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ENERGY EFFICIENCY OF A WATER AND WASTEWATER COMPANY – CASE STUDY

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Purpose: Producing energy from renewable sources is the challenge of our time, given the increasing demand for energy. Biomethane from the anaerobic digestion of sewage sludge is a valuable source of renewable energy. Its production is also environmentally beneficial, reducing greenhouse gas emissions and waste. Using the biomethane produced to generate electricity leads to energy self-sufficiency for the local authority in a closed loop economy.
Design/methodology/approach: The article presents the results of a detailed analysis of the biogas-energy management of Przedsiębiorstwo Wodociągów i Kanalizacji Spółka z ograniczoną odpowiedzialnością, based in Rybnik, with regard to the production of electricity from biogas produced at the sewage treatment plant.
Findings: The results collected from 2013 to 2023 allow us to conclude that the green energy produced at the Rybnik Wastewater Treatment Plant covers 40% of the plant's electricity needs, thus ensuring compliance with the provisions of the new EU Urban Wastewater Treatment Directive, which aims to achieve energy self-sufficiency for wastewater treatment plants by 2035. At the same time, the cogeneration system covers 100% of the heat requirements of the wastewater treatment plant. The environmentally friendly production of green energy also brings economic benefits to the company.
Originality/value: Maximising the use of biomethane produced at wastewater treatment plants results in the unit being self-sufficient in energy without the need to import energy from external sources. This means that the unit is able to generate enough energy from available internal sources (e.g. solar, wind, geothermal, biomass and energy from waste) to meet its needs. Energy self-sufficiency helps protect the environment by reducing greenhouse gas emissions and saves money by reducing the cost of purchasing energy from external sources. In addition, these measures can set an example for other companies, encouraging them to make similar investments in renewable energy and efficient energy technologies.
Keywords: biomethane, biogas, sewage treatment plant, energy, cogeneration, energy efficiency.
Category of the paper: Case study.

1. Introduction

Changing criteria for assessing the performance of wastewater treatment plants are leading to continuous improvements in treatment processes, which in turn are increasing the energy intensity of the plants. The energy transition programme implemented in the European Union is forcing the maximum use of all possible energy sources in order to achieve energy independence. This article presents the results of ongoing research in the field of biogas and energy management at the Rybnik-Orzepowice Wastewater Treatment Plant in the period 2013-2023 and presents the conditions and prospects for achieving energy independence.

1.1. Biogas balance in Poland

Biogas is one of the most important sources of renewable energy. Due to the high demand for gas and the promotion of climate protection, biogas production is of strategic importance for Europe. According to a report by the European Biogas Association (EBA), European biomethane production will increase by 20% in 2022 compared to 2021, reaching 21 billion cubic metres (https://e-magazyny.pl/…). Unfortunately, the use of biogas in Poland is still low. The share of biogas in energy production from various RES sources in Poland has practically stopped at 2.6% (Analizy statystyczne GUS…, 2023) (Table 1).

Table 1.
Share of individual renewable energy carriers in renewable energy generation 2018-2022

Specification	2018	2019	2020	2021	2022
	%				
Solid biofuels	76,1	73,4	71,6	69,3	64,5
Solar energy	0,7	1,1	2,0	3,3	6,0
Water energy	1,4	1,4	1,5	1,6	1,3
Wind energy	9,1	10,6	10,9	10,9	12,6
Biogas	2,4	2,4	2,6	2,5	2,6
Liquid biofuels	7,5	8,0	7,8	8,1	8,0
Geothermal energy	0,2	0,2	0,2	0,2	0,2
Municipal waste	0,8	0,8	1,1	1,2	0,8
Ambient heat from heat pumps	1,8	2,1	2,4	2,9	3,9

Analizy statystyczne GUS…, 2023.

According to estimates by the European Biogas Association (EBA), Poland will produce 1.98 billion cubic metres of biomethane in 2024 and 3.26 billion in 2030 (https://e-magazyny.pl/…). In our country, a large untapped source of biogas is wastewater, as only a small proportion of wastewater treatment plants produce and use biogas. According to CSO data, biogas production from wastewater treatment plants increased by only 1.21% from 2016 to 2020 (Analizy statystyczne GUS…, 2022) (Figure 1). The largest increase in biogas procurement occurred in the 'other biogases' group, with an increase of 81.25% over the period analysed. This group includes agricultural biogas and biogas from food industry waste.

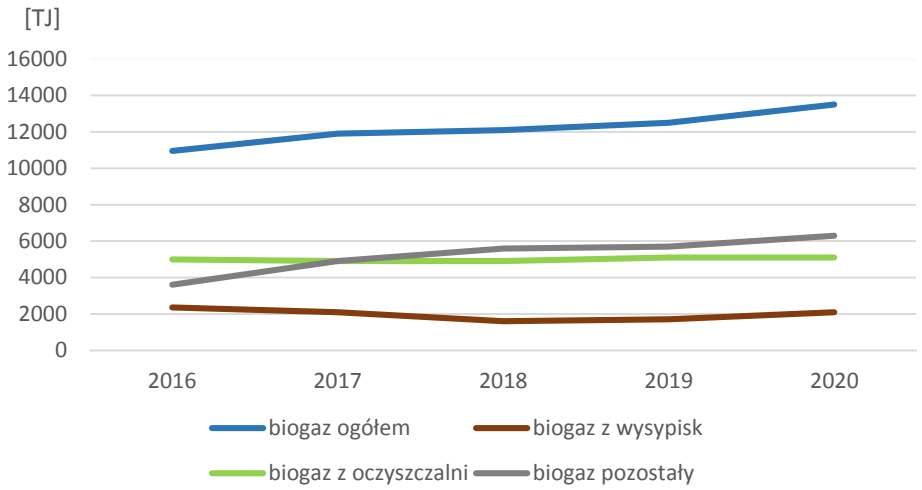

Figure 1. Biogas generation 2016-2020 in TJ.

Source: Analizy statystyczne GUS…, 2022.

1.2. Electricity production from renewable energy sources

Producing energy from renewable sources is the challenge of our time, given the growing demand for energy. Energy from renewable sources is environmentally friendly. In Poland, renewable energy from solar radiation, water, wind, geothermal resources, energy from solid biofuels, biogas and liquid biofuels, as well as ambient heat from heat pumps are used (Analizy statystyczne GUS…, 2023).

Table 2.

Electricity production from renewable energy sources

Specification	2018	2019	2020	2021	2022
	GWh				
Total	21617,2	25 458,8	28 226,6	30 568,5	37 688,6
Water	1 970,0	1 958,4	2 118,3	2 339,2	1 968,2
of which:	299,0	312,0	423,4	328,3	303,2
power plants with a generating capacity < 1 MW	528,5	538,2	526,3	632,9	558,7
power plants with a power output of 1-10 MW	1 142,5	1 107,6	1 168,6	1 378,0	1 106,4
power plants with a generating capacity > 10 MW	12 798,8	15 106,8	15 800,0	16 233,5	19 779,5
Wind	5 333,2	6 441,2	6 932,8	6 398,4	5 934,1
Solid biofuels	85,0	104,8	181,8	353,8	301,6
Municipal waste	1 127,6	1 135,0	1 233,9	1 307,3	1 394,2
Biogas	169,6	178,0	183,5	204,7	227,7
of which:	336,5	350,8	373,3	367,8	343,6
Biogas from landfills	621,6	606,2	677,0	734,9	822,9
Biogas from sewage treatment plants	2,0	2,0	1,9	1,7	1,3
Other biogas	300,5	710,7	1 957,9	3 934,4	8 309,7

Source: Analizy statystyczne GUS…, 2023.

Production of electricity from renewable sources in Poland is steadily increasing, with the largest share coming from wind power, which will increase by as much as 54.5% in 2022 compared to 2018. The largest increase, 28 times, is in photovoltaic energy production. In the case of biogas, although total energy production is on an upward trend, electricity

generation from biogas produced in wastewater treatment plants is slightly decreasing (Table 2). In Poland there are about 64 municipal biogas plants producing biogas from organic waste including municipal sewage sludge, 161 agricultural biogas plants and 70 microbiogas plants (https://magazynbiomasa.pl/…). Many WWTPs do not have biogas recovery facilities or, as in the case of the Rybnik-Orzepowice WWTP, do not make full use of them. Therefore, there is a need to modernise and expand existing facilities and build new biogas plants at municipal wastewater treatment plants in order for these facilities to achieve zero emissions in the future.

Table 3.
Capacity of renewable energy power plants

Specification	2018	2019	2020	2021	2022
	MW				
Total	**8 344**	**9 406**	**12 325**	**16 502**	**22 567**
Water of which:	968	974	977	975	984
power plants with a generating capacity < 1 MW	92	93	96	92	100
power plants with a power output of 1-10 MW	184	188	188	190	191
power plants with a power output > 10 MW	692	692	692	692	692
Wind	5 766	5 838	6 298	6 967	8 150
Solid biofuels	735	732	734	803	894
Municipal waste	87	91	100	91	91
Biogas	225	233	261	251	278
of which:	52	55	54	48	52
Biogas from landfills	**72**	**74**	**86**	**76**	**74**
Biogas from sewage treatment plants	102	104	121	127	152
Other biogas	562	1 539	3 955	7 416	12 170

Source: Analizy statystyczne GUS…, 2023.

1.3. Heat production

Renewable heat production plays a very important role in the energy mix. In Poland, the production of heat from renewable energy sources will increase by 57.7% between 2018 and 2022. The largest increase, by a factor of 3, is from municipal waste. There is a decrease in heat production from biogas (Table 4).

Table 4.
Heat generation from renewable energy sources

Specification	2018	2019	2020	2021	2022
	TJ				
Total	**14 809,1**	**17 644,6**	**21 204,8**	**23 511,4**	**23 353,2**
Solid biofuels	13 401,3	15 901,9	18 655,4	20 942,8	20 847,4
Municipal waste	476,6	730,7	1 611,9	1 598,9	1 574,5
Biogas	922,5	1 004,2	927,5	959,3	919,1
Of which:	31,4	35,5	47,7	38,6	45,2
Biogas from landfills	106,2	105,6	97,0	148,7	130,8
Biogas from sewage treatment plants	784,9	863,2	782,9	772,0	743,1
Other biogas	3,4	4,6	5,5	5,0	7,7
Bioliquids	5,3	3,1	4,5	5,3	4,6

Source: Analizy statystyczne GUS…, 2023.

2. Characteristics of sludge management at the sewage treatment plant Rybnik-Orzepowice

The Rybnik-Orzepowice WWTP is a mechanical-biological treatment plant with a design capacity of 27,500 m^3/d. The plant also includes a technological line for sludge treatment. It provides for sludge stabilisation by methane fermentation, final dewatering and hygienisation. The digestion process is carried out in two Separated Closed Digesters (SCC), each with a capacity of 2500 m^3. The main product of the digestion process is biogas, which is desulphurised on a bed of peat. The biogas is stored in a biogas tank (ZB) with a capacity of 550 m^3. The biogas produced by digestion is combusted in a CHP unit with an electrical output of 192 kW and a thermal output of 232 kW. The digested sludge is dewatered on a belt press, hygienised with quicklime and then sent for management. The heat from the CHP is used to heat the process facilities, including the WWTP chambers, the WWTP administration building and the hot water production (Fig. 1).

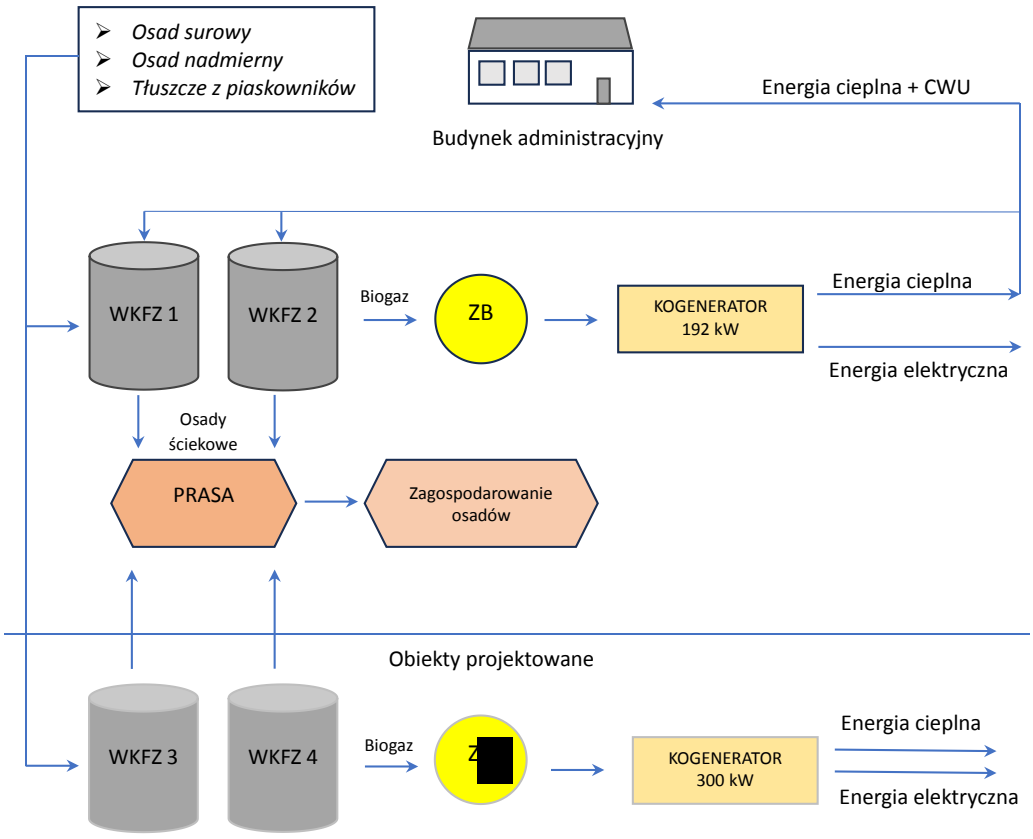

Figure 1. Diagram of the sludge section of the sewage treatment plant in Rybnik-Orzepowice with visualisation of the facilities planned as part of the expansion of the cogeneration system.

Source: company source data.

The WWTP in Rybnik-Orzepowice produces on average about 3000 m^3 of biogas per day. Annual summaries of the amount of biogas produced show that biogas production remains stable, and any decrease in production is due to maintenance work on the WWTP digesters (Fig. 2).

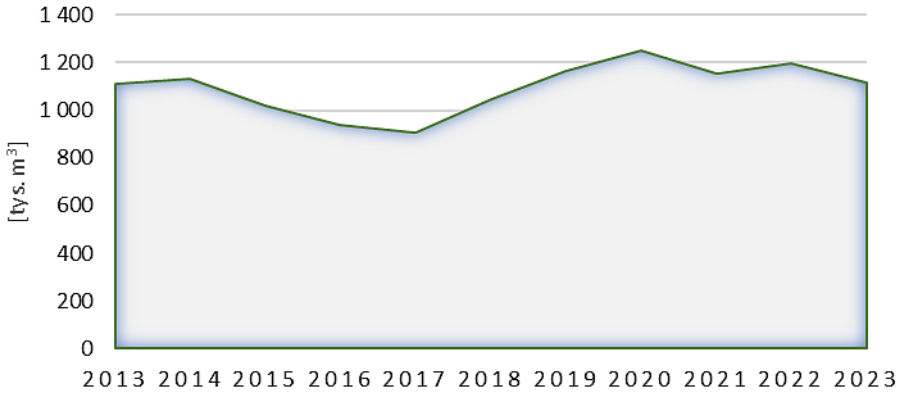

Figure 2. Biogas production [thousand m^3] at the Rybnik-Orzepowice wastewater treatment plant from 2013 to 2023.

Source: company source data.

3. Energy demand of the sewage treatment plant in Rybnik-Orzepowice

The electricity demand at the Rybnik-Orzepowice wastewater treatment plant is approximately 3300 MWh per year (Fig. 3).

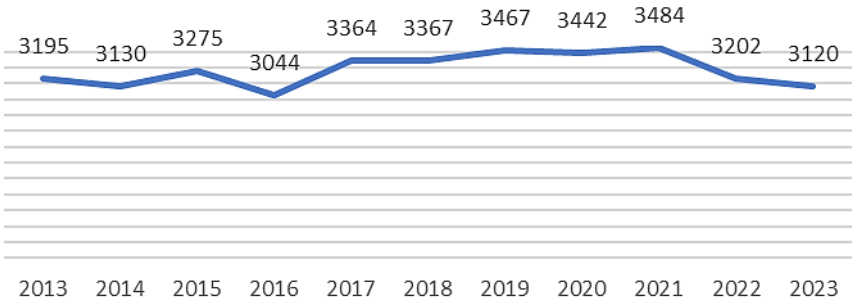

Figure 3. Total electricity consumption at the Rybnik-Orzepowice wastewater treatment plant [MWh] from 2013 to 2023.

Source: company source data.

The annual production of green electricity from biogas at the Rybnik-Orzepowice WWTP (data for 2023) is 1202 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 5% of the total energy produced. PWiK Sp. z o.o. receives certificates of origin for energy from renewable sources from the production of electricity. The current production of electricity at the Rybnik-Orzepowice

Wastewater Treatment Plant covers approximately 40% of the plant's total electricity needs. The structure of electricity consumption by year is shown in Figure 4.

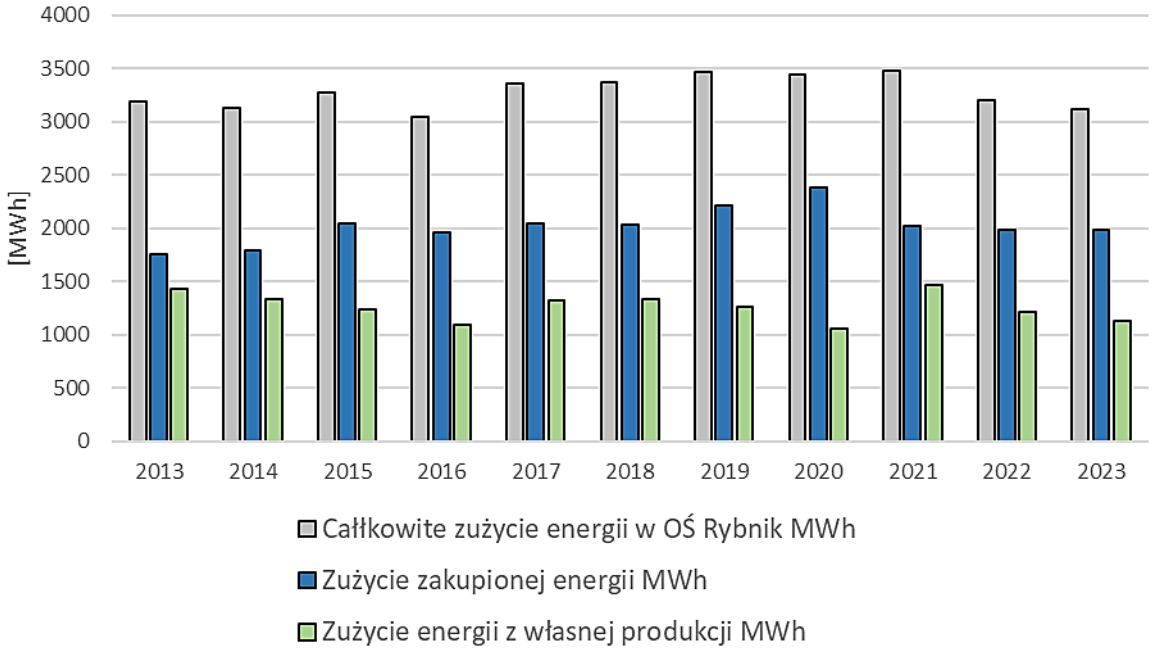

Figure 4. Consumption structure of purchased and own electricity [MWh] at the Rybnik-Orzepowice wastewater treatment plant in the period 2013-2023.

Source: company source data.

The sewage treatment plant in Rybnik-Orzepowice uses 60% of the biogas produced, which opens up the possibility of extending the cogeneration installation with another unit together with the necessary infrastructure to make full use of the biogas already extracted and even increase production (Fig. 5).

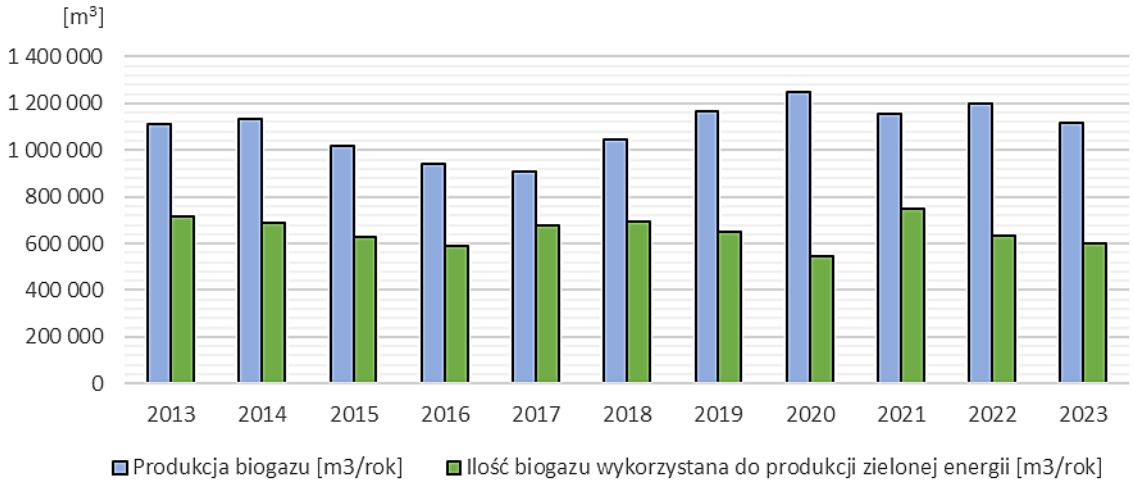

Figure 5. Use of biogas production at the Rybnik-Orzepowice wastewater treatment plant [m^3] for green energy production in 2013-2023.

Source: company source data.

4. Energy efficiency of electricity production from biogas

The biogas produced at the Rybnik-Orzepowice WWTP is characterised by relatively stable parameters and contains on average about 64% methane, 35% carbon dioxide and 0.002% hydrogen sulphide. The calorific value of biogas produced from sewage sludge is about 23 MJ/m^3. As mentioned in the previous chapter, 60% of the biogas produced is used to produce electricity and heat, assuming that there are no unforeseen failures of the CHP unit or other conditions that prevent production. On average, 1 m^3 of biogas produced in the Rybnik-Orzepowice treatment plant produces about 2 kWh of electricity. Based on the data on the amount of gas consumed and the amount of energy produced in the cogeneration process (Table 4), the efficiency of the cogeneration system was calculated using the following formula (Załuska, Piekutin, Magrel, 2018, pp. 51-56):

$$\textit{Energy efficiency} = \frac{\textit{Amount of biogas consumed for electricity and heat production [m}^3\textit{]}}{\textit{Amount of electricity produced from cogeneration [MWh]}}$$

As the analysis shows, the energy efficiency of the biogas extracted at the Rybnik-Orzepowice treatment plant is stable (Figure 6).

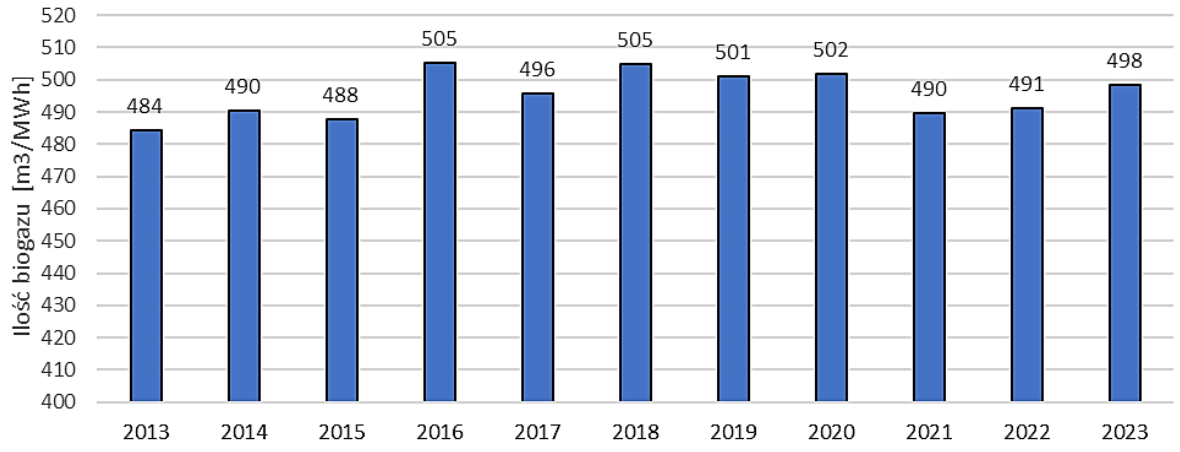

Figure 6. Use of biogas production at the Rybnik-Orzepowice wastewater treatment plant [m^3] for green energy production in 2013-2023.

Source: company source data.

5. Analysis of electricity purchase costs

Sewage treatment plants are among the facilities with a significant demand for electricity, and the price of energy is constantly rising. The Rybnik-Orzepowice WWTP consumes approximately 3300 MWh of electricity per year. The average cost of purchasing this amount of energy between 2013 and 2023 would be PLN 1.3 million/year. Thanks to the installation of

a cogeneration unit, 1300 MWh of the demand will be covered by own production. Taking into account the period from 2013 to 2023, the cogeneration unit produced more than 14,474 MWh of electricity, which corresponds to savings of PLN 5 million due to not buying energy from the grid. The calculations were based on the average price of energy including distribution (Fig. 7) (Table 5).

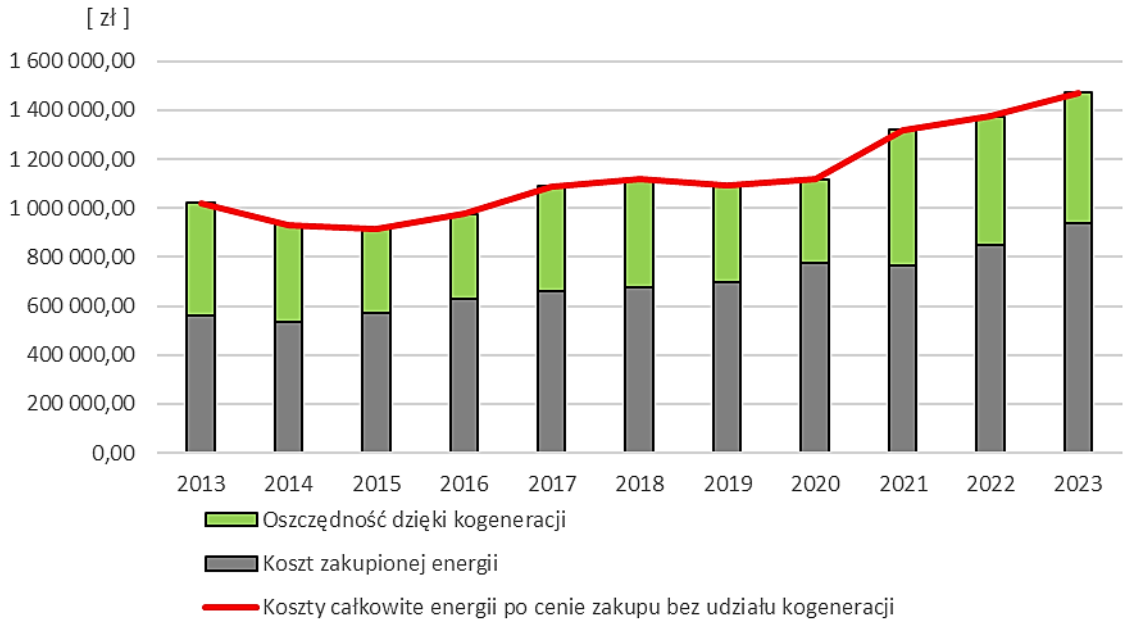

Figure 7. Analysis of the costs of purchasing electricity for the sewage treatment plant in Rybnik-Orzepowice [PLN] in the period 2013-2023.

Source: company source data.

Table 5.
Analysis and compilation of biogas production and energy use system data at the Rybnik-Orzepowice wastewater treatment plant

	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Amount of biogas used for electricity and heat production [m^3]	717 306	689 994	627 023	587 073	675 035	695 076	650 323	546 412	747 042	630 701	599 028
Amount of electricity produced from biogas [MWh]	1481	1407	1286	1162	1362	1377	1298	1089	1526	1284	1202
Volume of biogas consumed for the production of 1 MWh [m3] = energy efficiency (efficiency)	484	490	488	505	496	505	501	502	490	491	498
Profit from sold electricity [PLN]	9 263,76	12 625,99	8 556,88	12 762,21	6 838,01	8 700,10	9 891,17	5 574,92	15 834,15	25 998,76	55 561,77
The value of green certificates	227 837,04	268 599,82	148 318,67	87 928,54	48 442,94	158 833,51	165 913,61	176 326,00	271 437,25	245 099,55	176 389,88
Profit from non-purchased energy [PLN]	459 016,40	398 641,90	345 395,71	348 211,41	427 613,61	442 150,86	395 704,95	343 873,23	555 664,13	522 608,55	533 264,61
Profit from non-purchased fuel [PLN]	22 500,00	22 500,00	22 500,00	22 500,00	22 500,00	50 000,00	50 000,00	50 000,00	100 000,00	180 000,00	100 000,00
Final profit (from sold energy + certificates + unpurchased fuel + unpurchased energy [PLN])	718 617,20	702 367,71	524 771,25	471 402,16	505 394,55	659 684,47	621 509,72	575 774,15	942 935,53	973 706,86	865 216,25

Cont. table 5.

Final profit per MWh [PLN] Economic efficiency	485,22	499,20	408,06	405,68	371,07	479,07	478,82	528,72	617,91	758,34	719,81
Cogeneration operating costs [PLN]	553 747,37	548 111,70	538 245,09	482 292,84	656 927,80	552 653,38	517 044,95	541 874,42	628 141,28	448 651,32	653 716,12
Final profit minus operating costs of cogeneration [PLN]	164 869,83	154 256,01	-13 473,84	-10 890,68	-151 533,24	107 031,08	104 464,77	33 899,73	314 794,25	525 055,55	211 500,14
Final profit minus operating costs per MWh [PLN] Economic efficiency	111,32	109,63	-10,48	-9,37	-111,26	77,73	80,48	31,13	206,29	408,92	175,96

Source: own elaboration.

6. Energy efficiency

The green energy produced at the Rybnik WWTP covers 40% of the plant's electricity needs, ensuring compliance with the new EU directive on urban wastewater treatment, which aims to make the plant energy self-sufficient by 2035 (https://www.europarl.europa.eu/…). At the same time, the cogeneration system provides 100% of the thermal energy needs of the technological facilities and the administration building. An assessment was carried out to determine whether the environmentally beneficial production of green energy would also bring financial benefits to the company. For this purpose, a detailed economic analysis was carried out (Table 5) and the final profit per 1 MWh of electricity produced was calculated using the following formula (Załuska, Piekutin, Magrel, 2018, pp. 51-56):

$$\textit{Economic efficiency} = \frac{\begin{array}{c}\textit{(Profit from electricity not purchased}\\ \textit{+ value of certificates + profit from electricity sold}\\ \textit{+ cost of fuel not purchased) - operating costs}\end{array}}{\textit{Amount of produced electricity [MWh]}}$$

The results are given in Table 5 and visualised in the following graph (Fig. 8).

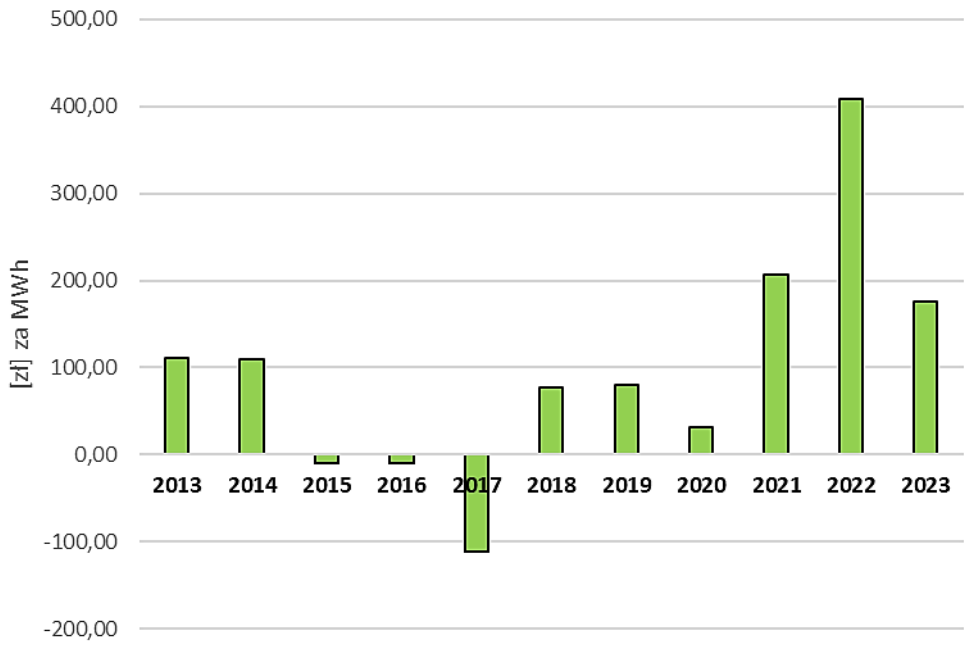

Figure 8. Final profit per 1 MWh [PLN]. Economic efficiency.

Source: company source data.

A loss was recorded between 2015 and 2017, which was largely due to the unit's operating costs including breakdowns. A sample statement of expenditure for 2017 showed that depreciation was the largest item (Fig. 9).

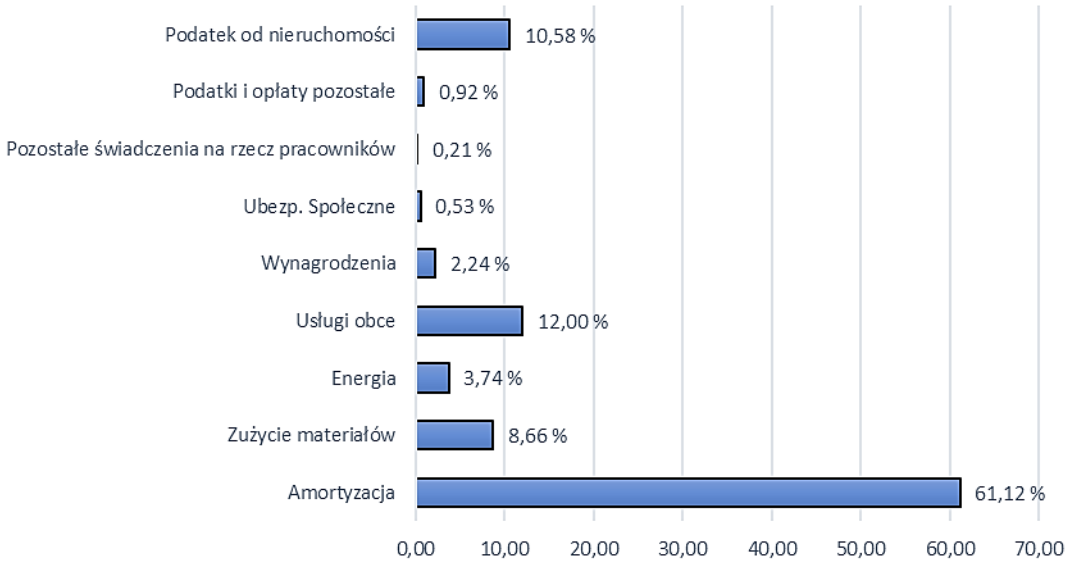

Figure 9. Percentage breakdown of CHP system operating costs - 2017.

Source: company source data.

The listing of ‘green certificates’ on the RES Rights Market also had a significant adverse effect on the economic performance, with a record decline in value in 2016, 2017 (Fig. 10).

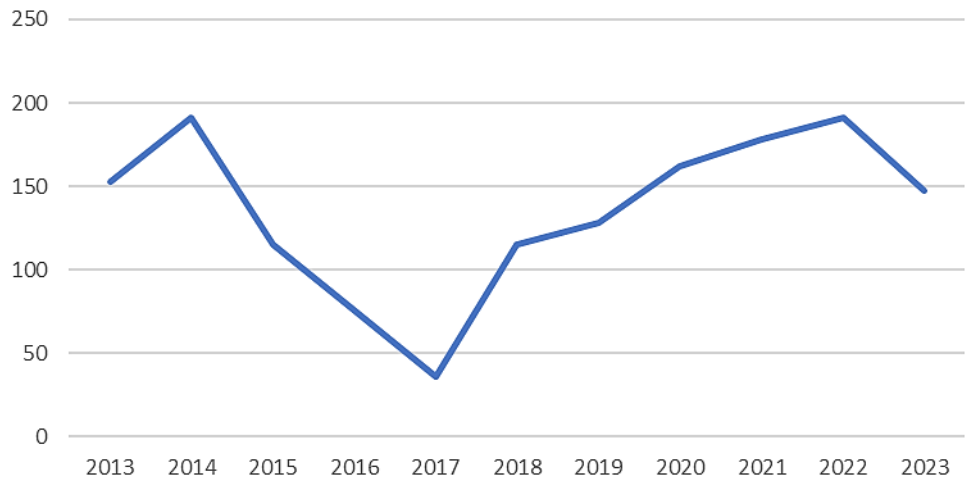

Figure 10. Value of "green certificates" [PLN/MWh].

Source: company source data.

In summary, the stand-alone production of energy from biogas is financially profitable for the company, especially in years when the CHP and digesters (WKFZ) have not undergone any maintenance and have been operating trouble-free. The above analysis confirms the rationale for building a second CHP unit with a double biogas production node to ensure a constant biogas flow and continuous production of electricity and heat from renewable energy sources.

7. Summary

The requirements for municipal wastewater treatment plants in the draft of the new Waste Water Directive are becoming increasingly stringent. This applies both to the reduction of the permissible values for the biogenic elements nitrogen and phosphorus in the treated wastewater and to the implementation of technology for the removal of micropollutants in the fourth treatment stage. Such high-efficiency wastewater treatment will require the provision of significant amounts of electricity and heat for the efficiency and effectiveness of the technological processes.

In parallel with the intensification of treatment processes, it will be necessary for the energy required for this to be generated by the operators of the treatment plants, with particular attention being paid to identifying and exploiting the potential for biogas production (https://www.europarl.europa.eu/…). This will ensure that these plants achieve energy neutrality while reducing greenhouse gas emissions.

The production of electricity from biogas at municipal wastewater treatment plants is the optimal solution. The sludge process waste generated during treatment, which is a continuous stream, can be stabilised in the digestion process and the biogas by-product obtained can be used to produce green energy.

As the evaluation of the economic and energy efficiency of the cogeneration system at the Rybnik-Orzepowice WWTP has shown, the production of electricity from biogas is cost-effective and there is still potential for increasing its efficiency. It is therefore necessary to extend the CHP node at the plant by building another pair of digesters to ensure greater stability and reliability of the CHP system. The additional plant will allow full use to be made of the biogas currently produced, increasing its production and achieving both environmental and economic benefits.

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