OVERVIEW AND ANALYSIS OF ELECTRIC ENERGY CONSUMPTION INDICATORS IN WASTEWATER TREATMENT PLANTS

Jovana M. BLAGOJEVIĆ [*1], Aleksandar M. JOVOVIĆ[2], Sanda S. MIDŽIĆ-KURTAGIĆ[3]

[*1]University of East Sarajevo, Faculty of Mechanical Engineering East Sarajevo, East Sarajevo, Bosnia and Herzegovina

[2]Faculty of Mechanical Engineering, University of Belgrade, Belgrade, Serbia

[3] Faculty of Mechanical Engineering, University of Sarajevo, Sarajevo, Bosnia and Herzegovina

[*] Corresponding author; E-mail: jovana.blagojevic@ues.rs.ba

Wastewater must be treated before discharge into the recipient to such an extent that it meets standards and regulations on wastewater quality, so as not to damage the environment. Depending on the quality of the influent, different technological procedures are applied, which are more or less energy intensive. Also, with the tightening of the conditions related to the quality of the effluent, the application of more energy-intensive purification technologies occurs, and thus the energy consumption at the plants increases. Wastewater treatment plants are among the biggest consumers of energy. In this paper, electric energy consumption at wastewater treatment plants was analyzed depending on different indicators of specific energy consumption, the applied technological process, and the level of purification.

Key words*: wastewater treatment plant, energy consumption indicators, energy analysis*

1. Introduction

Wastewater treatment technology consists of various physical, chemical and biological processes, depending on its quality, that is the degree of pollution. It is common for wastewater treatment to consist of five levels of treatment, namely: preliminary or pre-treatment, primary treatment, secondary treatment or purification, tertiary or final treatment and treatment of sludge formed [1,2]. Electric energy and heat energy are consumed at the wastewater treatment plant. The need for electric energy is present in almost all phases of wastewater and sludge treatment, as well as for obtaining heat, which is mainly used for heating individual facilities, maintaining the appropriate temperature in the digester and drying sludge. The paper focuses on the review and analysis of electric energy consumption indicators.

The biggest consumers of electric energy at wastewater treatment plants (WWTPs) are compressors, which are necessary to provide compressed air for aeration purposes, and then pumping stations that allow the movement of wastewater and sludge. Other consumers are also present, such as electric motors for mixing mixers, filter presses, fans, extractors, etc.

According to the IEA - International Energy Agency [3], electric energy consumption in the water sector, which includes wastewater collection and treatment, accounted for 4% of total global consumption, of which about a quarter was spent on wastewater treatment. Increasing energy consumption also raises concerns about climate change, where the water sector participates with about 3% of total greenhouse gas emissions (GHG). Emissions from wastewater treatment plants are categorized into direct and indirect emissions. Direct GHG emissions include those from treatment processes, the sewage collection system, and emissions from the receiving water environment where treated water is discharged. Indirect GHG emissions stem from electricity and chemical consumption, fossil fuel use for transportation and sludge disposal [4].

Wastewater is now recognized as a valuable resource capable of generating energy and valuable resources, such as organic residuals containing nutrients and elements needed by plants (nitrogen and phosphorus) and water for various uses [5,6,7]. In order to make an important contribution to environmental protection, it is necessary to enable wastewater treatment plants to become energy producers, that is to achieve energy self-sustainability of plants. The recovery of energy from the by-products of the wastewater treatment process can significantly contribute to the improvement of the energy balance of the plant [8,9,10]. Also, wastewater treatment plants can be an important part of circular sustainability due to integration of energy production and resource recovery during process [11,12].

The researchers used various indicators of specific electric energy consumption such as flow, pollution burden, population equivalent (PE), etc. The paper gives an overview of electric energy consumption taking into account the amount of treated water, number of population equivalent, removed amount of COD (chemical oxygen demand), BOD (biochemical oxygen demand), also analyses data on consumption in relation to technological operation and level of purification, and then compares consumption at the national level.

2. Energy consumption at wastewater treatment plants

2.1. Specific energy consumption indicators

The simplest energy indicator for monitoring electric energy consumption at wastewater treatment plants is the absolute (total) energy consumption in a given period of time. However, this method of measurement is not satisfactory because energy consumption depends on the size of the plant, type of treatment process, water quality requirements after the treatment process, age of the plant, hydraulic load per capita, COD, type of sewage system, etc. [13,14,15].

For the above reasons, energy consumption indicators (ECI) are used, which are defined as the relationship between the energy consumption and one relevant parameter in the plant. For the relevant parameters it is possible to use the amount of treated wastewater, the amount of COD removed, the BOD and the population equivalent.

ECI_{m^3} is defined as the ratio between the daily energy consumption and the daily volume treated (annual average is considered).

$$ECI_{m^3}\left[kWhm^{-3}\right]=\frac{\text{Energy consumption }\left[kWhd^{-1}\right]}{\text{Volume od treated water }\left[m^3d^{-1}\right]} \quad (1)$$

ECI_{COD} is defined as the ratio between the daily energy consumption and the COD mass daily removed in the plant (annual average is considered).

$$ECI_{COD}\left[kWhkgCOD_{removed}{}^{-1}\right]=\frac{\text{Energy consumption }\left[kWhd^{-1}\right]}{\text{COD load removed }\left[kgCOD_{removed}d^{-1}\right]} \quad (2)$$

ECI_{PE} is defined as the ratio between the annual energy consumption and the population equivalent served in the plant.

$$ECI_{PE}\left[kWhPE^{-1}year^{-1}\right]=\frac{\text{Energy consumption }\left[kWhyear^{-1}\right]}{\text{Population equivalent }\left[PE\right]} \quad (3)$$

ECI_{BOD} is defined as the ratio between the daily energy consumption and the BOD mass daily removed in the plant.

$$ECI_{BOD}\left[kWhkgBOD_{removed}{}^{-1}\right]=\frac{\text{Energy consumption }\left[kWhd^{-1}\right]}{\text{BOD load removed }\left[kgBOD_{removed}d^{-1}\right]} \quad (4)$$

In the paper [16], the authors report on electric energy consumption in plants taking as an indicator of consumption the mass of wastewater, which can be defined as the ratio of the daily energy consumption and the mass of treated wastewater.

$$ECI_{t}\left[kWht^{-1}\right]=\frac{\text{Energy consumption }\left[kWhd^{-1}\right]}{\text{Mass of treated wastewater }\left[td^{-1}\right]} \quad (5)$$

The data on electric energy consumption found in the literature for each of the previously defined indicators are presented in tab. 1.

Table 1. Energy consumption per energy consumption indicators (ECI)

	ECI_{m^3}	ECI_{COD}	ECI_{PE}	ECI_{BOD}	ECI_t	Reference
Slovakia, 68 plants 17 small plants up to 350 m^3/day, 500-2,500 PE Large plants 51 from 350 m^3/day, from 5000 to 1,050,000 PE	 0.915 kWh/m^3 0.485 kWh/m^3					[17]
Greece, 12 small plants - treatment capacity lower than 10,000 PE, applied extended aeration-activated sludge treatment processes 12 medium plants - treatment capacity ranging from 10,000 to 100,000 PE, at 10 plants was applied extended aeration activated sludge treatment processes,	 1.65 kWh/m^3 0.43 kWh/m^3		 0.374 kWh/PEd; 137 kWh/PEyear 0.132 kWh/PEd 48 kWh/PEyear			[18]

at 2 had Conventional Activated Sludge, sludge thickening, anaerobic digestion and dewatering. 7 large plants - treatment capacity of over 100,000 PE, at 5 plants applied Conventional Activated Sludge, sludge thickening, anaerobic digestion and dewatering, at 2 plants applied Conventional Activated Sludge, sludge thickening, anaerobic digestion, cogeneration and dewatering.	0.33 kWh/m^3		0.087 kWh/PEd; 32 kWh/PEyear			
Greece, 17 activated sludge WWTPs, serving between 1,100 and 56,000 PE, inflow 300-27,300 m^3/day, or 0.052-0.426 m^3/PEday	0.128-2.280 kWh/m^3 Average 0.903 ±0.509		0.041-0.407 kWh/PEd Average 0.167 ±0.101			[19]
The Rzeszów WWTP, Poland, designed capacity 54,500 m^3/day for 398,000 PE, average treatment capacity was 42,631 m^3/day, during 2016	0.367-0.557 kWh/m^3	0.49-0.68 kWh/kgCOD	26.11 kWh/PEyear	1.03-1.57 kWh/kgBOD_5		[20]
84 plants, PE < 2,000 87 plants, 2,000 < PE <10,000 89 plants, 10,000 < PE <50,000 35 plants, 50,000 < PE < 100,000 43 plants, PE >100,000		3.01 kWh/kgCOD 1.54 kWh/kgCOD 1.02 kWh/kgCOD 0.82 kWh/kgCOD 0.69 kWh/kgC				[21]

		OD				
The SMAT plant in Turin, Italy, capacity 615,000 m^3/day = 2.7 million PE	0.30 kWh/m^3	0.87 kWh/kgCOD	24.73 kWh/PEyear			[22]
The average electric energy consumption at 17 Portuguese plants for 5 years of study (2006 - 2010)		1.3 kWh/kgCOD		2.8 kWh/kgBOD$_5$		[23]
Shenzhen (China), 22 plants					0.12-0.38 average 0.20±0.06	[16]

Analyzing the previous table, it can be concluded that researchers do not use a unique approach when dividing wastewater treatment plants by size, or number of served PE. Also, data on energy consumption is expressed by different energy consumption indicators (ECI), where the predominant use is ECI_{m^3}, followed by ECI_{COD} and ECI_{PE}. It can be observed that large plants have less variation in energy consumption, unlike small plants. This can be attributed to the fact that at small plants there are greater variations in the number of served PE.

It is necessary to formulate a unique methodology for the division of plants by size and identify a unique indicator of energy consumption to be able to benchmark between plants. Also, it would be desirable to indicate the amount of treated wastewater in consumption reports.

2.2. Electric energy consumption in relation to technological operation and level of purification

The choice of applied treatment methods and technologies is correlated with the size of the plant and the type of pollutants [17]. Energy is consumed throughout the plant (Fig. 1), but is used most intensively in the primary and secondary phases of the conventional wastewater treatment process. In the primary phase, electric energy is mostly used to operate the pumps. The secondary process is more energy intensive than the primary one because it is necessary to provide large amounts of oxygen provided by aeration blowers and fans. The operation of pumps and aeration together account for 2/3 to 3/4 of the total energy consumption at a wastewater treatment plant, of which aeration accounts for about 3/4 [13,18,24,25].

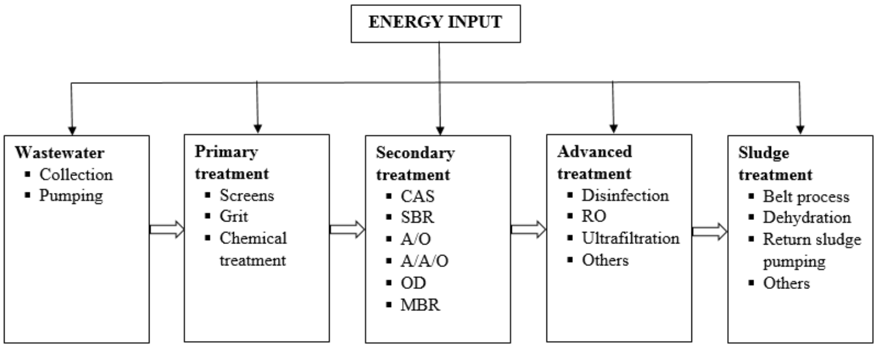

Figure 1. Application of electric energy at a wastewater treatment plant [26]

CAS - conventional activated sludge; SBR - sequence batch reactors; A/O – anoxic-oxic systems; A/A/O - anaerobic-anoxic-oxic systems; OD - oxidation ditch; MBR - membrane bioreactor; RO - reverse osmosis.

Tab. 2 presents various wastewater treatment plants and the share (in percentages) of electric energy consumption for individual technological operations. In most studies, electric energy consumption is given only for three operations: aeration, pumping, and sludge dewatering, which are identified as the largest consumers. It can be observed that aeration occupies between 50 and 70% of the total energy needs of the plant, making it a significant contributor to the overall operational expenses, and pumping between 9 and 17%.

Table 2. Energy consumption in relation to technological operations in wastewater treatment plants

Plant / the main consumers of energy	Aeration (%)	Buildings (%)	Pumping stations (%)	Anaerobic digestion (%)	Mechanical pretreatment (%)	Sludge dewatering (%)	Disinfection (%)	Reference
Activated sludge treatment process	54.1 (50-70)	8.1 (6-12)	14.7 (9-17)	14.2 (9-17)	2 (1-4.5)	4 (3-20)	1 (0.3-25)	[27]
14 wastewater treatment plants in Portugal	53		12					[28]
Wastewater treatment plant SMAT from Turin, Italy 615,000 m^3/d = 2.7 millions PE	50.34	-	-	14.04	1.56	9.42	-	[22]
3 wastewater treatment plants in Shenzhen, China	≈ 50.78*	-	-	-	≈ 29.46	≈ 16.67	≈ 3.49	
	≈ 68.58*	-	-	-	≈ 17.62	≈ 10.73	≈ 2.68	[16]
	≈ 59.95*	-	-	-	≈ 11.51	≈ 4.71	≈ 1.57	
Average Membrane Bioreactor (MBR) treatment systems in Singapore	60		12			12		[29]**
250,000 PE advanced WWTP in Poland	53		30					
Average Energy Distribution in	67		5			11		

Germany								
18,000 m^3/d WWTP in Spain	42		20			31		
800,000 m^3/d advanced WWTP in Singapore	13		24			9		
81,000 m^3/d CAS WWTP in Japan	46		18			31		
CAS WWTP in Singapore	50		15			30		
500,000 PE CAS WWTP in Sweden	48		9			14		
Benchmarking study on advanced WWTP in Austria	70		3			14		
250,000 PE advanced WWTPs in Austria	57		9			13		
2.4 million PE advance WWTP in China	57					5		
WWTP in Iran	77		11			7		

**. biochemical treatment; **. The presented data represent a compilation of the research results of the author Sarpong et al. 2020*

Tab. 3 shows the electric energy consumption for wastewater treatment levels and different types of treatments.

Table 3. Electric energy consumption for different levels and types of wastewater treatment

Levels of wastewater treatment	Type of treatment	Known information about plants	Electric energy consumption kWh/m^3	Reference
Primary level	Raw wastewater collection and pumping	Canada	0.02-0.1	[14]
		Hungary	0.045-0.14	[30]
		Australia	0.1-0.37	[14]
Secondary level	CAS method	Japan – inflow 600-283,000 m^3/dan	0.30-1.89	[31]
		Australia	0.46	[18]
		China – 36 wastewater treatment plants	0.269	[32]
		USA	0.33-0.60	[17]
		Slovakia – 51 large wastewater treatment	0.145-1.422 (average	[17]

		plants (5,000-105,000 PE)	0.485)	
		Slovakia – 17 small wastewater treatment plants (500-2,500 PE)	0.915	
	CAS method with incineration	Japan	0.38-1.49	[31]
	OD method	Japan – inflow 100-8,500 m^3/dan	0.44-2.07	[31]
		Australia	0.5-1.0	[33]
		China – 170 wastewater treatment plants	0.302	[32]
		Greece – 4 wastewater treatment plants	0.501-0.800	[19]
	extended aeration systems	China – 13 wastewater treatment plants	0.340	[32]
	sequence batch reactors	China – 103 wastewater treatment plants	0.336	[32]
	biomembrane systems	China – 36 wastewater treatment plants	0.330	[32]
		Australia	0.1-0.82	[33]
		USA	0.8-0.9; 0.49-1.5	[33]
	anoxic–oxic systems	China – 36 wastewater treatment plants	0.283	[32]
	anaerobic–anoxic–oxic systems	China – 97 wastewater treatment plants	0.267	[32]
	land treatment and constructed wetlands	China – 10 wastewater treatment plants	0.253	[32]
	adsorption-biology systems	China – 17 wastewater treatment plants	0.219	[32]
	upflow anaerobic sludge blanket (UASB) process	Ghana - Mudor WWTP located in Accra – 60,000 PE	0.23-0.31	[34]
	continuous stirred tank reactor (CSTR)	Greece - 10 wastewater treatment plants	0.440-1.646	[19]
	plug flow reactor (PFR)	Greece - 3 wastewater treatment plants	0.128-2.279	[19]
	mechanical – biological	Poland - WWTP Krosno	0.25-0.71 (average 0.51)	[35]
Tertiary or advanced	-	Japan	0.39-3.74	[31]
		USA	0.43	[14]

level		Taiwan	0.41	[14]
		New Zealand	0.49	[14]
		Hungary	0.45-0.75	[14]
		Poland – 250,000 PE	0.48	[29]
	Reverse osmosis	Spain	0.8	[36]
		Saudi Arabia	1.6	[36]

It can be observed that energy consumption depends on the applied level of wastewater treatment and the applied treatment technology. Lower energy consumption is observed in the primary level, while higher consumption is represented when applying secondary and tertiary levels of treatment.

2.3. Benchmarking of electric energy consumption - national level

Benchmarking energy consumption in wastewater treatment plants at the national level can be used to better understand energy efficiency in the same (Fig. 2). The difference in energy consumption in different regions depends on the applied technologies and the targeted quality of wastewater after treatment [26].

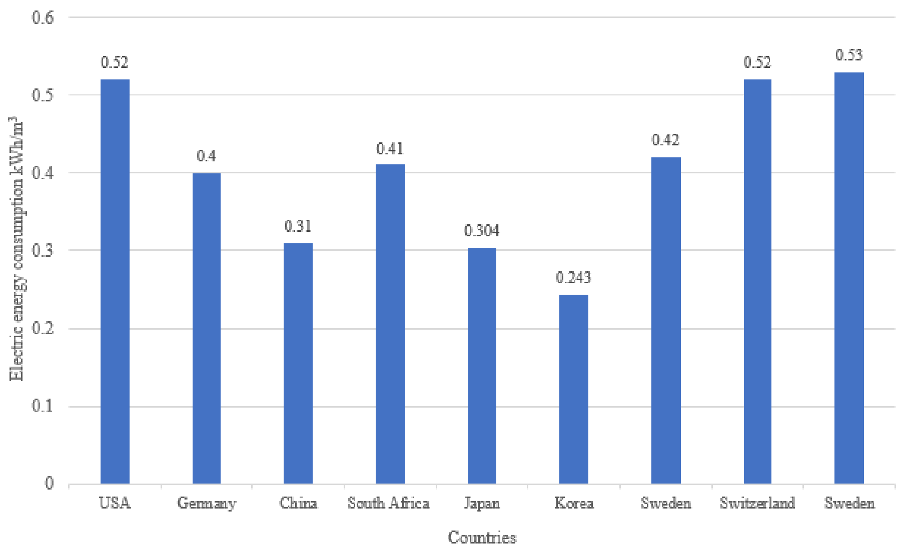

Figure 2. Electric energy consumption - national level

In the United States, electric energy consumption at wastewater treatment plants is estimated at 0.6% of annual electric energy consumption, which is 0.52 kWh/m^3 (according to 2008 data), while in Germany it is 0.7% or 0.40 kWh/m^3. In China, 0.25% of annual electric energy consumption goes to wastewater treatment, i.e. 0.31 kWh/m^3 (data from 2009), while in South Africa it varies from 0.079-0.41 kWh/m^3 [37]. In Iran it is 0.1% of the total annual electricity consumption or 241 million kWh/year [38]. The average electric energy consumption at wastewater treatment plants was: 0.304 kWh/m^3 in Japan; 0.243 kWh/m^3 in Korea; 0.42 kWh/m^3 in Sweden; 0.52 kWh/m^3 in Switzerland; 0.53 kWh/m^3 in Spain; [39,40,41,42]. Gu et al. [26] state that the reason for the relatively low energy consumption at Chinese plants is that the consumption of electricity for sludge treatment is not usually included in the mentioned consumption.

3. Discussion

Wastewater treatment is an energy-intensive industry. The paper first defines the indicators through which it is possible to monitor the specific consumption of electric energy and for each of them is given data from different plants found in the literature. According to [20,21,43,44], it is common to take the amount of treated wastewater, the amount of COD removed and the population equivalent as parameters for expressing specific energy consumption. However, Longo et al. [21] showed that in most of the analyzed studies (about 90%) energy data from wastewater treatment plants are expressed as total electric energy consumption [kWh] or relate to the volume of treated wastewater [$kWhm^{-3}$], while consumption expressed in relation to the number of population equivalent and the amount of COD and BOD removed is rarely used. Also, Maslon et al. [35] state that the indicator $ECI_{m}{}^{3}$ is most often used to show the consumption of electric energy at wastewater treatment plants.

The ECI_{COD} and ECI_{PE} indicators have a high positive correlation, i.e. both provide the same information and are interchangeable, due to the 120 gCOD/PEday per capita load being used to convert organic load to PE and vice versa. Wastewater can be diluted under the influence of atmospheric water, groundwater infiltration, melting ice in the sewer system, etc. For this reason, $ECI_{m}{}^{3}$ gives an inaccurate picture of energy consumption, because this indicator depends on the flow and tends to decrease with increasing amount of purified water [13,15,21,43]. However, the energy consumption at pumping stations, which are also a significant consumer, depends on the flow [13], and the $ECI_{m}{}^{3}$ indicator is suitable for them as well as for other phases designed based on hydraulic parameters [45]. Also, the paper [46] proposes the use of ECI_{COD} to measure energy intensity due to the fact that this indicator increases with decreasing COD concentration in the influent, so this can explain the large energy loss when the plant receives higher atmospheric water (diluted wastewater), as well as the fact that plants with mixed sewage have a lower $ECI_{m}{}^{3}$ than plants with separate. Wastewater treatment plants serving a mixed sewage system show high values of specific energy consumption expressed through ECI_{PE} indicators due to additional electric energy consumption of equipment that is directly related to hydraulic parameters, such as pumps, gratings and filters. Which is in contrast to the $ECI_{m}{}^{3}$ indicator at the same plants [47].

The paper [21] states that the best way to report energy consumption per unit of pollutants removed is to remove the total amount of suspended matter, BOD, COD, nitrogen and/or phosphorus, etc. This is because the removal of organic and nutrients contributes to the increase of energy consumption in wastewater treatment plants, so preference should be given to an indicator that can include all types of pollution loads in one variable.

Energy consumption expressed on the basis of the amount of BOD removed - biochemical oxygen consumption is a good way to measure energy intensity, because the concentration of pollutants affects the needs of aeration, which is the largest source of energy consumption [13]. The same authors state that, in order to monitor and obtain more accurate data on electric energy consumption, wastewater treatment plants do not have to be limited to only one indicator of specific consumption. That is, separate indicators for primary and secondary levels of purification can be developed. The primary level of treatment is dominated by the use of electric energy for pumping, and the use of flow-based indicators is recommended, while in the secondary level, where the use of electric energy for aeration is dominated, the indicator based on BOD is recommended.

Then, the consumption of electric energy in relation to the technological operation and the level of purification was considered, where it was noticed that the most energy intensive are aeration and pumping, 50-70% and 3-30% respectively. However, if there is a sludge disposal line at the plant, a significant part of the electric energy is spent on aerobic digestion, as well as on the process of sludge drainage. The difference in the applied levels and technologies of wastewater treatment significantly affects the specific electricity consumption. As the level of purification increases, so does the need for electric energy. Also, it can be noticed that in the secondary level of purification, the most energy-intensive technology is the MBR membrane bioreactor technology.

Finally, a benchmarking of electric energy consumption at wastewater treatment plants was made at the national level, which can be used to better understand the energy efficiency of the plant.

4. Conclusion

Energy consumption at wastewater treatment plants can be expressed by different indicators, such as the amount of treated wastewater, the amount of COD and BOD removed and the population equivalent (PE). The paper presents the advantages and disadvantages of each of the energy consumption indicators, as well as their values in individual plants. Also, electricity consumption was analyzed depending on the size of the plant, applied technological operation and level of purification, as well as the location of the plant. What can be noticed is that large plants have lower energy consumption compared to small ones. Aeration and pumping stations are the most energy-intensive, and the sludge disposal line if it exists. It can be concluded that wastewater treatment plants need a lot of energy and therefore they have a significant impact on the environment. For these reasons, it is necessary to constantly monitor energy data from the plant, analyze it, and use it to identify possible savings, especially within technological operations, which are identified as the largest consumers. Energy audits show that, regardless of the size of the wastewater treatment plant, each has opportunities for improving energy savings, which can vary from 20 to 40%, and in some specific cases, up to 75% [28]. Some of the proposals for saving electric energy at wastewater treatment plants found in the literature are the replacement of old equipment (blowers, mixers, and pumps) with highly efficient ones, or redesign of aeration facilities and implementing intelligent monitoring as well as implementation advanced control systems for the WWTP operation. Then, greater efficiency of primary treatment, that is, removal of as much total suspended solids (TSS) as possible before biological treatments. This reduces the need for oxidation, which leads to less energy demand [8,29,35,48,49]. Sarpong et al. [29] also suggest replacing the aeration unit with a technology that consumes much less energy, such as a trickling filter or a high-rate microalgae pond.

Additionally, the improvement of technologies, process optimization, and the implementation of advanced energy management methods are key factors that can contribute to the sustainable operation of these facilities. Future research should focus on the development of software solutions for real-time energy consumption optimization, based on data analytics and machine learning. This way, the plants will be able to adjust operating parameters according to needs, reducing unnecessary energy losses.

Also, it is necessary to create the conditions for plants to become energy producers, to become energy neutral or otherwise positive. One way is the integration of renewable energy sources like solar and wind power and biogas production from wastewater treatment by-products.

References

[1] ***FAO, Food and Agriculture Organization of the United Nations, Wastewater treatment, https://www.fao.org/3/t0551e/t0551e05.htm

[2] Crini, G., Lichtfouse, E., Advantages and disadvantages of techniques used for wastewater treatment, *Environmental Chemistry Letters, 17* (2019), pp. 145-155, https://doi.org/10.1007/s10311-018-0785-9

[3] ***, The energy sector should care about wastewater, IEA, Paris, (2018), https://www.iea.org/commentaries/the-energy-sector-should-care-about-wastewater

[4] Karakas, A., *et al.*, Carbon footprint analysis of advanced biological wastewater treatment plant, *Journal of Water Process Engineering, 61* (2024), 105254, https://doi.org/10.1016/j.jwpe.2024.105254

[5] Hao, X., *et al.*, Making waves: A sea change in treating wastewater – why thermodynamics supports resource recovery and recycling, *Water Res, 218* (2022), 118516, doi:10.1016/j.watres.2022.118516

[6] Hamda, A. S., *et al*., Carbon Emissions, Energy Reduction, and Energy Recovery from Wastewater Treatment Plants, *Sewage and Biomass from Wastewater to Energy*, (2024), pp. 93-112. https://doi.org/10.1002/9781394204502.ch4

[7] Chmielewski, A. G., *et al*., Advanced Technology for Energy, Plant Nutrients and Water Recovery at Wastewater Treatment Plants, *Energies*, *17* (2024), 11, 2749, https://doi.org/10.3390/en17112749

[8] Capodaglio, A. G., Callegari, A., Energy Use and Recovery in Wastewater Treatment Facilities, *Renewble Energy and Power Quality Journal (RE&PQJ)*, 18 (2020), pp. 425-430, https://doi.org/10.24084/repqj18.368

[9] Guven, H., *et al.*, Energy self-sufficiency in wastewater treatment plants: perspectives, challenges, and opportunities, *Clean Energy and Resource Recovery*, (2022), pp.105-122, https://doi.org/10.1016/B978-0-323-90178-9.00019-6

[10] Cairone, S., *et al*., Revolutionizing wastewater treatment toward circular economy and carbon neutrality goals: Pioneering sustainable and efficient solutions for automation and advanced process control with smart and cutting-edge technologies, *Journal of Water Process Engineering*, *63* (2024), 105486, https://doi.org/10.1016/j.jwpe.2024.105486

[11] Neczaj, E., Grosser, A., Circular economy in wastewater treatment plant–challenges and barriers, Proceedings, Multidisciplinary Digital Publishing Institute, 2018, Vol. 2, No. 11, p. 614, https://doi.org/10.3390/proceedings2110614

[12] Hernández-Chover, V., *et al*., Circular economy and efficiency to ensure the sustainability in the wastewater treatment plants. *Journal of cleaner production*, *384* (2023), 135563, https://doi.org/10.1016/j.jclepro.2022.135563

[13] Lemar, P., De Fontaine, A., Energy Data Management Manual for the Wastewater Treatment Sector, United States, 2017, https://doi.org/10.2172/1432164

[14] Gu, Y., et al. Energy self-sufficient wastewater treatment plants, *Energy Procedia, 105* (2017), pp. 3741-3751, https://doi.org/10.1016/j.egypro.2017.03.868

[15] Vaccari, M., *et al.*, Benchmarking of energy consumption in municipal wastewater treatment plants–a survey of over 200 plants in Italy, *Water Science and Technology, 77* (2018), 9, pp. 2242-2252, https://doi.org/10.2166/wst.2018.035

[16] Li, W., *et al.*, Energy consumption and economic cost of typical wastewater treatment systems in Shenzhen, China, *Journal of Cleaner Production, 163* (2016) pp. S374 – S378, https://doi.org/10.1016/j.jclepro.2015.12.109

[17] Bodik, I., Kubaska, M., Energy and sustainability of operation of a wastewater treatment plant, *Environment Protection Engineering*, *39* (2013), 2, pp. 15-24.

[18] Goliopoulos, N., *et al*., Energy Consumption and Carbon Footprint of Greek Wastewater Treatment Plants, *Water*, *14* (2022), 3, 320, https://doi.org/10.3390/w14030320

[19] Siatou, A., *et al*., Energy consumption and internal distribution in activated sludge wastewater treatment plants of Greece, *Water, 12* (2020), 4, 1204, https://doi.org/10.3390/w12041204

[20] Masłoń, A., Analysis of energy consumption at the Rzeszów Wastewater Treatment Plant, *E3S Web of Conferences, EDP Sciences,* 2017, p. 00115, https://doi.org/10.1051/e3sconf/20172200115

[21] Longo S., *et al*., Monitoring and diagnosis of energy consumption in wastewater, A*pplied Energy, 179 (*2016), pp. 1251-1268, http://dx.doi.org/10.1016/j.apenergy.2016.07.043

[22] Panepinto, D., Evaluation of the energy efficiency of a large wastewater treatment plant, *Applied Energy, 161* (2016), pp 404-411, http://dx.doi.org/10.1016/j.apenergy.2015.10.027

[23] Silva, C., Rosa, M. J., Energy performance indicators of wastewater treatment: a field study with 17 Portuguese plants, *Water Science and Technology, 72* (2015), 4, pp. 510-519, https://doi.org/10.2166/wst.2015.189

[24] Baquero-Rodríguez, G. A., *et al.*, How elevation dictates technology selection in biological wastewater treatment, *Journal of Environmental Management, 307* (2022), 114588, https://doi.org/10.1016/j.jenvman.2022.114588

[25] Li, Z., *et al*., Energy Efficiency Evaluation and Optimization for Wastewater Treatment Plant, *Desalination and Water Treatment, 319* (2024), 100487, https://doi.org/10.1016/j.dwt.2024.100487

[26] Gu, Y., *et al*., The feasibility and challenges of energy self-sufficient wastewater treatment plants, App*lied Energy*, *204* (2017), pp. 1463-1475, http://dx.doi.org/10.1016/j.apenergy.2017.02.069

[27] Capodaglio, A. G., Olsson, G., Energy issues in sustainable urban wastewater management: Use, demand reduction and recovery in the urban water cycle. *Sustainability, 12* (2020), 1, 266, https://doi.org/10.3390/su12010266

[28] Henriques, J., Catarino J., Sustainable value - An energy efficiency indicator in wastewater, *Journal of Cleaner Production*, *142* (2011), Part 1, p.p. 323-330, http://dx.doi.org/10.1016/j.jclepro.2016.03.173

[29] Sarpong, G., *et al.*, Evaluation of energy recovery potential in wastewater treatment based on codigestion and combined heat and power schemes, *Energy Conversion and Management, 222* (2020), 113147, https://doi.org/10.1016/j.enconman.2020.113147

[30] Pitas, V., *et al.*, Energy efficiency of the municipal wastewater treatment, *Journal of Biotechnology, 150 (*2010), pp. 163-164.

[31] Mizuta, K., Shimada, M., Benchmarking energy consumption in municipal wastewater treatment plants in Japan, *Water Science and Technology, 62* (2010), 10, pp. 2256-2262. https://doi.org/10.2166/wst.2010.510

[32] Yang, L., *et al.*, Operational energy performance assessment system of municipal wastewater treatment plants, *Water Science and Technology, 62* (2010), 6, pp. 1361-1370, https://doi.org/10.2166/wst.2010.394

[33] Plappally, A. K., Energy requirements for water production, treatment, end use, reclamation, and disposal, *Renewable and Sustainable Energy Reviews*, *16* (2012), 7, pp. 4818-4848, https://doi.org/10.1016/j.rser.2012.05.022

[34] Arthur, P. M. A., *et al*., Evaluating the Potential of Renewable Energy Sources in a Full-Scale Upflow Anaerobic Sludge Blanket Reactor Treating Municipal Wastewater in Ghana, *Sustainability*, *15* (2023), 4, 3743, https://doi.org/10.3390/su15043743

[35] Masłoń, A., *et al*., Assessment of Energy Self-Sufficiency of Wastewater Treatment Plants—A Case Study from Poland, *Energies*, *1 7*(2024), 5, 1164, https://doi.org/10.3390/en17051164

[36] Wakeel, M., *et al*., Energy consumption for water use cycles in different countries: A review. *Applied Energy, 178* (2016), pp. 868-885, https://doi.org/10.1016/j.apenergy.2016.06.114

[37] Wang, H., *et* al., Comparative analysis of energy intensity and carbon emissions in wastewater treatment in USA, Germany, China and South Africa, *Applied Energy, 184* (2016), pp. 873-881, https://doi.org/10.1016/j.apenergy.2016.07.061

[38] Akbarzadeh, A., *et al.*, Municipal Wastewater Treatment in Iran: Current Situation, Barriers and Future Policies, *Journal of Advances in Environmental Health Research*, *11* (2023), 1, pp. 60-71, doi: 10.34172/jaehr.2023.08

[39] Tao, G., *et al*., Energy reduction and optimisation in membrane bioreactor systems, *Water Practice and Technology, 5* (2010), 4, https://doi.org/10.2166/wpt.2010.088

[40] Chae, K. J., Kang, J., Estimating the energy independence of a municipal wastewater treatment plant incorporating green energy resources, *Energy Conversion and Management*, *75* (2013), pp. 664-672, https://doi.org/10.1016/j.enconman.2013.08.028

[41] Olsson G., Water and energy nexus. In: Meyers RA, editor. Encyclopedia of sustainability science and technology. New York, NY: Springer New York; (2012), pp. 11932–46.

[42] Hernández-Sancho, F., *et al*., Energy efficiency in Spanish wastewater treatment plants: A non-radial DEA approach, *Science of the Total Environment*, *409* (2011), 14, pp. 2693-2699, https://doi.org/10.1016/j.scitotenv.2011.04.018

[43] Gurung, K., *et al*., Unit energy consumption as benchmark to select energy positive retrofitting strategies for Finnish wastewater treatment plants (WWTPs): a case study of Mikkeli WWTP, *Environmental Processes*, *5* (2018), pp. 667-681.

[44] Soares, R. B., *et al*., Comparative analysis of the energy consumption of different wastewater treatment plants, *International Journal of Architecture, Arts and Applications*, *3* (2017), 6, pp. 79-86.

[45] Foladori, P., *et al*., Energy audit in small wastewater treatment plants, *Water Sci Technol*, *72* (2015), 6, pp. 1007-1015, https://doi.org/10.2166/wst.2015.306

[46] Niu, K., *et al*., Energy intensity of wastewater treatment plants and influencing factors in China. *Science of the total environment*, *670* (2019), pp. 961-970. https://doi.org/10.1016/j.scitotenv.2019.03.159

[47] Christoforidou, P., *et al*., Energy Benchmarking and Optimization of Wastewater Treatment Plants in Greece, *Proceedings*, Environmental Sciences Proceedings, Multidisciplinary Digital Publishing Institute, *2* (2020), 1, pp. 36, https://doi.org/10.3390/environsciproc2020002036

[48] Gikas P., *et al*., Towards energy positive wastewater treatment plants, *Journal of Environmental Management*, *203* (2016), pp. 621 – 629, https://doi.org/10.1016/j.jenvman.2016.05.061

[49] Tsalas, N., *et al*., Optimization of Energy Consumption in a Wastewater Treatment Plant: An Overview, *Energies*, *17* (2024), 12, 2808, https://doi.org/10.3390/en17122808

Paper submitted: December 8, 2023
Paper revised: November 4, 2024
Paper accepted: November 13, 2024