sustainability

MDPI

Article

Analysis of the Efficiency of Landfill Gas Treatment for Power Generation in a Cogeneration System in Terms of the European Green Deal

Józef Ciuła [1], Agnieszka Generowicz [2,*], Anna Gronba-Chyła [3], Iwona Wiewiórska [1], Paweł Kwaśnicki [3] and Mariusz Cygnar [1]

1 Faculty of Engineering Sciences, State University of Applied Sciences in Nowy Sącz, Zamenhofa 1A, 33-300 Nowy Sącz, Poland; jciula@ans-ns.edu.pl (J.C.); iwiewiorska@ans-ns.edu.pl (I.W.); mcygnar@ans-ns.edu.pl (M.C.)
2 Department of Environmental Technologies, Cracow University of Technology, ul. Warszawska 24, 31-155 Cracow, Poland
3 Faculty of Natural and Technical Sciences, John Paul II Catholic University of Lublin, ul. Konstantynów 1 H, 20-708 Lublin, Poland; amgronba@kul.pl (A.G.-C.); pawel.kwasnicki@kul.pl (P.K.)
* Correspondence: agnieszka.generowicz@pk.edu.pl

Abstract: Climate change and environmental degradation pose a threat to Europe and the world. The mechanism that will address these challenges is the European Green Deal, which envisions transforming the EU into a modern, resourceful, economical and competitive economy, aiming for zero greenhouse gas emissions. Landfill gas generated in a landfill waste deposit poses a threat to the environment and people. In this aspect, its capture, treatment and safe neutralization or use for energy purposes are important. Treatment of landfill gas, which is the fuel for gas engines in cogeneration units, is crucial for their proper operation and the quantity and quality of electricity and heat generated. The purpose of this study was to perform research to determine the hydrogen sulfide content of landfill gas and the actual efficiency of hydrogen sulfide removal from the gas using activated carbon. The tests performed constitute the basis for the reliable operation of gas engines in cogeneration installations and are dedicated mainly to the operators of these installations. Accordingly, three measurement campaigns were carried out, each with 42 measurements, the first for the "raw" gas obtained directly from the landfill, the second for the gas before entering the carbon filter and the third after its treatment. In addition, surface analysis was performed, and the elemental composition of the "fresh" molded activated carbon constituting the filter material was determined using a scanning electron microscope with an EDS system. The results showed a high elemental content of carbon in the test sample at 92.78%, while the efficiency of hydrogen sulfide removal from landfill gas by activated carbon, calculated from the measurements, was 97.05%. The obtained test results confirmed the validity of using impregnated activated carbon to remove hydrogen sulfide from landfill gas and its high adsorption efficiency, which can consequently result in reliable operation of the gas engine in the cogeneration unit and ultimately fit in with the objectives of the European Green Deal. The research results are an incentive for operators of cogeneration installations to systematically examine the quality of landfill gas and the efficiency of biogas purification devices.

Keywords: landfill gas; biogas treatment; activated carbon; hydrogen sulfide; cogeneration; European Green Deal

check for updates

Citation: Ciuła, J.; Generowicz, A.; Gronba-Chyła, A.; Wiewiórska, I.; Kwaśnicki, P.; Cygnar, M. Analysis of the Efficiency of Landfill Gas Treatment for Power Generation in a Cogeneration System in Terms of the European Green Deal. *Sustainability* **2024**, *16*, 1479. https://doi.org/10.3390/su16041479

Academic Editor: Georgios Archimidis Tsalidis

Received: 15 January 2024
Revised: 4 February 2024
Accepted: 7 February 2024
Published: 9 February 2024

1. Introduction

The economic activities of man over the past centuries, including industrial development and the extraction and use of the Earth's energy resources, have resulted in visible climate change and progressive environmental degradation. As a result, measures are needed to transform the economies of individual EU countries into modern, resourceful, economical and competitive economies, aiming for zero net greenhouse gas emissions by 2050. These actions included in the European Green Deal (EGD) [1] include, among other things, energy transformation and moving toward a closed-loop economy, including in the municipal waste sector [2,3]. Reducing the generation of municipal waste is a major challenge for individual countries, while the ways to manage it challenge technologists in the processes of its treatment and disposal [4,5]. These processes must be implemented in accordance with the waste hierarchy, within which landfilling is the least desirable process [6]. Modern legal requirements in the field of municipal waste management force the need for comprehensive measures to implement a closed-loop economy that is fully scalable and can respond to current raw material needs [7,8]. The legal acts of the European Union, being the directives and the conclusions on Best Available Techniques (BATs) for municipal waste, define measures to prevent and reduce waste generation, along with recycling [9,10].

Municipal waste collected for disposal in landfills undergoes physical and chemical processes throughout the period of deposition. The result of these processes is the "products of the landfill", among other things, the formation of wastewater, which, captured using drainage, is discharged and treated before it enters sanitary sewer facilities [11]. Proper water and wastewater management during the operation of a landfill prevents the migration of wastewater into the ground layer and surface- and groundwater, which consequently reduces the negative environmental impact of the landfill as a facility [12,13]. Another "product" is landfill gas (LFG), which is formed during anaerobic digestion of the biodegradable fraction in a bed of waste subjected to appropriate compression. LFG, containing large amounts of methane and carbon dioxide, is a source of fugitive emissions from the landfill surface into the atmospheric air, which are greenhouse gases that contribute to climate change on Earth [14]. Therefore, a key issue during the operation of landfills where bio-waste has been stored is to reduce the air emissions of the biogas generated [15,16].

One effective way to reduce and control LFG emissions is to perform landfill degassing, capture the gas and use it for energy purposes, provided it has an optimal calorific value [17,18]. The use of landfill biogas as a fuel for energy generation requires a detailed analysis in terms of quality parameters and the efficiency of the thermodynamic processes carried out [19,20]. Examples of the capture and energy management of LFG, mainly focus on the combustion of gas in gas engines integrated with combined heat and power (CHP) systems [21,22]. This way of managing the gas guarantees the optimal use of the chemical energy contained in LFG, the products of which are electricity and heat, produced in a combined system [23,24]. Since raw LFG sourced directly from the landfill contains harmful impurities, including hydrogen sulfide, ammonia and silicon compounds, it is required to undergo a purification process as a target gas fuel [25,26]. The LFG cleaning techniques used throughout the world are mainly wet and dry technologies, which effectively reduce contaminants and allow gas engines to operate properly. Dry technology, which is increasingly used in LFG conditioning plants, is the use of activated carbon to remove mainly sulfur and silicon compounds [27,28].

The efficiency of removal of compounds contaminating the gas mainly depends on the size of the compounds and the moisture content. Therefore, in installations with high gas moisture content, intermediate heating and cooling devices are used before feeding the gas to the gas engine [29,30]. The most commonly used method for drying biogas is condensation dehydration by gravity or using waste heat from the engine cooling block, providing a lower heat source for the heat pump. The cooled biogas is directed to the next point to avoid further condensation. In most biogas plants, a water condenser is set at the lowest point in the pipeline to avoid condensation [31,32]. The process by which hydrogen sulfide is removed from biogas is carried out mainly to prevent corrosion of equipment involved in the gas transmission process, to protect the mechanical parts of the gas engine and to reduce the sulfur compounds emitted into the atmosphere in the flue gas [33,34]. LFG generated in the landfill waste bed is a renewable source of energy, while electricity and heat that are the product of cogeneration are counted from the so-called "green energy", which is part of the closed-loop economy and green energy transition [35,36]. In recent years, the European Union has been placing a heavy emphasis on the energy transition, pointing to the need for intensive development of renewable energy generation technologies, reducing the use of fossil fuels [37,38].

The European Green Deal includes initiatives in a number of closely related areas such as climate, environment, energy, transportation, industry, agriculture and sustainable financing [39,40]. The implementation of this program envisages a thorough energy transformation implemented through investments in renewable energy sources to achieve EU energy independence and security of energy supply [41]. Projects and investments aimed at curbing climate change as a result of reducing fugitive methane emissions into the air from landfill surfaces are part of these principles. Capturing landfill gas and purifying it of sulfur, silicon, ammonia, chlorine and ammonia compounds before it undergoes combustion reduces the amount of gas and dust emissions into the air as a result of its conversion into energy [42]. The revised Renewable Energy Promotion Directive [43] sets a target for the EU of 32% in 2030, which was agreed upon by EU leaders and represents some compromise between the European Parliament and some member states [44]. Further developments in this regard include new support mechanisms, a regulatory framework adapted to the actual consumption of the energy sector and precisely defining sustainability criteria for biofuels and bioenergy [45]. Of particular importance is the fact of support for small-scale installations using, for example, landfill gas, which are key to increasing public acceptance and ensuring the implementation of renewable energy projects, particularly at the local level.

2. Object of Research

The object of this study was a biogas extraction, purification and energy utilization facility located at the landfill. LFG is extracted from the landfill's vertical and horizontal degassing wells by means of a gas suction device with a capacity of up to 200 m^3 per hour and is burned in a gas engine which, in a cogeneration system, drives a generator with an electrical output of 320 kW. Annually, the installation extracts about 1.2 million m^3 of biogas from the landfill, which, before being fed into the gas engine, is purified mainly from sulfur and silicon compounds in a filter containing activated carbon with a capacity of 1.5 cubic meters. The installation for the energetic use of landfill gas, including measurement points, is shown in Figure 1.

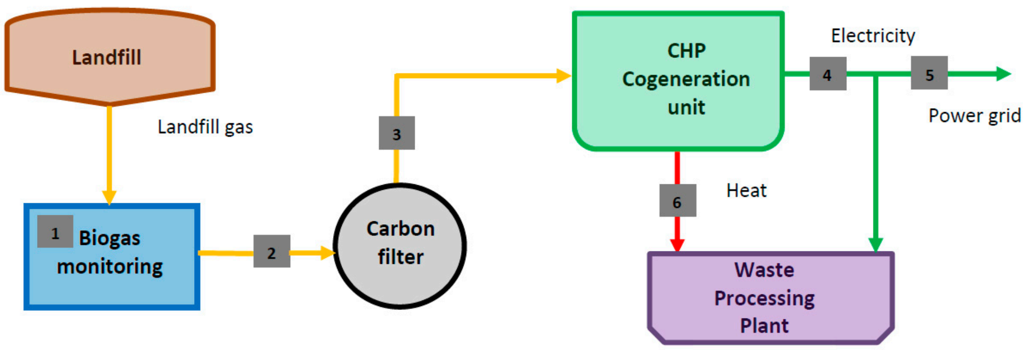

Figure 1. Installation of biogas energy utilization at the landfill.

Landfill gas is extracted from the waste bed using a gas squeegee installed at the biogas extraction station and is then subject to regulation by a maintenance worker with manual valves using rotameters and measurement at point (1). Subsequently, the gas undergoes primary treatment with a particulate filter, is metered using a gas flow meter and is subject to quality measurements at point (2). Secondary purification of biogas is carried out in an activated carbon filter in which reduction takes place, among other things, of sulfur compounds, and measurement of biogas quality parameters is carried out at measuring point (3). The purified biogas is thus directed as gaseous fuel to a reciprocating engine that drives an electric generator.

Electricity produced at the generator is metered with a gross energy meter (4) at the generator terminals and is primarily used for the facility's own needs, while excess electricity is sent to the external power grid and metered with a two-way electricity meter (5). Heat recovered from the cooling of the engine block and from the exhaust gas heat exchanger is recovered in the main heat exchanger in the form of hot water. The heat is used for social purposes and technological processes and is metered with a heat meter (6).

3. Materials and Methods

3.1. Landfill Gas

In this work, three measurement campaigns of basic LFG parameters were carried out, each containing 6 measurement series of 7 measurements each, at 5-day intervals. Measurement campaign No. 1 concerned measurements of raw gas extracted directly from the degassing plant (measurement point 1). In the other two measurement campaigns, the quality of LFG before and after purification was analyzed, in such a way that campaign No. 2 included measurements of untreated gas measured at the measurement port before the carbon filter (measurement point 2) and campaign No. 3 concerned measurements of purified gas after the carbon filter (measurement point 3), according to Figure 1. The following LFG parameters were analyzed: methane, carbon dioxide, oxygen and hydrogen sulfide. Measurements of biogas quality parameters were made using a portable biogas analyzer, allowing qualitative analysis of the gas mixture. The measurements were performed based on the "Methodology for performing landfill gas composition measurements for control and monitoring of landfill degassing installations" in effect at the plant. The methodology in question includes the procedure for measuring the composition of landfill gas and includes identifying persons authorized to perform measurements, checking the technical condition of the analyzer, calibrating it using calibration gases, identifying measurement points, principles of measurement, including quantity and time, the way and place of recording the results, their archiving and the ways of making research findings available. The analyzer has an ATEX II, a current quality certificate, and was properly calibrated in accordance with the applicable procedure. Since the quality of landfill gas is crucial for the proper operation of the cogeneration unit, cyclic monitoring of its quality is required, especially for hydrogen sulfide content, which due to its aggressive properties can cause operational problems mainly for the gas engine.

3.2. Activated Carbon

In this study, tests were also performed on "fresh" activated carbon before it was backfilled into the carbon filter. Tests on the collected sample of activated carbon were performed in the laboratory using a scanning electron microscope (SEM) with an Energy Dispersive Spectroscopy (EDS) system to analyze the surface and determine its elemental composition. To statistically process the results of the study, Statistica software version 14.1.0.4, as used, within which a cluster analysis was performed in the form of a hierarchical tree. The weighted center of gravity (median) method was used as the agglomeration method, which is the average point in the multidimensional space defined by these dimensions. In this method, the distance between two clusters is defined as the difference between the centers of gravity, and weighting is introduced in the calculation to account for differences between the sizes of the clusters (i.e., the number of objects contained in them). To determine the measure of distance between objects in the agglomeration method, the 1-r Pearson method was used in the formation of clusters. In addition, in order to analyze the interrelationships between the various parameters of hydrogen sulfide and the effectiveness of its reduction, 3D surface plots were used for three values of the variables X, Y and Z [46].

4. Results and Discussion

4.1. Landfill Gas Research

In the case of operating a distributed renewable energy source such as landfill gas as a fuel for cogeneration in a cogeneration unit, a key issue is the quality of the gas. Therefore, in the first measurement campaign, the results of measurements of untreated (raw) gas, representing a total of 42 measurements taken as part of six series of seven measurements every 5 days, were analyzed. Table 1 shows the basic parameters of the "raw" untreated gas obtained directly from the landfill as averages of the six-measurement series.

Table 1. Basic parameters of untreated landfill gas.

Test Series Number	Parameters of Untreated Landfill Gas				
	CH_4 [%]	CO_2 [%]	O_2 [%]	H_2S [%]	H_2S [ppm]
Series 1	57.3	30.4	0.6	0.62	618.6
Series 2	59.6	31.1	0.5	0.67	667.1
Series 3	55.7	30.1	0.5	0.62	615.7
Series 4	59.3	30.9	0.4	0.53	531.4
Series 5	58.7	34.0	0.1	0.58	577.9
Series 6	57.6	33.7	0.4	0.55	552.0
Average	58.2	31.7	0.4	0.59	593.8

Performed at the landfill gas energy utilization facility, measurements of basic gas parameters during the first measurement campaign showed a high methane content averaging 58.2 [%] as the main fuel for the gas engine, which is a good prognosis for this gas fuel. Figure 2 shows the interrelationship of methane and hydrogen sulfide as a result of the first measurement campaign and analysis.

Figure 2. Methane and hydrogen sulfide parameters for "raw" untreated gas.

The high hydrogen sulfide content, averaging 593.8 [ppm], disqualifies LFG as a fuel for the gas engine powering the cogeneration unit. This raises the need to treat the landfill gas to reduce the hydrogen sulfide content to a maximum of 100 [ppm], as recommended by the equipment supplier. Therefore, it was decided to apply dry landfill gas treatment technology in the form of a filtration device using activated carbon. The proposed filter material is molded impregnated activated carbon with enhanced adsorption properties for hydrogen sulfide. The carbon is produced by steam activation from selected grades of anthracite to ensure consistent quality and a high degree of hardness and is then impregnated with chemicals to achieve optimal chemisorption properties.

The efficiency of removal of siloxanes in biogas using an activated carbon filter was carried out by [47,48], comparing the efficiency with the gas engine manufacturer's data. The results of the obtained tests showed more than 98% removal efficiency of organic sulfur compounds and thus the lowest level of hydrogen sulfide at the biogas outlet. Activated carbon also showed high removal efficiency of silicon compounds including siloxanes at 95%. The high efficiency of the process of reducing sulfur compounds and siloxanes contained in biogas, using activated carbon, was confirmed in their study [49,50], performing tests on 12 different types of activated carbon. The results showed that the reduction in carbon adsorption capacity in biogas purification is affected by the level of relative humidity, as well as the percentage of methane in the LFG. Industry consultation and a literature analysis confirmed the high efficiency of hydrogen sulfide removal from the gas, which is a good recommendation for this solution.

4.2. Research on Activated Carbon

In order to check the surface and grain condition of the "fresh" activated carbon, tests were performed using a scanning electron microscope with an EDS system in order to have comparative material in the future. Figure 3 shows the state of the surface and grains of the new activated carbon at magnifications of 100, 500, 1000 and 2000 times.

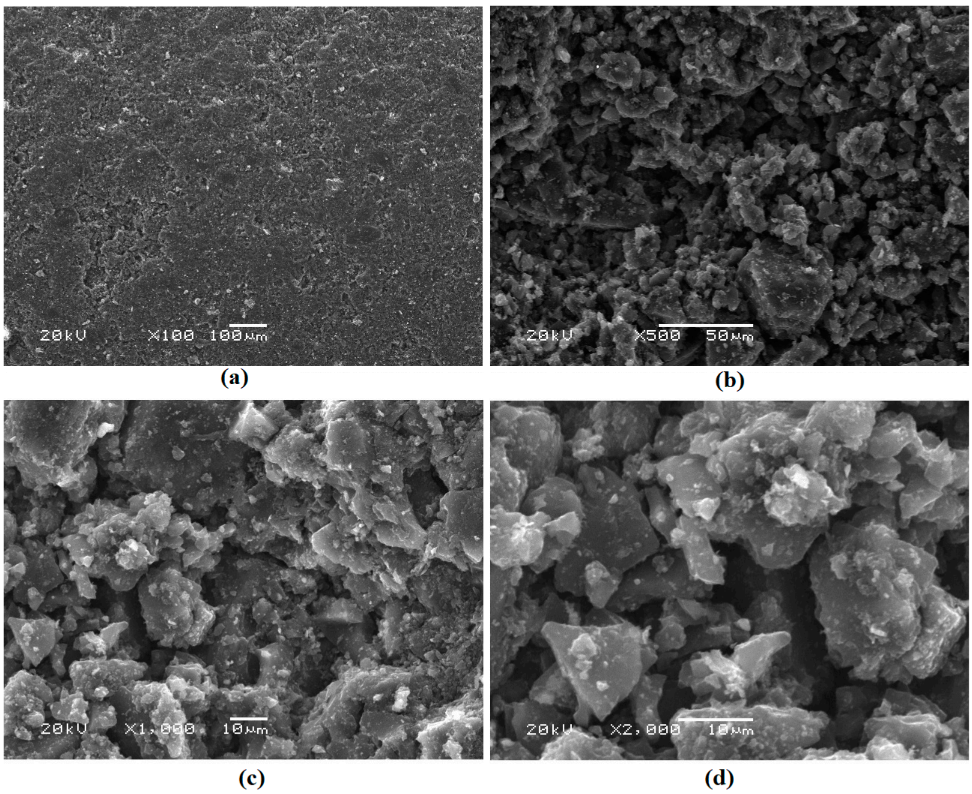

Figure 3. Images of the surface state of the new activated carbon under appropriate magnification: (**a**) 100; (**b**) 500; (**c**) 1000; (**d**) 2000 times.

The test results revealed the high quality of the adsorption material, which is the proposed activated carbon. The coal used does not contain dust impurities that often occur in low-quality coal, which adversely affects the gas purification process.

In order to check the elemental composition of the "fresh" activated carbon, with a perspective of further studies of the adsorption rate of sulfur compounds planned in the future, tests and elemental balances were carried out using a scanning electron microscope with an EDS system. Figure 4 shows the surface condition of the washed activated carbon sample for a magnification of 500 times, along with the chemical composition for the three points analyzed.

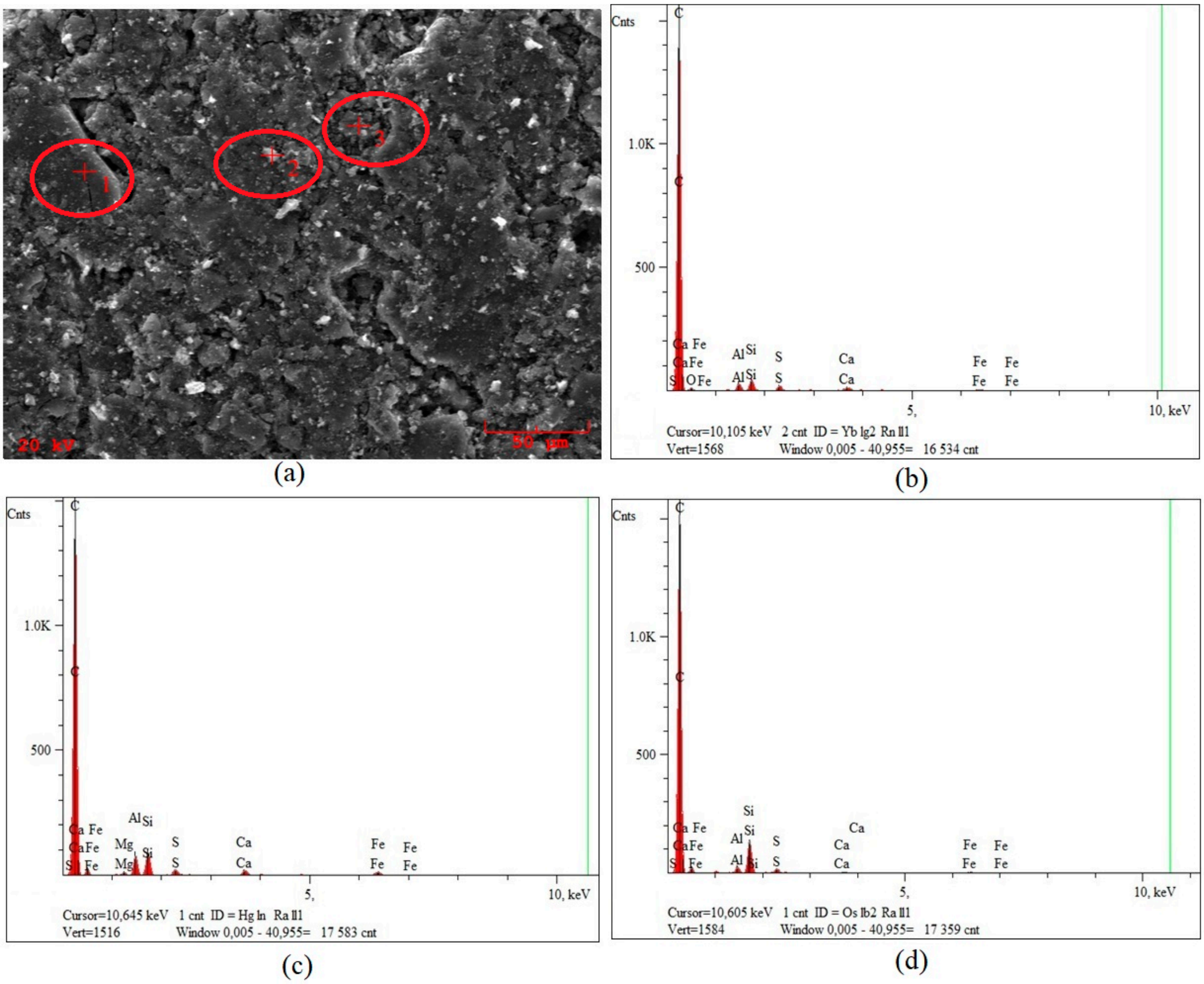

Figure 4. Scanning analysis of activated carbon: (**a**) SEM microscopic image; (**b**–**d**) chemical composition of points 1, 2, 3.

The test results showed that activated carbon as a porous material has been used for many years in the purification of propellant and waste gases. The activated carbon used is characterized by optimal physicochemical properties. It has a very large specific surface area and a large pore volume. From the point of view of the processes occurring at the solid–gas interface, the surface area available to the gas molecules, it includes both its outer surface and the inner surface active in the adsorption process.

The elemental composition shown during the test shows the highest carbon content as the main medium where excess substances accumulate. The size of the adsorber's specific surface favors the accumulation of particles due to the action of physical and chemical forces. Figure 5 shows the percentage elemental composition of activated carbon at the three points analyzed.

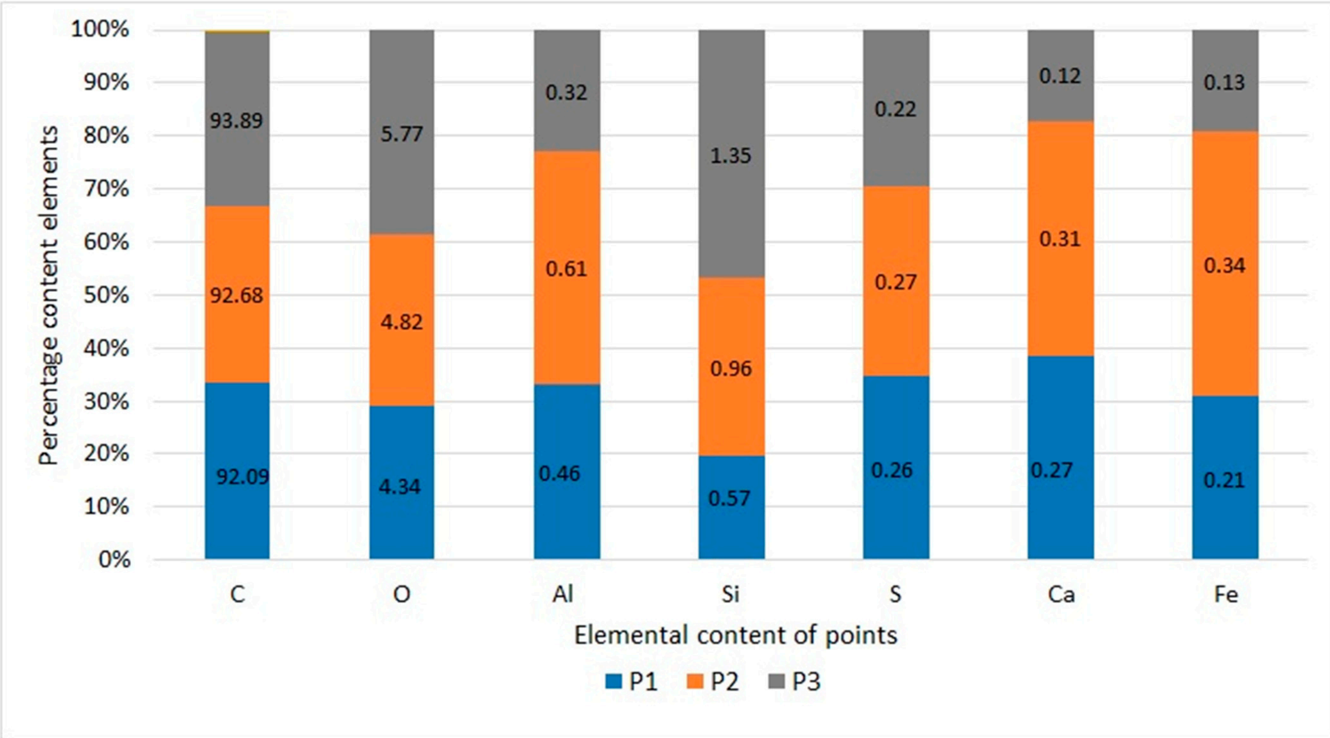

Figure 5. Percentage elemental composition of activated carbon.

Analysis of the composition of the activated carbon sample showed an average elemental content of carbon of 92.89%, while the other elements accounted for 7.11% including an average content of sulfur of 0.25% and silicon of 0.96%. The research confirmed the correct elemental composition of activated carbon, which was used in the landfill gas treatment installation. Figure 6 presents the results of the analysis in the form of a dendrogram, or binary tree, for the elemental balance of activated carbon used in the landfill gas treatment plant.

Analysis of the results of the study revealed that the objects form clusters resulting in four main groupings (concentrations). The first contains calcium and sulfur, the second includes clusters of aluminum and iron, the third includes oxygen and silicon content, while the fourth involves carbon content. The smallest bond distance occurs at the level of the first cluster for the agglomeration distance ($x = 1.0$; $y = 6.49$), while within the second cluster, it is the distance ($x = 2.0$; $y = 4.50$) between aluminum and iron. The third cluster has parameters ($x = 3.0$; $y = 1.52$), while the largest distance is in the fourth cluster for carbon of ($x = 5.0$; $y = 4.25$). All clusters are connected by a bond with parameters ($x = 6.0$; $y = 2.62$). This state of bonds within the dendrogram indicates the highest content and carbon in the samples and the lowest contents of sulfur, calcium and silicon, which proves the very good adsorption parameters of activated carbon used in the landfill gas treatment plant.

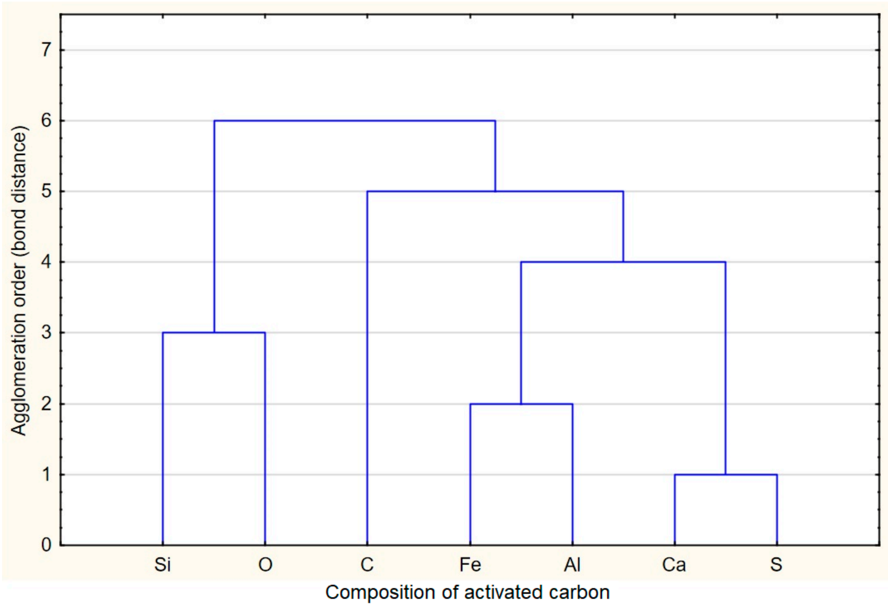

Figure 6. Dendrogram of bond distances for individual activated carbon elements.

The measurement campaigns No. 2 and No. 3, performed in the study, had as their main objective to check the effectiveness (efficiency) of hydrogen sulfide removal from LFG by the activated carbon bed in order to reduce the value of hydrogen sulfide to the permissible value specified by the equipment supplier to 100 ppm. Table 2 shows the results of measurements of LFG parameters before entering the gas purification device and after the gas purification process before feeding into the gas engine.

Table 2. Gas quality gas parameters before and after treatment.

Test Series Number	LFG Parameters before the Carbon Filter				LFG Parameters after the Carbon Filter			
	CH_4 [%]	CO_2 [%]	O_2 [%]	H_2S [ppm]	CH_4 [%]	CO_2 [%]	O_2 [%]	H_2S [ppm]
Series 1	58.4	34.1	0.4	577.0	58.8	33.8	0.3	17.7
Series 2	58.6	33.3	0.3	541.6	57.9	32.5	0.3	16.0
Series 3	59.9	32.7	0.3	556.4	59.1	32.1	0.4	16.0
Series 4	59.6	33.6	0.3	558.7	58.8	32.9	0.3	16.4
Series 5	57.7	35.3	0.1	595.6	58.1	35.8	0.2	17.3
Series 6	56.1	32.7	0.2	567.6	57.2	33.1	0.2	17.3
Average	58.4	33.6	0.3	566.1	58.3	33.4	0.3	16.8

After the landfill gas treatment process, its basic parameters, such as methane, carbon dioxide and oxygen, underwent little change, confirming the proper operation of the filtration unit and its tightness. On the other hand, the hydrogen sulfide content of the LFG was significantly reduced, confirming the proper response of the activated carbon in contact with sulfur compounds. The average hydrogen sulfide content in the treated gas was 16.8 ppm, while the average content of the treated gas was 566.1 ppm. Figure 7 shows the reciprocal relationship of methane and hydrogen sulfide for the purified gas, which is the result of the third measurement campaign and the analyses performed.

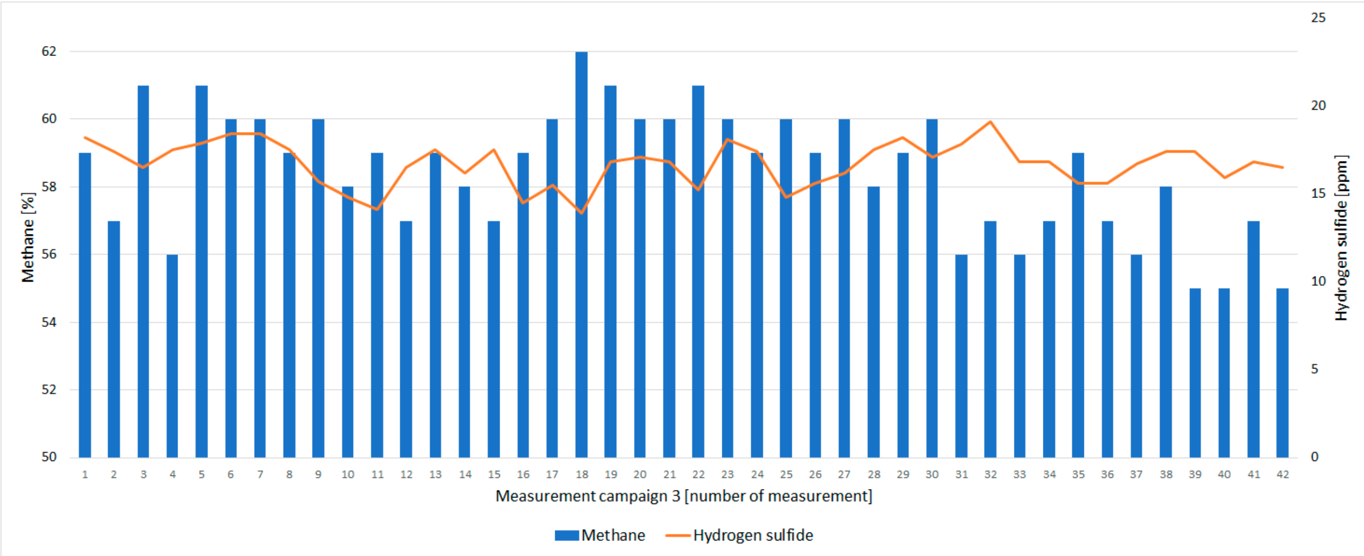

Figure 7. Methane and hydrogen sulfide parameters for treated gas.

4.3. Hydrogen Sulfide Removal Efficiency

In order to determine the degree of reduction in the parameter (hydrogen sulfide removal efficiency) by activated carbon from LFG, calculations were made using expression (1) for six measurement series in campaigns No. 1 and No. 2.

$$\eta_{HS} = \frac{HS_u - HS_p}{HS_u} \cdot 100\% \quad (1)$$

where

η_{HS}—effectiveness of hydrogen sulfide reduction (%),

HS_p—value of the parameter in treated biogas (ppm),

HS_u—value of the parameter in untreated biogas (ppm).

The resulting values are summarized in Table 3 and represent average values for each measurement series.

Table 3. Hydrogen sulfide values and efficiency of its removal.

Number Series Badań	Hydrogen Sulfide Content in Untreated Gas HS_u [ppm]	Hydrogen Sulfide Content in Treated Gas HS_p [ppm]	Efficiency of Hydrogen Sulfide Removal η_{HS} [%]
Series 1	577.0	17.7	96.92
Series 2	541.6	16.0	97.03
Series 3	556.4	16.0	97.12
Series 4	558.7	16.4	97.07
Series 5	595.6	17.3	97.08
Series 6	567.6	17.3	97.07
Average	566.1	16.8	97.05

Calculations based on the results of the second and third measurement campaigns showed an average hydrogen sulfide removal efficiency of 97.05%, which confirms the practical effectiveness of using activated carbon in a landfill gas treatment plant. In order to maintain high hydrogen sulfide removal efficiency, the parameters of landfill gas should be monitored on an ongoing basis, including, in particular, its relative humidity and temperature. The average annual stream of landfill gas feeding the cogeneration installation that was the object of the research was 150.35 m^3 per hour. The pressure of gas injected into the engine was on average 125 mbar per year. The above parameters affect the efficiency of hydrogen sulfide removal. This mainly concerns the gas stream that flows through the purification device, which determines the capacity of the activated carbon charge and the efficiency of hydrogen sulfide adsorption.

The effect of relative humidity on the adsorption process of activated carbon, used to remove hydrogen sulfide compounds contained in biogas, was analyzed in their work [51,52]. The results showed that an increase in relative humidity in the range of 60 to 80% causes the adsorption capacity of activated carbon to begin to decrease, which is due to the interference of water directly into the pores of activated carbon. The second parameter affecting the removal rate of contaminants in biogas is temperature. When the operating temperature of the gas treatment plant increases, the adsorption capacity of the bed shows a decreasing trend. The optimal adsorption capacity of the bed was obtained in the temperature range from +5 °C to +20 °C [53,54]. Measurements of the relative humidity and temperature of the biogas are provided by the LFG monitoring system as part of the plant's operation at the landfill. The average annual relative humidity of the gas was 50.7%, while the average annual gas temperature was 12.7 °C. The humidity parameters testify to the efficient operation of the landfill's leachate removal system, which excludes flooding of degassing wells and dehydrators in the waste bed. On the other hand, the gas temperature is directly related to the temperature prevailing in the waste bed where biogas is produced [55,56]. The maintenance of optimal gas temperatures is due to the high compression (compaction) of the waste by the machine (compactor) used to evenly spread and compact the waste on the surface of the landfill. Figure 8 shows the reciprocal correlation between hydrogen sulfide removal efficiency and hydrogen sulfide content resulting from the second and third measurement campaigns.

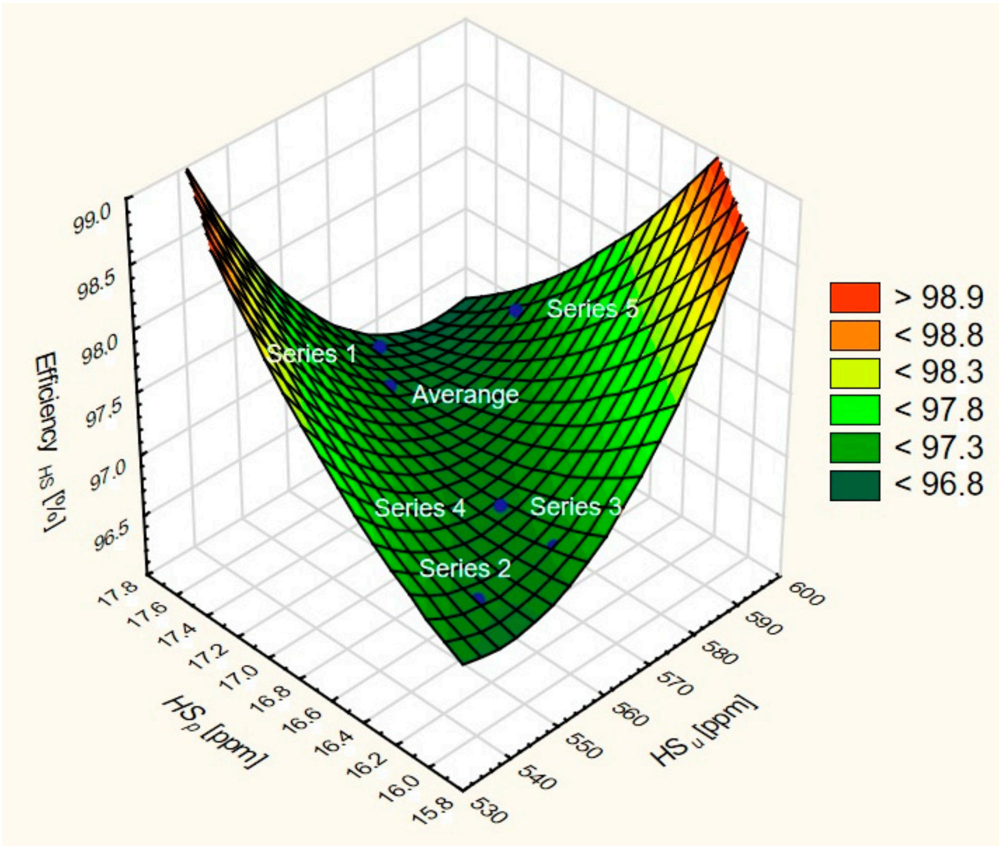

Figure 8. Efficiency of hydrogen sulfide removal depending on its content.

Measurements of hydrogen sulfide content in landfill gas and calculations of its reduction efficiency presented in this paper demonstrated that LFG can be reported in a cogeneration installation as a gaseous fuel for eclectic power and heat generation. The permissible values of hydrogen sulfide specified by gas engine manufacturers in the technical documentation by the manufacturer meet the relevant requirements and lie well below 100 ppm, amounting to 16.6 ppm. Such a condition ensures proper and reliable operation of the cogeneration unit and confirms the correctness of the decision to choose activated carbon as a material for reducing the hydrogen sulfide content in landfill gas intended for energy use.

In quantitative terms, representing reductions in hydrogen sulfide with the use of activated carbon in the LFG treatment plant, the values obtained directly correlate with the European Green Deal requirements for the reduction in particulate and gaseous pollutants to ambient air. The results of the measurement series for hydrogen sulfide expressed in mg per cubic meter, along with the reduction value, are shown in Figure 9.

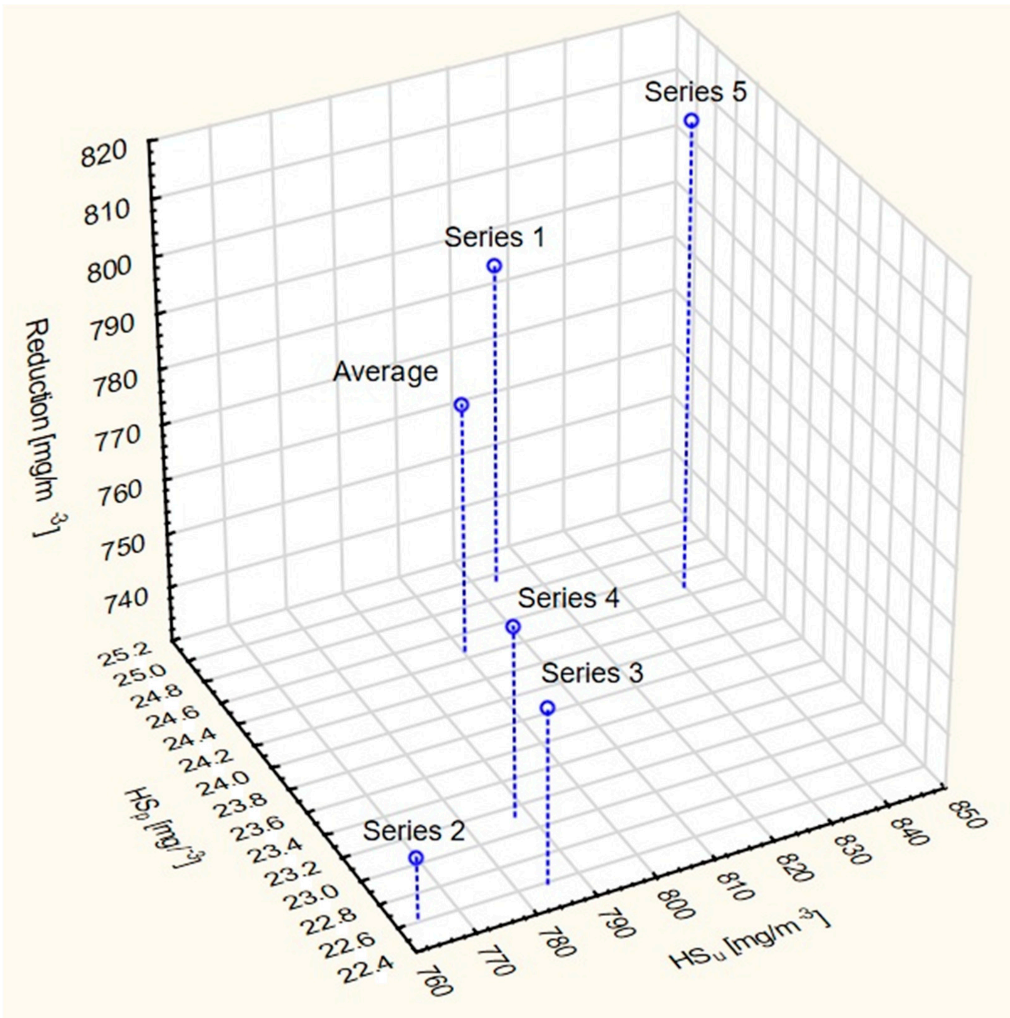

Figure 9. Quantitative reduction in hydrogen sulfide.

Conversions from ppm to mg were performed for a cubic meter of LFG for hydrogen sulfide, which allowed calculating the average annual reduction in hydrogen sulfide in the case of gas treatment using activated carbon, with an average reduction efficiency of 97.05%. Assuming the actual conditions for LFG, it was calculated that the annual reduction in H_2S in activated carbon during the energetic use of gas in the amount of 1.2 million $m^3 \cdot year^{-1}$ would be 929.48 kg on an annual basis. Taking into account the gradual decrease in the efficiency of hydrogen sulfide reduction over the year, it is reasonable to assume that the target reduction may oscillate around 650 kg. Adsorption of hydrogen sulfide in activated carbon results in the reduction in sulfur oxides into the air in the fuel gas, which, in a situation where landfill CHP plants are not equipped to reduce these compounds, activated carbon plays a dual role in this process. Firstly, it provides a high-quality fuel for the CHP unit, and secondly, it reduces organized emissions resulting from the combustion of landfill gas in a gas engine as an energy source.

The use of landfill gas as biofuel in cogeneration units producing electricity and heat requires a detailed analysis in terms of quantitative and qualitative parameters, including the selection of the optimal treatment technology. This form of obtaining and managing biogas contributes to the use of a source of renewable energy, diversification of energy carriers and reduction in gas and dust emissions into the air resulting from the combustion of LFG.

5. Conclusions

The EU directive on the use of renewable energy, including biogas, sets a target for the EU of 32% of energy from renewable sources by 2030. These assumptions are in line with the European Green Deal, which defines sustainability criteria for the energy transition. The capture and use of biogas produced in a landfill whose main component is methane, for energy purposes, is a dedicated way to reduce its negative impact on the environment. Considered in two aspects: energetically, it represents the optimal use of a renewable fuel for energy generation, and environmentally, it represents the abandoned emission of the greenhouse gas methane into the environment. A key aspect in this process is the preparation of biofuel of sufficient quality to power a gas engine operating in a cogeneration unit. The high content of hydrogen sulfide in the tested landfill gas, amounting to an average of 593.8 [ppm], disqualifies LFG as a fuel for the gas engine powering the cogeneration unit. Therefore, the installation operator is forced to purify the biogas in order to reduce the hydrogen sulfide content to a maximum of 100 [ppm], recommended by the equipment supplier. The molded and at the same time impregnated activated carbon used in the biogas purification plant has enhanced adsorption properties for hydrogen sulfide and acidic compounds, as confirmed by tests conducted in this paper. The test results of the activated carbon used showed a high carbon content in the tested sample of 92.78%, while the efficiency of removing hydrogen sulfide from landfill gas by activated carbon, calculated on the basis of measurements, was 97.05%. In order to properly operate landfill gas treatment plants, systematic quality control of activated carbon in the treatment plant is required to ascertain its adsorption capacity. The research results are dedicated to operators of cogeneration installations in order to systematically test the quality of landfill gas and the efficiency of biogas purification devices, which constitute the basis for the reliable operation of gas engines in cogeneration installations and are dedicated mainly to the operators of these installations. Currently, renewable gaseous fuels, such as biogas, biomethane and bio-hydrogen, being a "green" source of energy, in the near future will play an increasingly important role in the energy sectors of individual countries oriented to the so-called bio-economy, reducing the negative impact of energy processes on the environment.

Author Contributions: Conceptualization, J.C. and A.G.; methodology, J.C., A.G.-C. and A.G.; software, P.K. and M.C.; validation, I.W., A.G. and A.G.-C.; formal analysis, M.C., A.G. and J.C.; investigation, J.C., A.G. and I.W.; resources, J.C. and A.G.-C.; data curation, J.C., A.G. and P.K. writing—original draft preparation, J.C. and A.G.; writing—review and editing, J.C. and I.W.; visualization, P.K., A.G. and A.G.-C.; supervision, A.G.; project administration, A.G.-C., J.C. and M.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data is contained within the article.

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

References

1. EC—European Commission. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. 11.12.2019 COM (2019) 640 Final. In *The European Green Deal*; EC: Brussels, Belgium, 2019.
2. Tutak, M.; Brodny, J.; Bindzár, P. Assessing the Level of Energy and Climate Sustainability in the European Union Countries in the Context of the European Green Deal Strategy and Agenda 2030. *Energies* **2021**, *14*, 1767. [CrossRef]
3. Graz, K.; Gronba-Chyla, A.; Chyla, K. Microplastics found in compost as a barrier to the circular economy (CE). *Przemysł Chem.* **2023**, *102*, 381–383. [CrossRef]
4. Generowicz, A.; Gronba-Chyła, A.; Kulczycka, J.; Harazin, P.; Gaska, K.; Ciuła, J.; Ocłoń, P. Life Cycle Assessment for the environmental impact assessment of a city' cleaning system. The case of Cracow (Poland). *J. Clean. Prod.* **2023**, *382*, 135184. [CrossRef]
5. Ravani, M.; Georgiou, K.; Tselempi, S.; Monokrousos, N.; Ntinas, G.K. Carbon Footprint of Greenhouse Production in EU—How Close Are We to Green Deal Goals? *Sustainability* **2024**, *16*, 191. [CrossRef]
6. Przydatek, G.; Basta, E. Systemic Efficiency Assessment of Municipal Solid Waste Management in the Suburban Municipality. *E3S Web Conf.* **2020**, *154*, 03001. [CrossRef]
7. Directive (EU) 2018/850 of the European Parliament and of the Council of 30 May 2018 Amending Directive 1999/31/EC on the Landfill of Waste. 2018. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32018L0850 (accessed on 10 November 2023).
8. Husgafvel, R. Company Perspectives on Circular Economy Management, Assessment and Reporting in the Kymenlaakso Region in Finland. *Sustainability* **2024**, *16*, 20. [CrossRef]
9. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain Directives, L 312/3. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0098 (accessed on 14 November 2023).
10. Vakalis, S.; Moustakas, K. Applications of the 3T Method and the R1 Formula as Efficiency Assessment Tools for Comparing Waste-to-Energy and Landfilling. *Energies* **2019**, *12*, 1066. [CrossRef]
11. Wysowska, E.; Kicińska, A. Assessment of health risks with water consumption in terms of content of selected organic xenobiotics. *Desalination Water Treat.* **2021**, *234*, 1–14. [CrossRef]
12. Wysowska, E.; Wiewiórska, I.; Kicińska, A. Minerals in tap water and bottled waters and their impact on human health. *Desalination Water Treat.* **2022**, *259*, 133–151. [CrossRef]
13. Makara, A.; Kowalski, Z.; Radomski, P.; Olczak, P. Treatment of wastewater from the production of meat and bone meal by the Fenton process and coagulation. *Pol. J. Chem. Technol.* **2022**, *24*, 51–60. [CrossRef]
14. Shitophyta, L.M.; Padya, S.A.; Zufar, A.F.; Rahmawati, N. The Impact of Alkali Pretreatment and Organic Solvent Pretreatment on Biogas Production from Anaerobic Digestion of Food Waste. *J. Ecol. Eng.* **2022**, *23*, 179–188. [CrossRef]
15. Barzegaravval, H.; Hosseini, S.E.; Wahid, M.A.; Saat, A. Effects of fuel composition on the economic performance of biogas-based power generation systems. *Appl. Therm. Eng.* **2018**, *128*, 1543–1554. [CrossRef]
16. Hwang, H.; Kweon, T.; Kang, H.; Hwang, Y. Resource and Greenhouse Gas Reduction Effects through Recycling of Platinum-Containing Waste. *Sustainability* **2024**, *16*, 80. [CrossRef]
17. Adamcová, D.; Vaverková, M.; Břoušková, E. Emission assessment at the Štěpánovice municipal solid waste landfill focusing on CH_4 emissions. *J. Ecol. Eng.* **2016**, *17*, 9–17. [CrossRef]
18. Labianca, M.; Faccilongo, N.; Monarca, U.; Lombardi, M. A Location Model for the Agro-Biomethane Plants in Supporting the REPowerEU Energy Policy Program. *Sustainability* **2024**, *16*, 215. [CrossRef]
19. Ciuła, J.; Kowalski, S.; Generowicz, A.; Barbusiński, K.; Matuszak, Z.; Gaska, K. Analysis of Energy Generation Efficiency and Reliability of a Cogeneration Unit Powered by Biogas. *Energies* **2023**, *16*, 2180. [CrossRef]
20. Tsompanoglou, K.; Koutsou, O.P.; Stasinakis, A.S. Evaluating the Operation of a Full-Scale Sequencing Batch Reactor–Reverse Os-mosis–Evaporation System Used to Treat Landfill Leachates: Removal of Pollutants, Energy Consumption and Greenhouse Gas Emissions. *Energies* **2023**, *16*, 6872. [CrossRef]
21. Díaz, I.; Ramos, I.; Fdz-Polanco, M. Economic analysis of microaerobic removal of H_2S from biogas in full-scale sludge digesters. *Bioresour. Technol.* **2015**, *192*, 280–286. [CrossRef] [PubMed]
22. Kowalski, Z.; Kulczycka, J.; Verhé, R.; Desender, L.; De Clercq, G.; Makara, A.; Generowicz, N.; Harazin, P. Second-generation biofuel production from the organic fraction of municipal solid waste. *Front. Energy Res.* **2022**, *10*, 919415. [CrossRef]
23. Zhang, D.; Zhang, R.; Zheng, Y.; Zhang, B.; Jiang, Y.; An, Z.; Bai, J. Carbon emission reduction analysis of CHP system driven by biogas based on emission factors. *Energy Build. Environ.* **2022**, *9*, 576–588. [CrossRef]
24. Un, C. A Sustainable Approach to the Conversion of Waste into Energy: Landfill Gas-to-Fuel Technology. *Sustainability* **2023**, *15*, 14782. [CrossRef]
25. Dyachok, V.; Venhe, L.; Huhlych, S. The Biomethanization Gas Purification of Using Chlorophyll-Synthesizing Microalgae. *J. Ecol. Eng.* **2022**, *23*, 259–264. [CrossRef]

26. Nocete, E.S.; Rodríguez, J.P. A Simple Methodology for Estimating the Potential Biomethane Production in a Region: Application in a Case Study. *Sustainability* **2022**, *14*, 15978. [CrossRef]
27. Amaraibi, R.J.; Joseph, B.; Kuhn, J. Techno-economic and sustainability analysis of siloxane removal from landfill gas used for electricity generation. *J. Environ. Manag.* **2022**, *314*, 115070. [CrossRef] [PubMed]
28. Ciuła, J.; Kowalski, S.; Wiewiórska, I. Pollution Indicator of a Megawatt Hour Produced in Cogeneration—The Efficiency of Biogas Purification Process as an Energy Source for Wastewater Treatment Plants. *J. Ecol. Eng.* **2023**, *24*, 232–245. [CrossRef] [PubMed]
29. Salah, W.A.; Atatri, M.; Zaid, A.; Abuhafeza, R.; Abuhelwa, M.; Bashir, M.J.K.; Abu Zneid, B. Analysis of Energy Recovery from Municipal Solid Waste and Its Environmental and Economic Impact in Tulkarm, Palestine. *Energies* **2023**, *16*, 5590. [CrossRef]
30. Marcoberardino, G.D.; Vitali, D.; Spinelli, F.; Binotti, M.; Manzolini, G. Green Hydrogen Production from Raw Biogas: A Techno-Economic Investigation of Conventional Processes Using Pressure Swing Adsorption Unit. *Processes* **2018**, *6*, 19. [CrossRef]
31. Xu, J.; Tian, O.; Li, Y. Toward the truth of condensing-water membrane for efficient biogas purification: Experimental and modeling analyses. *J. Membr. Sci.* **2022**, *662*, 120967. [CrossRef]
32. Liu, D.; Sun, W.; Kong, Y.; Zhang, S. Effect of Dry and Wet Cycles on the Strength Characteristics of Biochar–Clay Mixture. *Processes* **2023**, *11*, 970. [CrossRef]
33. Dimitriu, M. Considerations Over a Biogas Plant Components. *Sci. Pap. Ser. Manag. Econ. Eng. Agric. Rural. Dev.* **2014**, *14*, 121–126. Available online: http://managementjournal.usamv.ro/pdf/vol4_1/Art19.pdf (accessed on 12 December 2023).
34. Batista, M.; Pinto, M.L.; Antunes, F.; Pires, J.; Carvalho, S. Chitosan Biocomposites for the Adsorption and Release of H_2S. *Materials* **2021**, *14*, 6701. [CrossRef] [PubMed]
35. Lee, U.; Han, J.; Wang, M. Evaluation of landfill gas emissions from municipal solid waste landfills for the life-cycle analysis of waste-to-energy pathways. *J. Clean. Prod.* **2017**, *166*, 335–342. [CrossRef]
36. González, R.; Cabeza, I.O.; Casallas-Ojeda, M.; Gómez, X. Biological Hydrogen Methanation with Carbon Dioxide Utilization: Methanation Acting as Mediator in the Hydrogen Economy. *Environments* **2023**, *10*, 82. [CrossRef]
37. Swain, R.B.; Karimu, A.; Gråd, E. Sustainable development, renewable energy transformation and employment impact in the EU. *Int. J. Sustain. Dev. Word Ecol.* **2022**, *29*, 695–708. [CrossRef]
38. Achinas, S.; Euverink, G.J.W. Effect of Temperature and Organic Load on the Performance of Anaerobic Bioreactors Treating Grasses. *Environments* **2020**, *7*, 82. [CrossRef]
39. Kwon, Y.; Lee, S.; Bae, J.; Park, S.; Moon, H.; Lee, T.; Kim, K.; Kang, J.; Jeon, T. Evaluation of Incinerator Performance and Policy Framework for Effective Waste Management and Energy Recovery: A Case Study of South Korea. *Sustainability* **2024**, *16*, 448. [CrossRef]
40. Kowalski, S.; Opoka, K.; Ciuła, J. Analysis of the end-of-life the front suspension beam of a vehicle. *Eksploat. I Niezawodn.-Maint. Reliab.* **2022**, *24*, 446–454. [CrossRef]
41. Kwaśnicki, P.; Jarzebski, M.; Kardasz, P.; Inglotf, M. Characterization techniques of sandwich-type TiO2/QD composites for low-cost quantum dots' solar cel. *Opto-Electron. Rev.* **2019**, *27*, 105–112. [CrossRef]
42. Sikora, A. European Green Deal—Legal and financial challenges of the climate change. *ERA Forum* **2021**, *21*, 681–697. [CrossRef]
43. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the Promotion of the Use of Energy from Renewable Source 2018. Available online: https://eur-lex.europa.eu (accessed on 8 December 2023).
44. Augustowski, D.; Kwaśnicki, P.; Dziedzic, J.; Rysz, J. Magnetron Sputtered Electron Blocking Layer as an Efficient Method to Improve Dye-Sensitized Solar Cell Performance. *Energies* **2020**, *13*, 2690. [CrossRef]
45. Skjærseth, J.B. Towards a European Green Deal: The evolution of EU climate and energy policy mixes. *Int. Environ. Agreem.* **2021**, *21*, 25–41. [CrossRef]
46. *Statistica*, version 14.1.0.4; TIBCOI Software Inc.: Palo Alto, CA, USA, 2023.
47. Kajolinna, T.; Aakko-Saksa, P.; Roine, J.; Kåll, L. Efficiency testing of three biogas siloxane removal systems in the presence of D5, D6, limonene and toluene. *Fuel Process. Technol.* **2015**, *138*, 242–247. [CrossRef]
48. Coppola, G.; Papurello, D. Biogas Cleaning: Activated Carbon Regeneration for H_2S Removal. *Clean. Technol.* **2019**, *1*, 40–57. [CrossRef]
49. Cabrera-Codony, A.; Montes-Morán, M.A.; Sánchez-Polo, M.; Martín, M.J.; Gonzalez-Olmos, R. Biogas Upgrading: Optimal Activated Carbon Properties for Siloxane Removal. *Environ. Sci. Technol.* **2014**, *48*, 7187–7195. [CrossRef] [PubMed]
50. Ledesma, B.; Sabio, E.; González-García, C.M.; Román, S.; Fernandez, M.E.; Bonelli, P.; Cukierman, A.L. Batch and Continuous Column Adsorption of p-Nitrophenol onto Activated Carbons with Different Particle Sizes. *Processes* **2023**, *11*, 2045. [CrossRef]
51. Papurello, D.; Tomasi, L.; Silvestri, S.; Santarelli, M. Evaluation of the Wheeler-Jonas parameters for biogas trace compounds removal with activated carbons. *Fuel Process. Technol.* **2016**, *152*, 93–101. [CrossRef]
52. Yao, Z.; Zhang, W.; Yu, X. Fabricating Porous Carbon Materials by One-Step Hydrothermal Carbonization of Glucose. *Processes* **2023**, *11*, 1923. [CrossRef]
53. Cinar, S.; Cinar, S.O.; Wieczorek, N.; Sohoo, I.; Kuchta, K. Integration of Artificial Intelligence into Biogas Plant Operation. *Processes* **2021**, *9*, 85. [CrossRef]
54. Wang, P.; Lai, J.; Lin, X.; Li, X.; Xu, S. A Study on the Influence and Mechanism of Temperature and Dosage on PCDD/Fs Adsorption via Coal-Based Activated Carbon. *Recycling* **2023**, *8*, 98. [CrossRef]

55. Niu, J.; Zhang, H.; Xu, W.; Guo, Y.; Li, L.; Cheng, F. Utilization of inherent minerals in coal for high-performance activated carbon production: The mechanism of deSO_2 and/or deNOx enhanced by in situ transformed calcium sulfide (CaS). *Energy* **2024**, *289*, 129902. [CrossRef]
56. Liu, N.; Jiang, J. Effects of activated carbon on the in-situ control of odorous gases emitted from anaerobic digestion of food waste and the microbial community response. *Environ. Technol. Innov.* **2021**, *21*, 101170. [CrossRef]