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Morawskiego 19 street, 35-321 Rzeszów
eps@instytutpe.pl
tel. + 48 17 85 77 907
http://www.instytutpe.pl/eps/

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EFFICIENT USE OF ENERGY IN WASTEWATER TREATMENT PLANTS

Adam Masłoń[1], *Marta Wójcik*[2], *Krzysztof Chmielowski*[3]

Abstract

Saving energy and increasing energy efficiency constitutes a rationalisation of energy use, which is becoming increasingly important in the context of sustainable development and security of energy supply, as well as the fight against global climate change. In line with the global trend, the issue of energy intensity of water and wastewater management is currently dynamically developing in terms of research. Consideration is therefore being given to the use of electricity in wastewater treatment systems, as well as the assessment of the energy efficiency of wastewater treatment plants.

This paper presents the issues of electricity consumption in wastewater treatment systems and the possibilities of improving the energy efficiency of wastewater treatment plants.

Keywords: wastewater treatment, energy intensity, energy consumption, biogas, aeration

Introduction

The largest consumer of electricity in cities is the water and wastewater infrastructure, which is responsible for 25-40% of its total consumption. The entire water sector is currently responsible for around 4% of global electricity consumption. Water demand will continue to grow over the next 25 years, so energy efficiency measures are needed in this sector (Danfoss 2018). Electricity accounts for as much as 40% of the operating budgets of water companies and about 20% of the costs associated with the supply and treatment of water intended for consumption. Over the next 15 years a further increase in energy consumption of 60-100% is expected (Biedrzycka 2016, p. 14).

The need to intensify the removal of pollutants from wastewater, which has been observed in recent years, translates into increased costs associated with the operation of wastewater treatment systems – both for the main part of wastewater, as well as for the treatment and disposal of sewage sludge. The observed systematic increase in pollutant loads in wastewater flowing into municipal treatment plants, which makes it difficult to maintain the stability of technological processes, additionally results in a further increase in the plant's operating costs. In order for a wastewater treatment plant to operate properly, it is necessary to supply significant amounts of electricity, which is necessary for the transport of wastewater, technological processes and the operation of administrative facilities (Masłoń 2017, p. 332).

The energy consumption of wastewater treatment systems varies greatly. It depends on the technological system used and varies from year to year. The research indicates that the demand for electricity in wastewater treatment plants amounts to almost 1% of total domestic consumption, e.g. in Poland (Orchowski et al. 2017, p. 68-69), Germany (Reinders et al. 2012), or in Italy (Faladori et al. 2015, p. 1007) In other countries, e.g. Spain, electricity consumption in wastewater treatment plants is already higher and accounts for 2-3% of national energy

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[1] PhD, Eng., Rzeszow University of Technology, Department of Chemistry and Environmental Engineering, e-mail: amaslon@prz.edu.pl

[2] PhD, Eng., Rzeszow University of Technology, Department of Materials Forming and Processing

[3] DSc, PhD, Eng., Uniwersity of Agriculture in Krakow, Department of Sanitary Engineering and Water Management

consumption (Fundación OPTI 2012, p. 6). In the USA, electricity consumption for municipal wastewater treatment plants accounts for as much as 5.4% of total domestic energy consumption and may increase by 20% over the next 20 years (Gromiec 2016). At present, the energy demand in Poland in wastewater treatment plants is not high compared to other countries, as it amounts to approx. 1TWh/year (Orchowski et al. 2017, p. 68). For comparison, wastewater treatment plants in Germany, Great Britain and the United States use 3.49 TWh/year, 3.7 TWh/year and 21 TWh/year respectively (GWRC 2008 p. 45). However, forecasts for the development of municipal infrastructure indicate an increase in energy consumption for wastewater treatment in Poland to the level of 5.5 TWh/year, which will then constitute about 2.5-3.5% of national electricity consumption (Wójtowicz 2013).

The high energy consumption of wastewater treatment plants (WWTP) determines the need to optimise technological processes, as well as the purposeful use of wastewater or sewage waste, such as sewage sludge, for the production of electricity and heat. It is becoming appropriate to develop energy audits for wastewater treatment plants, on the basis of which the energy intensity of individual wastewater treatment processes can be determined, and thus energy intensity guidelines for other investments can be defined. Creating a database of indicators is a valuable activity. Reducing electricity consumption can never be the overriding objective in the management of a wastewater treatment system, but there is a possibility to reduce the energy intensity of the installation without compromising the quality of the treated wastewater (Masłoń 2017, p. 332). Therefore, it is necessary to look at comprehensive solutions to the municipal wastewater treatment system in a different way from previously. Nowadays, the minimisation of energy consumption and the ecological sourcing of energy from alternative sources is gaining in importance and constitutes an important element of sustainable development, also in relation to water and wastewater management. Improving the energy efficiency of wastewater treatment plants is one of the challenges posed by the idea of a closed-circuit economy (Rytelewska-Chilczuk 2017).

The aim of this paper is to present the issue of energy intensity of wastewater treatment systems in the aspect of rational and efficient use of energy.

Energy balance of wastewater treatment plants

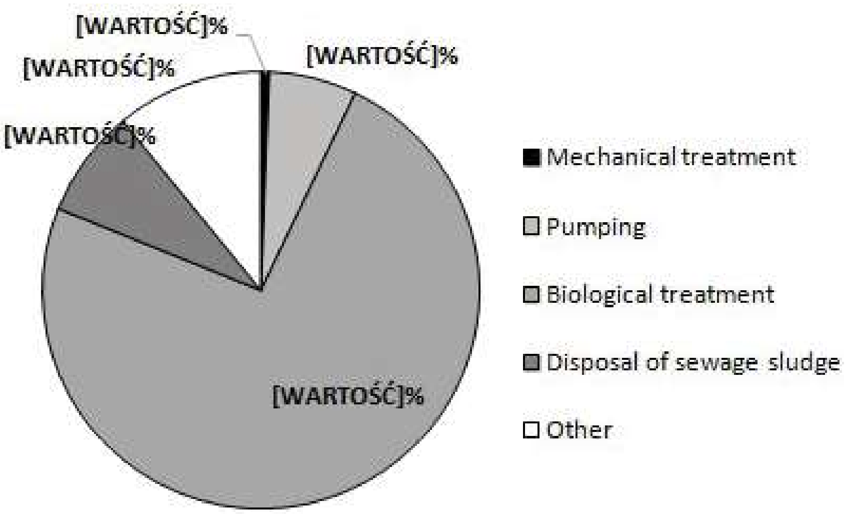
The wastewater treatment structure should be considered as a heat and power system. Electricity is used in the wastewater treatment plant to supply electric drives, among other things. Electric drive systems consist mainly of electric motors, which are used for increasing pressure (compression), pumping and transporting liquids and gases by means of pumps, fans, compressors and are additionally used in mixers, presses and other equipment for processing waste from wastewater (debris, sand, and sewage sludge). At each stage of wastewater treatment electric drive systems are used, so all technological operations such as mixing, aeration, and pumping, which are part of the wastewater treatment system, determine the consumption of electric energy. Thermal energy, in turn, is used for sewage sludge processing – in fermentation chambers and sludge dryers, etc. In a wastewater treatment plant, electricity and heat are also used for the social needs of employees, heating of technical and administrative buildings, and illumination of the area, etc.

The urban wastewater treatment process consists of two main stages – mechanical treatment (removal of floating or dragged impurities, suspended solids) and biological treatment (removal of organic pollutants, nitrogen and phosphorus compounds). It is also possible to use the third stage of wastewater treatment, which includes the removal of refractive contamination and the disinfection of wastewater. The first stage of treatment is the pumping of wastewater (wastewater pumping stations), removal of debris in travelling screens, removal of mineral suspension in the sandbox and sedimentation of easily falling suspension in the primary settling tanks. These processes display a relatively low electricity demand (with the exception of pumping the wastewater). Mechanical wastewater treatment devices consume less than 1% of the energy consumed by the entire plant (Orchowski et al. 2018, p. 71). The first degree of energy consumption data indicated in the literature varies considerably. Energy consumption for pumping raw wastewater depends mainly on the pumping height and is 0.02-0.1 kWh/m^3 (Canada), 0.045-0.14 kWh/m^3 (Hungary) and 0.1-0.37 kWh/m^3 (Australia), 0.041 kWh/m^3 (Poland) (Bodík and Kubaská 2013, p. 16; Orchowski et al. 2018, p. 72). According to a WssTP report (2011), electricity consumption in European countries up to the biological stage of wastewater treatment with activated sludge is between 0.15 and 0.7 kWh/m^3. In the biological stage of wastewater treatment the most energy-intensive process is aeration of aerobic chambers (nitrification). Aeration accounts for up to 60% of energy consumption in the biological pipeline and 44% of energy consumption in the entire wastewater treatment plant (Orchowski et al. 2018, p. 72). In addition to aeration of bioreactors, a large energy consumer is also the mixing of activated sludge in anaerobic and anoxic chambers and sludge recirculation. Conventional activated sludge processes consume on average 0.46 kWh/m^3 (Australia), 0.269 kWh/m^3 (China), 0.33-0.60 kWh/m^3 (USA), 0.30-1.89 kWh/m3 (Japan) (Bodík and Kubaská 2013, p. 16), and 0.53 kWh/m^3 (Poland) (Orchowski et al. 2018, p. 72). The processes used in the third stage of the treatment consume the most electricity (e.g. UV lamps, ozone generators, pumps, etc.). The literature review indicates a highly diversified energy intake for the so-called "advanced processes" of wastewater treatment. For example, in Japan, advanced wastewater treatment processes have an energy demand of between 0.39 and 3.74 kWh/m^3. In the USA, this third degree of purification consumes an average of 0.43 kWh/m^3. This value is similar to the energy consumption reported in the literature for treatment plants in Taiwan (0.41 kWh/m^3), New Zealand (0.49 kWh/m^3) and Hungary (0.45-0.75 kWh/m^3) (Bodík and Kubaská 2013, p. 16).

One of the inseparable elements of the wastewater treatment process is the treatment and disposal of sewage sludge. The sludge management loop, unlike the rest of the wastewater treatment plant equipment, usually operates in a cyclical manner. The processes of compaction, aerobic or anaerobic stabilisation (methane fermentation) and sludge dewatering are used here. In large wastewater treatment plants, methane fermentation processes and additional drying or incineration of sewage sludge are used. The production of biogas from sewage sludge in fermentation chambers allows for its use for power generation. Biogas production from sewage sludge for energy production is justified in large wastewater treatment plants with an average capacity of more than 8-10,000 m^3/day. The biogas produced by anaerobic digestion consists of methane (40% to 70%), carbon dioxide (about 40-50%) and a small amount of other gases, e.g. hydrogen sulphide, ammonia, etc. (Kołodziejak 2012, p. 1036-1037). Biogas after desulphurisation can be used for energy purposes (production of heat, electricity) or in other technological processes (heating of buildings). The energy consumption of sewage sludge treatment varies and depends on the size of the wastewater treatment plant, the type of technology used and the nature of the plant's operation. For example, the energy intensity of the sludge management loop in the Sandomierz WWTP (Poland) amounts to 0.055 kWh/m^3, which accounts for 8% of the energy consumed by the entire plant (Orchowski et al. 2018, p. 73).

The analysis of electricity consumption in individual units of the wastewater treatment plant technological line allows the structure of energy consumption, and thus the possibilities of its rationalisation, to be determined. Figure 1 shows an example of the structure of electricity consumption in the different stages of wastewater treatment.

Figure 1. Structure of electricity consumption in individual parts of the Sandomierz WWTP (Poland)



Source: own research

The energy balance of wastewater treatment plants should be considered as a whole, taking into account the energy consumption of wastewater treatment and sludge treatment processes as well as the use of energy for non-technological and social purposes. To assess the energy intensity of wastewater treatment plants, it is helpful to determine the KPIs (energy key performance indicators) in relation to the amount of wastewater, the equivalent number of inhabitants or the load of organic pollutants discharged during wastewater treatment (Tab. 1).

Table 1. Electricity consumption indicators in the wastewater treatment plant

Abbreviation	Unit
KPI_1	kWh/m^3
KPI_2	kWh/(p.e.·year) or kWh/(p.e.·day)
KPI_3	kWh/kg COD_{rem} lub kWh/kg $BOD_{5\ rem}$

p.e. – equivalent population

COD_{rem} – quantity COD removed

$BOD_{5\ rem}$ - quantity of BOD_5 removed

Source: Longo et al. 2016, p. 1253-1254

According to Wróblewski and Heidrich's (2017b) studies, unit electricity consumption in municipal wastewater treatment plants in Poland ranges from 0.45 to 1.29 kWh/m^3, with the average value equal to 0.84 kWh/m^3. The report of the Chamber of Commerce "Polish Waterworks" determined the average energy intensity index for Polish wastewater treatment plants at the level of 0.77 kWh/m^3 in 2015. (Benchmarking 2016). According to Gromiec (2016), the average values of the energy intensity index of the process of collecting and treating wastewater are 0.84 kWh/m^3 for facilities for 20-100 thousand inhabitants and 0.62 kWh/m^3 for facilities of more than 100 thousand inhabitants. Table 2 presents detailed energy intensity indices of wastewater treatment plants determined for selected installations.

Table 2. Unit electricity consumption in selected wastewater treatment plants in Poland

Location; name of the treatment plant	Average daily amount of wastewater [m^3/d]	P.E.	Indicators of specific electricity consumption		
			KPI_1 kWh/m^3	KPI_2 kWh/(p.e.·day)	KPI_3 kWh/kg $BOD_{5\ rem}$
Błonie	4 211	33 605	1.034	0.137	2.279
Sandomierz	4 258	42 090	0.69	0.071	1.2
Biała Podlaska	8 991	56 035	0.879	0.163	2.714
Skarżysko Kamienna	9 333	43 596	0.361	0.077	1.283
Otwock	12 352	94 415	0.801	0.125	2.08
Kalisz	16 997	153 679	0.631	0.07	1.162
Kołobrzeg	17 278	214 381	0.698	0.065	1.088
Krosno	21 000	117 000	0.510		
Koszalin	26 952	342 961	0.398	0.032	0.533
Chorzów; the Klimzowiec WWTP	29 200	200 000	0.620	-	-
Rzeszów	42 631	276 099	0.468	0.07	-
Kraków; the Kujawy WWTP	54 990	388 178	0.35		0.88
Gdynia, the Dęgoborze, WWTP	57 200	463 000	0.69	0.085	1.57
Kraków; the Płaszów WWTP	144 600	630 670	0.42	-	1.7
Warszawa; the Czajka WWTP	410 200	-	0.43	-	-

Source: Wróblewski and Heidrich 2017a, p. 328-329; Banaszek 2014, p. 28; Orchowski et al. 2018, p. 71; Trojanowicz and Karamus 2016, p. 51; Masłoń 2017, p. 4; Styka et al. 2017, p. 331-332; Bisak et al. 2017, p. 372-373; ETV4WATER Raport 2017, p. 36

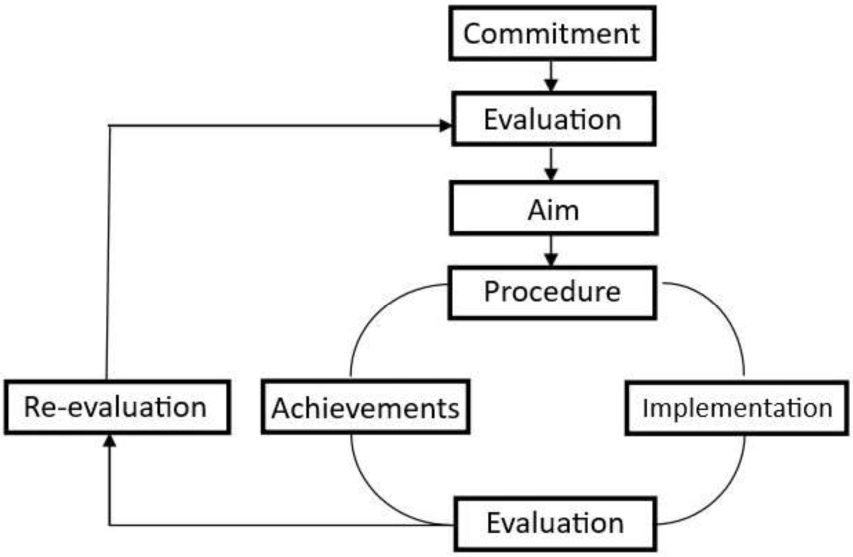
Electricity consumption depends primarily on the type of wastewater flowing in and the technological system of the wastewater treatment plant. The analysis of the topic indicates that the energy intensity of wastewater treatment varies greatly from country to country (Maktabifard et al. 2018).

Improving the energy efficiency of wastewater treatment plants

High energy consumption of wastewater treatment plants translates into the need to optimise technological processes, as well as the search for alternative energy sources, thanks to which the purchase of electricity from the distribution network can be minimised.
Recognising current and future energy consumption is important to identify opportunities for energy efficiency improvements and financial benefits. It is necessary to identify the activities and operations that consume the most energy or are inefficient. A key aspect of the wastewater treatment plant strategy in the near future will be to minimise the energy intensity of the technological process, taking into account ecological, economic and innovation criteria. Apart from the traditional role of water and wastewater systems, i.e. wastewater treatment and sewage sludge treatment, the production of resources (e.g. phosphorus recovery from sewage) and energy is playing a new role (Gromiec 2016, ETV4WATER Report 2017, p. 6).

The basic analytical method of energy demand assessment in a wastewater treatment plant is energy audits. They make it possible to assess the total energy demand of a given system, in addition to determining the most important processes and operations in terms of energy. Evaluation of the energy efficiency of the technology makes it possible to determine the energy saving procedure in the wastewater treatment plant. Based on the results of the energy audit, an energy improvement strategy should be identified, evaluated and established (Figure 2).

Figure 2. Energy management strategy for wastewater treatment plants



Source: ETV4WATER Raport 2017, p. 11

Energy savings in wastewater treatment plants are primarily related to the improvement or replacement of energy-intensive equipment (pumps, mixers, blowers) and the introduction of intelligent control and monitoring systems for wastewater treatment processes. This should be followed by the production of electricity and heat from wastewater sludge (thermal hydrolysis, fermentation, co-fermentation, sludge incineration) as well as the recovery of energy from wastewater (heat pumps, water turbines). Intensification of electricity production can be additionally achieved through the use of small cogeneration systems, photovoltaic panels or wind turbines. However, wastewater treatment processes have the greatest potential for improving energy efficiency (Table 3).

Table 3. Energy saving matrix in a wastewater treatment plant

Device, technological process	**Wastewater pumping, wastewater transport**	**Wastewater treatment**	**Treatment and disposal of sewage sludge**
Energy consumption in %	**25**	**60**	**15**
Pumping	X		
Pre-sedimentary settling tank		X	
Mixing/coagulation		X	
Removal of biogenic compounds		X	
Recirculation of activated sludge		X	
Sludge compaction/dewatering		X	
Fermentation/co-fermentation of sludge		X	
Sludge drying		X	
Biogas production/generation		X	
Solar energy		X	
Mini water turbines	X		
Wind turbines			X

Source: ETV4WATER Raport 2017, p. 17

The use of innovative wastewater treatment methods with simultaneous energy efficiency leads to an energy self-sufficient facility. However, in order to meet the expectations in the field of sustainable development and a closed-circuit economy, it is also possible to produce electricity and heat in excess of the facility's demand. The surplus electricity and heat can then be transferred to the distribution grids. The potential energy savings in the wastewater treatment plant are shown in Table 4.

Table 4. Distribution of energy consumption and energy saving potential in a selected wastewater treatment plant with activated sludge system

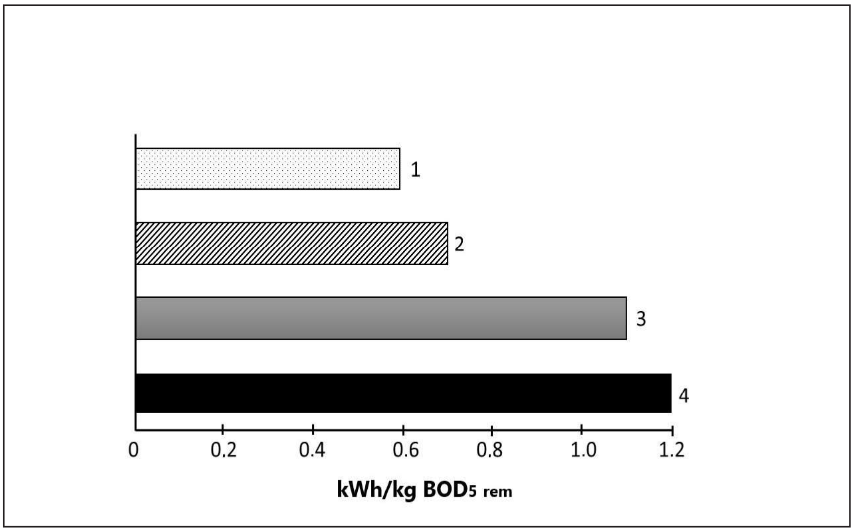
Purification stage	Share in energy consumption [%]	Energy saving potential	Comments
Wastewater collection (pumping station)	10	5-10% by retrofitting existing pumps; up to 30% by better maintenance and adaptation to capacity	Dependent on the share of gravity-induced collection
Biological wastewater treatment	55	20-50% through optimization of technological parameters, aeration optimization, online control application	Mostly for aeration of wastewater
Treatment and disposal of sewage sludge (sludge dewatering, sludge transport)	35	30% energy efficiency can be achieved by using classic mesophilic fermentation with additional cogeneration. Sludge pre-treatment or thermophilic fermentation can increase energy efficiency by up to 50%. Further application of advanced integrated co-fermentation processes, high-efficiency cogeneration can increase efficiency by up to 80%.	Anaerobic fermentation energy production

Source: Parsons et al. 2012, p. 41

The aeration system in the activated sludge chambers in wastewater treatment plants is the dominant electricity receiver. The share of the installed aeration system capacity in the total installed capacity of the wastewater treatment plant is usually at the level of 30 to 70% (Roksela and Heidrich 2017, p. 366). Properly selected devices and the operating parameters of the aeration system determine the consumption of electricity.

The electricity consumption for aeration of activated sludge depends mainly on the depth of the bioreactors and the type of equipment used (fig. 3). According to the literature, the consumption of electricity by aeration equipment in selected treatment plants is as follows: 0.46 kWh/m^3 in the Tychy-Urbanowice WWTP (Roksela and Heidrich 2017, p. 366), 0.421 kWh/m^3 in the Hajdów WWTP in Lublin (Kurek 2018, p. 58), 0.318 kWh/m^3 in Sandomierz (Orchowski et al. 2018, p. 72), 0.23 kWh/m^3 in the Dęgoborze WWTP in Gdynia (ETV4WATER Report 2017, p. 36). This represents up to 50% of the energy consumption of the entire wastewater treatment plant.

Figure 3. Electricity consumption of selected activated sludge aeration systems; 1-spinners, 2-small bubble diffusers, 3-thick and medium-bubble diffusers, 4-surface mechanical operators

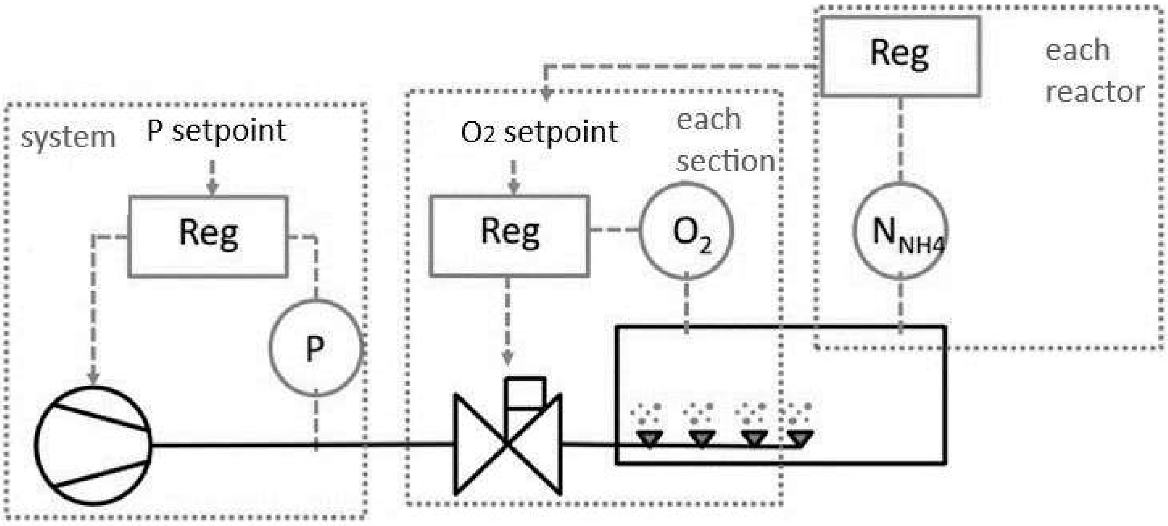


Source: Masłoń and Tomaszek 2017, p. 80.

The simplest example of improving the energy efficiency of an aeration system is the optimisation of equipment time control. At the Bad Oeynhausen WWTP (Germany), periodic shutdown of aeration in the nitrification chamber resulted in savings of 105 MWh/year without adversely affecting wastewater treatment efficiency (Szklarz and Reclaff 2016, p. 33). In turn, the replacement of blowers, diffusers and improved control of wastewater treatment plants in Sternö (Sweden, 26,000 p.e.) led to a reduction in the electricity consumption of bioreactors by as much as 65%. In the entire energy balance of the wastewater treatment plant, due to the modernisation of the aeration system, the energy consumption of the wastewater treatment plant was reduced by 13%. These savings corresponded to savings of 178 MWh/year, with an ROI (Return on Investment) period of 3.7 years for the modernisation of the aeration and control system (Larsson 2011).

The energy efficiency of aeration can also be intensified by using online measurements of ammonium nitrogen concentration (Fig. 4) (Masłoń and Tomaszek 2017, p. 115; Dąda and Pacuła 2018, p. 32). This control system reduces the amount of electricity despite the increase in the amount of wastewater and the pollution load in the inlet. The use of intelligent control of aeration blowers allowed the total energy consumption to be reduced to <0.4 kWh/m3 in the Kujawy WWTP (Kraków) (Łuszczek 2016) and from 3.5 kWh/p.e. to <2.0 kWh/p.e. in the Otwock WWTP (Jabłoński and Lech 2018, p. 29). In turn, the change in the method of controlling the operation of bioreactors in the Płaszów WWTP in Kraków allowed for savings in electricity consumption at a level of 20% (Biedrzycka 2016, p. 17).

Figure 4. The idea of aeration control using online measurements of ammonium nitrogen concentration; Reg-regulator, P - flow measurement, O2 – oxygen probe, NNH4- ammonium nitrogen probe



Source: Łuszczek 2016

Due to the significant energy potential of the organic fraction in wastewater, which is 5÷10 MJ/m^3 and 1.4÷2.8 kWh/m^3 (Wójtowicz 2015) and 4.92-7.97 kWh/kg COD (Heidrich et al. 2011, p. 381), it is advisable to use anaerobic fermentation of sewage sludge. The use of biogas in high-efficiency cogeneration processes leads to the generation of both electricity and heat. Co-fermentation of sewage sludge with other organic substrates (e.g. fatty waste) intensifies biogas production in fermentation chambers. Studies show that the use of additional co-fermentation leads to an increase in the amount of biogas from 100% to as much as 300% (Barbusiński 2017). Biogas production is a very important element in the operation of wastewater treatment plants. Thanks to this, the treatment plant becomes self-sufficient in terms of securing the supply of heat for technological and heating purposes (Biedrzycka, Lager 2012, p. 31).

Continuous optimisation of wastewater treatment processes and energy efficiency are essential today. An inseparable element of the energy strategy of a wastewater treatment plant should be the search for further, often innovative, ways of recovering energy from sewage. An example of this is the production of electricity by means of water turbines installed in the outlet drain from the wastewater treatment plant. In order to improve the energy balance in the wastewater treatment plant, it is possible to use photovoltaic farms on the premises.

Modernisation of wastewater treatment plants in Poland in recent years has led on the one hand to high efficiency in removing pollutants from wastewater and on the other to the minimisation of electricity consumption. Although the primary objective of wastewater treatment plants is to reduce pollution in wastewater, comprehensive technological and energy modernisation is possible, as evidenced by various examples of investment projects. The wastewater treatment plant in the Tychy-Urbanowice WWTP has been fully modernised in recent years, resulting in significant energy savings (Table 5).

Table 5. Reduction of energy consumption in the Tychy – Urbanowice WWTP

Type of operation	Level of energy intensity reduction [%]	Energy savings per year [MWh]
Modernisation of the main wastewater pumping station	47,0	241,0
Highly efficient interior lighting of rooms	41,0	3,0
Modernisation of aeration in bioreactors	29,0	1 223,0
Modernisation of activated sludge pumping station (recirculation)	78,0	512
Replacement of external lighting of the treatment plant	61,5	58,0

Source: RCGW 2018

The total installed capacity and electricity consumption after the modernisation of the plant was reduced by 25% with a 2-fold increase in the number of devices installed in the plant. Currently, the Tychy-Urbanowice WWTP is completely self-sufficient in terms of energy, and the average annual production of renewable energy is 150% in relation to the facility's own energy consumption. The amount of energy produced can satisfy the energy needs of a city of 16,000 inhabitants. In order to fully utilise this energy potential, the surplus energy covers the energy demand of the Tychy Water Park. The Tychy Water Park is the first facility in Poland that is entirely powered by electricity and is heated by the energy generated from biogas induced by the treatment of sewage sludge in the Tychy WWTP. The Tychy-Urbanowice WWTP is the first passive wastewater treatment plant in Poland (RCGW 2018).

Conclusion

The issue concerning the energy intensity of water and wastewater management is currently becoming one of the most dynamically developing research areas. Consideration is therefore being given to the use of electricity in wastewater treatment systems, as well as the assessment of their energy efficiency. Electricity is used in the wastewater treatment plant to supply electric drive systems, among other things. Electricity consumption depends on the type of wastewater and the technological system used in the treatment plant. Additionally, electric and thermal energy are used for the social needs of employees, heating of technical and administrative buildings, lighting of the area, etc.

The high energy consumption of wastewater treatment plants translates into the need to optimise technological processes, as well as the search for alternative energy sources, due to which the purchase of electricity from the distribution network can be minimised. It is necessary to identify the activities and operations that consume the most energy or are inefficient, which may result in the implementation of an energy saving procedure in the wastewater treatment plant.

Energy savings in wastewater treatment plants are primarily related to the improvement or replacement of energy-intensive equipment (pumps, mixers, blowers) and the introduction of intelligent control and monitoring systems for wastewater treatment processes. The optimisation of individual processes and the operation of machinery and equipment allows for energy savings in the purchase of several to a dozen or so percent. This is followed by the production of electricity and heat from sewage sludge (thermal hydrolysis, fermentation, co-fermentation, sludge incineration), in addition to energy recovery from wastewater (heat pumps, water turbines). The use of innovative wastewater treatment methods with simultaneous energy efficiency leads to an energy self-sufficient facility. Modern wastewater treatment plants should now be seen as technological and energy works, because on the one hand they remove pollutants from wastewater, and on the other they can be producers of raw materials (phosphorus recovery, fertiliser production) as well as electric and thermal energy.

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Adam Masłoń, PhD, Eng.
ORCID: 0000-0002-3676-0031

Assistant Professor of Department of Chemistry and Environmental Engineering at Rzeszow University of Technology. The author of many scientific articles, analyses, reports and books. The area of scientific interests related to wastewater technology (activated sludge technology, sequencing batch reactors, aerobic granular sludge, energy consumption of wastewater treatment) as well as sewage sludge utilisation.

Marta Wójcik, PhD, Eng.
ORCID: 0000-0003-3764-1058

She is an assistant professor on the Department of Materials Forming and Processing at Rzeszow University of Technology. In 2015, she graduated with a Master's degree at Rzeszow University of Technology. In 2018, she received a doctoral degree in the field of environmental engineering. She is an author of several papers associated with the environmental and mechanical engineering. Her academic research is related with sewage sludge and waste management, recycling as well as fuzzy sets theory in engineering applications.

Krzysztof Chmielowski, DSc, PhD, Eng.
ORCID 0000-0001-9758-0854

In the period of 2002-2007 he completed doctoral studies at the Faculty of Environmental Engineering and Land Surveying of the University of Agriculture in Krakow. In 2007 at the home department, he defended his doctoral thesis entitled „Effectiveness of treatment using vertical flow sand filters in domestic sewage treatment plants" obtaining the PhD degree in agricultural sciences in the field of environmental development. By decision of the Faculty Board, the doctoral dissertation was awarded a distinction. He obtained the degree of habilitated doctor in agricultural sciences, in the field of environmental protection and development, specialty of water and wastewater management, at the same Faculty, based on the habilitation thesis „Effectiveness of sewage treatment in a domestic treatment plant using a modified gravel-sand filter".