

## Efficiency Analysis of the Generation of Energy in a Biogas CHP System and its Management in a Waste Landfill – Case Study

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### ABSTRACT

As a waste neutralization facility, the landfill is a kind of bioreactor producing landfill gas or (LFG) - biogas, which should be captured and neutralised for environmental reasons. One of the ways of its utilisation is the combined production of heat and electrical energy in combined heat and power (CHP) cogeneration systems. For that purpose, the assessment of the energy efficiency of a cogeneration unit was undertaken in this work on the basis of the unit performance over the last 5 years. The analysis of the CHP system energy performance demonstrated that the ratios range at the lower limits for units up to 0.5 MW. The lower efficiency of fuel chemical conversion in the CHP plant (0.70) stems from the failure to use the rated thermal and electrical power fully (74.2%), which is caused by the insufficient stream of biogas collected from the landfill (161.46 m<sup>3</sup>·h<sup>-1</sup>). The analysis of the generated energy usage, particularly in terms of heat, has shown a surplus which is not used and therefore is a loss. The proposed solutions in this area should optimize the use of heat generated from the renewable source, i.e. landfill biogas.

**Keywords:** cogeneration; energy efficiency; energy ratios; landfill gas; municipal waste; renewable energy.

### INTRODUCTION

The neutralisation of municipal waste through landfilling is used in many countries around the world. Numerous countries, including the European Union member states, are introducing a prohibition on the landfilling of biodegradable waste and that with specific energy content. Leachate originating from a waste deposit may be a threat to human health if it penetrates into groundwater. It seems advisable to conduct regular tests of the water intended for consumption from individual intakes located near the landfill, as is the case with bacteriological tests. Such measures were undertaken due to a potential leakage of leachate from the landfill into groundwater and then due to the

transport of pollutants in the aquifer to water intakes, including watercourses, e.g. such as rivers [Wysowska et al., 2020; Ciuła, 2021; Wysowska et al., 2021]. Prohibition on bio-waste landfilling is aimed at implementing the principles of circular economy and waste recovery to use waste in organic, material and thermal recycling processes [Liikanen et al., 2018; Połomka and Jędrzak, 2020; Gronba-Chyła and Generowicz, 2020; Wasąg and Grabarczyk, 2021]. In the past, waste landfilling followed from the lack of specific policies of the various countries that allowed for the landfilling of the municipal waste stream, which was driven by the high costs of using alternative methods in municipal management. The implemented current legal conditions in the field of

biodegradable waste management in the EU countries regulate this area, excluding the storage of bio waste in favor of other available technologies including aerobic and anaerobic processes under controlled conditions [Malovanyy et al., 2021; den Boer et al., 2020; Gronba-Chyła et al., 2021].

The consequence of the current legal regulations is the waste management hierarchy, within which the potential of the biogas generated at landfills should be disposed of in an environmentally safe manner [Ciula et al., 2020; Okwu et al., 2021; Adamcová et al., 2016]. As landfill biogas is a source of renewable energy, the method of biogas utilisation should be as efficient as possible. Among the current biogas utilisation methods used at a landfill, there are the neutralisation methods by means of biofilters as well as combustion in flares (without energy recovery), in gas boilers (with energy recovery), combustion in gas boilers, as well as combustion in gas engines in a Combined Heat and Power (CHP) cogeneration system. The latter method of biogas utilisation is the most effective way to convert the fuel chemical energy into another type of energy [Gambinia and Vellinia, 2015; Ciula et al., 2018; Oukili et al., 2022]. Among the technologies of biogas utilisation for the purposes other than heat and electrical energy production, biogas conversion to biomethane or electrolysis for the production of fuel, namely bio hydrogen for motor vehicles in public or municipal transport are also used. The use of biofuels in transport reduces the emission of harmful substances into the environment and increases the utilisation of fuels from renewable sources in that sector [Wilslow et al., 2019; Amiri et al., 2013; Keršys et al., 2013].

The production of basic energy carriers, i.e. heat and electrical energy, is mainly based on thermal processes as a result of the use of chemical energy contained in the fuel. Combined energy production (cogeneration), which is used more and more often, is a thermodynamic process of the conversion of fuel chemical energy into useful carriers in the form of heat and electrical energy. That process can be conducted in a single device or in a group of interconnected ones [Lund, 2021; Koval et al., 2019; Skorek, 2012]. Gaseous fuels utilised in cogeneration systems and combusted in gas engines increasingly often come from renewable sources. This also applies to the biogas generated within a landfill as a result of biodegradable fraction decomposition in the process of anaerobic digestion. Bearing in mind the above,

every effort should be made to use the energy generated in that process in the optimal way [Kowalski et al., 2015; Dregulo and Bobylev, 2021]. As a waste neutralization facility, a landfill may have a negative impact on air, soil, groundwater and surface waters, particularly at a place where the landfill is located. Capture of biogas and neutralisation of methane, which is the basic biogas component (approx. 55 %) reduce the emission of a greenhouse gas, i.e. methane. Collection of biogas as a fuel and its utilisation is one of the arguments for implementing modern energy technologies in order to reduce the adverse environmental impact of the landfill [Vaverková and Adamcová 2012; Gaska et al., 2019]. The use of landfill biogas as a biofuel in the cogeneration units producing heat and power requires prior detailed analysis of gas in terms of quality parameters, due to pollutants. In addition to its energy properties, biogas is distinguished by a very complex organic matrix. Landfill gas contains over 400 different compounds of organic origin, from simple hydrocarbons to complex terpene derivatives. These pollutants can cause mechanical damage to the gas engines used in cogeneration systems, especially in the area of non-detachable connections inside the gas engine [Kowalski, 2016; Stanuch et al., 2020].

Those pollutants may damage biogas utilisation systems and devices, increase operating costs and capital expenditure, as well as increase the failure rate of plant. The majority of the following are most severely exposed to the activity of microcrystalline deposits: combustion chambers, valves, valve seats, cylinder heads, cylinder walls, piston heads, push fit joint and bushings. Biogas conditioning systems best purify biogas, which should meet the requirements of gas engine suppliers [Piechota, 2017; Kowalski, 2020]. The efficient operation of a cogeneration system means the production of electrical energy and also its distribution following the transmission to the medium voltage power grid. In the event of power decay in the external power grid, the cogeneration unit reduces efficiency and switches to the off-grid operation mode (island operation) without the option to distribute the generated electrical energy. Therefore, the availability of the power grid and its reliability at the required voltage levels (high, medium and low) is a necessary condition for the proper operation of combined heat and power generation systems. Reliable operation of the power grid in the era of intensive development of renewable energy sources will

have a direct impact on the employment process and on the transformation of the energy sector towards its decarbonisation [Kornatka, 2018; Moqbel, 2012]. The collection and utilisation of biogas generated within a landfill, the main component of such gas being methane, is the best way to reduce its adverse environmental impact. In terms of energy, biogas means the use of a renewable fuel to generate energy and in terms of the environment it corresponds to the abandoned emission of a greenhouse gas, i.e. methane [Nikhah et al., 2018; Papadimitriou et al., 2020; Pandyaswargo et al., 2012].

## OBJECT OF RESEARCH

The object of research was a containerised biogas CHP system with a heat recovery unit with the electric power of 365 kW and thermal power of 455 kW, which has been used at a landfill since the beginning of 2010. The landfill was constructed as an above-ground level landfill with an area of approximately 2.8 ha, which has a separate storage cell of approximately 450,000 m<sup>3</sup>. The landfill holds residual waste after mechanical treatment and other waste approved for storage. The landfill is part of a Waste Processing Enterprise (WPE) which comprises a mechanical and biological waste treatment plant and a Refuse-Derived fuel (RDF) station. The gas piston engine driving the generator is supplied by the biogas collected from the landfill degassing plant with the use of vertical degassing wells. Sucked in with a suction nozzle up to 300 m<sup>3</sup> h<sup>-1</sup>, biogas is then sent to a treatment station, where it is conditioned and prepared for combustion in a gas engine. The engine is a V-shape, four-stroke, turbocharged, 12-cylinder engine with a supercharged mixture cooler, and is factory-adapted to run on biogas with a variable methane content from 30% to 65% and oxygen content from 0% to 3%.

The CHP unit is built in a sound-proof 8.0×3.0×3.0 m container and consists of the following main components: biogas engine, synchronous power generator, internal biogas plant, heat recovery block (the engine and exhaust gases), backup cooling system with an external cooler, control, metering and electrical energy output system, steering and visualisation system. The technical parameters of the cogeneration unit are as follows:

• electric power	365 kW
• thermal power	455 kW
• voltage	400/230 V
• heat-carrying agent temperature	70/90 °C
• electric efficiency	39.25%
• heat (thermal) efficiency	48.82%

The diagram of the installation for energy use of landfill biogas in a cogeneration unit is presented in Figure 1. Six circuits have been distinguished, which carry out the processes related to biogas treatment, its combustion with heat recovery and the generation of electrical energy. Owing to the application of the supervisory control and data acquisition Supervisory Control and Data Acquisition (SCADA) system, which plays an overriding role in relation to the reference and metering devices in the individual circuits, it was possible to carry out parameterization in terms of quantity and quality. The Human Machine Interface (HMI) system cooperating with SCADA is a tool that allows for a graphical representation of the process along with information about its run, the possibility of reception and transmission of commands to the devices controlling the process.

The landfill biogas collected from the waste bed is treated in the plant comprising a carbon filter and condensate settling tank. Before feeding into the gas engine, biogas is measured with a flow meter. The amount of heat and electrical energy produced in the cogeneration system over 5 years is shown in Table 1.

The amount of electrical energy produced by the generator is measured at its terminals as gross energy with a multi-meter. This energy is in the first place consumed for the in-house requirements of the facility, i.e. the landfill and waste processing enterprise, and power surplus is sent to the external power grid. The biogas power plant is connected to the power grid in an on-grid system with bidirectional electrical energy measurement. The heat generated during the combustion of biogas in the engine is recovered in heat exchangers in the engine cooling and exhaust gas discharge systems. The amount of heat produced, as well as its utilisation by the WPE, is measured and archived. Through a manifold heat exchanger, thermal energy is transferred to hot water, which becomes the heat carrier. Thermal energy is used for welfare purposes and technological processes. The control and software system in the CHP enables graphic visualisation of the process in the on-line system from anywhere in the world through the Internet

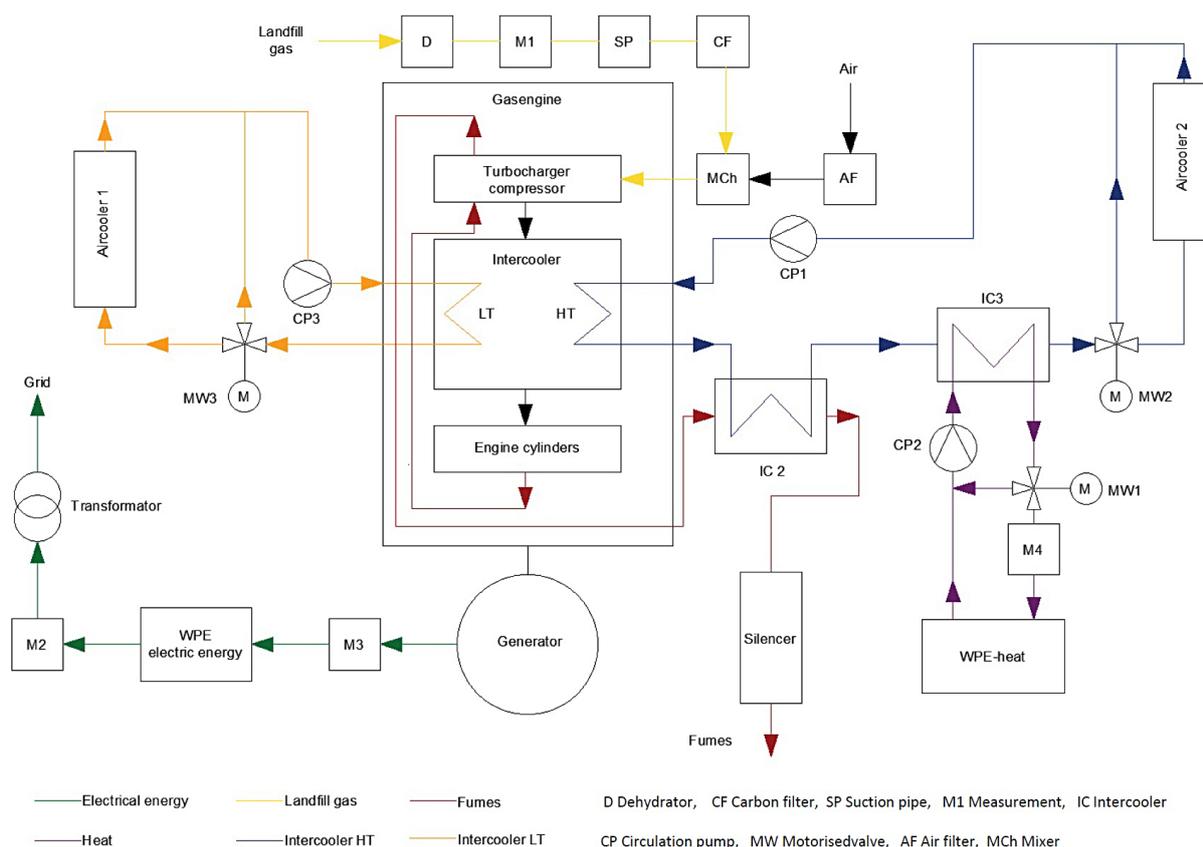


Figure 1. Diagram of the installation for energy use of landfill gas in a CHP system

Table 1. Energy generated in the CHP plant

Parameter	Unit	2016	2017	2018	2019	2010
Biogas stream	m <sup>3</sup> ·year <sup>-1</sup>	1306298	1276732	1286321	1248464	1218451
Amount of generated electrical energy	MWh·year <sup>-1</sup>	2327.82	2073.41	2181.60	2128.63	1944.65
Amount of heat generated	MWh·year <sup>-1</sup>	2821.60	2788.38	2863.35	2815.29	2708.62

and Global System for Mobile (GSM) communications cellular network. The user can remotely check the system operation parameters in real time, as well as change the parameters and receive alerts about breaks in plant operation.

## MATERIAL AND METHODS

The operational data for 5 years, i.e. 2016–2020 have been used as input parameters for the analysis of the heat and electrical energy generation efficiency in the cogeneration system, and the method of heat utilisation in the WPE. These data are the outcome of the measurements, calculations, and analyses of biogas chemical composition. The formulas for the calculation of energy parameters come from the review of reference

literature relevant for this branch of science. The results of the measurements and calculations have been subject to statistical analysis with the use of the Statistica, v13.3 TIBCOI Software Inc. [Statistica, 2017]. Correlation (the coefficient of correlation), which is the main measure of the relation between two variables, was used. In order to compare the various energy ratios with one another, cluster analysis was conducted, in which the Ward agglomeration method was used. That method is applied for the estimation of the distance between clusters and uses the variance analysis approach that results in minimising the sum of squared deviations of any two clusters. However, the Euclidean distance was used as a measure of distance in this method. The 3W surface charts for three XYZ variables were used to analyse the method of managing the energy generated in the CHP system.

## Energy ratios of the cogeneration system operation

The assessment of the energy efficiency of the combined heat and power generation process differs from single-purpose processes, because all the products made in cogeneration have a useful value, and their production takes place in accordance with the recipients' requirements. In order to conduct the thermodynamic analyses of associated systems, the ratios describing energy conversion efficiency in a cogeneration system are used [Rostocki, 2013; Skorek, 2012]. The basic ratios of the operation of CHP systems include:

- efficiency of electrical energy generation (electric efficiency)

$$\eta_{el\_EC} = \frac{E_{el}}{\dot{E}_{ch}} = \frac{E_{el}}{\dot{P} \cdot W_d} \quad (1)$$

where:  $\eta_{el\_EC}$  – electric efficiency [-],  
 $E_{el}$  – is the amount of electrical energy generated [kWh],  
 $\dot{E}_{ch}$  – biogas chemical energy stream [kW],  
 $\dot{P}$  – annual biogas stream [m<sup>3</sup>·year<sup>-1</sup>],  
 $W_d$  – biogas calorific value [kW·m<sup>3</sup>].

- heat generation (efficiency thermal efficiency)

$$\eta_{t\_EC} = \frac{Q}{\dot{E}_{ch}} = \frac{Q}{\dot{P} \cdot W_d} \quad (2)$$

where:  $\eta_{t\_EC}$  – efficiency thermal efficiency [-],  
 $Q$  – amount of heat generated [kWh].

- total combined heat and power plant efficiency

This is one of the most important ratios showing fuel (biogas) chemical energy conversion efficiency in the CHP. In reference literature, this value is called the chemical energy and fuel utilisation factor and marked as the *EUF* (*Energy Utilization Factor*). It is determined from the following relationship:

$$\eta_{c\_EC} = EUF = \frac{E_{el} + Q}{\dot{E}_{ch}} = \frac{E_{el} + Q}{\dot{P} \cdot W_d} \quad (3)$$

where: *EUF* – total combined heat and power plant efficiency [-].

- cogeneration factor (degree)

The relationship of electrical energy produced in the cogeneration system (on the stream of the agent used for heat production) to the thermal power of the system is expressed by the so-called cogeneration ratio:

$$\sigma = \frac{E_{el}}{Q} \quad (4)$$

where:  $\sigma$  – cogeneration factor [-].

- fuel (biogas) energy savings ratio

One of the most important energy efficiency ratios for combined heat and power production is the amount of chemical energy in biogas that can be saved compared to separate production (a heating boiler and power generator set). Thus, the fuel economy in a combined system is mainly determined by electrical energy production. The fuel (biogas) energy savings ratio was determined from the following relationship:

$$\Delta E_{ch} = E_{el} \left( \frac{1}{\eta_{E,el}} - \frac{1}{EUF} \right) \quad (5)$$

where:  $\Delta E_{ch}$  – fuel energy savings ratio [MWh]

- relative *FESR* (*Fuel Energy Savings Ratio*)

The *FESR* value shows the saving in relation to fuel chemical energy as a result of the use of the combined heat and power generation process:

$$FESR = \frac{\Delta E_{ch}}{\dot{E}_{ch}} \quad (6)$$

where: *FESR* – relative fuel energy savings ratio [-].

The basic energy ratios for the operation of cogeneration systems as presented above, depicting the conversion efficiency of chemical energy contained in biogas, constitute the basis for the technical and economic analyses well as environmental impact.

## RESULTS AND DISCUSSION

### Energy ratios

The evaluation of the efficiency of cogeneration units, especially those supplied by the fuel from renewable sources (landfill biogas), requires integrated energy management. This applies to the optimisation of the heat and power generation process and of the methods of co-generated energy utilisation. The thermodynamic analysis used in this assessment focuses on the quantitative energy parameters of the combined system operation, thus describing the biogas chemical energy conversion efficiency. Energy ratios were calculated with the use of formulae from (1) to (6) and

**Table 2.** Energy ratios of the cogeneration system operation

Parameter	Unit	2016	2017	2018	2019	2020
$\eta_{el\_EC}$	-	0.32	0.31	0.31	0.30	0.30
$\eta_{t\_EC}$	-	0.39	0.41	0.40	0.40	0.41
$EUF$	-	0.70	0.72	0.71	0.69	0.71
$\sigma$	-	0.82	0.74	0.76	0.76	0.72
$\Delta E_{ch}$	MWh	3159.27	2873.68	3000.64	2848.93	2652.11
$FESR$	-	0.43	0.42	0.42	0.40	0.40
$\Delta E_{ch}/E_{el}$	-	1.36	1.39	1.38	1.34	0.98
$\Delta E_{ch}/E_t$	-	1.12	1.03	1.05	1.01	0.98
$P_{Nel}/P_{Ael}$	-	0.81	0.72	0.76	0.76	0.67
$P_{Nt}/P_{At}$	-	0.79	0.78	0.80	0.80	0.75

then completed with additional ratios ( $\Delta E_{ch}/E_{el}$ ,  $\Delta E_{ch}/E_t$ ,  $P_{Nel}/P_{Ael}$ ,  $P_{Nt}/P_{At}$ ), as presented in Table 2.

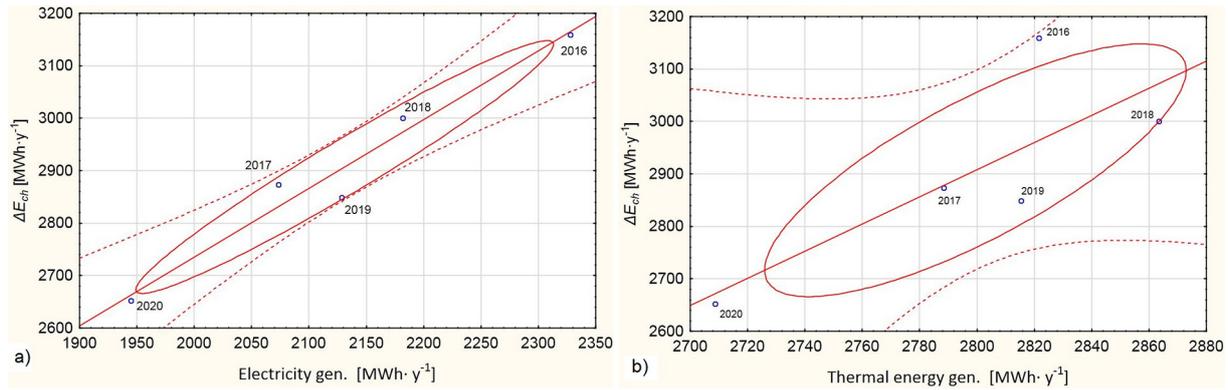
The five-year average efficiency of electrical energy generation  $\eta_{el\_EC}$  was 0.31, with nominal efficiency of 0.39. The achieved lower efficiency follows from the fact that the plant operated at the level of about 74% of the rated electric power. However, the average efficiency of heat generation  $\eta_{t\_EC}$  during 5 years was 0.40, with the nominal efficiency amounting to 0.48. The achieved value is lower by 8.8% than the nominal figure, which is the result of the plant operating at the level of 78% of the rated thermal power. The total heat and power plant efficiency calculated on the basis of the operating parameters was 0.71, which for reciprocating gas engines up to 0.5 MW is in the range of 70 to 90%. The energy parameters of the operated cogeneration systems in Europe and elsewhere in the world show that the efficiency of electrical energy generation ranges from 0.32 to 0.41, while the efficiency of heat generation ranges from 0.44 to 0.55 for a comparable electric and thermal power of the CHP unit [Purmesur and Surroop, 2019]. Lower energy efficiency parameters achieved by the CHP system and the lower energy conversion factor in the CHP plant  $\eta_{c\_EC} = EUF$  result from the failure to utilise the full rated thermal and electrical power of the CHP system. The average 5-year load of the unit was 74.2% of the rated power of the generator with the average methane content in the biogas being 50.1%. That situation is caused by the decreasing methane content and too small a stream of biogas from the landfill. This condition stems from the intensive operation of the landfill degassing plant over more than 12 years, the prohibition on the storage of organic waste and the storage of

only processed and biologically stabilized waste [Themelis and Ulloa, 2017].

As a result of combined heat and power generation, the calculated fuel (biogas) energy savings ratio  $\Delta E_{ch}$  demonstrated energy savings of 2906.93 MWh on fuel as the 5-year average. This is the amount of energy saved in comparison to the energy which would have been consumed in the case of separate generation. In combined heat and power systems,  $FESR$  is from 0.3 to 0.5. The obtained average result for 5 years at the level of 0.42 for the plant under analysis is a good result. The use of a renewable fuel, i.e. landfill biogas, means rational energy economy with the reduction of the negative impact on the various components of the environment compared to fossil fuels [Winquist et al., 2019].

The energy ratios for the combined heat and power generation unit showed that these values were in the average range of good results for facilities up to 0.5 MW. As the CHP system is operated in the range of 70 to 80% of the rated power, the obtained results should be considered satisfactory for that power range. The interrelation between the variable amount of electrical energy generated and fuel (biogas) energy savings is shown in Figure 2a.

The diagram showing the relationship between electrical energy generated  $E_{el}$  and fuel (biogas) energy savings ratio  $\Delta E_{ch}$  indicates a positive correlation. Such a relationship means that an increase of the results of the variable Y,  $\Delta E_{ch}$ , is accompanied by an increase of the results of the other variable, X, i.e.  $E_{el}$ . The least correlated points are ( $x = 2073.41$ ;  $y = 2710.34$ ) and ( $x = 2128.63$ ;  $y = 2956.43$ ). The interrelation between the variable amount of heat generated and the value of fuel (biogas) energy savings is shown in Figure 2b.

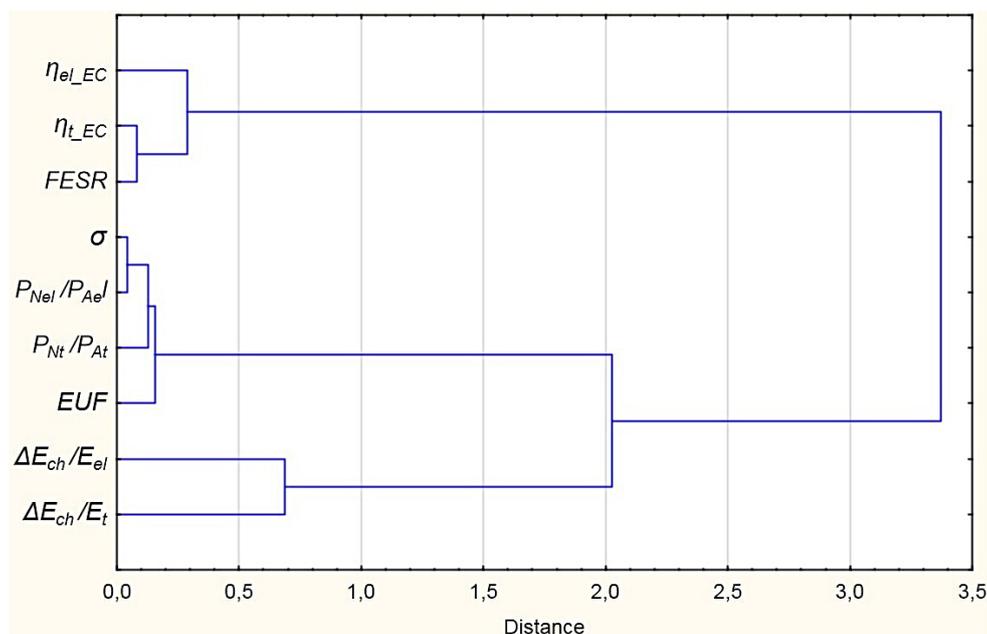


**Figure 2.** a) The correlation between electrical energy generated and fuel (biogas) energy savings; b) the correlation between heat generated and fuel (biogas) energy savings

The diagram showing the correlation between heat generated  $Q$  and the fuel (biogas) energy savings ratio  $\Delta E_{ch}$  is a positive correlation. Such a relationship means that an increase of the results of the variable  $Y$ , i.e.  $\Delta E_{ch}$ , is accompanied by an increase of the results of the other variable  $X$ , that being  $Q$ . The least correlated points are the following values: ( $x = 2815.29$ ;  $y = 2956.43$ ) and ( $x = 2788.38$ ;  $y = 2710.34$ ). The calculated amounts of chemical energy saved in the fuel, in the case of cogeneration, are confirmed by the tests carried out on real facilities up to 0.5 MW, as well as on those with a greater capacity, the latter being municipal combined heat and power plants. Energy balance sheets for CHP systems have shown that the fuel energy savings ratio in the separate heat and power

generation process is the appropriate measure of energy efficiency in the case of cogeneration [Ziębik and Gładysz, 2017].

In order to compare the energy ratios for the combined heat and power generation process, a cluster analysis was performed, which is a tool for exploratory data analysis. The goal is to sort the objects into groups and present the results as a dendrogram. The calculated energy ratios of the cogeneration unit as included in Table 2 were used as input data. Moreover, for cluster analysis, four ratios were implemented: the rated power utilisation ratio  $P_{NeI}$  and thermal power utilisation ratio  $P_{Nt}$ , and amount of biogas chemical energy  $\Delta E_{ch}$  as the quotient of  $E_{eI}$  and  $E_t$ . The aim of the analysis was to group the calculated energy ratios for the operation of the cogeneration system



**Figure 3.** The energy ratio dendrogram

depending on the obtained parameters. Figure 3 shows the results of the hierarchical grouping as a binary tree (the dendrogram).

The analysis of energy ratios demonstrated that the objects create clusters as a result of which three main groupings have emerged; the first one containing  $FESR$ ,  $\eta_{t\_EC}$  and  $\eta_{el\_EC}$ , the second comprising  $EUR$ ,  $\sigma$ ,  $P_{Nel}/P_{Ael}$ ,  $P_{Nt}/P_{At}$  and the third one comprising  $\Delta E_{ch}/E_{el}$  and  $\Delta E_{ch}/E_t$ . The smallest bond distance at the level  $y = 0.2$  is represented by the second group, which results from the fact that the ratios are distinguished by comparable variable parameters in the range of 0.69 to 0.82. The average bond distance at the level  $y = 0.29$  is comprised by the second group parameters, while the bond size for the third group  $y = 0.63$ . The dendrogram also contains bonds between the major groups, which are  $y = 1.98$  and  $y = 3.38$  respectively. The analysis of the cogeneration system energy efficiency on the basis of the ratios showed that the fuel chemical energy conversion efficiency at the current level of operation of the unit is acceptable, despite the rated values not having been reached. The experience of other landfill degassing plant operators, as well as biogas generation simulations indicate that the biogas amount will decrease in the next years. Such a situation will result in a reduction of the biogas stream by approximately 15% over 5 years and approximately 40% over 10 years. Given that amount of fuel, as well as the decreasing methane content in the biogas, the further operation of the CHP unit after 10 years will be impossible. In such a situation, the plant manager should have an alternative plan, e.g. biogas combustion in a gas boiler (heat generation for the facility) and the use of a gas turbine to generate electrical energy fuels [Gong et al., 2018]. The relationship between the amount of fuel (biogas) consumed over 5 years and the amount of heat and electrical energy generated in the CHP unit is shown in Figure 4.

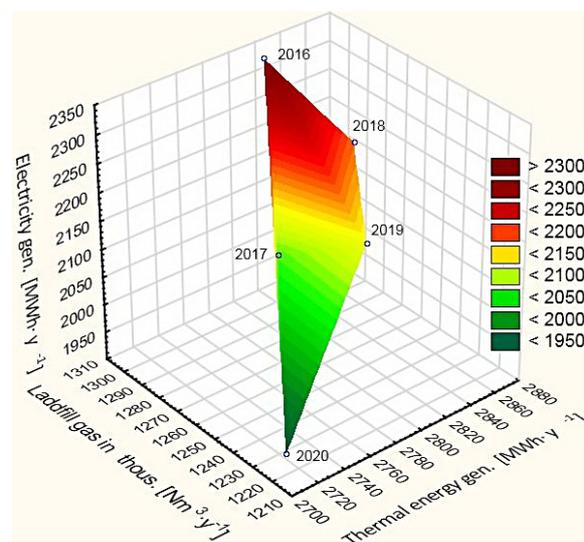
The average amount of electrical energy generated in the CHP unit over 5 years was  $1.68 \text{ kW}\cdot\text{m}^{-3}$ , and the amount of heat was  $2.21 \text{ kW}\cdot\text{m}^{-3}$ . The total amount of energy generated from  $1 \text{ m}^3$  of biogas in the cogeneration plant was  $3.98 \text{ kW}\cdot\text{m}^{-3}$ , with the average calorific value over 5 years equal to  $5.5 \text{ kW}\cdot\text{m}^{-3}$ . The actual values confirm the calculated the total energy utilisation factor (EUF) of the CHP for 5 years amounting to 0.72. The technological aspect area is the basis for energy generation in CHP units; however, without proper operation and supervision of the

plant at the required technical level, the reliability of CHP operation may be jeopardized. As the persons involved in the operation of the cogeneration system at a landfill work in the multitasking system, efficient time schedules must be prepared which are less sensitive to the disturbance caused by uncontrolled factors, such as absence from work, the need for a transfer to another position or the termination of the employment relationship. Having human resources with the required competencies in place is a determinant factor for the organisation culture and, consequently, ensures the correct operation of the cogeneration system at a landfill [Bocewicz et al., 2012]. When used locally, captured and conditioned landfill biogas improves the plant operator's energy and economic balance. Methane utilisation is also an important environmental aspect.

### Energy utilisation at the facility

Heat and electrical energy produced in the CHP system powered by landfill biogas should be utilised in the best possible way, in which the in-house requirements of the facility, i.e. WPE, are the priority, with the requirements of other customers coming next. The energy balance and the method of energy utilisation in 2016–2020 are presented in Table 3.

The CHP plant located at the landfill has generated an average of 2131.22 MWh of electrical energy in the last 5 years, of which 80.19% (1700.46 MWh) is used for the in-house requirements of the facility, and the rest is sold as a



**Figure 4.** The correlation between the amount of biogas consumed and energy produced

**Table 3.** Energy and the ways of its utilisation at the facility [own study]

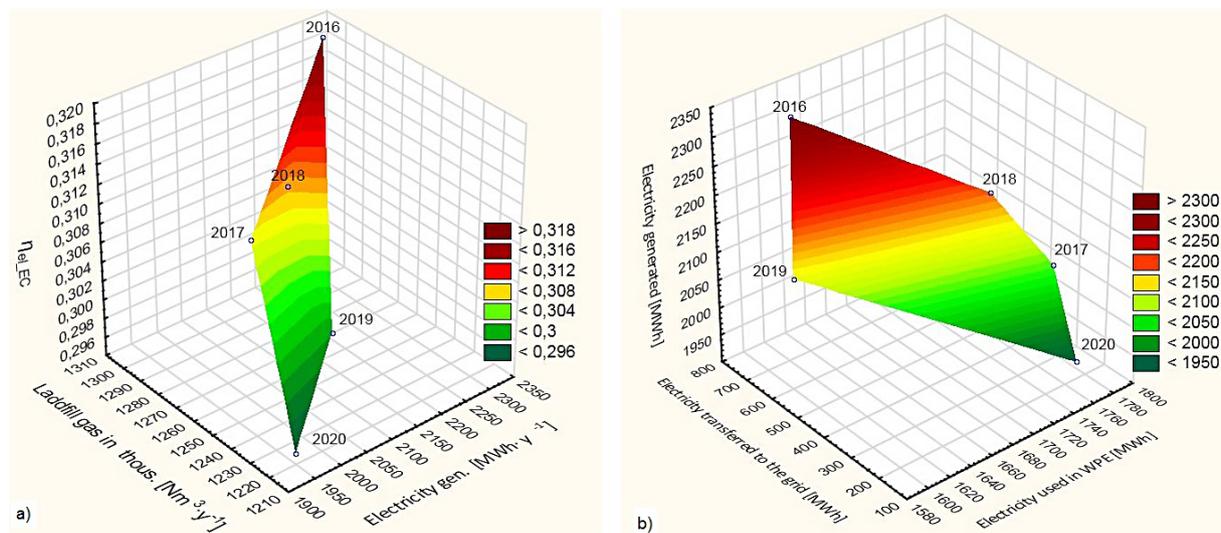
Parameter	Unit	2016	2017	2018	2019	2020	Average
Electrical energy							
Used by the WPE	MWh %	1627.63 69.92	1773.64 85.54	1747.61 80.11	1588.78 74.64	1764.65 90.74	1700.46 80.19
Transmitted to the power grid	MWh %	700.19 30.08	299.77 14.46	433.99 19.89	539.85 25.36	180.00 9.26	430.76 19.81
Heat energy							
Used by the WPE	MWh %	1842.51 65.30	1857.06 66.60	1929.90 67.40	1928.47 68.50	1885.20 69.60	1888.63 67.48
Not utilised	MWh %	979.10 34.70	931.32 33.40	933.45 32.60	886.82 31.50	823.42 30.40	910.82 32.52

result of transmission to the external power grid. Figure 5a shows the amount of electrical energy produced from biogas in the function of electrical energy generation efficiency.

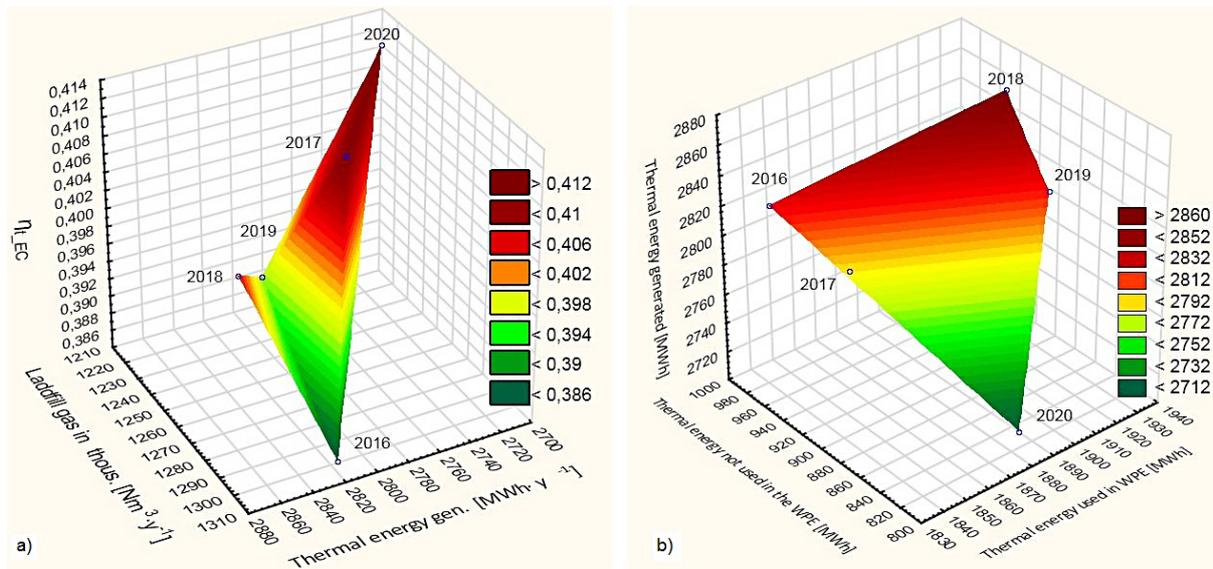
Electrical energy is used, first of all, to supply the electrical devices of a landfill including the mechanical-biological waste treatment plant and the RDF station, such electrical energy fully covering the electrical energy demand of the entire facility. The highest efficiency of electricity generation  $\eta_{el\_EC}$  amounting to 0.33, occurred in 2016, when landfill biogas was used in the amount of 1,218,451 m<sup>3</sup>·year<sup>-1</sup>, which resulted in electricity production in the amount of 2,327.82 MWh·year<sup>-1</sup>. The mutual correlations between the amount of electrical energy produced and its utilisation are shown in Figure 5b.

The energy efficiency of a landfill as a waste disposal facility is defined by the amount of its own electricity generated in the CHP plant for the facility needs. The largest amount of electricity

used by WPE occurred in 2020, which accounted for 90.74 of its total production. In order to manage the electrical energy generation and distribution process efficiently, it is necessary to adhere to the schedule of inspections and repairs and remove failures competently. The examples of operating cogeneration plants clearly show that the maximum plant operation time per year is a function of many components and ranges from 80 to 96% of the cogeneration unit availability. These components include: the punctuality and quality of service, which is crucial, and the failures that extend the downtime of the CHP system. The analysed cogeneration plant at a landfill operated for an average of 7848 hours per year over 5 years, which is 89.6% of the available time [Dużyński, 2011]. Heat utilisation at the WPE is another challenge faced by the producer of energy in a cogeneration system. As there is no option of the heat distribution network connection, heat should be used at the place where it



**Figure 5.** a) The relationship between the amount of electrical energy produced and generation efficiency; b) utilisation of electrical energy generated



**Figure 6.** a) The relationship between the amount of heat generated and production efficiency; b) heat utilisation at the facility

is produced. The amount of heat produced from biogas in the function of its production efficiency is shown in Figure 6a.

The highest efficiency of heat generation in the CHP installation at the landfill occurred in 2017 and 2022 and was 42%. This value did not contribute to the achievement of the highest heat production, because in those years, due to the small flux of obtained biogas and its low energy value. Figure 6b shows how the amount of heat produced is related to its utilisation in WPE.

To optimize the energy economy at the landfill, the process of combined energy generation should be correlated with effective energy utilisation. At the facility which was the subject of the study, the five year average showed that 2799.45 MWh of heat was produced per year, of which 1888.63 MWh was utilised for welfare and technological purposes. The remaining 910.82 MWh of heat per year is not utilised. Taking into account the available methods of heat utilisation, the need to utilize 100 % of heat should be considered. Supporting the process of leachate removal by partial leachate vaporisation with the use of heat from the cogeneration process may be one of the ways of using the heat generated in a landfill WPE. That method is most commonly used at landfill sites in southern Spain. Vaporised leachate becomes more concentrated, which facilitates its neutralisation [Chacartegui et al., 2015; Gewald et al., 2012]. The unused excess heat may also be used in Organic Rankine Cycle (ORC) systems which offer heat conversion to electrical

energy. The system based on the Rankine cycle is a two-circuit system: one circuit is created by the so-called indirect factor i.e. the heating factor, e.g. thermal oil, while the other circuit, the main one, is created by the working medium i.e. an organic fluid. Solutions of that type are successfully used all over the world within a wide power range [Kouvo, 2016]. Unused heat can also be a potential source for cold generation for office, welfare and engineering room air conditioning. The absorption chillers used in that technology, which utilise heat as the lower-temperature source, perform the process of heat-to-cold conversion and achieve the Coefficient Of Performance (COP) over 1.0. That solution is an expansion of the cogeneration system into a trigeneration system in which, in addition to heat and electrical energy, cold is also produced [Li et al., 2017].

A UK biogas utilisation environmental research showed that increasing the landfill gas recovery from 53 to 75% and using that gas in CHP systems will increase energy production by 35 to 50%, thus reducing the carbon footprint by half [Jeswani et al., 2013]. In Finland, however, the use of biomass for biogas production for energy production follows from the fact that biomass is a CO<sub>2</sub> neutral fuel and its potential is obtained from local resources. The efficient use of biogas in small-scale CHP plants requires those plants to achieve a higher level of fuel energy conversion efficiency than at present. For that purpose, mainly new technologies should be used, the purpose of which is to increase energy

conversion on a small scale in micro and small generation units [IRENA, 2018]. The need for the efficient use of chemical energy in the fuel (biogas) is recommended at the EU level by the European Commission. Where biogas is used locally in a cogeneration unit to produce heat and electrical energy, and heat from CHP is treated as a by-product, increased net heat utilisation from a CHP will reduce the resulting electrical energy production costs [Buck et al., 2019; Kampman et al., 2020]. Rational landfill biogas management is an important element of local energy security and circular economy. In this context, particularly important is the need to maintain the high efficiency of the biogas chemical energy conversion process in cogeneration units and the effective use of that process to save bio-fuel, i.e. a renewable energy source.

## CONCLUSIONS

Heat and electrical energy production in cogeneration processes, consisting in the conversion of fuel (biogas) chemical energy, translates into the utilisation of a renewable energy source. In order for this process to be effective in terms of quantity and quality in relation to heat and electrical energy produced, the process should be subjected to an in-depth energy analysis. On the basis of the operating data, measurements and analyses, the basic CHP operating factors were determined, which show that the total CHP plant efficiency calculated on the basis of the operating parameters was 0.71, which is in the range of 0.7 to 0.9 for 0.5 MW reciprocating gas engines. The lower total efficiency achieved by the unit and the lower fuel chemical conversion efficiency in the CHP plant results from the failure to use the rated thermal and electric power of the CHP unit, which is caused by an insufficient biogas stream from the landfill. The FESR fuel (biogas) energy savings ratio, which was calculated too, as a result of combined heat and electrical energy production, showed energy savings of 2906.93MWh on the fuel (biogas) as a five-year average. In combined heat and power systems, FESR is from 0.3 to 0.5. The obtained average result for 5 years at the level of 0.42 for the landfill plant under analysis is a good result. The analysis of energy generation efficiency for a biogas cogeneration unit located at landfill, as performed in the study, showed the validity of the application of such a solution.

The main benefit for the landfill as one of the WPE facilities is having its own source of heat and electrical energy, which fully covers the energy demand for welfare social and technological purposes during the year. In order to optimize the use of heat, 33.52% of which is not utilized, the option of its use in other processes in the facility should be taken into consideration. The capture of biogas and the utilisation of methane contained in biogas make a significant contribution to the reduction of emission of that greenhouse gas. This solution speaks in favour of the implementation of modern energy technologies in the CHP area in order to reduce the adverse environmental impact of the landfill and improve the utilisation of renewable energy sources. The use of renewable sources of energy from biomass means the potential of biomass local utilisation, which is correlated with sustainable development. Renewable gas fuels such as biogas, biomethane and bio hydrogen as the sources of energy will play an increasingly important role in the nearest future in different sectors of the various states focused on the so-called bio-economy.

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