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ENERGY SELF-SUFFICIENCY OF A MUNICIPAL COMPANY IN A CIRCULAR ECONOMY – CASE STUDY

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Purpose: Energy self-sufficiency of a municipal company in a circular economy refers to the ability of the company to meet its own energy needs through the use of renewable energy sources and efficient energy technologies. The closed loop economy, also known as the circular economy, is about minimising waste by maximising the use and reprocessing of raw materials and energy.
Design/methodology/approach: The paper provides a detailed analysis of the energy self-sufficiency of Przedsiębiorstwo Wodociągów i Kanalizacji sp. z o.o. based in Rybnik, in the production of heat and electricity from biogas produced at a sewage treatment plant.
Findings: Collected over the period 2013-2022, the data of the analysed company allows us to conclude that in the process of wastewater treatment, the biogas burned for the needs of the wastewater treatment plant in Rybnik-Orzepowice makes it self-sufficient in terms of thermal needs. In turn, the production of electricity from cogeneration covers 43% of the electricity demand. A deeper analysis of the amount of biogas produced showed the need to build a new generator to produce electricity, which will result in the analysed company being self-sufficient in energy.
Biogas plants at municipal wastewater treatment plants bring many environmental and economic benefits, such as:
- Reducing greenhouse gas emissions by avoiding the release of methane into the atmosphere and replacing fossil fuels with biogas.
- Saving the cost of operating the treatment plant by reducing the consumption of grid electricity and heat and fossil fuels, and reducing the amount of waste to be landfilled or disposed of.
Originality/value: Energy self-sufficiency for a municipal company not only contributes to environmental protection by reducing greenhouse gas emissions, but can also result in financial savings by reducing the cost of purchasing energy from external sources. Furthermore, these actions can set an example for other businesses and communities, encouraging them to make similar investments in renewable energy and efficient energy technologies.

Keywords: wastewater treatment plant, biogas, heat and power, cogeneration, circular economy.

1. Introduction

1.1. Municipal wastewater treatment plants as a source of raw materials and renewable energy

Wastewater treatment plants play a key role in environmental protection by removing pollutants contained in incoming wastewater. According to the Central Statistical Office, there were 3260 municipal wastewater treatment plants in Poland in 2022. The proportion of the population using wastewater treatment plants was 75%, with approximately 95% in urban areas and 47% in rural areas (Bocheński, 2016, pp. 403-406).

Changing economic and environmental needs and the development of new technologies are now also treating wastewater treatment facilities as a source of raw materials and renewable energy with many economic and ecological benefits.

The production of electricity and heat and fuel from biogas produced by sewage sludge digestion is currently a technology that is widely used at many facilities, and efforts are being made to optimise this process as much as possible in order to achieve energy independence (Fukas-Płonka, Zielewicz-Madej, 2000, pp. 37-48) and even to sell heat, electricity and fuel, e.g. to power means of transport (Grzesik, 2005; Krupa, 2015, pp. 101-112).

The sewage sludge that is produced in wastewater treatment plants during the treatment process, which was previously a nuisance, has gained a new perspective as a substrate that is a valuable raw material rather than waste. The ashes left over after sewage sludge incineration are used to produce construction materials. Incineration of dried sewage sludge provides additional energy. Sewage sludge is a source of the nutrient elements - nitrogen and phosphorus. At present, the most implemented uses for sewage sludge are the production of fertiliser preparations or plant aids, which are a very attractive alternative to very expensive artificial fertilisers. Due to the limited supply of phosphorus in the environment, which is a non-renewable resource and of key importance for the development of life and agricultural production, recovery of this element from sewage sludge is increasingly being carried out (Prusek, Tytko, 2018, pp. 16-17).

The separation from wastewater of fertiliser products containing nitrogen, phosphorus or potassium that can be used to fertilise plants is included in the Strategy for dealing with municipal sewage sludge for 2019-2022 developed by the Ministry of the Environment (Skoczko, Piekutin, Barszczewska, 2016).

1.2. Process of biogas formation - methane digestion - course and significance

Methane digestion - is the microbiological process of decomposition of organic matter under anaerobic conditions with the production of a mixture of gases of which methane is the main component. Records have been found that biogas was used as early as the 10th century BC to heat water baths in Assyria, and in 1776 Alexander Volta demonstrated that gas extracted from bottom sediments burns. The development of knowledge about methane digestion began with the development of microbiology in the 1930s. Today, methane digestion has found its way into various industries (Wawrzyniak, 2007, pp. 39-46).

In wastewater treatment technology, methane digestion is used as an effective method to stabilise the sludge generated during the wastewater treatment process in order to reduce the content of organic compounds in the sludge, thereby reducing the rotability and removing pathogens. This stabilisation reduces the volume of sludge generated, eliminates odours and increases the potential for further use (Dyrektywa 2003/30/WE…).

The end product is biogas, which, as defined by European Union Directive 2003/30/EU, is 'a gaseous fuel produced from biomass and/or the biodegradable fraction of waste' and is a valuable energy resource (https://www.gov.pl/attachment/...).

1.3. Biogas from wastewater treatment plants as a source of renewable energy

At most large and medium-sized treatment plants, the sludge generated is subjected to anaerobic stabilisation. Methane digestion is the primary process used in sludge treatment and is, to date, the most economical and environmentally friendly form of utilising the residues from the wastewater treatment process. The waste product of this process is biogas, which is a mixture of gases, mainly methane and carbon dioxide, as well as small amounts of other gases such as hydrogen, carbon monoxide, nitrogen or hydrogen sulphide (https://stat.gov.pl).

Biogas is recognised as a renewable RES energy source, i.e.: one whose use for the production of heat and electricity does not involve a long-term deficit of raw material, and its resources in the form of sludge available as biomass in the wastewater treatment process are readily renewable (https://www.teraz-srodowisko.pl/...).

Biogas can be used as a source of renewable energy to produce heat and electricity or to power vehicles. Biogas plants at municipal wastewater treatment plants bring many environmental and economic benefits (https://pl.wikipedia.org/...; https://wysokienapiecie.pl/...) which include:

- Reducing greenhouse gas emissions by avoiding atmospheric methane emissions and replacing fossil fuels with biogas.
- Improving wastewater quality by stabilising sludge and reducing organic waste.
- Saving the cost of operating the treatment plant by reducing the consumption of grid electricity and heat and fossil fuels, and reducing the amount of waste to be landfilled or disposed of.
- Creating new jobs and income for local communities through the sale of surplus biogas or energy derived from it.

The number of biogas plants at municipal wastewater treatment plants in Poland is difficult to determine, as there is no uniform register of such installations. However, based on various sources, it can be estimated that there are around 300 (Krupa, 2015, pp. 101-112).

2. Biogas production at the Rybnik-Orzepowice wastewater treatment plant

2.1. Characteristics of the Rybnik-Orzepowice wastewater treatment plant together with a synthetic description of the technology used

The sewage treatment plant in Rybnik-Orzepowice is a mechanical-biological treatment plant with removal of nitrogen and phosphorus compounds by biological means. The treatment plant has been equipped to chemically support phosphorus removal. The designed capacity of the facility is 27 500 m^3/d. The biological treatment stage uses the flow- sequential activated sludge process BIODENIPHO®, with a preliminary anaerobic chamber and a phase sequence in the reactors, adapted to the biological removal of nitrogen and phosphorus. The treatment plant also includes a process line for sludge treatment. Provision is made for sludge stabilisation by methane digestion, final dewatering and hygienisation. The biogas produced by the digestion process is combusted in a cogeneration unit with an electrical power in a cogenerator with an electrical output of 192kW and a thermal output of 232kW, as well as two gas boilers with an output of 320 kW each. Excess biogas produced is burned in a flare.

2.2. Biogas production at the Rybnik-Orzepowice Sewage Treatment Plant

The anaerobic stabilisation process in separate closed digesters (SCD) produces biogas, which has been used to produce electricity and heat since 2012. On a daily basis, the Sewage Treatment Plant in Rybnik-Orzepowice produces approximately 3000 m^3 of biogas. On average, about 0.16 m^3 of biogas is generated from 1 m^3 of sewage flowing into the treatment plant (Table 1) and (Fig. 1-2).

Table 1.
Waste water intake and biogas production

Year	Amount of incoming wastewater [m^3]	Biogas production [m^3]	Average biogas production from 1 m^3 wastewater
2013	6 805 430	1 112 200	0,16
2014	6 540 800	1 132 272	0,17
2015	5 938 820	1 017 258	0,17
2016	6 400 050	939 083	0,15
2017	7 223 900	906 740	0,13
2018	6 380 780	1 046 217	0,16
2019	6 537 300	1 165 582	0,18
2020	7 172 100	1 249 509	0,17
2021	7 506 770	1 155 194	0,15
2022	6 951 530	1 197 007	0,17

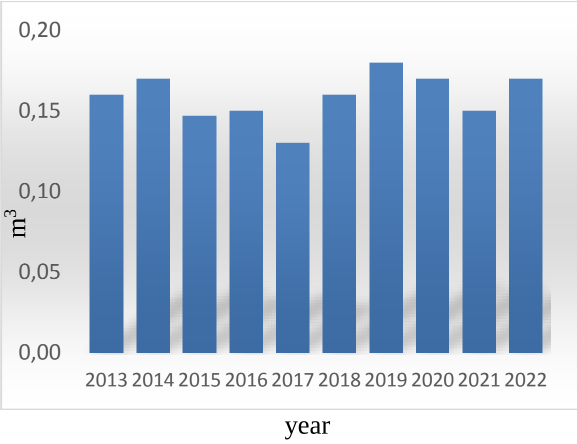


Figure 1. Biogas production thousand m^3/year.

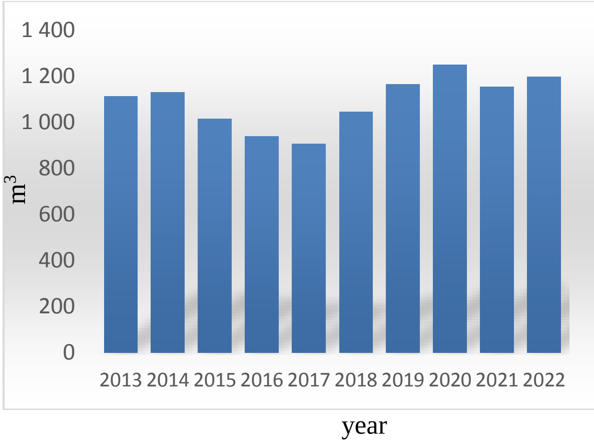


Figure 2. Average biogas production from 1 m^3 wastewater

An analysis of the quantity and quality of wastewater carried out between 2013 and 2022 showed that biogas production remained constant despite the varying flow and pollutant load.

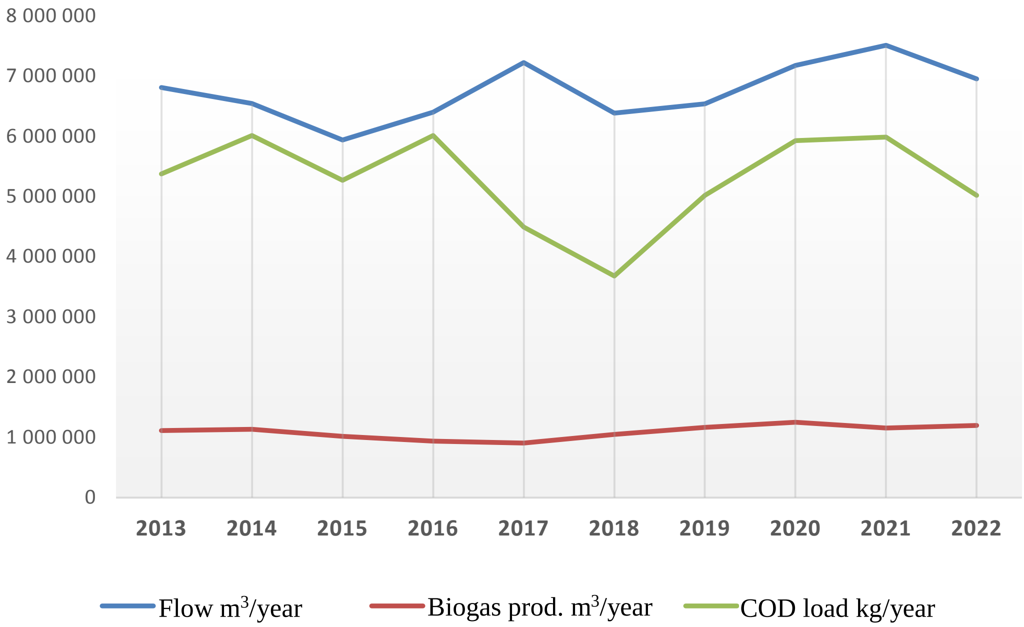


Figure 3. Diagram of the dependence of biogas production on the quantity and quality of incoming wastewater.

The chemical oxygen demand (COD) load was used for the analysis (Fig. 3).

3. Characteristics of biogas and its use

3.1. Composition and quality of biogas produced at the Rybnik-Orzepowice sewage treatment plant

The biogas produced during the digestion process at the SCD is captured, then purified by removing water vapour in subsequent condensate wells and hydrogen sulphide in a turf ore bed desulphuriser. Biogas produced at the Rybnik-Orzepowice wastewater treatment plant is characterised by relatively stable parameters and contains an average of approx. 64% methane, 35% carbon dioxide and 0.002% hydrogen sulphide. The calorific value of biogas produced from sewage sludge is approximately 23 MJ/m^3.

Table 2.
Biogas composition and quality tested after desulphurisation, upstream of the cogeneration unit

Parameter	Unit	2018	2019	Year 2020	2021	2022
Relative humidity	%	63	60.4	50.8	47.6	43.3
Methane CH4	vol. %	65.9	65.2	63.7	65	60.7
Carbon dioxide CO2	vol. %	34.1	34.8	32.8	35	37.8
Oxygen O2	vol. %	<0.1	<0.1	<0.1	<0.1	<1
Carbon monoxide CO	vol. %	<0.0001	0.0005	0.0005	0.001	0.0018
Hydrogen sulphide $H S_2$	ppm	6	6	12	27	46
Hydrogen sulphide $H S_2$	%	0.0006	0.0006	0.0012	0.0027	0.0046
Hydrogen sulphide $H S_2$	mg/m^3	9	9.2	18.47	41.36	70.8
Hydrogen H_2	%obj.	<0.1	<0.1	<0.1	<0.1	0.0074
Sum of Siloxanes	mg/m^3CH_4	6.86	0.2	0.16	0.05	0.77
Ammonia NH3	mg/m^3	1.04	0.67	1.43	1.12	0.01
Calorific value of biogas	kJ/m^3	23655	23400	22900	23300	21800

The biogas extracted to ensure a stable supply to the cogeneration unit is stored in a 550 m^3 three-layer membrane tank.

3.2. Biogas utilisation.

Biogas produced at the Rybnik wastewater treatment plant, assuming there are no unforeseen breakdowns of the cogeneration unit or other conditions preventing energy production, is used at 75%. The structure of gas consumption by individual units of the energy and heat production system, i.e.: CHP unit, gas boilers and flares varies from year to year (figure 4).

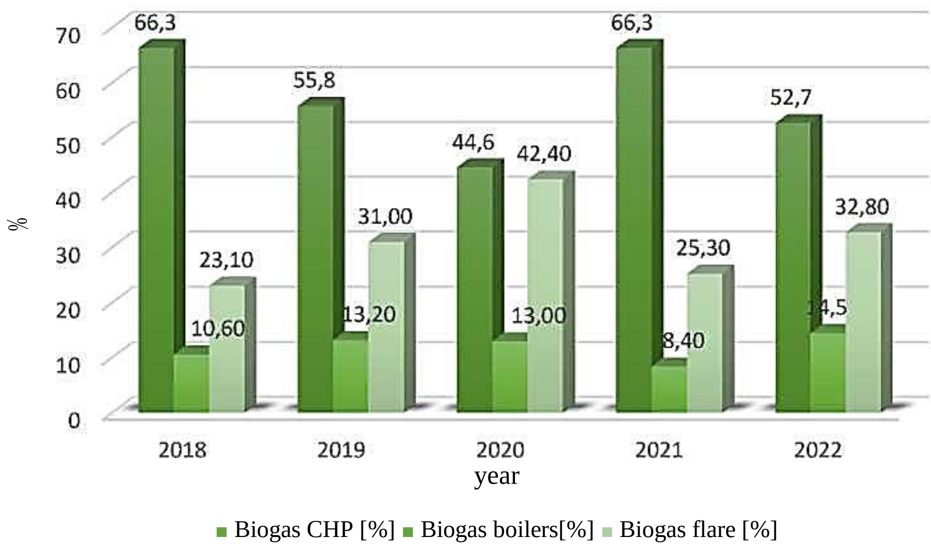


Figure 4. Utilisation structure of the produced biogas in the individual units of the cogeneration system.

This is influenced by a number of factors, of which the main ones are inspections and maintenance of the CHP unit, the aforementioned breakdowns, as well as the heat demand used to heat the process facilities, the administration building and the production of domestic hot water (DHW).

4. Electricity production

The demand for electricity at the Rybnik-Orzepowice wastewater treatment plant is at a level of approximately 3400 MWh per year. Annual production of green electricity from the biogas generated at the Rybnik-Orzepowice WWTP (data for 2021) is at a level of 1467 MWh. 96 % of the electricity produced is used for the plant's own needs. The part of the energy that cannot be consumed due to technical conditions is sold to the TAURON network, which accounts for approximately 4% of the total energy produced. From the production of electricity PWiK Sp. z o.o. obtains certificates of origin for energy from renewable sources. The current production of electricity at the Rybnik-Orzepowice sewage treatment plant covers approx. 40% of the plant's total demand for electricity.

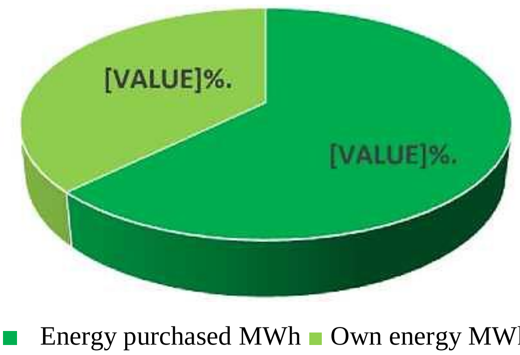


Figure 5. Electricity demand coverage of the Sewage Treatment Plant in Rybnik-Orzepowice from its own sources - average for 2018-2022.

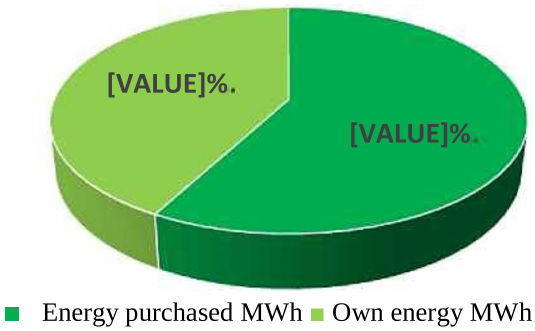


Figure 6. Coverage of electricity demand of the Sewage Treatment Plant in Rybnik-Orzepowice from its own sources - year 2021.

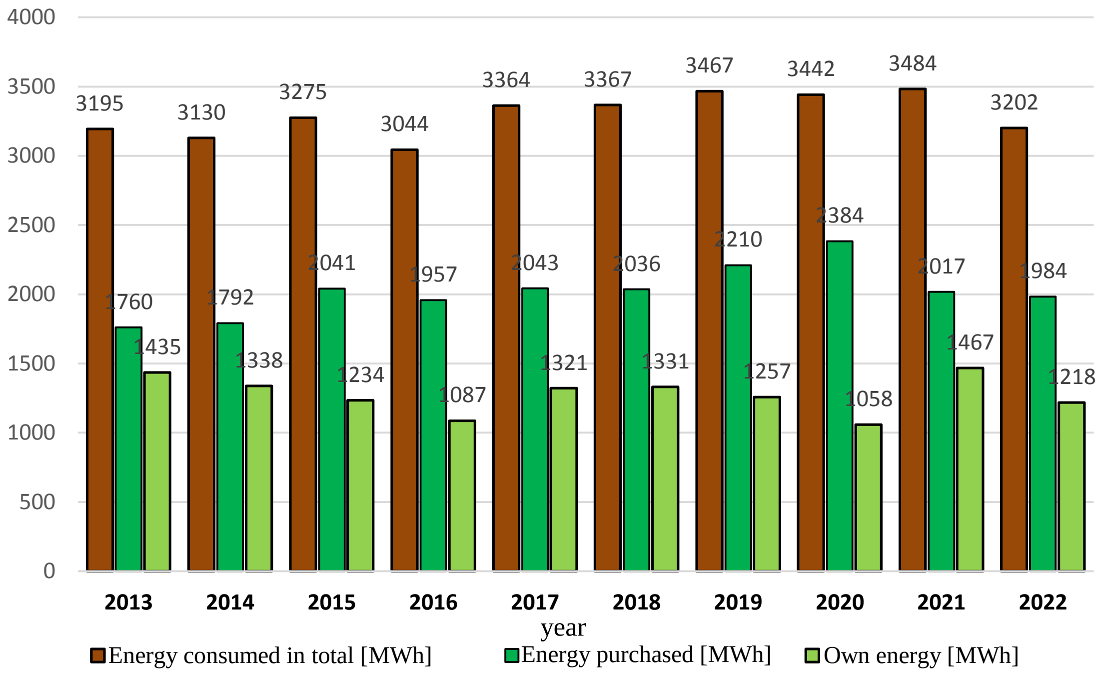
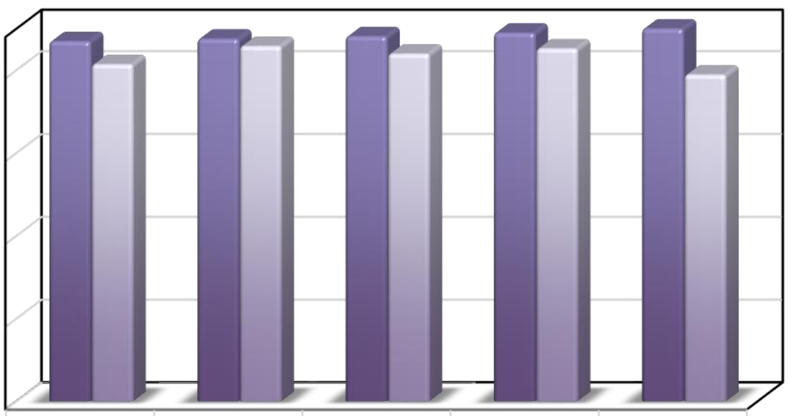


Figure 7. Structure of energy consumption [MWh] at the Rybnik-Orzepowice treatment plant.

Since, as previously shown, biogas production remains relatively constant, the amount of electricity production is mainly determined by the standstill of the CHP unit due to breakdowns or maintenance and repair work.

Biogas production and energy demand fluctuates throughout the year and shows variability depending on the seasons. This is mainly related to the outside temperature and the length of the day. In summer, electricity consumption at the Rybnik-Orzepowice wastewater treatment plant is lower by 10% than in the winter months Fig. 8.



	2018	2019	2020	2021	2022
Winter	1 739	1 751	1 763	1 780	1 909
Summer	1 628	1 716	1 679	1 704	1 578

Figure 8. Electricity consumption [MWh] in summer (April to September) and winter (October to March) at the Rybnik-Orzepowice WWTP.

5. Combined heat and power energy

The production of electricity in the cogeneration system is accompanied by the production of thermal energy. The heat from the CHP unit is used to heat the process buildings including heating the digestion process in the SCD. It provides heat for the administrative building of the treatment plant, and is also used to produce DHW supplied to the staff baths. The heat demand during winter periods is higher Fig. 10. therefore, heat production from the generator is often insufficient and must be compensated by high-efficiency biogas boilers. In 2021, when the generator was operating without failure Fig. 11, 105,000 m^3 of biogas was burned on the boilers to provide sufficient heat for the facility.

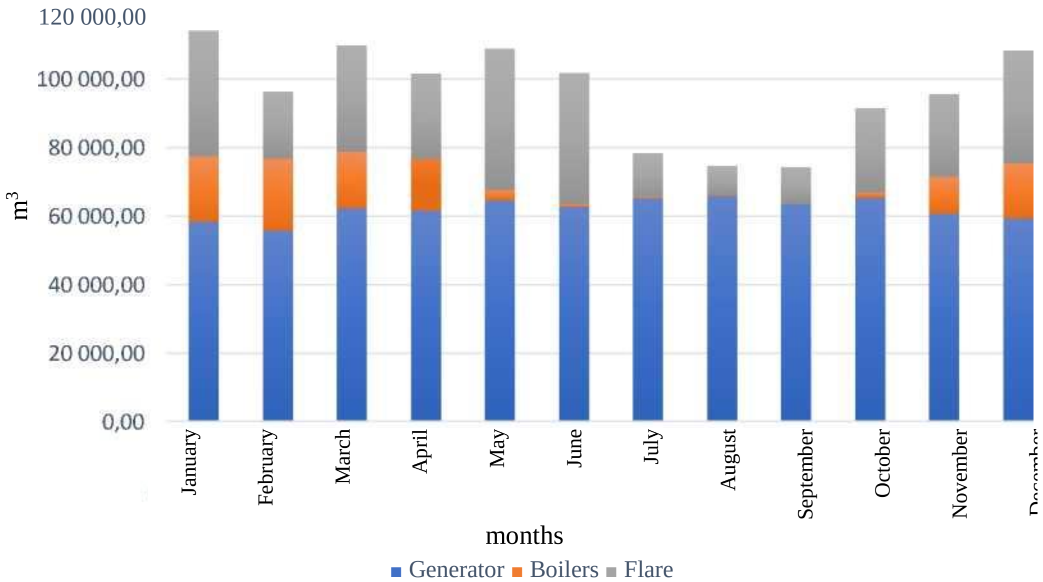


Figure 10. Biogas consumption [m^3] at individual facilities.

The combined heat and power production system at the sewage treatment plant in Rybnik-Orzepowice does not have metering of the generated heat energy, therefore the amount of heat generated is determined based on calculations (Table 2).

Table 3.
Calculated thermal energy production from biogas combustion

Year	COGENERATOR		GAS BOILERS	
	Biogas consumption m^3/year	Heat energy production MJ/year	Biogas consumption m^3/year	Heat energy production MJ/year
2018	695 076	8 070 070	109 869	2 365 040
2019	650 323	7 550 445	154 762	3 331 407
2020	546 412	6 344 007	165 371	3 559 776
2021	774 042	8 673 382	104 564	2 250 845
2022	630 701	7 322 628	172 978	3 723 524

In Poland, to produce 1 MWh of electricity, it is necessary to burn approx. 144 kilograms of hard coal with a calorific value of approximately 25 MJ/kg. It is worth remembering, however, that the amount of coal needed to produce 1 MWh depends on the efficiency of the boiler, as well as the calorific value of the coal. The lower the calorific value, the more coal needs to be burned. In view of this, in a nutshell, it can be said that the production of approximately 1 400 MWh/year of electricity from biogas cogeneration saves about 200 tonnes of coal, not including the losses associated with the transmission and transfer of electricity. In addition, the production of heat for preheating sludge as well as rooms and DHW heating is estimated to save around 300 tonnes of coal per year.

6. Summary and conclusions

Analysis of the data shows that the biogas produced in the sewage treatment process and burned for the needs of the sewage treatment plant in Rybnik-Orzepowice makes it self-sufficient in terms of heat needs. In turn, the production of electricity from cogeneration covers the plant's electricity needs by 43%. The biogas burned represents approximately 30% of production, which argues for the addition of a second 40-50kW engine. The installation of an additional unit would make it possible to utilise biogas to a much greater extent - perhaps even entirely. An analysis of the heat demand of the treatment plant showed that, especially in winter, it is necessary to run a gas-fired boiler plant for additional heat production. An additional CHP unit, despite the lower thermal efficiency of the generator, would make it possible to provide sufficient heat without having to run the boilers. This, in turn, would free up an additional biogas stream that could be used to produce electricity. Since it is estimated that the supply of a smaller engine involves a high unit investment cost and subsequently an operating cost, an investment decision would have to be made to install a generator with the same capacity as the current one, i.e.: 190 kW and 231 kW thermal output. There are many arguments in favour of such a solution for the Rybnik-Orzepowice WWTP, i.e.:

- ✓ Use of the entire available biogas stream.
- ✓ Covering the deficit in heat demand from CHP in the winter months.
- ✓ The ability to continuously produce energy despite the failure of one of the units or ongoing maintenance activities.
- ✓ Increasing the production of renewable energy for own consumption to around 70% of current consumption.

Not insignificant for the application of the 190 kW CHP variant is the ongoing extension of the sewage network in the Chwałęcice-Stodoły districts, which will result in an additional sewage load flowing into the treatment plant, thereby increasing the amount of sludge generated and biogas production.

Furthermore, in view of the climate policy of the European Union and Poland, which aims to make electricity generation independent of fossil fuels, the construction of a third closed SCD, together with a gas storage tank, should also be included in the forthcoming investment plans. This will secure the reliability of the reception of sludge generated at the sewage treatment plant and enable the lengthening of the digestion process, thus increasing biogas and energy production and reducing the amount of sludge generated.

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