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Pollution Indicator of a Megawatt Hour Produced in Cogeneration – the Efficiency of Biogas Purification Process as an Energy Source for Wastewater Treatment Plants

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ABSTRACT

The sewage treatment plant, as a producer of renewable energy, should make every effort to ensure that the biogas used as a fuel meets the quality requirements, including those of the manufacturers of cogeneration units. Such measures necessitate the application of a conditioning process of biogas in order to remove harmful compounds, so that its parameters ensure failure-free operation of engines. The aim of the research was to evaluate the effectiveness of biogas treatment in the A-type installation using the "wet biogas treatment" technology, and in the B-type installation, which is a comprehensive solution comprising sulfur removal as a result of a simultaneous regeneration of the bed with oxygen, removal of siloxanes on activated carbon, cooling and heating of biogas along with its filtration. The analysis of the results of biogas testing for these two installations demonstrated fundamental qualitative differences for the benefit of the installation B, in which the biogas was characterized by a much lower content, mainly of sulfur, hydrogen sulfide, siloxanes and humidity. The introduced pollution indicator of a megawatt hour produced in cogeneration one has confirmed much higher pollution load from the A-type installation. The hybrid solution applied in the work with simultaneous regeneration of the bed has confirmed the efficiency of biogas conditioning. Such a solution contributes to a safe and reliable operation of the cogeneration system for generating energy from a renewable source, which in turn contributes to the optimization of energy.

Keywords: biogas purification, cogeneration, pollution indicator renewable energy, sewage treatment plant.

INTRODUCTION

Generation of electricity and heat in local energy systems based on waste biomass from forests, orchards, parks, agriculture, wood industry, but also in the form of wastewater sludge, is an element of renewable energy source (RES). Such measures are aimed at implementing solutions for sustainable development at the local level in terms of economic and environmental issues. The production of biogas in a wastewater treatment plant based on the fermentation of wastewater sludge is a targeted process, carried out in installations along with a system of its transmission and storage at the wastewater treatment plant [den Boer et al., 2020; Dyjakon et al., 2019]. Biogas obtained from the fermentation of wastewater sludge biogas (SSB), just like landfill gas (LG) in the process of biogas production, have similar chemical compositions. This mainly concerns substances contained in municipal waste and wastewater, which have a crucial impact on the final composition of biogas. The production of biogas in a landfill is an uncontrolled process, and in addition, a landfill, unlike a wastewater treatment plant, has a negative impact on surface and underground waters in its area [Gronba-Chyła et al., 2022; Kowalski et al., 2022; Hamed et al., 2004]. In view of energy recovering from wastewater sludge in effect of fermentation, the principles of closed loop economy correlated with energy efficiency of these processes are implemented.

Taking into account the dynamics of the development of biogas production installations, it should be admitted that the European Union is one of the world leaders in the production of electricity from biogas [Ishchenko et al., 2017; Koc-Jurczyk et al., 2022; Czekała et al., 2017]. Mechanical and biological wastewater treatment processes, which are essential for the production of wastewater sludge for the fermentation process, are usually energy-intensive. This fact means that most entities who manage wastewater treatment plants make decisions, already at the design stage of the treatment plant, to build a biogas production installation for energy generation purposes [Ciuła, 2022; Pittmann and Steinmetz, 2017]. In this way, a wastewater treatment plant becomes a producer and consumer of renewable energy, satisfying its internal energy needs and striving to close the so-called waste-to-energy loop [Garrido-Baserba et al., 2014; Kozłowski and Ignatowicz, 2021]. The differences in the content of siloxanes in the biogas from the fermentation of wastewater sludge depend primarily on their solubility. Water-soluble silicon compounds are removed by ozonation already at the stage of water treatment, and then they are reduced by absorption together with heavy metals in the activated carbon bed. Purified and treated water goes to the water supply network to be used for industrial purposes, but above all for social and living purposes [Grosser and Neczaj, 2016; Wysowska et al., 2021; Wiewiórska and Rybicki, 2022]. During the intake and use of drinking water, the part used for sanitary purposes changes its status and becomes municipal wastewater. By absorbing silicon compounds contained, for example, in cosmetics, the wastewater is passed to treatment plants where it is treated in the processes of coagulation and sedimentation, and as treated wastewater it goes to receiving waters. Insoluble or poorly soluble siloxanes adsorb in wastewater sludge, and thus they get along with the sludge to fermentation chambers, where anaerobic fermentation and biogas production take place [Szlęk, 2012; Smol et al., 2017; Graz and Kwaśny, 2021].

The use of biogas in combined energy production systems requires its purification to the parameters recommended by the manufacturers of biogas combustion engines. The presence of sulfur compounds and siloxanes in biogas has a negative impact on the reliability of engine operation and, consequently, on the efficiency of energy production [Stanuch and Biegańska, 2014]. The combustion chamber of the engine is fed with silica (silicon compounds) contained in the biogas, and then by decomposing during the combustion process, it produces silicic acid, which, when deposited in the cylinders and on pistons, leads to mechanical damage, including non-separable connections. Therefore, the selection of an appropriate biogas purification technology in conjunction with its chemical composition guarantees operational reliability of combined heat and power (CHP) units [Kowalski, 2018; Álvarez-Flórez and Egusquiza, 2015]. During the combustion of biogas in the engine compartment, silicon, which is released from siloxanes, combines, among others, with oxygen to form microcrystalline silica with glass-like properties. Layers of silica adhere to hot walls of the engine, reducing the efficiency of heat transfer and leading to faster wear of engine parts. As a result, the efficiency of energy production is reduced, and therefore it is necessary to carry out more frequent servicing works or even replace individual elements, which is associated with additional costs [Tappen et al., 2017; Tansel and Surita, 2019; Arnold and Kajolinna, 2010]. The way out to reduce harmful compounds contained in biogas is to build a biogas conditioning installation, which should be equipped with at least three basic modules: desulphurization, drying and removal of silicon compounds. The very construction process of the installation should be characterized by careful selection of applied building materials and the segregation of generated waste mainly in terms of recycling and optimal use of energy and water in this process. Due to the fact that this type of installations are most often located outdoor and they are set on foundations, particular attention should be paid to the stability of the ground, including its drainage [Williams at al., 2014; Dyachok et al., 2022].

Hydrogen sulfide is a harmful gas that reacts with most metals, leading to corrosion of equipment and transmission pipes. Additionally, it can be transformed into H_2SO_4 and SO_2, which pose a threat to the environment and human health. There are many methods of biogas desulphurization, mainly in terms of the content of H_2S in the gas, and thus “dry and wet” methods are used [Khoiyangbam et al., 2011; Li, 2017; Turker et al., 2012]. The improvement of biogas quality is obtained by its drying. Moisture contained in biogas in combination with hydrogen sulfide can cause colmatation in the installation during the removal of siloxanes and can reduce gas combustion heat.

For this reason, it is necessary to dehydrate the biogas before its further conditioning [Sun et al., 2014; Kalsum et al., 2022]. One of the effective methods of the removal of siloxanes (organic silicon compounds) is the adsorption on activated carbon beds due to their unique adsorption properties. In addition to siloxanes, other chemical compounds are also adsorbed, which leads to quick clogging of the filtering material. After the carbon has been fully saturated, the bed should be regenerated or replaced with a new one [Soreanu et al, 2011; Gaj, 2020]. The use of the activated carbon technique is recommended when biogas is used in cogeneration systems. During combustion, silicon is released from them, which in combination with oxygen or other elements creates, among others, silicates and deposits containing silica, which in turn can lead to severe failures of the equipment [Laizāns and Vardanjan, 2017; Amaraibi, 2022].

Silica deposits formed in the gas engine are visible in the form of a white powdery substance and they have a crystal structure with a thickness of even up to several millimeters. This poses a serious threat to the operation of gas engines, which translates into frequent breakdowns. The erosive phenomena developed on the surfaces of cylinders and pistons of gas engines which burn biogas shorten the service life of cogeneration units. One of ways to protect surfaces exposed to abrasion is the use of coatings characterized by low friction coefficient and high resistance to abrasion and temperature fluctuations [Kowalski, 2021; Kowalski et al., 2022]. Generation of energy in a combined system requires a systematic control of this process through parametric analysis of the energy efficiency of a cogeneration unit. The availability of such a unit depends primarily on the quality of fuel, which is biogas, which in turn translates into operation indexes of the cogeneration unit. The basic indexes include: the efficiency of electricity and heat generation, the combination index and the savings index of chemical energy of fuel in the form of biogas [Ciuła et al., 2022; Sowa, 2020].

The use of the biogas conditioning process, which removes, among others, sulfur and silicon compounds, is a key element in the operation of cogeneration units. A properly selected, configured and operated biogas treatment installation ensures reliable operation of mechanical systems, and thus the efficiency of electricity and heat generation for a wastewater treatment plant.

OBJECT OF RESEARCH

The subject of the research involves two biogas conditioning installations, type A (the existing one) and type B (a new installation), located on the premises of one sewage treatment plant, collaborating with a cogeneration installation with an electric power of 325 kW and heat capacity of 465 kW. The treatment plant is equipped with a sewage sludge fermentation unit. The annual amount of own energy allows the sewage treatment plant to meet its own needs in the range of 70 to 75% for electricity and 100% for heat. Biogas flux, the amount of energy power production, operating time of the CHP involve two biogas conditioning installations, type A and type B, on an annual basis (12 months), analogically for year A and year B. The results are respectively: V_b = 1172289 and 1184473 $m^3 \cdot year^{-1}$, E_{el} = 2475.9 and 2404.5 $MWh \cdot rok^{-1}$, t_y = 7683 and 8052 $hours \cdot y^{-1}$.

For the period of 10 years since the construction of the cogeneration installation along with biogas treatment, tests have been carried out on the quality of sewage flowing into the treatment plant. The results of the research demonstrate that there are changes in their chemical composition which have taken place in one decade. This primarily involves anthropogenic components present in sewage, containing organ silicon compounds, which are common in personal care products, such as cosmetics, shampoos, deodorants, detergents and varnishes. The content of these components in the wastewater means that organic silicon compounds called siloxanes are found in the biogas after the fermentation of sewage sludge. Their presence significantly accelerates the wear of the engines of cogeneration units and causes frequent failures resulting from the formation of microcrystalline silica coating in the combustion process, which may lead to permanent damage to the valves, cylinders and spark plugs in the engine.

Type A biogas conditioning installation

In the wastewater treatment plant, biogas is produced in separate fermentation chambers (SFC) and through a dehydrator it is directed to the type A biogas treatment plant, using a wet catalytic method. In this biogas purification method, hydrogen sulfide is broken down with a catalyst which circulates in a closed circuit to the form of sulfur pulp. The purified biogas is transferred from the desulphurization unit to the biogas buffer

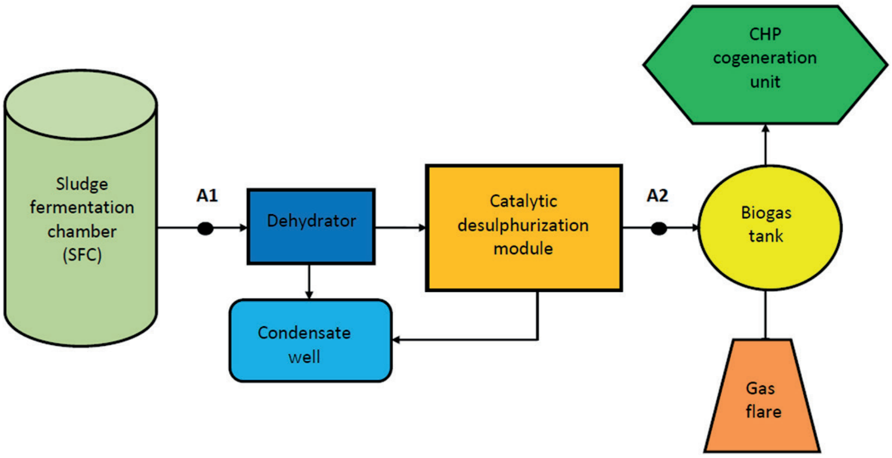

Figure 1. Technological flowchart of type A biogas conditioning installation

tank and then to a gas engine in the CHP unit. And in the case of overproduction of biogas, failure or servicing works of the unit, the untreated biogas is passed to the flare used for its combustion or to the plant's boiler room. The technological schematic of the type A biogas conditioning installation in a sewage treatment plant is presented in (Fig. 1).

In order to assess the efficiency of biogas conditioning in the installation A, biogas samples were collected at two points. The first biogas sample was collected directly at the sludge fermentation chamber (SFC) outlet as "raw biogas" at point A1, while the second sample was collected after its treatment process on the gas path before the inlet to the engine at point A2. The obtained results of biogas quality tests for type A installations are presented in Table 1.

Type B biogas conditioning installation

In effect of the modernization of the existing A-type biogas purification installation, a new B-type biogas conditioning installation was created, which is the subject of the research. This installation uses hybrid solutions in terms of the best available technologies (BAT). In effect of the modernization of the biogas conditioning node, a new installation was developed, which is the object of research. In the designed installation, new elements were introduced to improve the quality of biogas, i.e. drying station and cooling station of biogas, carbon filter, and the previously used catalytic desulphurization method (wet method) was replaced with a technology based on a fixed bed reactor. Figure 2 shows the technological schematic of biogas conditioning in the type B installation in a sewage treatment plant.

The study involves the analysis of the quality of purified biogas in the existing A-type installation and in the new B-type installation, which was developed through the modernization of the A-type installation. Consequently, in the B-type installation, the hybrid solution was applied, which consisted in the application of a simultaneous bed

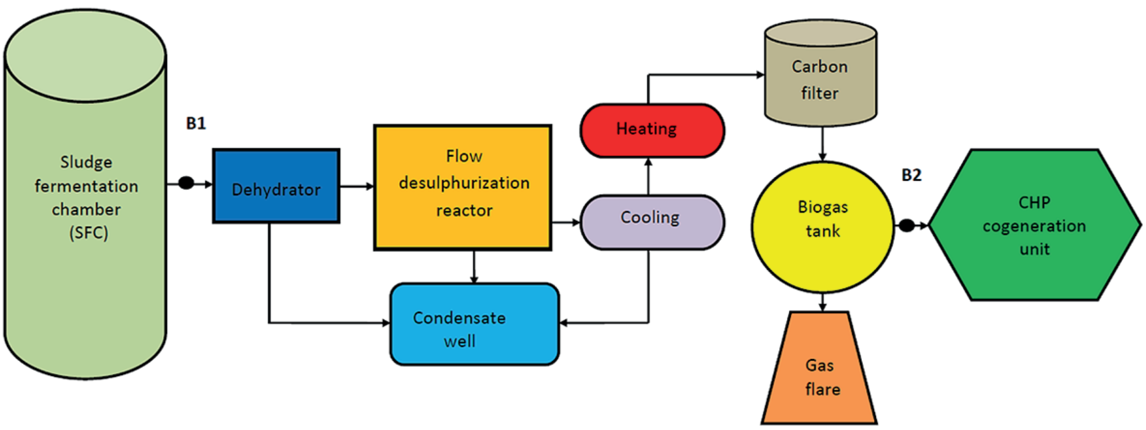

Figure 2. Technological flowchart of type B biogas conditioning installation

regeneration method which for biogas treatment process uses the "dry method" to remove sulfur compounds and siloxanes from the biogas. The purpose of such an approach is to improve the quality of biogas, which is the fuel for the cogeneration unit, in order to protect the engine against silica deposits, and to increase the energy efficiency of energy production. A desulphurization module was used in the form of a fixed bed flow reactor, which is a batch reactor, with hydraulic gas distribution in the bed. Hydrogen sulphide is chemically bound by granulated, highly porous material, while the simultaneous regeneration of the bed with oxygen extends the service life of the desulfurizing material.

The designed drying module of biogas consists of a gas dryer and a gas heater mounted on a foundation in the form of a container station. The biogas in the first module is cooled down to 10 °C, which results in the formation of condensate. In order to avoid this, the biogas in the second module is heated to 40 °C in the next stages of treatment. The cooling process is possible owing to the work of a cooling compressor unit (heat pump), shell and tube heat exchanger and the heating medium being hot water from the heat recovery unit of the engine. A key element of the conditioning installation of biogas is the removal of siloxanes. The selected carbon filter was filled with a bed that adsorbs siloxane compounds in the form of activated carbon granules and equipped with manometers to measure the drop of pressure on the filter and the drain of condensate. The calculated minimum service life of the filter bed is about 12 months. In order to confirm the adopted solutions and to assess the efficiency of biogas treatment in the installation B, biogas samples were collected at two points. The first biogas sample was collected directly at the outlet from SFC as "raw biogas" at point B1, while the second sample was collected after its treatment process on the gas path downstream of the siloxane filter and before the engine inlet at point B2. The obtained results of biogas quality tests for type B installations are presented in Table 1.

MATERIALS AND METHODS

Laboratory tests and calculations

For the purposes of this study, the biogas purification installation operating in the wastewater treatment plant, which makes use of the catalytic method (wet method), was referred to as A-type installation. The new biogas purification installation constituting a hybrid system, using a fixed bed reactor with a simultaneous regeneration of the bed with oxygen, a siloxane removal module as well as the cooling and heating system, was referred to as B-type installation. The biogas composition was verified at the working A type biogas conditioning installation in the "wet desulphurization" technology, which consisted in collecting 3 biogas samples at point A1 (untreated biogas) and 3 biogas samples at point A2 after the treatment process. Having been delivered to the laboratory, the samples were conditioned and derivatized, and then the biogas samples were tested with 3 repetitions for statistical purposes. Eighteen parameters of untreated and purified biogas were analyzed, and the results were presented in the tabular form.

In the same way as in the installation of A-type, the quality of biogas was tested in the B-type installation also for 18 parameters of raw and purified biogas, collected in points B1 and B2, and the results were presented as average values in a tabular form. Additionally, calculations were carried out as part of the study involving the efficiency of biogas treatment (reduction of load and concentration) for eight basic parameters of biogas produced in the sewage treatment plant.

Processing of research results

As input parameters for the analysis of biogas quality before and after its conditioning, the results of calculations, measurements and laboratory tests for type A and type B installations were applied. The key biogas parameters, which determined the reliability of the cogeneration installation and the efficiency of energy production, were statistically analyzed using the Statistica software, v 13.3 TIBCOI Software Inc. [Statistica, 2017]. For this purpose, a correlation (correlation coefficient) was used in the form of a 2D scatter plot, which is used to visualize the relationship between the X and Y variables, being a measure of the relationship between these variables. Additionally, in order to analyze the interrelationships between the individual parameters of the treated biogas in type A and type B installations, 3D surface plots were used for three variables: X, Y, Z.

Pollution indicator of a megawatt hour produced in cogeneration

The quality of biogas purification in A-type and B-type installations was correlated with the quality of produced electricity by introducing Pollution Indicator of a Megawatt hour (PIMh) of electricity produced in cogeneration. This indicator, expressed as percentage, accounts for the amount of pollutant remaining in the biogas, and it was referenced to one megawatt hour of electricity produced in the cogeneration unit. For the calculation of the indicator, data from the biogas treatment in the conditioning installations of type A and type B were used, as well as the amount of biogas produced, the operating time of the CHP installation and the amount of electricity produced in MWh. The indicator was referenced to the following impurities: hydrogen sulphide, total sulfur, chlorine, ammonia, sum of siloxanes and sum of silicon. The indicator value should aim towards zero as target value.

RESULTS AND DISCUSSION

The type A biogas conditioning installation operating in the wastewater treatment plant was subjected to parametric analysis following the collection of samples in order to test in laboratory conditions the individual parameters of the composition of untreated biogas (A1 sampling point) as well as that of purified biogas (A2 sampling point). The results of the laboratory tests for 18 biogas parameters in the installation A are presented in Table 1 in columns 3 and 4.

The analysis of the biogas test results for the installation A confirmed the operator's assumptions concerning high content of silicon and siloxanes in the biogas, which could potentially have been the cause of frequent failures of the drive unit. The results of laboratory tests for 18 biogas parameters in the installation B are presented in Table 1 in columns 5 and 6.

The analysis of the test results for the installation B indicated the presence of total silicon in the untreated biogas in the amount of 3.3 mg·m^{-3}, while after the treatment the said value was 0.04 mg·m^{-3}. In the case of total siloxanes, these values were respectively: 12.83 mg·m^{-3} and 0.21 mg·m^{-3}. The obtained results confirmed high removal efficiency of silicon compounds in the installation B, as well as the reduction of purified biogas moisture from 94.2 to 44.5% and that of chlorine content from3.24 mg·m^{-3} to 1.63 mg·m^{-3}. Taking into account the test results for the installation B, the decision to change the conditioning technology was justified.

Table 1. Average values of the parameters of raw and purified biogas in A-type and B-type installations

Parameter	Unit	Installation A		Installation B	
		Untreated biogas (x_{A_U})	Purified biogas (x_{A_p})	Untreated biogas (x_{B_U})	Purified biogas (x_{B_p})
Temperature	°C.	34	20.2	30	18.2
Relative humidity	%	96.5	71.3	94.2	44.5
Methane, CH_4	% vol.	66.3	66.3	58.6	58.6
Carbon dioxide, CO_2	% vol.	32.7	32.5	35.5	35.4
Oxygen, O_2	% vol.	0.2	0.1	0.1	2.6
Hydrogen sulfide, H_2S	ppm	471.4	5.3	324.3	2.1
Hydrogen sulfide, H_2S	mg·m^{-3}	215.2	2.83	218.3	0.64
Total sulfur	mg·m^{-3}	154.3	10.93	149.64	0.4
Hydrogen, H_2	% vol.	0.2	0.01	0.2	0.005
Nitrogen, N_2	% vol.	0.4	0.2	0.7	0.2
Chlorine, Cl	mg·m^{-3}	8.21	3.24	10.21	1.62
Fluorine, Fl	mg·m^{-3}	1.2	0.88	1.1	0.72
Ammonia, NH_3	mg·m^{-3}	11.8	0.85	12.4	0.32
Total ash	mg·m^{-3}	0.38	0.35	0.31	0.29
Total siloxanes	mg·m^{-3}	9.4	3.21	8.9	0.12
Total silicon	mg·m^{-3}	4.2	1.32	3.3	0.04
Calorific value	kJ·m^{-3}	23 758	21 700	22 471	21 200
Gas density	kg·m^{-3}	1.03	1.0	1.08	1.1

The need of biogas conditioning for fuel purposes for cogeneration units, as well as during the conversion of biogas to biomethane, has been confirmed in the works of (Cavaignac et al. 2015) and (Dewil et al. 2006), where they also recommend systematic modernization of the units in terms of the available modern technologies. They emphasize that the key element in this process is the appropriate choice of biogas purification technology and its upgrading to its quality requirements specified in the recommendations of suppliers and producers of CHP units and engines [Cavaignac et al., 2012; Barzegaravva et al., 2018]. The test results of the untreated biogas from the fermentation of sewage sludge in the type A and type B installations are comparable to those presented in the work Santos-Clotas et al. [2019]. He proposed the removal of siloxanes and volatile organic pollutants in a filter based on a biological bed with an absorbent in the form of volcanic rocks. The activated carbon, additionally used in the biogas treatment system, effectively ensured the growth of biomass, while maintaining the hydrolysis reactions. And critical comments on the removal of siloxanes with the use of active carbon have been presented in Zamorska-Wojdyla et al., [2012] and Sigot et. al., [2014] where she argued that the disadvantage of activated carbon lies in its difficult desorption during the regeneration due to high humidity of biogas. Taking these suggestions into account, it is advisable to carry out the drying process of biogas before it is fed to the filter with carbon bed. The above-mentioned studies show that regardless of the type of technology used, relative humidity has a large impact on the efficiency of gas treatment, especially in the case of the removal of siloxanes.

The research aimed at assessing the technologies of hydrogen sulfide removal based on a biological bed and iron oxide-based adsorbents, integrated with a filter for the removal of siloxanes in the form of active carbon, was carried out by Zhang et al., [2020], Díaz et al., [2015]. The research results demonstrated high reduction of hydrogen sulfide as well as that of silicon compounds in the system of biological filter plus carbon filter as compared to the system: iron oxide-based filter plus carbon filter. Also in terms of economic benefits, the solution based on a biological bed turned out to be more optimal. Mutual relations between the individual parameters of untreated and purified biogas in the type A and type B installations, for the content of siloxanes, silicon, sulfur, hydrogen sulfide, relative humidity and oxygen, are shown in (Fig. 3).

The best fitting of the parameters of siloxanes, silicon and relative humidity (Fig. 3a) for the biogas treated in the installations A and B is represented by the point with the following parameters: (x = 0.21; y = 44.5; z = 0.078) which stands for the parameters of purified biogas in the installation B. And in the case of purified gas in the installation A, the analogous point has the following parameters: (x = 3.47; y = 71.3; z = 1.32). In terms of these three parameters, the installation B has proved to be more effective than the installation A.

When comparing the results of the research involving the reduction of sulfur compounds and hydrogen sulfide in relation to oxygen content (Fig.

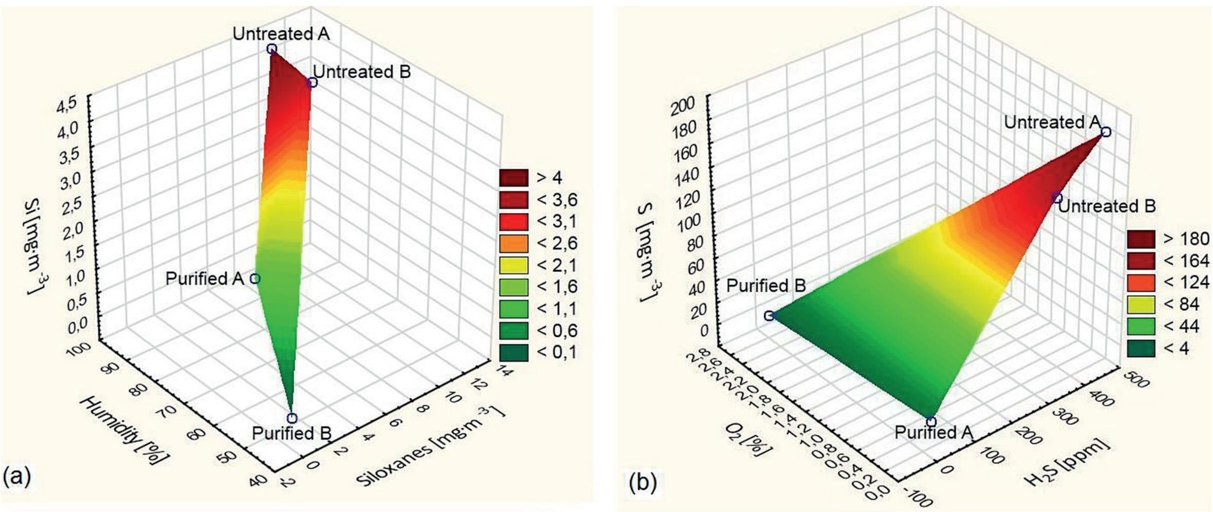

Figure 3. Mutual relations between the content of siloxanes, silicon, sulfur, hydrogen sulfide, relative humidity and oxygen in the installations A and B

3b), for the biogas conditioned in both installations, it should be noted that the point representing the highest efficiency of sulfur and hydrogen sulfide reduction has the following parameters: (x = 2.83; y = 0.1; z = 10.93) which stands for biogas purified in the installation B, while similarly in the case of the installation B, these parameters are as follows: (x = 2.1; y = 2.6; z = 0.5). The obtained results bespeak of an effective removal of sulfur compounds in the installation B, despite higher oxygen content which in this case increases the efficiency of the process.

Based on the obtained measurement results of relative humidity for both installations, Figure 4 shows the mutual relations between biogas humidity, ammonia, chlorine, methane, oxygen and carbon dioxide for untreated and purified biogas in the installations A and B.

With respect to mutual correlations between the main parameters of biogas (Fig. 4a), higher oxygen content in the installation B can be observed, which is caused by the addition of oxygen to the desulphurization process of biogas. Thus, the point with the lowest reduction has the following parameters: (x = 31.5; y = 65.0; z = 0.1) in the installation A. And in the case of gas purified in the installation B, the parameters of this point are: (x = 34.8; y = 57.5; z = 2.6), representing the value of oxygen in the purified biogas in the amount of 2.6%. The treatment of biogas in terms of the removal of ammonia and chlorine compounds is more effective in the installation B (Fig. 4b), which is represented by the point with the following parameters: (x = 0.42; y = 44.5; z = 1.62). And in the case of biogas treated in the installation A, the parameters of this point are: (x = 0.68; y = 71.3; z = 3.24). It is worth indicating similar values of ammonia removal in both installations, 0.68 mg·m^{-3} in the installation A and 0.42 mg·m^{-3} in the installation B.

In order to compare the two applied biogas treatment technologies, in the installation A and in the installation B, in terms of reduction efficiency of the individual parameters of biogas, on the basis of Equestion (1), efficiency calculations for 8 main biogas parameters were performed.

$$\eta_{A..B} = \frac{P_u - P_p}{P_u} \cdot 100\% \tag{1}$$

where: $\eta_{A..B}$ – reduction effectiveness of parameter value [%];
P_u – value of the parameter in untreated biogas [mg·m^{-3}];
P_p – value of the parameter in purified biogas [mg·m^{-3}].

Table 2. Reduction effectiveness of biogas parameters in type A and type B installations

Parameter	Reduction effectiveness of parameter value reduction [%]	
	Installation A (η_A)	Installation B (η_B)
Relative humidity	26.11	52.76
Hydrogen sulfide	98.68	99.71
Total hydrogen sulfide	92.92	99.73
Total sulfur	94.06	99.54
Chlorine	60.54	84.13
Ammonia	92.80	97.42
Total siloxanes	65.85	98.65
Total silicone	68.57	98.79

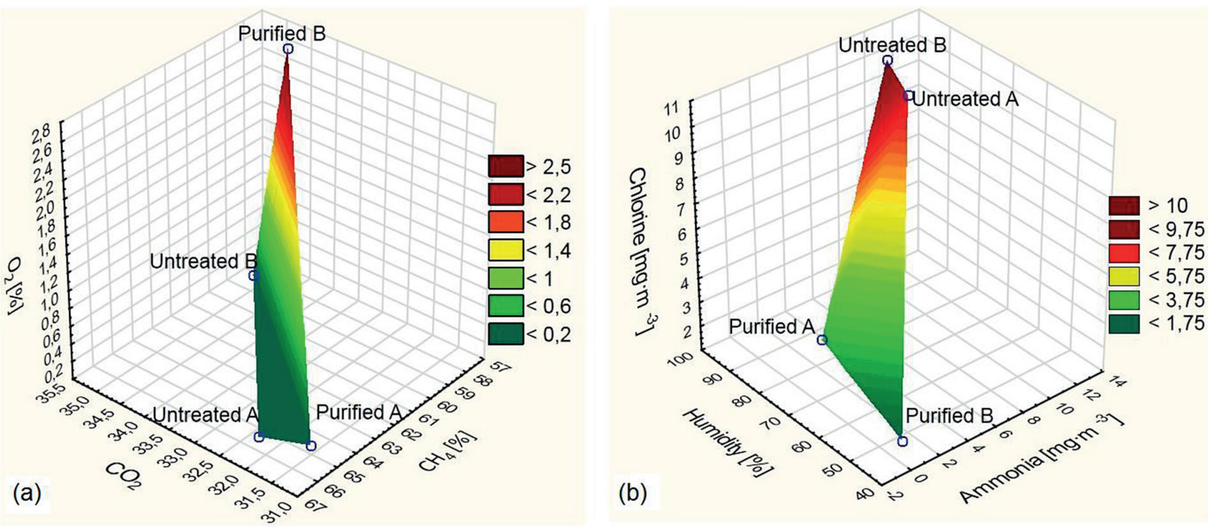

Figure 4. Mutual relations between the content of chlorine, ammonia, humidity, oxygen, methane and carbon dioxide in the installations A and B

The removal effectiveness of basic parameters of biogas in type A and type B installations is presented in Table 2.

For all basic parameters ensuring operational reliability of the CHP unit and the efficiency of energy production, the installation B represents the highest values, which bespeaks of the highest percentage of pollution reduction. The reduction efficiency of total siloxanes and total silicon is over 98%, while for sulfur and hydrogen sulfide it is over 99%.

The requirements in terms of acceptable parameters for biogas used to generate electricity and heat in CHP cogeneration units were defined individually for each country, as presented in the work (Nyamukamba et al, 2020). For example, the required content of siloxanes in biogas in Europe ranges from 5 to 10 $mg \cdot m^{-3}$ depending on the country. Accordingly, engine manufacturers adapt to these requirements, developing their own ranges depending on the type of engine and the country in which the CHP installation will be operated. The limit values provided most frequently by engine manufacturers for purified biogas mainly concern such parameters as: relative humidity up to 80%, H_2S below 20 $mg \cdot m^{-3}$, sulfur below40 $mg \cdot m^{-3}$, silicon below 2 $mg \cdot m^{-3}$, CH_4 from 30 to 70% and siloxanes below 10 $mg \cdot m^{-3}$ [Nyamukamba et al., 2020].

In order to compare the conditioning efficiency of biogas in type A and type B installations in correlation with the amount of electricity produced in a renewable source, which is biogas, an environmental quality analysis of the produced electricity was performed. For the purposes of this study, the pollution indicator of a megawatt hour of electricity (PIMh), expressed in percentage, was introduced for the biogas purified in the A-type installation, $i_{MWh\ A}$ and B-type installation, $i_{MWh\ B}$ being the source of energy in the cogeneration installation. The final value of this indicator depends: on the content of individual pollutants in the biogas before treatment and after conditioning in the type A and type B installations, on the amount of biogas produced, on the operating time of the CHP installation and on the amount of electricity produced in MWh. For the calculations as well as the selected biogas pollutants from Table 2. The value of the indicator will account for the percentage of pollutant remaining in the biogas that was used to produce one megawatt hour of electricity (pollution load). The indicator value should aim towards zero as target value.

The literature on the subject in the sector of energy generation from a renewable source, which is biogas, does not provide an indicator that would define the quality of produced megawatt-hour of electricity in relation to the contaminants contained in the biogas being the source for this energy. There are, e.g. energy efficiency indicators for electricity and heat production in relation to, e.g. greenhouse gas emissions, referred to as co-generation reduction ratio [Dev et al., 2014]. Another group of indicators used in cogeneration are energy efficiency indicators of the CHP unit in relation to the amount of used biogas and in relation to the methane content in order to improve exergy performance [Gvozdenac et al., 2017]. The correlation of methane to carbon dioxide in biogas allowed for the introduction of indicators determining the reduction of CO_2 and NO_x emissions, depending on the ratio of air quantity and load [Kim et al., 2016]. In the field of cogeneration in biogas, there are also indicators defining the amount of CO_2 emissions to the air from biogas combustion in terms of the amount of generated electricity and heat, expressed in kg of emissions per kWh of the produced electricity [Zhang et al., 2022]. Considering the above, the introduction of the indicator of the quality of a produced megawatt hour of electricity seems justified in order to supplement the volume of the already existing indicators in this sector.

For this purpose, calculations were made, introducing the content of individual pollutants in raw and purified biogas in $mg \cdot year^1$ for type A and type B installations in relation to the amount of electricity produced in year A and in year B in $MW \cdot year^{-1}$.

Using formulas 2 and 3, appropriate calculations were made for the main parameters polluting the biogas: hydrogen sulphide, total sulfur, chlorine, ammonia, siloxane sum and silicon sum. The calculated value of $m_{1\ A..B_u}$) accounts for the potential amount of pollutant per megawatt hour for raw biogas if the biogas was not conditioned in the type A and type B installation, expressed in $mg \cdot MWh^{-1}$.

$$m_{1\ A..B_u} = \frac{\left(x_{A..B_u} \cdot V_{bp_{A..B}}\right)}{E_{el_{A..B}}} \tag{2}$$

And the calculated value of $m_{2\ A..B_p}$ accounts for the amount of pollution in one megawatt hour (purified biogas) when it is conditioned in type A and type B installations, expressed in $mg \cdot MWh^{-1}$.

$$m_{2\ A..B_p} = \frac{\left(x_{A..B_p} \cdot V_{bp_{A..B}}\right)}{E_{el_{A..B}}} \quad (3)$$

where: $x_{A..B_u}$ – the content of a given parameter in untreated biogas from the installation of type A or type B [mg · year[1]];
$x_{A..B_p}$ – the content of a given parameter in biogas treated from the installation of type A or type B [mg · year[1]];
$V_{bp_{A..B}}$ – the annual biogas flux purified in the installation type A or B used in the CHP unit [m^3 · year[1]];
$E_{el_{A..B}}$ – the annual amount of electricity generated in the CHP unit for the conditioning installation of type A or type B [MW·year[-1]].

The amount of pollutants removed from one megawatt hour of produced electricity m_{MWh}, expressed in mg · MWh^{-1}, calculated using the formula 4.

$$m_{3\ A..B} = m_{1\ A..B_u} - m_{2\ A..B_p} \quad (4)$$

Relevant calculations were made separately for type A and type B installations, containing individual biogas pollutants, and the results of the calculations are presented in Table 3.

In terms of mass, the largest amount of pollution expressed in mg · MWh^{-1} of a given pollution was removed for one megawatt hour in the B-type biogas conditioning unit, and this applies to hydrogen sulphide. And the total amount of hydrogen sulphide removed in the B-type installation as a result of the production of 2404.5 MWh of electricity per year was 255.16 kg per year. It is also worthwhile to note the reduction of siloxanes and silicon in the type B installation, which amounted to 10.29 kg and 3.82 kg per year, respectively.

Effective removal of pollutants contained in biogas is crucial for the reliability of the cogeneration unit as well as for energy efficiency in terms of electricity and heat generation. The issue of energy balance and energy efficiency of the CHP unit in a wastewater treatment plant was presented in the paper Yingjian et al., [2017]. In the work, methods to reduce heat loss were proposed by cooling the gas engine with water (treated sewage) instead of air. As a result of such an approach, the amount of heat loss was reduced from 34.4% to 2.99%, which allowed to increase the efficiency of energy production.

Based on the data contained in Table 2 and Table 3, the value of the PIMh of electricity i_{MWh} was determined for particular types of pollutants contained in the biogas, based on formula 5.

$$i_{MWh\ A..B} = 100 - \left[\frac{\left(m_{1_{u\ A..B}} - m_{2_{p\ A..B}}\right)}{m_{1_{u\ A..B}}} \cdot \eta_{A..B}\right] \quad (5)$$

Table 3. Pollution values for the produced megawatt hour of electricity with the use of installation types A and B

Parameter	Installation A [mg·MWh^{-1}]			Installation B [mg·MWh^{-1}]		
	$m_{1_u A}$	$m_{2_p A}$	$m_{3 A}$	$m_{1_u B}$	$m_{2_p B}$	$m_{3 B}$
Hydrogen sulfide	103511.30	1361.23	102150.1	106430.8	312.0	106118.7
Total sulfur	74218.37	5257.34	68961.0	72956.0	195.0	72761.0
Chlorine	3949.01	1558.44	2390.6	4977.8	789.8	4188.0
Ammonia	5675.81	408.85	5267.0	6045.5	156.0	5889.5
Total siloxanes	4521.40	1544.01	2977.4	4339.1	58.5	4280.6
Total silicone	2020.20	634.92	1385.3	1608.9	19.5	1589.4

Table 4. Value of the pollution indicator of megawatt hour of electricity produced in cogeneration for type A and type B installations

Parameter	Pollution indicator of megawatt hour of electricity produced in cogeneration [%]	
	$i_{MWh A}$	$i_{MWh B}$
Hydrogen sulfide	2.61	0.59
Total sulfur	13.67	0.53
Chlorine	63.35	29.22
Ammonia	13.89	5.09
Total siloxanes	56.64	2.68
Total silicone	52.98	2.41

Value of the megawatt-hour pollution indicator of electricity produced in cogeneration, depending on the type of installation, is presented in Table 4.

The comparison of the values of the pollution indicator of a produced megawatt hour of electricity for type A and type B installations shows a clear advantage of the biogas conditioning technology used in type B installation (hybrid solution), represented by the indicator i_{MWhB}. This result accounts for the lowest pollution load of one MWh produced in cogeneration from a renewable source, i.e. biogas. For all parameters of the biogas conditioned in the type B installation, the indicator i_{MWhB} has the lowest values as compared to the type A installation. These values involve hydrogen sulphide and total sulfur, respectively 0.59% and 053% in the type B installation. And in the case of type A installation, the lowest values are obtained by the indicator i_{MWhA} also for hydrogen sulphide and total sulfur, but these values are respectively: 2.61% and 13.67%. And the highest values are obtained by the indicator for chlorine both in type A and type B installations: 29.22% and 63.35%, respectively. Such a state is caused by focusing the applied technology on the reduction of pollutants most dangerous in terms of proper operation of the cogeneration unit.

The necessity to use a treatment installation of biogas produced in a sewage treatment plant for the purposes of energy production is a basic element in the pursuit to ensure energy self-sufficiency of the sewage treatment plant as a facility. The use of hybrid systems in wastewater treatment plants based solely on renewable sources was presented in the work Halaby et al., [2017], which suggested the operation of the wastewater treatment plant as an energy-autonomous off-grid facility. Treatment plants generating biogas and producing energy from cogeneration units, depending on the size of the treatment plant, satisfy their energy needs at the level of 50 to 100%. The correlation of electricity and heat generated in a renewable source with the quality of purified biogas is the basis for the reliability of cogeneration systems, which can be controlled by the quality indicator of the produced megawatt hour of electricity.

The proposed solution, which is introducing pollution indicator of a produced megawatt hour of electricity in a cogeneration installation using biogas from a sewage treatment plant, is a universal solution that can be used to compare types of applied technologies to purify a given type of biogas. The indicator can be used in conditioning installations, e.g. for landfill, agricultural or municipal gas. By introducing the above-mentioned indicator, the authors aimed to fill up a gap that would allow for the qualitative assessment of the produced electricity in terms of the environment, energy generation, and for the assessment of the operational reliability of CHP installations.

CONCLUSIONS

The use of biogas generated in the fermentation process of sewage sludge in cogeneration units for heat and electricity generation necessitates its conditioning. The objective of the said process is to remove or reduce the values of parameters of a given substance contained in biogas in order to burn it in gas engines in CHP units. It mainly concerns the reduction in the content of sulfur, hydrogen sulfide, silicon, siloxanes and ammonia. As for conditioning methods, the most frequently applied systems are fixed bed units for the removal of sulfur and silicon compounds, supplemented with a component to reduce humidity in biogas by heating and cooling it. The qualitative analysis of biogas subjected to the conditioning process in two types of installations, type A and type B, carried out in the study, based on the results of laboratory tests, demonstrated significant differences in the parameters of the purified biogas.

The hybrid biogas treatment system presented in the paper, containing four independent modules: hydrogen sulphide removal, siloxane removal, biogas cooling and heating, is a comprehensive solution in the field of biogas quality assurance for cogeneration units, which are a source of renewable energy for wastewater treatment plants.

The solution implemented in the installation B involves the use of aerobic processes (oxygen process) in the reactor which is filled with a fixed bed with continuous regeneration of the bed with oxygen. Such a solution results in a slight increase in oxygen content in the biogas to the level of 2.6% (without any negative impact on the operation of gas engine), but it significantly extends service life of the filter bed from 10 to 12 months. The key element of the conditioning installation is a module for siloxanes removal, which is a filter packed with an adsorbing bed of activated carbon. The reduction efficiency of organic sulfur compounds (siloxanes) in the installation B was 98.65%, while the installation A ensured the reduction of these compounds at the level of 65.85%. The drying and heating module of biogas applied in biogas conditioning makes use of a heat pump for which the lower source is the technological heat generated in the CHP unit. Such a solution allows to optimize the operation of a biogas energy-generation installation by preparing biogas of highest quality parameters, including the reduction of its humidity to the level of 44.5%. In addition, the parameters of biogas are optimal as a fuel dedicated to work in cogeneration units to generate energy and meet the requirements of gas engine manufacturers.

The pollution indicator of megawatt hour of electricity produced in cogeneration proposed in the study, using biogas from a sewage treatment plant, is an innovative approach to the qualitative assessment of electricity produced in relation to a specific type of biogas treatment plant.

The use of conditioning systems of biogas produced in a sewage treatment plant in order to apply it for energy purposes is a key element of the reliability of CHP cogeneration units as a source of electricity and heat for such facilities as sewage treatment plants. Considering the fact that a sewage treatment plant, as a result of the use of cogeneration, is in 70% powered by electricity from its own renewable energy source and in 100% in terms of heat, it is crucial to optimally prepare the quality of biogas, which is a source of renewable energy. An additional benefit resulting from the optimization of the biogas conditioning process involves the reduction of the emissions of harmful substances contained in the biogas to the atmosphere, such as chlorine, ammonia, hydrogen sulfide.

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