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The Use of Methane from Landfill Gas to Generate Energy and its Management at the Plant as a Way to Reduce Climate Change

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Abstract: In the era of consumerism, increasing amounts of waste constitute an ecological and logistical problem. Waste landfills are increasingly installing degassing installations and obtaining landfill gas containing methane as a renewable energy source. The work aims to analyse the production and management of energy at a selected waste landfill operating a cogeneration unit. The role of landfill gas, its production amount, composition and use in cogeneration units to produce energy were analysed. The biogas produced is used to produce electricity and heat at the analysed waste treatment plant. The research showed the extraction and energy use of biogas in the amount of 916,876 m^3 per year, which produced 1,558 MWh of electricity and 1,589 MWh of heat in cogeneration. The electricity produced is a power source for the enterprise and its infrastructure, and the surplus is sent to the power grid. However, 34% of the heat is used for the plant's needs. The remaining part can be used in ORC systems (Organic Rankine Cycle). The tests showed that the total efficiency of energy production is 85.80%, with the availability index of the cogeneration unit amounting to 0.95. The energetic use of landfill gas containing methane is an optimal solution from an energy and environmental perspective to limit climate change.

Keywords: methane, biogas, emissions, landfill gas, atmosphere

1. Introduction

Energy recovery in the form of biogas from landfills is one of the solutions for obtaining energy from renewable sources. Appropriate regulations regulate it. The energetic use of methane contained in landfill gas in combined heat and power plants (CHP) is an optimal solution from an environmental and energy perspective (Delgado et al. 2023, Ciuła et al. 2023a). A legal act in force in the European Union specifies the rules for producing electricity from renewable energy sources (RES): Directive 2009/28/EC of the European Parliament and of the Council of April 23 2009, on the promotion of the use of energy from renewable sources (Directive 2009/28/EC). In Poland, the essential legal act regulating the principles of renewable energy production is currently the Regulation of the Minister of Economy of August 14, 2008 on the detailed scope of obligations to obtain and submit for redemption certificates of origin, payment of the substitute fee and purchase of electricity and heat generated from renewable energy sources and the obligation to confirm data on the amount of electricity generated from a renewable energy source (as amended) (Journal of Laws No. 156, item 969, of 2008, Journal of Laws No. 34, item 182, 2010). The regulation specifies requirements regarding the measurement, registration and method of calculating the amount of electricity or heat generated from renewable energy sources using installations using energy carriers in the energy production process, as well as the places of measurement of the amount of electricity generated from renewable energy sources to fulfil the obligation to confirm data regarding this energy production. One such source is landfills, where a continuous increase in the amount of waste generated has been observed in recent years (Sokka et al. 2007, Przydat & Basta 2020, Kwaśnicki et al. 2023). According to data published by the World Bank, 2.01 billion tons of municipal waste was generated in 2016, and in 2050, it is expected that this value will reach a total of 3.40 billion tons (Kaza et al. 2018, Duan et al. 2021, Yuan et al. 2022). As a result of such disturbing data, the issue of landfill recultivation should be considered (Gronba-Chyła & Generowicz 2020). One such method is introducing the collection and energy use of biogas produced in landfills. This method is classified as renewable energy. To use biogas for energy, it is most often burned in cogeneration units after purification, which effectively use the energy contained in biogas, converting it into electricity and heat. Biogas is actively taken from the landfill to accelerate its recultivation and neutralise odours, using the so-called wells connected with special perforated pipes and then supplying biogas to the compression station, where devices adjust its parameters and transfer it to the cogeneration unit or units. Consequently, it is converted into thermal or electrical energy (Abanades et al. 2022, Zwolińska & Basta 2024). On the European scale, the amount of biogas produced is dominated by Germany, where the annual production is 120 TWh, Great Britain with

25 TWh and 9 TWh in France. Compared to these countries, the total production capacity of Denmark and the Netherlands is approximately 4 TWh, and the share of other countries is less than 3 TWh (Bioenergy 2019).

Municipal waste treatment plants often refer to their enterprises as "bioreactors" because, in one limited space, several transformations of organic matter naturally take place, resulting in the formation of biogas with a different spectrum of content of components such as methane, carbon dioxide or nitrogen (Nanda & Berutti 2021, Labatutat et al. 2011, Li et al. 2013). This fuel's composition varies at the operation stage, after waste storage, and after recultivation. The intensity and energy efficiency of biogas are mainly determined by the time of waste deposition and environmental conditions (Szyszlak-Bargłowicz et al. 2012, Angelidaki et al. 2005). The formation of biogas is a series of biochemical processes that primarily require an initial raw material: biomass, i.e., an organic substance unused by humans and unable to be re-used (Ciuła et al. 2023b). However, two concepts should be distinguished here. Organic substances and biomass are distinguished by how they are created, because biomass uses natural processes, i.e., the sun, living organisms, and organic substances originate from chemical and industrial syntheses, which require large amounts of work to decompose into simple organic compounds. Additionally, organic compounds originating from industrial processes during decomposition in municipal waste deposits also contribute to the formation of biogas (Stolze et al. 2015, Kowalski et al. 2011).

The chemical and biochemical processes leading to biogas creation occur during five primary phases. The first phase involves the substance's aerobic decomposition, and its duration is, on average, from 7 to 31 days. The next stage is the acid fermentation phase, lasting from 1 to 6 months, from which the fractions smoothly move to the next phase of unstable methanogenesis, lasting from 3 to 36 months. The last stage is the phase of stable methanogenesis, from 5 to 50 years, followed by the cessation of decomposition from 10 to 40 years (Nanda & Berutti 2021, Davidsson 2007). The resulting biogas is primarily a mixture of methane CH_4 and non-flammable carbon dioxide CO_2 in a 60% and 40% ratio, respectively. The mixture with carbon dioxide reduces the energy value of this biofuel, and obtaining it from landfills requires companies to install special shafts to suck in gases so that it can be converted into both electricity and heat in further processes. Additionally, the obtained biogas, the methane value of which exceeds 40% in the entire mixture, is often used as a fuel to drive gas turbines and produce energy, as a result of which it can replace natural gas or propane-butane (Panagiotis & Irini 2018). Attention should also be paid to the fact that methane cannot be converted from all raw materials; specialised equipment is necessary to convert methane (Bochmann & Montgomery 2013).

The raw material created in a landfill, straight from gas wells, flows through several monitoring and filtering devices up to the compressor and flare, where some of the ingredients are burned. Then, after checking the produced fuel, it is sent to heating networks and power lines or used in technological processes in natural gas networks. Environmental conditions play a vital role in the biogas production process, affecting the speed of the entire process (Groba-Chyla et al. 2024). The age of the deposit, humidity, temperature, structure of waste, or the method of collecting and storing the raw material in the landfill determines the content of the mixture of necessary gases, in particular for organic waste, which most often constitutes the raw material for the production of biogas from waste (Antoine Beylot et al. 2018, Luca & Cossu 2015).

The degassing of landfills can be done in two ways. Passive degassing, where biogas flows out through degassing wells through the overpressure prevailing in the landfill, and active degassing, when the gas is sucked out by a special installation as a result of creating a negative pressure. Each method requires horizontal or vertical perforated pipes placed in the landfill. Comparing both of these systems, we can achieve 50% speed in the case of the active deaeration system and only 25% in the case of the passive one. The indicator of biogas production with active and passive systems differs significantly. Active degassing has a clear advantage, being approximately half as high as the passive system. Still, both of these methods are, on average, approximately half lower than the biogas production potential. The landfill gas must be deprived of moisture and solid particles in each method and then compressed. The most dangerous pollutants in energy production from biogas are hydrogen sulfide, siloxanes, ammonia, aromatic hydrocarbons, and halogens (Hebda & Kołodziejak 2022, Nanda & Berutti 2021). An essential element of obtaining biogas at a landfill is an installation consisting of elements extracting biogas from the ground, collectors transmitting the gas and a collection station.

Landfill gas is used primarily in cogeneration units or directly burned in boilers. It applies not only to landfill gas but also to other types of biogas, agricultural, municipal or produced in sewage treatment plants due to fermentation of sewage sludge (Ciuła et al. 2023c). It must be appropriately purified technologically, then it can effectively help in the production of thermal, electrical or mechanical energy and can also be used in gas turbines, microturbines and fuel cells in CHP units (Kaparaju & Rintala 2013, Nikpey Somehsaraei et al. 2014). At the beginning of the process, the biogas is initially purified, impurities are removed, and then sent to the CHP unit or directly used in boilers. Pollutants contained in landfill gas contribute to mechanical damage, e.g. caused by corrosion in gas engines that are the driving units for electric generators (Kowalski et al. 2022). Gas transmission to the CHP unit allows for producing electricity and/or heat in cogeneration systems (Muche et al. 2016, Damyanova & Beschkov 2020).

It is also worth considering that even proper management of municipal waste in a landfill generates an environmental threat in the form of leachates and landfill gas produced in the waste deposit (Nanda & Berruti 2021, Balcerzak et al. 2014). Leachate from landfills threatens the contamination of soil, surface and groundwater, and their uncontrolled migration may lead to the contamination of individual and collective water intakes, threatening the health of people using these water reservoirs (Babenko et al. 2020, Wysowska & Kicińska 2021). Landfills need to monitor both surface and groundwater, especially in the vicinity of the landfill, thus preventing potential dangers of poisoning (Wysowska et al. 2022). One of the measures to prevent leachate from entering the environment is using a drainage system over foil, pre-treatment with aeration or purification before introducing it into sanitary sewage systems (Ciuła et al. 2019). In this way, it is possible to safely collect and treat leachate together with other municipal sewage and send it to sewage treatment plants. Sewage sludge generated at sewage treatment plants may constitute fractions of combustible waste as fuel, used to generate electricity and heat in waste transformation installations (Gaska et al. 2019, Xu et al. 2022).

This work aims to analyse the method of generating and managing energy at a selected waste landfill with a cogeneration unit, taking into account the method of managing the cogeneration unit and energy at the waste landfill. The current state of technology will be analysed regarding municipal waste landfills, biomass, landfill biogas production and the management of heat energy and electricity generated in the cogeneration unit by conducting a qualitative and quantitative analysis of the energy generated in the waste landfill, the efficiency of electricity and heat production in the unit. CHP and energy management at a landfill.

2. Tools and Methods

2.1. Object of research

The analysed research object is located at a waste landfill, part of the Municipal Waste Disposal Plant. The plant accepts approximately 96,000 $Mg \cdot rok^{-1}$ waste annually, mainly waste collected selectively at source (paper, plastics, metals, glass, green waste), mixed municipal waste, bulky waste, used electrical and electronic equipment, as well as problematic waste (hazardous from the municipal waste stream).

The plant operates an installation for the energy use of biogas, a cogeneration unit with an electrical power of 250 kW and a thermal power of 265 kW. Landfill biogas obtained from waste deposits using the landfill degassing installation is subjected to a purification process in the conditioning installation. This installation includes a biogas drying module, silicon compounds and siloxanes removal in a filter containing activated carbon, and a biogas desulfurisation module. The electricity produced in the cogeneration unit is first used for the facility's needs, while its surplus is sent to the external power grid. The heat recovered from the cogeneration process is used for social purposes at the Plant (preparation of domestic hot water and central heating), while its surplus is not utilised.

2.2. Research methodology

The study examined the quality of purified landfill gas, which is the fuel for a cogeneration unit. For this purpose, gas parameters were determined, including humidity, methane content, calorific value and other pollutants: carbon dioxide (CO_2), oxygen (O_2), nitrogen (N_2), hydrogen sulfide (H_2S), sulfur (S), ammonia (NH_3), chlorine (CL), silicon (Si) and siloxanes. The research was performed in an accredited laboratory based on applicable procedures and standards. Data provided by the installation operator regarding the amount of biogas obtained from the waste landfill for two years was used to analyse the energy production and management processes at the Plant. The amount of electricity and heat produced in the cogeneration unit and its management method (use for the facility's needs, transmission to the electricity network and heat network) were expressed as quantitative values for the examined period and recorded in [MWh].

3. Research Results and Discussion

3.1. Biogas quality analysis

The landfill gas tested was taken from the valve at the biogas inlet to the gas engine. Biogas was purified in the conditioning station, where in the initial phase, it was deprived of moisture – dew point, then it went to a tank with a capacity of approx. 1 m^3 filled with activated carbon. In this filter, the gas was cleaned of siloxanes and then went to another tank with a capacity of approx. 6 m^3, filled with Sulfur E granules, where it is finally cleaned. The biogas conditioning installation reduces the main pollutants in biogas, including CO_2, O_2,

N_2, H_2S, S, NH_3, Cl, Si, and siloxanes. The purpose of the biogas test was to check whether the gas parameters meet the quality requirements specified by the gas engine manufacturer.

The test results, presented in Table 1, showed the values of the analysed parameters as follows: siloxanes (15 mg·Nm^{-3}), sulphur (120 mg·Nm^{-3}) and silicon (2,74 mg·Nm^{-3}), hydrogen sulfide (50 mg·Nm^{-3}, below 10 ppm). These values are within the generally accepted limits of their permissible concentration in biogas (Santos-Clotas et al. 2020), which ranges for siloxane values up to 120 mg·Nm^{-3}. In their publication, Santos-Clotas et al. (2020) propose not to use them for gas engines powered by landfill biogas, as it could pose a risk of permanent damage. The permissible ranges for sulfur and silicon have been the subject of research for years, which show that the upper limits of silicon content should be below 5 mg·Nm^{-3}, while for sulfur, this value should be below 120 mg·Nm^{-3} (Molenda & Steczko 2000).

Table 1. Basic parameters of landfill gas during tests (own study)

Parameter	Contaminant content in biogas	Unit
Relative humidity	65.6	%
Carbon dioxide CO_2	41.3	% vol.
Oxygen O_2	0.004	% vol.
Nitrogen N_2	7.78	% vol.
Hydrogen sulfide H_2S	50	mg·Nm^{-3}
Methane CH_4	49.9	% vol.
Sulfur S	120	mg·Nm^{-3}
Ammonia NH_3	34.9	mg·Nm^{-3}
Chlorine Cl	<2	mg·Nm^{-3}
Siloxanes	15	mg·Nm^{-3}
Silicon Si	2.74	mg·Nm^{-3}
Gas density	1.212	kg·m^{-3}

The hydrogen sulphide content in landfill biogas adversely affects the functioning of cogeneration units, resulting in frequent failures of gas engines. Due to the above, it is necessary to reduce hydrogen sulphide to a level below 100 mg·Nm^{-3}, which guarantees stable and failure-free operation of the cogeneration unit (Nitkiewicz & Duda 2011). Moreover, typical concentrations of siloxanes in biogas in landfills range from 1 to 400 mg·Nm^{-3} (Dewil et al. 2006). There is no specific legislation regulating the amount of siloxanes in biogas in mg·Nm^{-3} order to avoid damage during its combustion, but attempts have been made to limit these concentrations from 0.3 to 28.0 mg·Nm^{-3} (Gaj 2017). The obtained biogas is also characterised by a humidity of 65.6%, which corresponds to generally accepted assumptions according to which this humidity should not exceed 80-90% (Klimek 2009, Wiśniewska 2020). If the upper limit is exceeded, the installation could fail or be destroyed, or it could accelerate the destruction of the installation. The purification system ensures that the quality of biogas meets the requirements of the gas engine manufacturer.

The main component of landfill biogas is methane, one of the main sources of greenhouse gases (Ramprasad et al. 2022, Zwolińska & Basta 2024). Its production occurs during the four-phase fermentation of raw materials collected in landfills, and its composition largely depends on the type of raw materials from which it is obtained. It is assumed that landfills contain nearly 50-60% of organic substances, which undergo anaerobic decomposition during waste deposition, contributing to a higher percentage of methane emissions from the landfill (Ramprasad et al. 2022). Based on research on the ratio of the amount of biogas production to the tonnage of waste, it appears that, on average, 0.024 tons of CH_4·ton^{-1} of waste is captured (Themelis & Bourtsalas 2021). Table 2 shows the weighted average values of methane in biogas obtained at the Plant from the waste landfill in 2020 and 2021.

The methane content in biogas per year is 42.82% in 2020 and 43.44% in 2021. These values indicate the optimal methane content in biogas because it is assumed that biogas plants cooperating with cogeneration systems can burn gas with methane content, with its average content of approximately 45% (Igliński et al. 2020). These values result from the natural properties of landfill biogas, as it has a lower calorific value compared to natural gas due to the content of both methane (CH_4) and the addition of 25-55% carbon dioxide (CO_2) and other pollutants (Kadam & Panwar 2017).

Table 2. Methane content in biogas for 2020 and 2021 (own study)

Month	Weighted average methane content in biogas in 2020 [%]	Weighted average methane content in biogas in 2021 [%]
January	46.86	38.72
February	46.12	39.40
March	45.43	41.22
April	43.82	45.46
May	42.93	47.09
June	42.18	47.61
July	40.21	49.08
August	42.46	44.28
September	41.67	42.45
October	41.03	43.79
November	41.66	40.84
December	39.42	41.37
Annual average	42.82	43.44

Landfill gas obtained from waste deposits is produced due to waste degradation and its direct oxidation into the atmosphere, and it has been the subject of research for many years. (Duan et al. 2021, Yuan et al. 2022). Biogas produced in anaerobic conditions contains methane (CH_4) and carbon dioxide (CO_2), as well as other gases such as nitrogen (N_2), oxygen (O_2) and hydrogen sulfide (H_2S), benzene (C_6H_6) and mercury vapour (Oonk 1994, Krause et al. 2016). The research carried out shows that in 2017, the largest share of total greenhouse gas emissions had CO_2 (about 76%) and CH_4 (about 18%) (Mikhaylov et al. 2020). These compounds have an inherent impact on global warming of up to 94%. It is necessary to develop methods of utilisation and reduction of CO_2 and CH_4 as fuel. One such method is to convert compounds generated in a landfill into electricity and/or heat using a generation unit (Jang et al. 2022). Energy yield from landfills depends on the amount of biogas produced. Table 3 shows, in detail, divided by month, the amount of biogas produced at the landfill in 2020 and 2021.

Table 3. Amount of biogas produced at the waste treatment plant in individual months of 2020 and 2021 (own study)

Month	Biogas in 2020 [m^3]	Biogas in 2021 [m^3]
January	82,897	82,063
February	73,167	67,557
March	89,910	76,607
April	87,077	72,272
May	76,929	82,950
June	75,389	76,177
July	84,526	64,803
August	69,519	78,148
September	68,675	65,585
October	78,212	69,859
November	86,822	80,195
December	81,334	63,079
Together	954,457	879,295

In 2020, the amount of biogas obtained from approximately 96,000 $Mg \cdot rok^{-1}$ of waste accepted at the waste treatment plant amounted to 954,457 m^3. In 2021, this value decreased slightly to 878,295 m^3. It is estimated that from 1 Mg of municipal waste, 60 to 180 m^3 of biogas can be produced (Mavridis & Voudrias 2021). The values of obtaining the amount of biogas at the analysed facility correspond to the adopted ratio of the amount of waste to the amount of biogas produced by it, suggesting the proper functioning of the landfill and the landfill gas treatment plant.

3.2. Energy management on the premises of the plant

As part of the quantitative and qualitative analysis of biogas produced at the waste treatment plant, parameters regarding the amount of electricity and heat produced in the cogeneration unit operated at the plant were considered. The research results showed that the average methane content of approximately 43% maintains the stability of the methane production process, which implies the presence of a current methanogenic phase in the landfill and constitutes the optimal energy value of biogas as a fuel for the gas engine. The process during which energy is received involves degassing the deposit, compressing and dehydrating landfill gas and delivering this fuel to a cogeneration unit, where it is burned and converted during the chemical conversion of fuel (methane) into work and heat, and at a later stage in the generator into electricity. In the analysed company, from the data obtained, it was read that the amount of landfill biogas produced in 2020 was 954,457 m^3, and in 2021 879,295 m^3, which proves the correct operation of the landfill and devices extracting biogas from waste deposits, the average value the heating capacity of biogas ranges monthly from approximately 13 to 17 $MJ·m^{-3}$, and on an annual basis it is over 15 $MJ·m^{-3}$. The percentage of methane content in the biogas indicates the content ranges from about 40% to about 50% monthly; annually, these values fluctuate around 43%. Detailed data on energy management at the plant are presented in Figure 1.

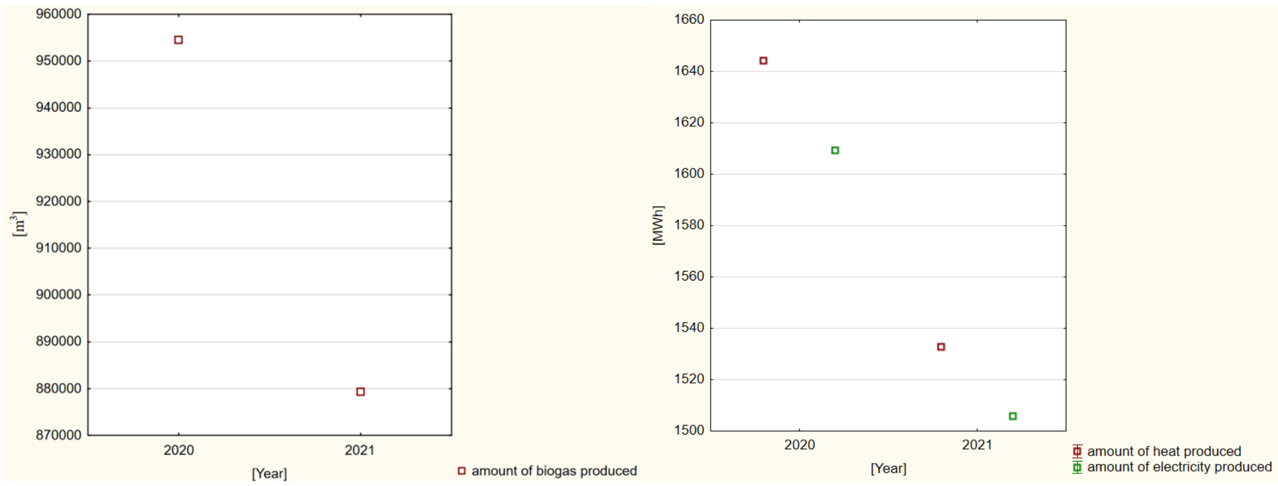

Fig. 1. Management of energy generated in cogeneration in the analysed years of operation of the waste treatment facility, taking into account the amount of energy consumption (own study)

The quantitative analysis showed that the waste landfill managed to produce a total of 1,609.22 MWh from 954,457.0 m^3 of biogas in 2020 and 2021 from 879,295.0 m^3 of biogas, 1,505.65 MWh of electricity (Figure 1). Additionally, biogas was used at the plant for heating purposes, receiving heat from the biogas engine through engine cooling water and exhaust gases 1,644.24 MWh of heat was produced in 2020 and 1,532.8 MWh in 2021. These data indicate the correct functioning of the cogeneration unit. Developing methods for processing waste for energy is also associated with long-term and future environmental protection activities. According to research, the amount of waste will increase yearly, so it is essential to effectively transform waste into energy benefits (Mavridis & Voudrias 2021). Figure 2 shows the quantitative electricity production and its management at the waste treatment plant.

From the analysed electricity source, located on the premises of the waste treatment plant, approximately 884.81 MWh was used for its own needs in 2020; in 2021, it was 948.99 MWh, using the energy mainly to power machines and electrical devices and facility lighting. Thanks to the production of its own electricity, the company purchased only approximately 196.06 MWh in 2020 and 294.76 MWh in 2021; these values may result from possible plant downtime or emergencies. 724.41 MWh were sold in 2020 and 556.67 MWh in 2021. The electricity produced in the cogeneration unit is first used for the facility's needs, while its surplus is sent to the external power grid.

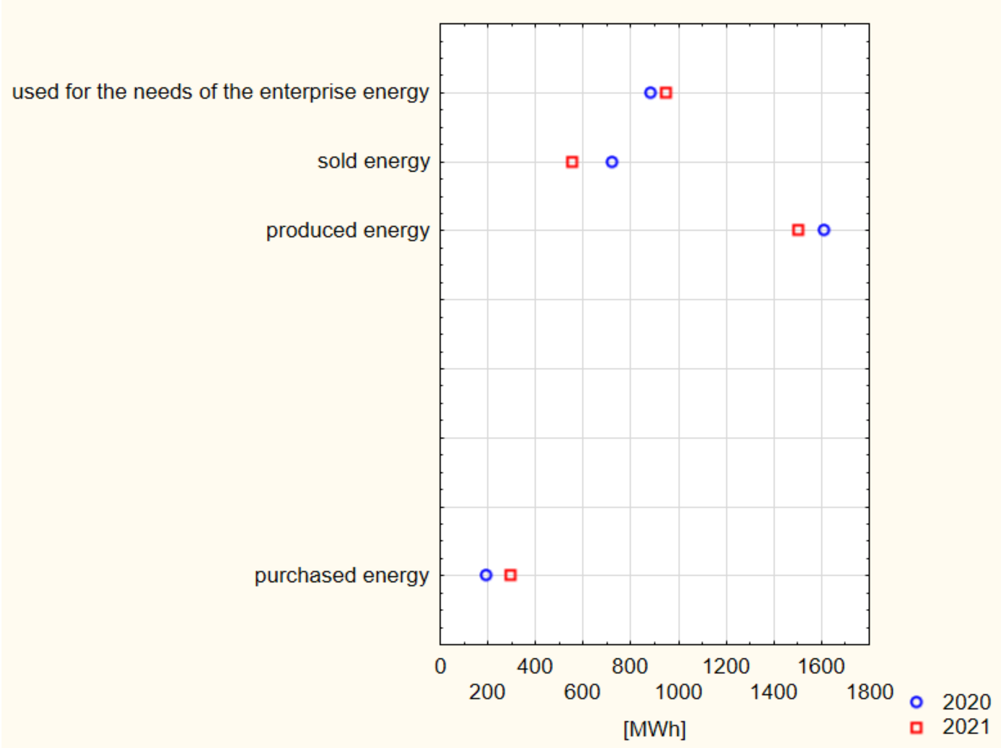

Fig. 2. Quantitative production of electricity and its management at the waste treatment plant (own study)

An additional benefit of using landfill biogas is the ability to recover heat from the cogeneration process and use it for social purposes at the plant (preparation of domestic hot water and central heating). Figure 3 shows detailed heat management at the plant.

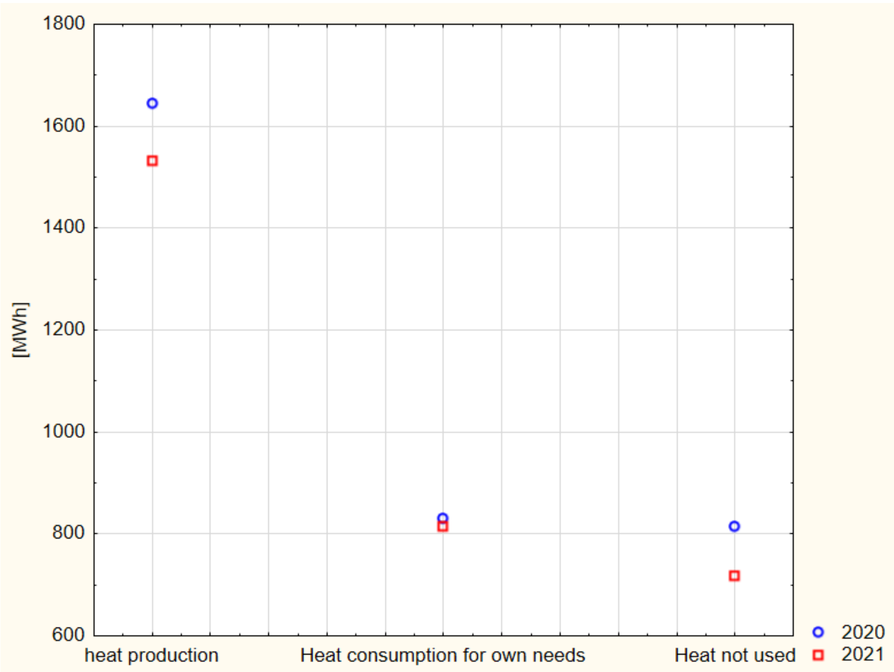

Fig. 3. Quantitative production of thermal energy and its management at the waste treatment plant (own study)

In 2020, 1,644.24 MWh of heat was produced in the analysed plant; in 2021, it was 1,532.80 MWh. Of this amount of thermal energy, 829.80 MWh was used for the plant's needs in 2020, and in 2021 it was 815.30 MWh. The difference between the energy produced and consumed was not utilised. The amount of thermal energy unused in the facility is much greater than the energy utilised. Therefore, it is necessary to consider how to use the surplus of this energy. Due to the lack of access to the heating network, it is impossible to transmit excess heat energy for heating purposes. Also, due to the considerable distance of the landfill from residential buildings, constructing a heating network to supply buildings with heat energy is not economically viable.

One way to utilise surplus thermal energy is to convert thermal energy into electricity or heat conversion using ORC (Organic Rankine Cycle) systems. It is one of the alternative ways of using surplus heat. Moreover, the production of electricity from biogas can take place both on and off the grid, which makes this fuel an ideal source of energy for decentralised generation (Kabeyi & Olanrewaju 2022, Kabeyi & Olanrewaju 2020, Zwolińska & Basta 2024).

The surplus heat generated in the waste treatment plant could be converted into electricity thanks to an additional system equipped with an evaporator, a turbine and an alternating current generator. The use of the ORC system in cogeneration systems powered by landfill biogas was proposed in the work by Caoi et al. (2021), pointing primarily to the issue of replacing fossil fuels with conventional fuels, and thus the use of landfill biogas in cogeneration systems. In this case, driving a gas turbine with biogas, from a thermodynamic and economic point of view, is resistant to changing temperature conditions and can produce electricity and heat (Barragán-Escandón et al. 2020). In ORC systems, the heat supplied to the evaporator causes the working medium to evaporate, contributing to the expansion of the steam in the turbine compressor and then changing in the alternating current generator, which is connected to the expansion machine, into electricity. After this treatment, the expanded factor, usually superheated steam, condenses and is pumped back into the evaporator, and the cycle repeats (Minea 2014, Zhang et al. 2018). Heat recovery using the ORC cycle is also described in their research by Arslan and Yilmaz (2022), where they show that heat recovery using the ORC cycle and integration of recovery with electricity generation systems improves the operating parameters of the entire system and also contributes to increasing savings and reducing economic costs for the company.

Additionally, ORC technology is one of the reliable ways of converting thermal energy into electricity and is one of the more evolutionary technologies used worldwide for many years (Tartiére & Astolfi 2017). Colonna et al. (2015) also show that ORC technology is one of the most flexible technologies in terms of efficiency and temperature level, and it is often the only technology used for the conversion of external sources of thermal energy. ORC power systems are suitable for cogeneration in various variants: only heating, only cooling, but also heating and cooling, which makes this technology a popular choice for distributed energy generation. One of the advantages of ORC units, taking into account the operating period, is their low sensitivity to load changes and a wide range of stable operations, where the technological minimum is up to 10% of the nominal load (Minea 2014). Additionally, industrial ORC systems are often equipped with an automatic system for starting, synchronising with the grid and shutting down the turbine set, allowing for their flexible operation and high availability. Such a high degree of automation also reduces operating costs, and the nominal efficiency of electricity generation in the ORC reactor reaches 18%, while the efficiency of heat production is approximately 79-80%. It is possible to convert thermal energy into electricity (Kabeyi & Olanrewaju 2022). Approximately 3 W of heat must be used to produce 1 W of electricity (Kneba 2011). It is a potential development opportunity for the analysed company.

3.3. Analysis of the efficiency of heat and electricity production

Based on the available data, it is also possible to analyse the electricity and heat production efficiency in the CHP unit. They are carried out as part of the quantitative and qualitative analysis of energy management at the waste treatment plant to perform calculations regarding the efficiency of electricity generation, heat generation efficiency, total efficiency of the heat and power plant and cogeneration indicator. As Skorek and Kalina (2005) point out, to assess the efficiency of energy production of heat and electricity, the values of indicators used in this process should be taken into account; the most frequently used indicators include:

- η_{el_EC} – efficiency of electricity generation (in a combined heat and power plant),
- η_{m_EC} – heat generation efficiency,
- η_{c_EC} – total efficiency of the combined heat and power plant,
- σ – cogeneration indicator.

The efficiency of electricity generation in a cogeneration system can be calculated using the formula presented below (Skorek & Kalina 2005).

$$\eta_{el_{EC}} = \frac{E_{el}}{PW_d} \cdot 100\% \tag{1}$$

where:
E_{el} – the amount of electricity produced in a given year [MWh],
P – the amount of fuel used to produce electricity [m^3],
W_d – the calorific value of the fuel used to produce electricity [$MWh \cdot m^{-3}$].

It was calculated that the average value of the efficiency of electricity generation for the analysed cogeneration unit system at the municipal waste treatment plant was 42.48%. The efficiency of electricity generation was calculated in the cogeneration heat and power system using the formula below (Skorek & Kalina 2005).

$$\eta_{m_{EC}} = \frac{Q}{PW_d} \, [\%] \quad (2)$$

where:
Q – the amount of heat produced in a given year [MWh],
P – the amount of fuel used to produce electricity [m^3],
W_d – the calorific value of the fuel used to produce electricity [$MWh \cdot m^{-3}$].

For the analysed cogeneration unit system was 43.33%, and the total efficiency of the cogeneration heat and power plant was calculated using the formula presented below (Skorek & Kalina 2005) and amounted to 85.8%

$$\eta_{c_{EC}} = \frac{E_{el+Q}}{PW_d} \, [\%] \quad (3)$$

where:
Q – amount of heat produced in a given year [MWh],
E_{el} – the amount of electricity produced in a given year [MWh],
P – the amount of fuel used to produce electricity [m^3],
W_d – the calorific value of the fuel used to produce electricity [$MWh \cdot m^{-3}$].

The cogeneration indicator in the analysed system can be calculated using the formula presented below (Skorek & Kalina 2005).

$$\sigma = \frac{E_{el}}{Q} \, [\%] \quad (4)$$

where:
E_{el} – the amount of electricity produced in a given year [MWh],
Q – amount of heat produced in a given year [MWh].

This indicator for the analysed facility amounted to 98.05% on average. The cogeneration indicator means the ratio of electricity generated in the cogeneration system to the amount of heat produced simultaneously (Skorek & Kalina 2005).

Table 1 presents data regarding the summary calculation of the energy efficiency produced at the plant.

Table 4. Energy production indicator in the CHP unit (own study)

Parameter name	Designation	Unit	Average value
efficiency of electricity generation (in a combined heat and power plant)	$\eta_{el_{EC}}$	%	42.48
heat generation efficiency	$\eta_{m_{EC}}$	%	43.33
overall efficiency of the combined heat and power plant	$\eta_{c_{EC}}$	%	85.80
cogeneration indicator	σ	%	98.05

From calculations regarding the efficiency of both electricity and energy production and heat, listed collectively in Table 4, it can be concluded that the efficiency of electricity generation in the analysed years is comparable to the generally accepted values for this power of the cogeneration unit in the range of 30-40%. Similarly, the total efficiency of the combined heat and power plant in the year is high and exceeds 85%, and the cogeneration indicator is close to 98%. The analysis of electricity and heat production efficiency showed the correct way to manage the biogas stream, which translates into optimising energy production.

Based on literature data, it can be assumed that the efficiency of electricity generation should range from 30 to 40%, while the efficiency of heat generation will depend on the configuration of the cogeneration unit and is most often higher than the efficiency of electricity generation (Różycki & Szramka 2001, Igliński et al. 2012). The data analysed in this work prove the correct operation of the cogeneration unit and the quality of the supplied biogas. The results of the literature analysis showed that the total efficiency of the cogeneration unit is within the range of optimal total efficiency, which ranges from 80 to 90% (Różycki & Szramka 2001, Iliew et al. 2021). Based on literature data that this indicator may exceed 90% in a properly operating cogeneration unit (Różycki & Szramka 2001), it can be concluded that with efficiencies close to 98%, the analysed cogeneration unit operates correctly, is operated properly and brings profits to the company. The analysed efficiency values of the cogeneration unit are included in generally accepted standards and prove the proper functioning of the landfill and the correct production of energy in the cogeneration system. Small exceedances of generally accepted standards regarding the efficiency of electricity generation may result from measurement data of the amount of energy generated and the amount of biogas produced, but these exceedances are small, up to approximately 3%.

3.4. Analysis of the availability of a cogeneration unit

As part of the analysis of energy management at the landfill, an analysis of the availability of the cogeneration unit operating within two years was also carried out. During the analysis, the following parameters were taken into account:

- total time equal to 8,760 h,
- time during which the installation is in use equal to 92%,
- the average amount of electricity generated in the given period equal to 1,557,435 kWh,
- average annual percentage utilisation of the generator's indicator electrical power of 77.01%,
- the power of the cogeneration unit is 250 kW,
- the period of downtime, maintenance work and failure is approximately 408 h.

Based on data obtained from the waste treatment plant, calculations were made to assess the failure indicator and availability of the analysed power unit.

Based on the available information about the maximum operating time of the cogeneration unit in the period under consideration, as well as the average time of failure during the operation of the cogeneration unit, the average annual operating time of the cogeneration installation was calculated, which can be expressed as follows:

$$T_{ś} = T_{max} - T_A \tag{5}$$

where:
T_{max} – maximum operating time of the cogeneration unit in the considered period,
T_A – average time of failure during operation of the cogeneration unit.

The average annual operating time of a cogeneration unit includes the difference in the total operating time of the unit in the period in question and the time spent on inspections, breakdowns and other random events. This time amounts to 8,352 h for the analysed company.

Based on the data provided by the waste treatment plant regarding the amount of electricity produced and the average annual operating time of the cogeneration unit calculated above, the average annual production of electricity in the cogeneration unit was also calculated, which can be expressed as follows:

$$E_{elś} = \frac{E_{el}}{T_{ś}} \tag{6}$$

where:
E_{el} – electricity produced,
$T_{ś}$ – average annual operating time of the cogeneration unit.

The average annual production of electricity in a cogeneration unit covers the amount of electricity produced in the period under consideration for the average annual operation time of this cogeneration unit. In the analysed cogeneration unit, the amount of electricity produced on average for one year is approximately 187 kW.

From the available data, it is also possible to calculate the availability indicator of the cogeneration unit, which can be expressed as follows:

$$A = \frac{T_{max} - T_A}{T_{max}} \tag{7}$$

where:
T_{max} – maximum operating time of the cogeneration unit in the considered period,
T_A – average time of failure during operation of the cogeneration unit.

This indicator includes the difference in the maximum operating time of the cogeneration unit during the period under consideration and the average time of failure occurrence during the operation of the cogeneration unit for the maximum operating time. The availability index for the analysed installation is 0.95.

The high availability of the cogeneration unit in the analysed waste treatment plant is 0.95, which primarily proves the CHP unit's very intensive and failure-free operation (Dużyński 2012). The small number of interruptions in its operation is mainly due to the quality of biogas after cleaning, the timeliness of inspections and renovations of the cogeneration unit, as well as the use of dedicated (manufacturer-recommended) consumables, i.e. engine oils, coolants, spark plugs, oil and air filters. Availability of 85-95% with a biogas operation time of approximately 8,000 hours is an optimal solution for the production of electricity and heat; availability of this order is extremely beneficial and, at the same time, unattainable for other renewable energy sources such as wind farms or photovoltaics, because these sources are unstable in terms of energy production (Zator 2018). Generating energy based on renewable energy sources, in this case biogas, is generally characterised by instability in their acquisition, thus reducing the availability of systems generating energy with their participation. Still, using this type of solution in a waste landfill eliminates this problem because the availability of biogas is continuous and controlled, thereby increasing the availability of the entire system (Gebhardt & Wojtowicz 2019). In enterprises using cogeneration systems, thanks to the gradual implementation of diagnostics and monitoring to maintain the machinery in this type of enterprises, the failure indicator of machine units decreases from year to year, and the number of electrical failures is much smaller than the number of mechanical failures (Szymaniec 2017).

The article presents a case study of a waste landfill equipped with a cogeneration unit, in which the energy generated from biogas is used to power the plant's buildings and for heating purposes. When analysing such landfills, it should be taken into account that each waste landfill is different in terms of waste composition and the geological and climatic conditions prevailing there. These factors mainly determine the adaptation of landfill gas management systems, taking into account regular monitoring of the composition of landfill gas, which is crucial to prevent uncontrolled emissions and minimise the risk of explosions. Additionally, the patency of the degassing installation should be checked to ensure its effectiveness and prevent failures of the cogeneration installation. The efficiency of energy generation from landfill gas also requires constant supervision to maximise process efficiency and minimise energy losses. The efficiency of the energy produced is crucial for the profitability of the entire project. Depending on the location and available infrastructure, the problem may be transmitting energy to consumers or using it directly on-site. Each of these aspects requires an individual approach and adapted technical solutions, highlighting the complexity of managing waste landfills and selecting appropriate solutions for the analysed landfills.

4. Summary

Obtaining energy from renewable energy sources is an essential issue in the functioning of every country. Energy recovery in a waste landfill is an optimal solution for this type of enterprise, combining the possibility of generating electricity and heat in cogeneration systems. The analysed waste treatment plant deals with collecting, recovering, recycling, and disposal of municipal waste. There is a landfill degassing installation at the plant, along with the energy use of biogas in a cogeneration unit. Based on documents provided by the company regarding the amount of biogas, electricity, heat produced and the use of output products for own use, an analysis was carried out to examine the processes of energy production and management at the landfill, using data on the amount of biogas obtained from the landfill over two years.

Electricity and heat generated in the cogeneration unit are managed within the plant facilities, which include a landfill. The scope of energy management generated in cogeneration systems includes the production of this energy, using it for the plant's needs, thus minimising maintenance costs and selling energy to external entities. The analysed waste disposal company produced a total of 1,833,752 m^3 of biogas during the analysed 2 years, of which 3,114.87 MWh of electricity was produced, 1,281.08 MWh was sold, and 1,833.3 MWh was used for its own needs], 490.82 MWh was purchased. Regarding thermal energy, 3,177.04 MWh was produced, and approximately 1,645.1 MWh was used for its own needs; the remaining amount was not used. The analysis of the efficiency of electricity and heat production showed that the biogas supplied to the cogeneration system contains small pollutants: siloxanes (15 $mg \cdot Nm^{-3}$), sulfur (120 $mg \cdot Nm^{-3}$) and silicon (2,74 $mg \cdot Nm^{-3}$), hydrogen sulfide (50 $mg \cdot Nm^{-3}$), meeting generally accepted standards, which proves its high quality and at the same time contributing to high efficiency, availability and optimal energy production results. The average value of the efficiency of electricity generation during the analysed two years of operation of the cogeneration system is 42.48%, the efficiency of heat production is 43.33%, the efficiency of the total heat and power plant is 85.8%, and the cogeneration indicators are 98.05%. Based on the data provided, it was also possible to determine the availability of the cogeneration unit, which in the analysed case was 0.95. Results of this order are possible, among others, due to the CHP unit's low failure indicator, attention to machinery inspections, and the supply of high-quality biogas.

The average electricity consumption over two years for the company's own needs accounted for 51% of the total energy obtained, and approximately 36% was intended for sale at reference prices. The plant purchases only about 12%, resulting from installation downtime caused by failure or periodic inspections and possible repairs. Heat recovered from the cogeneration process is used for social purposes at the plant (preparation of domestic hot water and central heating) and constitutes 33 to 35%, while its surplus is not utilised and amounts to 65-67% of the total heat produced. Due to the lack of access to the heating network, it is impossible to transmit excess heat energy for heating purposes. Also, due to the considerable distance of the landfill from residential buildings, constructing a heating network to supply external buildings with thermal energy is not economically viable.

5. Conclusions

Managing heat in landfills with cogeneration units is a challenge because the heat generated is often a by-product of the processes taking place in the cogeneration unit. These parameters may be unstable in terms of their quantity and quality. Additionally, the location of landfills, usually far from built-up areas, makes it difficult to effectively use the generated heat because transmitting it over long distances is expensive and inefficient. One of the promising solutions for heat management in landfills is the use of ORC technology. ORC enables the efficient conversion of low-temperature heat into electricity, which is ideal for landfill conditions. This technology can use lower-quality heat that would be difficult to use in traditional systems.

By using ORC, the energy efficiency of the process can be significantly increased, as this technology is well adapted to work with unstable heat sources. Moreover, the production of electricity directly on-site eliminates problems related to heat transport. ORC systems are also relatively easy to maintain and operate, which is important in landfill management. Therefore, the ORC system is recommended as an alternative to managing the surplus heat from cogeneration. The use of surplus thermal energy to generate electricity will result in the utilisation of irretrievably lost heat, which will result in additional income in the company's operations.

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