywords: anaerobic digestion, biogas, energy efficiency, sewage sludge

1. Introduction

The growing interest in renewable energy sources means that they are more and more often used to increase the energy efficiency of municipal facilities, also. The operators of wastewater treatment plants try to use the energy potential of sewage sludge as much as possible, at the same time ensuring their rational management and disposal [29]. By doing so, it is possible to solve the problem of retention of sewage sludge in wastewater treatment plants, which is prohibited by law, and to reduce the environmental risk posed by a high content of hazardous substances (e.g. heavy metals). Therefore, municipal plants are deciding to treat sewage sludge with simultaneous energy recovery, usually by producing biogas or by subjecting it to combustion processes (e.g. co-incineration in cement plants) [12].

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A rational way to treat sewage sludge is to use it as a substrate for biogas production in the anaerobic digestion process (AD) [2, 27]. Biogas is a mixture of gases, mainly methane and carbon dioxide, that can be used to produce electricity and heat. Additionally, the AD process leading to the formation of biogas has a positive effect on the dewatering of sludge and reduction of its volume. All the positive aspects resulting from biogas production are leading to increased use of the energy potential of sewage sludge [1]. Doing so can lead to an improvement in the energy efficiency of the entire treatment plant, and even enable it to become self-sufficient [6, 7, 27].

The article analyses the amount of energy consumption in wastewater treatment plants, the course of the biogas production process and examples of treatment plants that are close to becoming, or have managed to become, "ecologically sustainable" facilities thanks to the production of green energy.

2. Treatment of sewage sludge in the anaerobic digestion process

Biogas is a gas produced from biomass, obtained from the anaerobic decomposition of organic compounds in the AD process [16]. It is a multi-stage biochemical process, which is directly related to the chemical composition of the starting substrate, i.e. organic compounds introduced into the anaerobic digester (fermentation chamber) and the bacteria participating in the process. Any biodegradable compounds can be a substrate for anaerobic digestion, but they differ in the rate of decomposition and methane yield [4, 14, 23].

Anaerobic digestion is a complicated and time-consuming chemical process that has four main stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis. In each of the phases there is a gradual decomposition of organic compounds from complex to more and more simple forms, and finally to digested sludge and biogas [16]. Figure 1 shows a simplified course of the processes occurring during anaerobic digestion.

In order to obtain the highest possible amount of biogas, attention should be paid to ensuring optimal parameters of the AD process. Its course is influenced by temperature: the most effective are thermophilic conditions (40–50^{o}C); however, the process is usually carried out in mesophilic conditions (30–40^{o}C), due to the lower demand for the amount of thermal energy supplied for heating. It is also influenced by the holding time (which depends on the temperature of the process, substrates used and the rate of their decomposition); pH (methanogenic bacteria conduct processes close to neutral, if the reaction decreases, lime is used); the load of organic compounds (each mixture of substrates requires the determination of the optimal system load); the mixing method (which should be homogeneous and not leave dead zones); toxic substances and inhibitors (e.g. heavy metals, ammonia) and stimulants (in case of too low calorific value of the substrate used). The most important substrates for biogas production are organic compounds rich in proteins, fats and hydrocarbons. The fermented sewage sludge usually contains an appropriate mixture of substances from which biogas can be produced, but sometimes it is necessary to add an external source of biomass [8, 13, 14, 16].

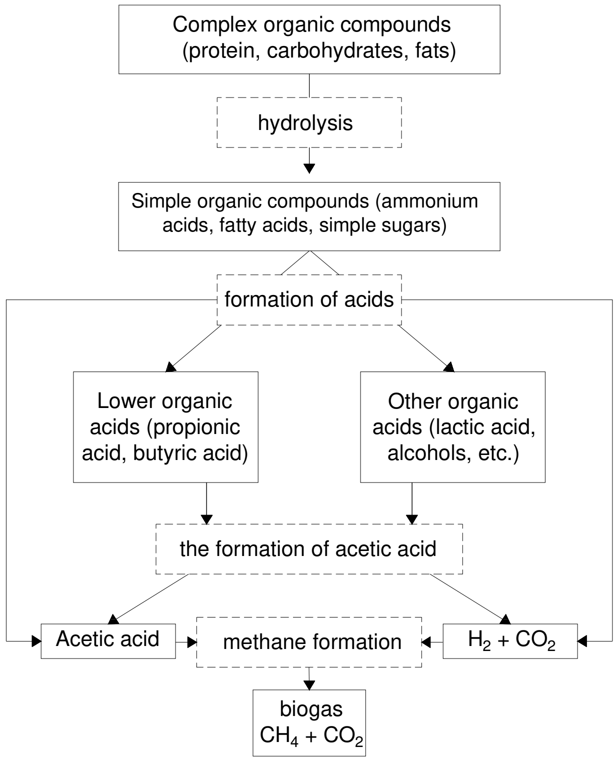

Fig. 1. Schematic course of the processes taking place during anaerobic digestion [16]

The advantages of subjecting sewage sludge to an AD process are stabilization and hygienization, reduction of malodorous substances – odours, increase in the efficiency of the dewatering process (by about 15–20%), reduction of the amount of organic matter by about 50%, reduction of the sludge volume and the possibility of using digested sludge as fertilizer [1, 4].

From the technical point of view, the treatment of sewage sludge for biogas production consists of the pre-treatment of the sludge (thickening, conditioning), anaerobic decomposition of organic matter in the process of anaerobic digestion, biogas treatment (desulphurization) and its conversion into electricity or heat, and the final treatment of the digested sludge (dewatering, drying) (Figure 2).

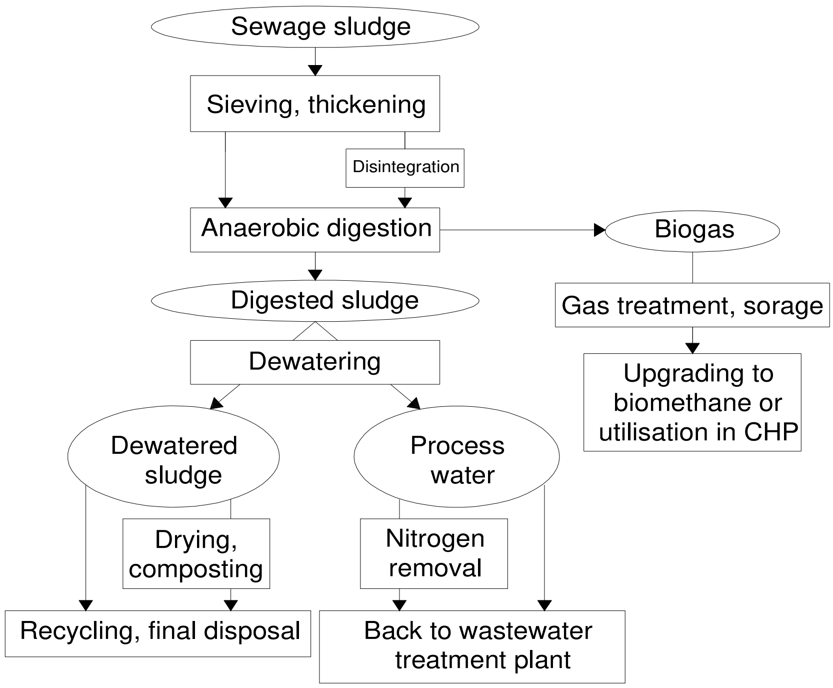

Fig. 2. Stages of treatment and disposal of sewage sludge [1]

The classic system for producing biogas in a wastewater treatment plant is a solution in which sewage sludge is initially thickened and then pumped to separate/closed anaerobic digester (SAD/CAD), where a mesophilic anaerobic digestion process takes place in the temperature range of 35–39°C. The holding time is about 20 days, which is the period in which biogas is produced by microorganisms. It is a mixture of gases, mainly methane, carbon dioxide and other gases, whose residual content is water vapor, H_2S, N_2, H_2, O_2 (Table 1) [1, 4, 13].

Table 1. The quality of biogas from the anaerobic digestion of sewage sludge [11]

Component	Content [%]
Methane CH_4	63–65
Carbon dioxide CO_2	33–36
Nitrogen N_2	0.5–2.0
Oxygen O_2	<1.7
Hydrogen H_2	<1.0
Hydrogen sulfide H_2S	0.1–0.2

A lot of research is being carried out to determine the optimal conditions for the anaerobic digestion of sewage sludge. The most important physical factor that is considered in the process of anaerobic decomposition is the temperature (Table 2). The most common method of biogas production is mesophilic digestion carried out at 35°C. In such a system, organics degrade up to 40% within 30 to 40 days of retention. It is important that the thermal conditions do not fluctuate, otherwise a population of non-methanogenic bacteria may develop, which will significantly reduce the proportion of methane in the biogas [28].

Table 2. Optimal and extreme values of anaerobic digestion parameters [29]

Parameter	Optimal value	Extreme value
Temperature, °C	35± 2°C	20–40
Odczyn	6.8–7.4	6.4–7.8
Volatile fatty acids (VFAs), mg CH_3COOH/dm^3	50–500	>2 000
Alkalinity, mg $CaCO_3/dm^3$	1 500–3 000	1 000–5 000

According to literature sources, raw sludge can produce about 315 – 400 Nm^3 of methane per ton of dry organic matter, while in the case of surplus sludge this number is lower and amounts to 190 – 240 Nm^3 of methane [9]. However, in terms of the amount of sewage, 1 000 m^3 of municipal sewage can produce 100 – 200 Nm^3 of biogas. It is also assumed that 1 m^3 of sludge (with 4–5% dry matter content) can produce 10 – 20 m^3 of biogas with a 60% proportion of methane [4, 16].

3. Energy use of biogas from anaerobic digestion of sewage sludge

Raw biogas must be subjected to treatment in order to be processed further. It is necessary to clean it and enrich it by removing carbon dioxide. This gas negatively affects the efficiency of biogas conversion and increases the cost of pumping the gas. The chemical energy contained in biogas can be converted into thermal, electrical, mechanical or chemical energy of other compounds, e.g. fuels. The treatment process itself consists in removing carbon dioxide, cleaning it of impurities, drying, desulfurization and deodorization [17]. The desulfurization process takes place in desulfurization plants, where water vapor and hydrogen sulphide, among others, are removed from biogas, which contributes to the obtaining of a flammable gas with less corrosive properties. After cleaning, the biogas can be sent to a cogeneration system also known as Combined Heat and Power (CHP). In the case of upgrading the gas obtained, it can be used as a biofuel or sold to the gas network [1]. One of the most cost-effective methods of treatment of biogas from large sewage treatment plants is CHP technology, which produces both electricity and heat (Figure 3). The literature shows that 6 m^3 of municipal sewage can produce 1 kWh of electricity and 1.2 kWh of heat energy. The amount of electricity produced in the generator unit depends on the methane content in the biogas and the efficiency of the engine. The average value of the amount of energy obtained with an engine efficiency equal to 40% is 4 kWh of electricity generated from 1 m^3 of methane [11]. The calorific value of pure methane is about 35.7 MJ/m^3 and depends on the percentage content of particular gases in the mixture, while the energy value of biogas is about 21.54 MJ/m^3 [16]

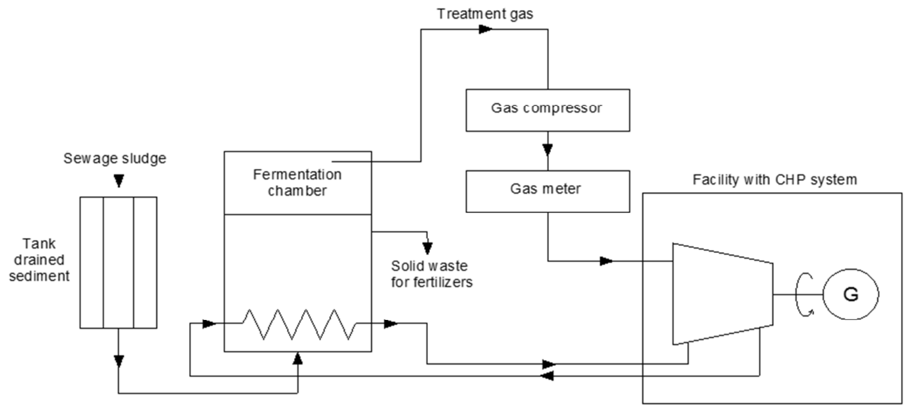

Fig. 3. Diagram of combined electricity and heat generation from biogas from sewage sludge [11]

Agricultural waste (animal manure) or waste from food production (slaughterhouse, brewery), which are an additional source of organic compounds needed for biogas production, can also be used as a substrate for biogas production in combination with sewage sludge. Then a co-digestion mixture is formed, consisting of two or more co-substrates (Table 3).

Table 3. Optimal and extreme values of anaerobic digestion parameters [29]

Type of substrate	The amount of biogas, dm^3/kg	Content, % v/v	
		CH_4	CO_2
Carbohydrates	790	50	50
Fats	1 250	68	32
Proteins	700	71	29

The use of organic waste of agricultural and food origins as a contribution to the digesters increases the efficiency of the process, because these products contain a high content of substances rich in proteins, fats and carbohydrates, thanks to which they have a greater energy potential than sewage sludge [1].

The amount of biogas obtained and the percentage of methane depends on the amount of individual organic components included in the fermentation mixture, as they ferment at different rates. Hence the conclusion that adding an external source of biomass can have positive effects on the final effect of anaerobic digestion [23].

Another process beneficial for the production of biogas is the disintegration of sludge particles, performed as initial hydrolysis, consisting in "breaking" the cell structure of the substrates, thanks to which microorganisms have better access to them during the AD process, which translates into an increase in the final amount of biogas [9].

Hydrolysis is the rate-limiting stage in sludge digestion. The acceleration of the transformation of organic compounds into soluble forms significantly improves the effectiveness of the subsequent phases of AD. The table shows the results of an experiment carried out to compare the effectiveness of the anaerobic stabilization of sewage sludge by anaerobic digestion: mesophilic, thermophilic and mesophilic preceded by thermophilic hydrolysis to reduce the content of organic substances in the sewage sludge and the production of biogas (methane). One-time samples were collected for the tests: a mixture of raw and excess sludge (RS + ES) sent to the digester and digested sludge (D) discharged from the closed anaerobic digester. Studies have shown that during mesophilic digestion preceded by thermophilic hydrolysis (55°C), higher biogas production was obtained than from mesophilic non-hydrolyzed sludge or thermophilic digestion [5]. It was also established that the mean content of methane in biogas during mesophilic digestion preceded by thermophilic hydrolysis was 61–64%, while during thermophilic and mesophilic digestion of non-hydrolysed sludge it was 57–62% and 59–64%, respectively. In order to obtain effective anaerobic digestion, it is therefore necessary to take into account the factors influencing this process and, by means of technological research, determine a method of intensifying biogas production [5].

4. Energy self-sufficient wastewater treatment plants

Many treatment plants strive to achieve a positive energy balance with the possibility of limiting the purchase of energy from the grid. First of all, all technical and technological measures are carried out to reduce electricity consumption, for example, improving the oxygenation of the active sludge and increasing the degree of oxygen use [22]. It is also advisable to look for ways to recover or produce energy from wastewater and sewage sludge [2, 6, 7]. The use of a biogas production node is also considered. For facilities where such an installation already exists, one should strive to increase the amount of biogas produced, increase the efficiency of the cogeneration system and use additional biomass sources as input to the reactors (co-digestion). The volume of the sludge formed is also important, as larger volumes require more energy for pumping [22].

As a result of increasing energy costs and concern for the natural environment and its resources, research is being carried out to ultimately lead to the achievement of self-sufficient – passive wastewater treatment plants (Figure 4), i.e. those that generate the energy needed to cover 100% of their needs or more [10]. This is possible, among others, thanks to the use of cogeneration units that are powered by biogas and thanks to which it is possible to generate electricity and heat, covering the entire energy demand in the treatment plant or even producing surplus energy that can be sold to the electricity network [12].

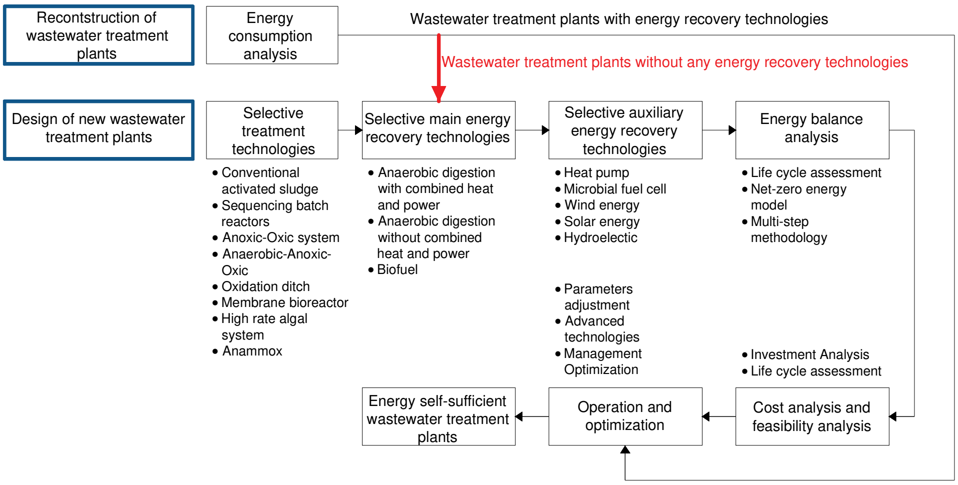

Fig. 4. Theoretical model of an energy self-sufficient wastewater treatment plant [10]

Research shows that the potential energy content of incoming sewage is higher than the energy consumption of the sewage treatment plant, and usually only a part of it is recovered as a result of AD. Many publications provide information that sewage contains 5 to 10 times more energy (about 1.93 kWh/m^3) than that needed for sewage treatment, but only 0.3 to 0.8 kWh/m^3 is usually used. Reports on sewage treatment plants in North America show that cogeneration can recover from anaerobic digestion about 30–40% of the total energy consumed. However, it is a cost-effective process only in medium and large sewage treatment plants [9]. Energy from biogas processing can be used, among others, for the production of electricity and heat in CHP technology, production of heat in gas boilers, production of electricity in engines, use as fuel for vehicles, use of gas in technological processes (e.g. methanol production) [12]. Most of the energy is used for the facility's own needs. It is estimated that 40% of the sludge's energy potential is used. This number can be increased by applying the intensification of biogas production, but then one should take into account the need to manage the excess heat, for example, to sell it to a heating plant [12, 15]. Excess heat can also be used to dry the sludge, it is possible to cover between 26 and 51% of the energy requirements of this process in the case of sealed digesters. In the absence of isolation, these numbers range from 9 to 46% [24].

5. Examples of passive and energy self-sufficient wastewater treatment plants

Many countries in Europe and North America have managed to achieve energy self-sufficiency in wastewater treatment facilities (Table 4). The heat and electricity produced from biogas are used for the facility's own needs – powering electrical equipment and supplying heat to buildings and anaerobic digesters.

Table 4. Examples of energy self-sufficient wastewater treatment plants [10]

Name of the wastewater treatment plant	Location	Wastewater flow [m^3/d]	Self-sufficiency [%]	Surplus energy sold to the grid [%]
Grevesmuhlen	Germany	15 142	100	≥ 20
Wolfgangsee-Ischl	Austria	18 927	100	>10
Strass im Zillertal	Austria	22 712	100	≥ 20
Gloversville–Johnstown Joint	USA	41 640	100	-
Sheboygan Regional	USA	41 640	100	-
Gresham	USA	49 210	100	-
Zürich Werdhölzli	Switzerland	253 623	100	-
East Bay Municipal Utility District	USA	264 979	100	≥ 20
Point Loma	USA	662 447	100	-

An example of such a treatment plant is the Sheboygan Regional Wastewater Treatment Facility, which serves over 68,000 inhabitants and has a throughput of approximately 41 640 m^3/d (Figure 5). As a result of the biogas surplus in 2010, thanks to the use of co-digestion, two 200 kW microturbines were installed on the site, which generated about 410 kW of electricity per hour. In 2012 another 300kW system was added to the facility, which gave a total cogeneration capacity of approximately 700 kW. Thanks to the installation described, it is currently possible to cover 90% of electricity and 85% of thermal energy needs per year. They are used to supply equipment with electricity and heat, as well as to heat digesters and buildings. Each day, the sewage treatment plant can generate more energy than it would require, and it is one of a few that have achieved such efficiency [11].

Fig. 5. The Sheboygan Regional Wastewater Treatment Facility [10]

The use of biogas as an energy source also brings benefits in Polish wastewater treatment plants. An example of such a facility is the municipal wastewater treatment plant in Mielec with an average daily flow of 14 600 m^3/d and 85 750 PE. Biogas produced from January 2013 to March 2015 contained 57–63% methane. From 1 m^3 of sludge 14 m^3 of biogas was produced. Additionally, ice cream waste was used as a substrate in the anaerobic digesters during the summer, which resulted in a seasonal increase in biogas production. Thanks to this, the Mielec WWTP is able to achieve self-sufficiency, and the surplus energy generated is sold to the grid, which improves the overall financial situation of the facility [21].

The facility in Iława can also be used as an example of a self-sufficient wastewater treatment plant. It was designed for a flow of 26 940 m^3/d and 154 117 PE. It has two digesters in which mesophilic digestion is carried out with a retention time of 37 days. Three CHP co-generators produce electricity (253 kWh) and heat (318 kWh). In addition, this treatment plant uses co-digestion, where the co-substrate is waste from poultry processing. Figure 6 illustrates how, since 2006, the percentage of self-sufficiency in the treatment plant has increased due to biogas production. In 2019, more than 90% of the energy demand was covered from renewable sources, resulting in a reduction in the purchase of energy from outside (Figure 6) [20].

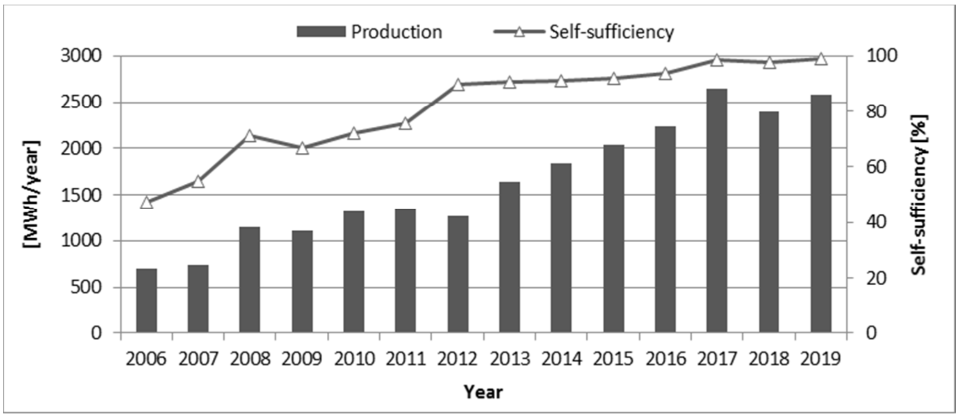

Fig. 6. Energy balance for the Iława WWTP [20]

Energy obtained from biogas is classified as energy generated from renewable sources. Nowadays, these sources are an important element of the energy economy of countries over almost the whole world. As a result of the development of civilization and activities for environmental protection, renewable sources have become a frequent object of interest and the subject of many research studies. This is due to the fact that their processing causes less environmental pollution. Moreover, they are assessed as inexhaustible sources, which is important in the era of greatly reduced amounts of natural resources [25].

It should be noted that the production of biogas in a wastewater treatment plant is relatively the most advantageous option in economic terms, as the efficiency of the entire biogas plant depends on the type of digestion substrate used and its price. Wastewater treatment plants have their own substrate in the form of sludge (unlike, for example, agricultural biogas plants). They can optionally add co-substrates to increase the intensity of the AD process, for the disposal of which they can receive additional payment [7, 15, 18, 19, 20, 26].

6. Conclusions

- Wastewater treatment plants require the supply of high amounts of electricity and heat, mainly for biological treatment, aeration and pumping of sludge.
- They also have a large energy potential in the form of sewage sludge, thanks to the treatment of which it is possible to obtain partial or full energy self-sufficiency in wastewater treatment plants.
- After the anaerobic digestion process, sewage sludge is still a valuable substrate for the production of green energy.
- The biogas production process can be additionally enhanced by the use of co-digestion or thermal hydrolysis.

- Thanks to anaerobic digestion process, stabilized sludge is obtained, which can be easily managed, thus increasing the energy efficiency of the treatment plant and reducing the costs of its maintenance.
- Through the development of this energy sector, wastewater treatment plants can become sustainable facilities in terms of energy consumption, as exemplified by treatment plants around the world, including Poland.
- Despite relatively low share of biogas energy in the energy currently obtained from renewable sources, thanks to its production in sewage treatment plants Poland may come closer to other European countries for which biogas is an important source of energy.

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