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Environmental and operational aspects of energy production from landfill gas and waste in a cogeneration plant

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ABSTRACT

The generation of waste and its disposal in landfills results in the formation of landfill gas as a source of renewable energy. Its use for energy in cogeneration units is the optimal use of the chemical energy of this fuel. The aim of the study was to test the used coolant operated in a cogeneration plant (CHP) located at a landfill site and powered by landfill gas. The tests carried out in the study were aimed at verifying whether the used coolant from the heat recovery system of the cogeneration unit should be treated as safe waste and thus requiring special management. The tests showed how the parameters in the coolant change after its use and what potential problems they may cause in the operation of the plant. The research showed significant variability in parameters such as pH, alkaline reserve, coolant density, and freezing point. The research and its results indicate elevated levels of heavy metals for zinc (Zn) and copper (Cu), as well as high levels of sodium (Na), boron (B), and potassium (K). As a result, used coolant should be classified as hazardous waste and managed in accordance with the rules for the management of such waste. A review of the literature and the results of the authors' own research confirmed that a cogeneration (CHP) plant that generates energy is also a producer of hazardous waste.

Keywords: landfill gas, renewable energy, used coolant, hazardous waste.

INTRODUCTION

Waste generation has been an inherent feature of human economic activity throughout the centuries, while waste treatment is becoming a major problem in terms of fuel and energy consumption, negative environmental impact, and the selection of appropriate best technologies. It is therefore necessary to avoid causing damage to the natural environment and to minimize the negative impact on people (Bereziuk et al., 2024; Jurczyk et al., 2024). Waste generation necessitates waste disposal, particularly in order to reduce resource exploitation, monitor and control the space for the construction of disposal, treatment, and storage facilities for waste that has no fuel or recycling value (Abbas and Budiyono, 2020; Przydatek and Basta, 2019). Decisions made in municipal waste management that recommend waste management methods should cover all issues related to applicable legal acts in terms of the circular economy. The measures taken should take into account climate change mitigation, balance in the use of environmental resources in terms of its anthropogenic impact, and the use of potential renewable energy resources, including landfill gas (Delgado et al., 2023; Shoqeir and Mansour, 2025). Waste management principles in Poland are regulated by legal acts covering, among other things, municipal waste treatment technologies, types of processes, waste codes, and the parameters required to be achieved for a given type of waste, contained in the following legal acts. These include: the Waste Act (Act, 2013; Announcement of the Marshal of the Sejm, 2023), the Act on maintaining cleanliness and order in municipalities (Act, 1996; Announcement of the Marshal of the Sejm, 2025), the Regulation on the Waste Catalogue (Regulation of the Minister of Climate, 2020), and the Regulation on the Mechanical-Biological Treatment of Unsorted (Mixed) Municipal Waste (Regulation of the Minister of Climate and Environment, 2022).

The Environmental Protection Law, on the other hand, defines the principles and the conditions for the use of its resources, taking into account the requirements of sustainable development (Act Environmental Protection Law, 2001). Any waste that is not managed and has no specific purpose cannot be recycled. All waste becomes a potential raw material or resource once it is managed or designated for management. Therefore, any material obtained, processed, and transported by humans can be a resource and a useful product or waste with varying degrees of environmental impact (Jomit and Sajith, 2023; Czekała et al., 2023).

In Poland, there has been a clear shift in waste management from disposal to processing and recycling. This is confirmed by statistics showing an increase in selectively collected waste and a reduction in landfill. Between 2014 and 2024, the share of municipal waste destined for landfill in total waste generated decreased by almost half, from 58.3% in 2014 to 30.1% in 2024. At the end of 2024, there were 247 municipal waste landfills in operation. At the end of 2024, 93.9% of all active landfills were equipped with degassing installations. Among them, 53.0% were installations discharging gas directly into the atmosphere. The gas generated at the landfill was neutralized with heat energy recovery in 10.3% of such installations, while in 29.3% (landfill degassing installations) it was used to produce electricity. In 2024, as a result of the disposal by incineration of gas captured from landfills, 132.1 million MJ of thermal energy and 129.4 million kWh of electricity were recovered. (GUS, 2025).

The storage of waste, including biodegradable fractions, is inextricably linked to the production of leachate that can migrate to groundwater in the landfill area and biogas in the landfill, processes that have been and continue to be present. Biogas generated in landfills should be considered in two aspects: first, as a source of air pollution (mainly methane and carbon dioxide) as fugitive emissions, and second, as a source of renewable energy (Ciuła et al., 2024; Brigagão et al., 2025). The processes occurring in landfilled municipal waste are complex and take place under anaerobic conditions as a result of waste compaction (Lombardi and Castaldi, 2025; Tawfik et al., 2025). In biochemical transformation processes, the organic components of waste undergo hydrolysis and then, with the participation of initially aerobic bacteria, and then mainly anaerobic bacteria, they are broken down into organic acids, and in the final stage, biogas is produced, mainly carbon dioxide and methane, which is a source of renewable energy (Basta and Szewczyk, 2024; Zwolńska and Basta, 2024). The biogas produced in the landfill should be captured using the best available technologies in order to preserve its physicochemical parameters and prevent the absorption of oxygen from the environment. (Huang and Fooladi, 2021). Landfill degassing installations are implemented using vertical and horizontal degassing wells and pipelines transporting biogas to conditioning installations. Installations of this type are built on landfills that have been reclaimed, but also on those that are still in operation (Firmansyah et al., 2025).

Currently, in Poland, an increasingly common method of utilizing landfill gas is cogeneration, i.e., a process in which the chemical energy contained in the fuel is converted into electrical and thermal energy in a single technological process (Wierzbińska and Juraszek, 2024; Kluczek et al., 2025). The main advantage of cogeneration is that the overall efficiency of energy conversion in a combined process is much higher than in separate electricity and heat generation. The overall efficiency of the combined process exceeds 85% (Kochanek et al., 2025; Sobiecka, 2022). The electricity produced can first be used for the landfill's own needs, while the surplus is transmitted (sold) to the power grid as "green energy" produced from a renewable source. The thermal energy obtained can be used for the landfill's own needs, i.e., heating rooms and hot water, or, in the case of a favorable location, transmitted to the district heating network. Energy production from landfill gas can be correlated with hybrid renewable energy systems, e.g., photovoltaic installations (Karemdabeh et al., 2025; Kwaśnicki et al., 2023). The benefit of using landfill gas for energy is the environmental effect resulting from the avoidance of emissions into the air. An added value is the economic effect of using the energy for own needs and selling surplus electricity and heat to the external grid (Kochanek et al., 2025; Bajdur et al., 2023).

The consequence of the current waste management hierarchy is the potential of landfill gas generated in landfills, which should be safely disposed of in an environmentally friendly manner. Since landfill biogas is a source of renewable energy, it should be used as efficiently as possible. This also applies to the conversion of biogas into other energy carriers, such as gaseous biofuels used in transport (Gewald et al., 2021; Kowalski et al., 2022). Currently, available technologies are used in landfills, including methods of neutralizing landfill gas through the use of appropriate biofilters and other technologies without energy recovery. Geographic information systems (GIS) are used to select the optimal locations for these technologies (Kochanek et al., 2025; Benezzine et al., 2022). Systems for the energy recovery of landfill gas include the combustion of landfill gas in flares (without energy recovery), combustion with energy recovery in gas boilers, and the most energy-efficient method, which involves the combustion of landfill gas in gas engines in a combined heat and power (CHP) system. This method of energy utilization of biogas is the most efficient way to convert the chemical energy of fuel into other types of energy (electricity and heat) (Amiri et al., 2013; Pilarski et al., 2025). Other technologies include the conversion of biogas to biomethane or electrolysis to produce biohydrogen fuel for powering public or municipal transport vehicles, alongside bio-oil (Winquist et al., 2019; Stelmach et al., 2023). Landfill gas captured by a landfill degassing system from a waste deposit contains physical and chemical impurities. In view of the above, it is necessary to reduce the harmful compounds contained in landfill gas in a gas conditioning installation in order to purify it (Przydatek et al., 2024; Dyachok et al., 2022). The process of obtaining and conditioning biogas involves the possibility of leachate occurring as a result of gas condensation. The collected leachate should be subjected to physicochemical testing, sent for purification, and then introduced into the sanitary sewage system (Wiewiórska and Rybicki 2024; Rybicki and Wiewiórska, 2017). For this purpose, equipment meeting the best available technologies for sludge formation processes and materials meeting stringent requirements for use in renewable energy installations should be used (Gronba-Chyła et al., 2025; Zhang et al., 2022). The production of electricity and heat from landfill gas is the use of a renewable energy source in a combined cycle (cogeneration). The product of this process is “green energy,” but its production has a negative impact on the environment (Mats et al., 2025; Sun et al., 2014). The combustion of landfill gas in a gas engine results, among other things, in the emission of carbon dioxide and dust contained in the exhaust gases, which constitutes organized emissions into the air. This process generates waste, including hazardous waste, in particular consumables in the form of used oils, fluids, leachate, condensate, mineral deposits, and spent activated carbon (Tappen et al., 2017; Saffiee et al., 2024). Waste generated in a CHP plant powered by landfill gas should be managed in accordance with the hierarchy of waste management, in which prevention, recycling, and recovery are the most preferred options (Sinem Erdoğdu, 2025). This principle must also apply to cogeneration plants, where the waste generated must be identified in terms of its physical and chemical properties for further treatment (Amaraibi et al., 2022; Alazzani and Wan-Hussin, 2013). The waste generated should be balanced in terms of quantity and quality and reported in the relevant reports, databases, and environmental fees (De Sousa et al., 2021; Firmansyah et al., 2025).

Contaminated ethylene glycol-based coolants cause corrosion in cooling and heat recovery systems, restrict fluid flow, and negatively affect the efficiency of heat exchangers. As a result, the entire system consumes more energy and generates higher operating costs (Saka, 2023; Novotny et al., 2021). Improper condition of the coolant, including sediment accumulation, restricts fluid flow, which can lead to an increase in system temperature and a decrease in cooling and heat recovery efficiency. In addition, incorrect glycol parameters can cause uncontrolled changes in the crystallization temperature, which may damage the system. This applies in particular to components operating outside the cogeneration unit (Yechiel and Shenvah, 2016; Pang et al., 2012). A key aspect in the process of producing energy from a renewable source such as landfill gas is the waste generated, including hazardous waste, which requires management in accordance with the waste hierarchy. This applies to solid waste but also to liquid waste. In particular, this includes operating fluids such as used oil, used coolant, and condensate separated from landfill gas in a condenser (Lund, 2021; Gewald et al., 2012).

The literature on the subject and the authors’ own research show that a cogeneration (CHP) plant producing energy from renewable sources is also a producer of waste, including hazardous waste. In this way, “green energy” is largely “contaminated” by pollutants generated in the process of its production (Rarosue et al., 2022; de Souza Ribeiro et al., 2021). Therefore, all waste generated during combined energy production should be identified by the plant operator and balanced in terms of quantity and quality. This approach to waste will allow for the determination of appropriate disposal or recovery processes and correct reporting, including the payment of applicable environmental fees

(Announcement of the Minister of Climate and Environment, 2025; Wang et al., 2022).

The main objective of the research was to determine whether used coolant should be treated as hazardous waste for humans and the environment, requiring special treatment. A secondary objective was to demonstrate how the parameters of the coolant change after two years of operation in a cogeneration plant powered by landfill gas and how this may affect the efficiency of energy production from a renewable source.

RESEARCH OBJECT

The subject of the study was a combined heat and power generation unit housed in a container, located at an operational landfill site, powered by landfill gas obtained from the waste deposit using an internal degassing system. The gas undergoes a two-stage conditioning process to remove physical impurities (fabric filter) and chemical impurities in a carbon filter. Figure 1 shows a diagram of the landfill gas energy recovery system.

The cogeneration unit (CHP) installed in a metal container consists of a 12-cylinder V-type spark ignition piston engine with a displacement of 21.9 dm^3 powered by landfill gas, which drives a synchronous generator. The generator is a three-phase, brushless, self-excited electric machine with a built-in excitation system and voltage regulator.

Landfill gas purified of impurities with a variable methane content of 45% to 60% and oxygen content of 0% to 0.5% is extracted from the landfill using a degassing system consisting of degassing wells and biogas transport pipelines. A diagram of the combined heat and power (CHP) plant is shown in Figure 2.

The generation of electricity and heat in a cogeneration unit powered by landfill gas produces waste that should be identified and managed in accordance with the waste management hierarchy. One of the wastes generated in the plant is used coolant, which is used to collect heat from the engine cooling system (HT and LT) and transfer heat in exchangers (IC2 and IC3) located in a metal container together with the gas engine. The heat recovery system uses a coolant consisting of ethylene glycol, sodium salt of diethylhexanoic acid, auxiliary substances, and water. The symbols in Figure 2 represent: WPT electricity consumers, WPE heat consumer, M4 heat metering.

There are two circuits in the engine cooling system. The first is the engine cooling circuit (HT), which is equipped with the necessary fittings to protect the engine in terms of temperature, pressure, and flow control. The operating parameters of the coolant in the HT circuit are: coolant temperature at the engine inlet 80 °C–83 °C, coolant temperature at the engine outlet 86–88 °C, and the alarm will be activated when the temperature exceeds 95 °C. The second mixture cooling circuit (LT) is also equipped with the necessary fittings required for safe engine operation, so that the coolant temperature (intercooler inlet - 2nd stage) is between 35 and 80 °C. Each of the engine cooling circuits has its own backup radiator, located outside the container, which acts as a safeguard in the event of insufficient heat removal from the engine block. The total amount of coolant in both engine cooling circuits and heat exchangers is approximately 140 dm^3.

Each operating fluid, including the coolant used in the CHP system, has its own safety data sheet for the new coolant supplied by the manufacturer, which specifies the basic parameters and potential

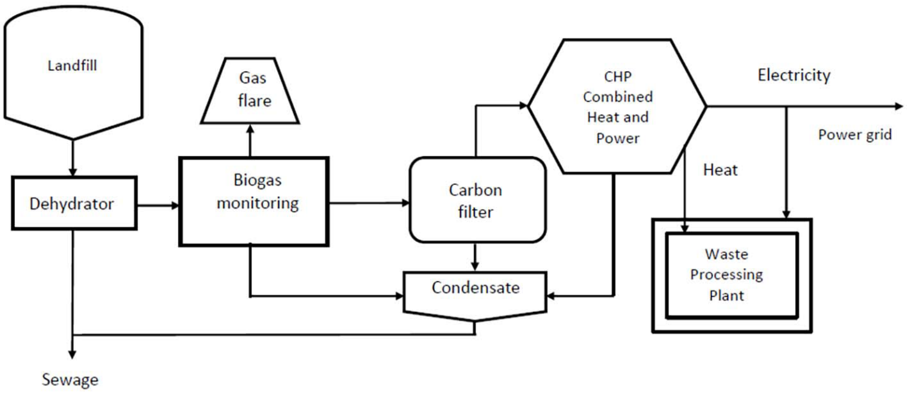

Figure 1. Diagram of the landfill gas extraction, purification, and energy utilization system

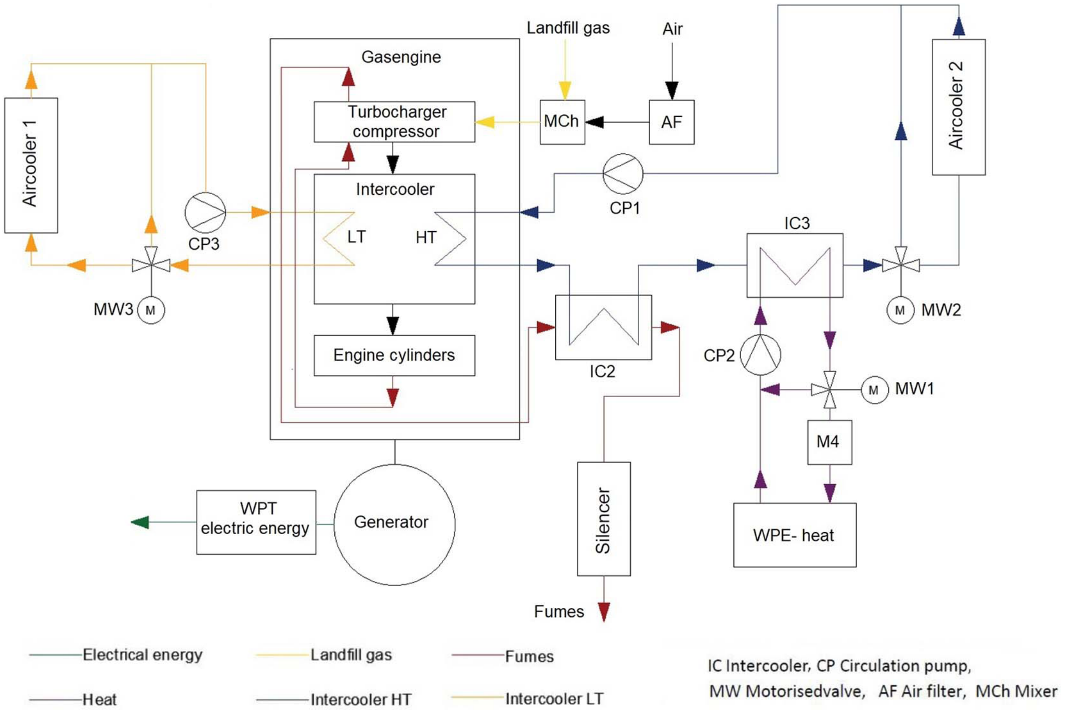

Figure 2. Diagram of a combined heat and power plant using landfill gas

hazards to humans and the environment. The basic physical and chemical properties of the coolant are:

- freezing point $\leq$ -35 °C,
- boiling point 109 °C,
- flammable product,
- lower and upper explosion limits: LEL: 4.9% vol. UEL: 14.6% vol.,
- flash point 115 °C (closed cup method),
- pH: 8.5–9.5,
- solubility miscible with water,
- vapor pressure y(37.8 °C): < 0.01 mmHg,
- relative density (15.6 °C): 1.11.

Environmental protection and exposure control precautions for the new coolant, as specified in the product safety data sheet, are to prevent the coolant from entering the sewage system, soil, groundwater, and surface water (Product Safety Data Sheet, 2023).

MATERIALS AND METHODS

Two samples of coolant, each with a volume of 1.0 dm^3, were studied: the first sample, A, was new, unused coolant, while the second sample, B, was used (worn-out) coolant. Both fluids are of the same type and manufacturer, and are based on ethylene glycol. The coolant acts as a heat transfer medium from the engine cooling system and two heat exchangers, and needs to be replaced every two years because it loses its properties. The used coolant had been in service in the cogeneration plant for a total of 15,779 hours, including 7.925 hours in the first year and 7.854 hours in the second year. The used coolant was removed from the two cooling circuits and collected in containers from which it was originally pumped as new coolant into the cooling systems. Both samples were studied in an accredited laboratory and compared in four test categories. The first category analyzed the condition of the used coolant, comparing the following parameters: iron, copper, chromium, lead, selenium, nickel and molybdenum. The second category concerned the type of contaminants that appeared in the coolant and consisted of: aluminium, sodium silicon, and potassium (K). The third comparative category concerned the physicochemical state of the new and used fluid samples for the following parameters: glycol, freezing point, density at 20 °C, pH, chlorides, nitrates, nitrites, and silicates in water. The fourth comparative analysis concerned the physicochemical state of additives such as phosphorus, zinc, calcium, magnesium, boron and alkaline reserve.-

In an accredited laboratory, sample A, which was a new coolant, was registered under number 25130008848, while sample B, which contained used coolant, was registered under number 25130008849. In order to test the physicochemical parameters of both samples, accredited methods and procedures based internal labotatory. The study utilized Statistica software, version 14.1.0.4; TIBCOI Software Inc.: Palo Alto, CA, USA, 2023, as a tool for statistical analysis of the test results. Within this software, the test results were presented using a raw data graph in the form of a surface graph in a 3W sequence. In addition, cluster analysis in the form of a hierarchical tree was also used. The Ward method was used as the agglomeration method in this analysis. This method presents the distances between clusters and uses a variance analysis approach, resulting in the minimization of the sum of squares of deviations of any two clusters. On the other hand, in order to determine the measure of distance between objects in the method of agglomeration when forming clusters, Euclidean distance was used, i.e., geometric distance in multidimensional space. In this method, Euclidean distances (and squares of Euclidean distances) are calculated based on raw data rather than standardized data (Statistica, 2023).

RESULTS AND DISCUSSION

Proper operation of cogeneration (CHP) systems powered by landfill gas ensures high efficiency of combined renewable energy production, minimizes potential failures, and ensures proper waste management during energy production. In the first category of tests, the condition of the coolant was analyzed by comparing the parameters of sample A, which was new coolant, with the parameters of sample B, which was used coolant. The results of the seven parameters are presented in Table 1.

The test results showed differences in only two parameters, i.e., iron (Fe) content at 2 ppm in sample B and copper (Cu) at 9 ppm in sample B compared to <1 ppm in sample A. This condition of the used coolant sample may indicate corrosion of the cooling and heat recovery system components in the exchangers. The conclusions are based on the increased copper and iron content, which may lead to failures in the cogeneration unit.

The second category of tests concerned the type of contaminants that appeared in the used coolant (sample B) compared to the new coolant (sample A). Table 2 presents the results of the comparative analysis for these parameters.

The test results showed that only the aluminum content remained unchanged. The other values for sodium, silicon and potassium were significantly higher than in sample A. The largest difference was observed for potassium, which increased more than 140 times compared to the value of the new fluid. Contaminated glycol can adversely affect the operation of the heat recovery system in a cogeneration unit. Solid particles and deposits block the flow in the pipes, resulting in lower efficiency of the devices operating in the heat recovery system and faster wear of their components. The condition of sample B, used coolant, may indicate the possibility of inhibitor breakdown in the coolant, which in turn may result in the coolant losing its protective properties. In addition, elevated sodium and potassium levels may suggest the appearance of corrosion of aluminum or steel components in the engine cooling system and reserve coolers, resulting in the release of sodium and potassium ions into the fluid. On the other hand, elevated silicon content may suggest the presence of silicon compounds (mainly siloxanes) in landfill gas and degradation of seals in the cooling system. This situation may occur in landfill gas conditioning systems in the event of a decrease in the efficiency of gas purification by an activated carbon filter. This is confirmed by research in which the authors point to the lack of standardization for biogas quality, mainly for hydrogen sulfide and siloxane content, as a potential threat to the stable operation of cogeneration plants (Laskowski et al., 2025).

In the third category of tests, the physicochemical state of the new fluid sample A and the used fluid sample B were compared. The results of these tests are presented in Table 3.

Laboratory test results showed no changes in parameters for chlorides < 15 mg/dm^3 and for nitrites at a level of <7.5 mg/dm^3. Other parameters

Table 1. Parameters in samples A and B

Sample type	Fe	Cu	Cr	Pb	Sn	Ni	Mo
	mg/dm^3	mg/dm^3	mg/dm^3	mg/dm^3	mg/dm^3	mg/dm^3	mg/dm^3
Sample A	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Sample B	2	9	< 1	< 1	< 1	< 1	< 1

Table 2. Contaminant levels in sample A compared to sample B

Sample type	Al	Na	Si	K
	mg/dm³	mg/dm³	mg/dm³	mg/dm³
Sample A	< 1	567	< 1	3
Sample B	< 1	1623	11	428

in sample B showed changes, with the largest difference occurring in the case of nitrates, exceeding the value from sample A by more than 18 times. Changes in pH, glycol, density, and silicates in water were noted. The pH level of the fluid affects the protection of the cooling and heat recovery system against corrosion. Tests have shown that the pH value in sample B, which is 6.88, is acidic, which can cause damage to metal components in the system, leading to malfunctions of pipes, pumps, and IC2 and IC3 heat exchangers. To analyze the impact of water content and other contaminants in glycol-based coolant, a stationary approach can be used or the process can be carried out remotely using online sensors. This approach to monitoring the operation of a cogeneration plant allows for ongoing monitoring and possible preventive measures to be taken to prevent failures of equipment that operates continuously with breaks for technical inspections (Paes Leao et al., 2022). On the other hand, the correct glycol concentration is crucial to protect the system from freezing and overheating. Tests revealed an elevated glycol level in sample B, at 51.3%, which is due to the fact that the engine cooling system is equipped with a bleed valve that operates at atmospheric pressure. This results in the systematic evaporation of mainly the water used to dilute the glycol, which consequently leads to an increase in the fluid's viscosity. This condition, in turn, can cause excessive strain on the circulation pumps and lead to a decrease in heat exchange efficiency within the recovery system.

Figure 3 shows a graphical presentation of changes in chlorides, nitrates, nitrites, and silicates in water in samples A and B.

The change in chloride, nitrate, nitrite, and silicate content in samples A and B showed the greatest increase for two values, namely nitrates and silicates in water, in relation to sample A.

The comparative analysis performed as part of the fourth category of laboratory tests concerned the physicochemical state of additives in the coolant contained in sample A and sample B. The results of the analysis are presented in Table 4.

Analysis of the results obtained from testing the condition of additives in the coolant showed no change for phosphorus (P), while for the other parameters the increase was clearly visible. The largest increase in the parameter was recorded for boron (B), from < 1 mg/dm³ to 690 < 1 mg/dm³. The parameter that changed (decreased) was the alkaline reserve of the liquid, from 4.1 to 3.3, expressed in ml HCl/10 ml. The decrease in the alkalinity of the coolant during the explantation of the CHP installation is related to the oxidation of glycol to glycolic and formic acids, which neutralize the alkaline salts contained in the fresh liquid. This is accompanied by a decrease in the pH of the liquid, which was noted in the tests (Table 3).

The results of the tests representing the highest and lowest exceedances of individual parameters in sample B were also subjected to statistical analysis. The results of the tests of the parameters that showed the greatest increase in sample B in relation to the initial value of sample A in the tests performed in the first, second, and fourth categories are presented in Figure 4.

Analysis of the test results for the parameters that showed the greatest increase in sample B compared to the value shown in sample A showed that the objects form clusters, resulting in three main groups (clusters). The first contains potassium (K) and boron (B), the second contains iron (Fe), and the third includes sodium (Na). The smallest

Table 3. Comparison of the physicochemical state of sample A and sample B

Sample type	Glycol	Freezing point	Density at 20 °C	pH	Chlorides	Nitrates	Nitrites	Silicates in water
	%	°C	kg/m³	-	mg/dm³	mg/dm³	mg/dm³	mg/dm³
Sample A	46.9	-35	1054.3	8.27	< 15	< 10	< 7.5	< 5
Sample B	53.1	-41	1075.6	6.88	< 15	184	< 7.5	13.7

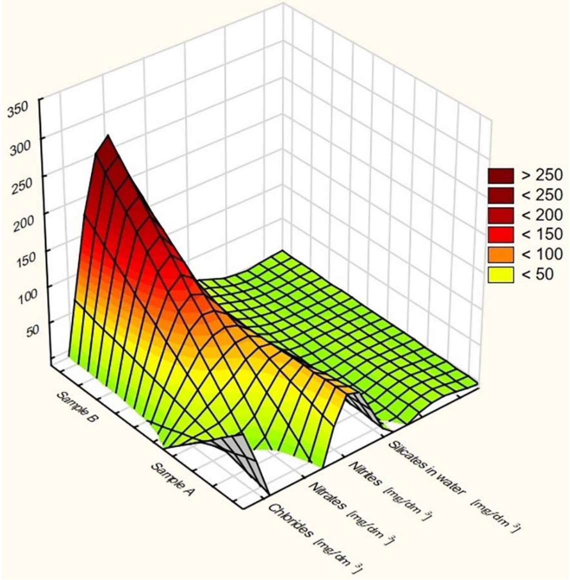

Figure 3. Physicochemical state of selected parameters for samples A and B

bond distance occurs at the level of the first cluster for the agglomeration distance (x = 263.81; y = 2.50), while in the second cluster it is (x = 657.53; y = 1.71). The third cluster has parameters (x = 1244.71; y = 3.98), representing the largest distance in these bonds. This state of bonds within the dendrogram indicates a large discrepancy in parameters and confirms the clear predominance of sodium (Na) over the other values.

The results of the tests of the parameters that showed the smallest increase in sample B compared to the values in sample A in the tests performed in the first, second, and fourth categories are presented in Figure 5.

The results of the analysis of the coolant parameters that showed the smallest increase in sample B in relation to the value shown in sample A showed that the objects form clusters, resulting in three main groups (clusters). The first contains copper and silicon, the second contains calcium and magnesium, while the third includes zinc. The analysis confirmed that the smallest bond distance occurs at the level of the first cluster for the agglomeration distance (x = 2.05; y = 1.51), while within the second cluster it is (x = 9.38; y = 3.11). The third cluster has parameters (x = 32.81; y = 4.98), representing the largest distance in these bonds. This state of bonds resulting from the obtained dendrogram indicates a moderate divergence of parameters and confirms the clear predominance of zinc in relation to the other values.

The correct parameters of the coolant in the heat collection system in a cogeneration unit powered by landfill gas ensure its proper operation and the generation of renewable energy in the form of electricity and heat with high efficiency. In this way, the chemical energy contained in biogas is used efficiently and biogas emissions into the air, especially methane as a greenhouse gas, are reduced. Used glycol negatively affects the efficiency of engine cooling systems and increases the risk of failure. As it is used in the cooling and heat recovery systems of cogeneration plants, it loses its chemical stability, changes the pH value, and contributes to corrosion. If the coolant replacement schedule is not followed, decomposing glycol can lead to clogging of pipes and reduce the efficiency of heat exchangers. In such a situation, the flow of coolant may be restricted, leading to an increase in temperature in the heat recovery system and a decrease in cooling efficiency. As a result of seal leaks, engine oil may become contaminated with glycol (Abdulmunem et al., 2020).

The key issue in handling used ethylene glycol-based coolant, used in gas engine cooling systems and heat recovery systems in exchangers, is its disposal after the end of its service life. The tests carried out and their results showed the content of heavy metals in used coolant in the form of elevated values for zinc and copper. In addition, high levels of sodium (Na), boron (B), and potassium indicate that used coolant, as waste, should be disposed of or recycled in accordance with the rules for the management of such waste. This conclusion of the study is confirmed by the entries in the product data sheet issued by its manufacturer, who classifies this waste as code: 16 01 14*. Antifreeze fluids containing dangerous substances. In view of the above, it is recommended that this waste be collected in its original containers, not disposed of in

Table 4. Condition of additives in sample A and sample B

Sample type	Alkaline reserve	P	Zn	Ca	Mg	B
	ml HCl/10 ml.	mg/dm³	mg/dm³	mg/dm³	mg/dm³	mg/dm³
Sample A	4.1	< 1	< 1	< 1	< 1	< 1
Sample B	3.3	< 1	33	16	6	690

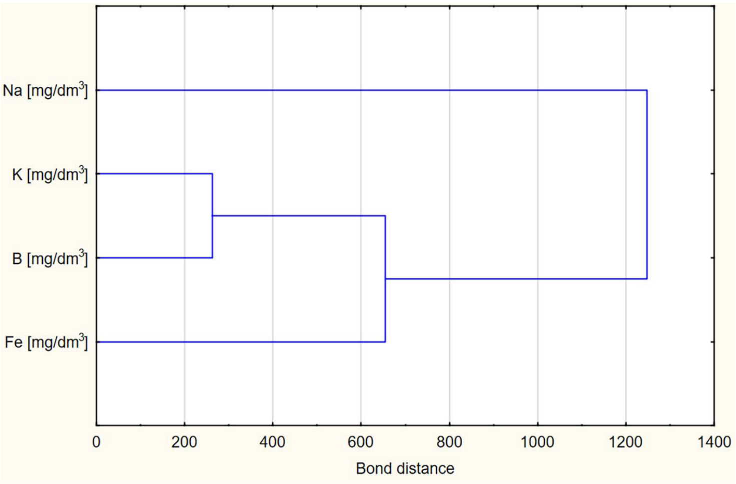

Figure 4. Parameters with the largest increase in their values

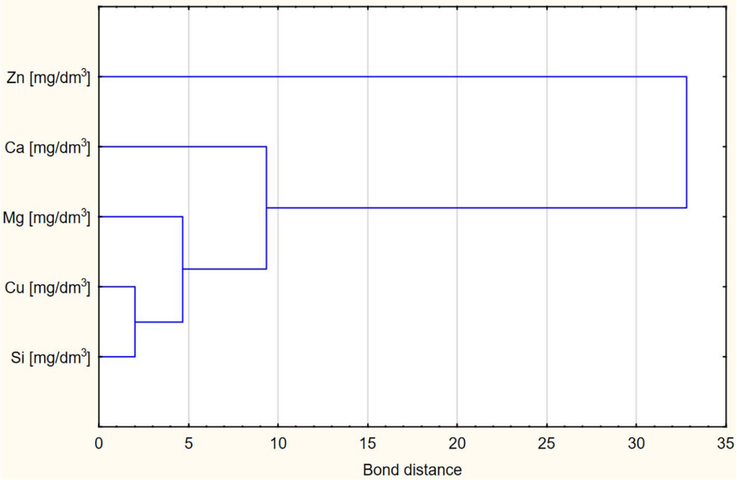

Figure 5. Parameters with the smallest increase in their values

the sewage system, not allowed to contaminate surface and ground water, and not stored in municipal waste landfills. Used coolant, as hazardous waste, should be sent for disposal to a facility licensed for the collection, transport, recovery, or disposal of waste and disposed of in accordance with applicable regulations. A similar situation applies to the disposal of used packaging for used coolant, which should be subjected to a process of recovery (recycling) or disposal of packaging waste in accordance with applicable regulations. For this type of packaging, the following waste code is assigned: 15 01 10* Packaging containing residues of or contaminated by dangerous substances (Regulation of the Minister of Climate, 2020).

Used refrigerant fluid constituting hazardous waste with code: 16 01 14* Antifreeze fluids containing hazardous substances should be collected in containers and transferred to the appropriate entity dealing with the management of this type of waste. The best technologies currently available allow for its disposal or recovery in regeneration processes that are safe for humans and the environment. Ongoing research and available technologies allow for the regeneration of most used coolants, provided that they are partially fit for use. Restoring the functional properties of used coolant involves alkalizing the liquid to a pH ≥ 8.5 and removing free oil particles, mechanical impurities, and emulsified petroleum-based impurities (Ji et al. 2016). Polypropylene nonwoven filters commonly used for sanitary water treatment can be successfully used to remove these impurities. The treated fluids have parameters comparable to those of fresh liquids and can be reused as heat carriers in cogeneration systems. Currently available glycol regeneration methods allow glycol concentrations of over 99% to be achieved. The choice of regeneration method is mainly determined by financial and technical considerations (Ahmed et al. 2018). The approach to hazardous waste management should first and foremost involve a potential analysis of possible recycling methods, and only as a last resort should it indicate the need for waste disposal.

CONCLUSIONS

The study examined used coolant fluid from a cogeneration plant (CHP) located at a landfill site and powered by landfill gas as a renewable energy source. The plant generates electricity and heat for the needs of facilities located on and near the landfill site. The aim of the research was to determine whether the used coolant from the heat recovery system of the cogeneration unit should be treated as safe waste and therefore require special management. The research showed how the parameters of the coolant change after two years of operation and what potential operational problems this may cause in the production of energy from a renewable source such as landfill gas. The results of comparative tests of the physicochemical parameters of new and used coolant showed significant differences that could potentially affect energy production efficiency.

The tests showed that the pH value is acidic, which can cause damage to metal components in the system, leading to malfunctions of pipes, pumps, and IC2 and IC3 heat exchangers. On the other hand, glycol tests showed a reduced percentage content, which may indicate an increase in fluid viscosity, which in turn may place an excessive load on the circulation pumps and cause a decrease in heat exchange efficiency in the recovery system. The reduction in the alkalinity of the coolant during the decommissioning of the CHP plant is associated with the oxidation of glycol to glycolic and formic acids, which neutralize the alkaline salts contained in the fresh liquid. This is accompanied by a reduction in the pH of the liquid, as shown by tests. Used glycol negatively affects the performance of engine cooling systems and increases the risk of failure. If the coolant replacement schedule is not followed, decomposing glycol can lead to clogging of pipes and reduce the efficiency of heat exchangers.

The tests carried out and their results showed the content of heavy metals in overworked (used) coolant in the form of elevated values for zinc and copper. In addition, high levels of sodium, boron, and potassium indicate that used coolant, as waste, should be disposed of or recycled in accordance with the rules for managing such waste. Therefore, based on the waste catalog, the waste was classified as hazardous with the code: 16 01 14*.

The scientific contribution of this study is to demonstrate that changes in the parameters of the refrigerant can affect the operational reliability of a cogeneration system. It was also found that spent refrigerant constitutes hazardous waste that requires special handling due to its properties.

Thus, energy generated from a renewable source such as landfill gas is largely contaminated with pollutants produced during its generation. Therefore, all waste generated at a cogeneration plant (solid and liquid waste) should first be located, identified, and balanced by the plant operator. This approach to waste will allow for the determination of appropriate disposal or recovery processes and correct reporting, including the payment of applicable environmental fees.

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