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ENERGY AND SUSTAINABILITY OF OPERATION OF A WASTEWATER TREATMENT PLANT

The study summarises the energy consumption data obtained from the Slovak wastewater treatment plants. Overall, 51 large WWTPs using mesophilic anaerobic sludge digestion and biogas utilisation (the total capacity of 2.5 mil. p.e.) and 17 small rural WWTPs (the total capacity 15 000 p.e.) were compared in many technological and energy parameters. The average energy consumption in large WWTPs in Slovakia is 0.485 kWh/m^3 and 0.915 kWh/m^3 in small rural plants. The average energy demand related to BOD_5 load represents the value of 2.27 kWh/kg BOD_5, in Slovak plants. The specific energy production is relatively low – in average 1.2 kWh$_{el}$/m^3 of produced biogas and 0.1 kWh$_{el}$/m^3 of treated wastewater, respectively. The average energy autarky in Slovak plants is 25.2%. Some plants have high energy autarky (>65%), despite no external biowastes being dosed to these during operation.

1. INTRODUCTION

Water is a significant life component, and as such, it plays a very important role in all aspects of energy balance in nature, industry, human body, etc. Production of drinking water, water for industry, and also wastewater treatment are processes comprising various energy demanding phases. Water pumping, treatment, distribution and supply systems, wastewater collection and treatment are important energy consuming technological steps in the water–wastewater cycle system. Processes included in the water–wastewater cycle demand represent an important part of the worldwide energy consumption. In Sweden, for example, these represent ca. 1%, in the USA and the UK about 3% of the overall energy consumption in country; and these figures are much higher in countries with higher water scarcity (Israel – 10%) [1].

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Wastewater collection and treatment systems are an important energy-consuming part within the whole water–wastewater cycle. Wastewater collection systems are designed and operated primarily to protect human health and the environment, and to transport wastewater from the pollution source to the treatment facility. On the other hand, wastewater treatment systems are designed and operated to reduce the pollution transported and diluted in water. All steps of wastewater treatment and sludge disposal technologies require energy for pumping, mixing and aeration of water, wastewater or sludge. Energy demand of wastewater treatment technology depends on the location of the plant, its size (population equivalent, organic or hydraulic load), type of the treatment process and the aeration system, effluent quality requirements, age of the plant, experience of its managers, etc. [2].

A conventional municipal wastewater treatment plant consists of three principal treatment steps: primary (suspended solids removal), secondary (organic pollution removal) and tertiary (nitrogen and phosphorus removal) stages. The primary treatment phase includes wastewater collection and pumping, screening, grit removal and sedimentation in primary sedimentation tanks. The processes in this treatment phase are low energy demand ones (except for wastewater pumping). Data on the primary treatment process energy intensity given in the literature vary widely. Energy intensity of raw wastewater collection and pumping ranges from 0.02 to 0.1 kWh/m^3 in Canada, from 0.045 to 0.14 kWh/m^3 in Hungary , and from 0.1 to 0.37 kWh/m^3 in Australia [1, 3, 4].

The secondary treatment aeration is the highest energy consumption part of the wastewater treatment technology. Besides aeration, also mixing of activated sludge in denitrification basins and recirculation (pumping) of sludge are very important energy consumers in this treatment phase. Typical aeration (fine-bubble technology) system in biological step of wastewater treatment plant (WWTP) with nutrient removal represents around 60–65% of the overall wastewater operating costs [4, 5]. The range of the energy intensity of secondary wastewater treatment systems is relatively wide. Conventional activated sludge treatment systems consume in average 0.46 kWh/m^3 (Australia), 0.269 kWh/m^3 (China), 0.33–0.60 kWh/m^3 (USA) and 0.30–1.89 kWh/m^3 (Japan). On the other hand, oxidation ditch as a part of secondary treatment step has higher energy demand of 0.5–1.0 kWh/m^3 (Australia), 0.302 kWh/m^3 (China) or 0.43–2.07 kWh/m^3 (Japan) [2, 6–8].

Tertiary (advanced) wastewater treatment consumes relatively higher amount of energy due to intensification of nutrient removal processes (nitrification, denitrification, and bio-P-removal). In Japan, for example, the advanced wastewater treatment processes are highly energy intensive with energy demand ranging from 0.39 up to 3.74 kWh/m^3. Conventional municipal WWTPs in the USA consume 0.43 kWh/m^3, on average. This value is similar to the energy consumption given in the literature for Taiwan (0.41 kWh/m^3), New Zealand (0.49 kWh/m^3), and Hungary (0.45–0.75 kWh/m^3). In Singapore, for example, the NEWater Factories consume 0.72–0.92 kWh/m^3 to produce drinking water from municipal effluent [2, 4, 7].

Sustainability of wastewater treatment systems can be estimated through various assessment tools, such as economic or energy analysis; the recent ones are based on the life cycle assessment (LCA) systems. A very simple sustainability assessment system takes into consideration only the energy demand of technological units within the wastewater treatment processes. In fact, energy is becoming a very important cost factor in wastewater treatment given the increasing energy costs in the recent years. According to the official EU statistics, one can see a continuous rise in energy costs in the EU-27, which increased from the average amount of 0.0756 €/kWh in 2005 up to 0.110 €/kWh in 2011 [9, 10].

The importance of optimisation of energy consumption, energy recovery processes, efficiency of equipment and technology operations, and good management of energy costs is growing in the field of wastewater treatment systems. The energy demand of this sector will grow in time due to a numerous factors, such as population and pollution growth, as well as increasing requirements for effluent quality and residual water reuse. These requirements are expected to result in higher energy consumption processes on WWTPs, in future. Measures to increase the energy demand and production efficiency are a long-standing issue also for water companies all over the world. Nevertheless, these tools are scarcely used in the field of wastewater treatment systems, especially in the new EU member states.

Taking into consideration the economic importance of energy demand in the municipal wastewater treatment sector, the primary goal of this study is to contribute to the analysis of energy consumption and production, as well as energy efficiency of wastewater treatment plants, in the Slovak Republic. In order to map the latest situation in the production and utilization of biogas and energy in municipal WWTPs, a questionnaire regarding the actual technological and energy parameters was prepared and distributed to all operators of large Slovak WWTPs. The first comprehensive and real survey of basic parameters of WWTPs, digestion tanks, biogas and energy production in the WWTPs was obtained in 2009 [11], however the actual energy consumption values (2011) in the Slovak plants are presented now, in this paper. So far, no comparable study dealing with energy consumption, specific energy demand related to flow, load, and also energy production from biogas, respectively, has been carried out in the Slovak Republic.

2. WASTEWATER TREATMENT PLANTS IN THE SLOVAK REPUBLIC

607 municipal wastewater treatment plants (WWTPs) were in operation in Slovakia in 2011, with the total capacity of 2.2 mil. m^3/day and the actual volume of 1.39 mil. m^3/day (63.2% of capacity) of treated water. Mechanical-biological plants are the most commonly used systems representing 93.5% of all plants operated in

Slovakia. Following the requirements of the Directive 91/271/EEC and also based on the statistical data of Slovak WWTPs, a geographical system of 356 agglomerations with more than 2,000 p.e. was created, with 281 operated WWTPs. Only 225 plans there of fulfil the Directive effluent requirements for organic pollution [12].

Table 1

Distribution of capacity groups of WWTPs in the Slovak Republic [12]

WWTP capacity groups	Operated WWTPs
<2,000 p.e.	326
2001–10 000 p.e.	201
10 001–15 000 p.e.	21
15 001–150 000 p.e.	54
>150 000 p.e.	5
Total	607

The capacity of the fifty largest WWTPs in Slovakia is designed for more than 6.9 mil. p.e., though the real load slightly exceeds 2.8 mil. p.e. The reason for the high portion of unused designed capacity is a rapid drop of industrial pollution contribution into the municipal wastewater during the last twenty years. The total inflow to the fifty largest WWTPs in Slovakia is more than 800 000 m^3/day, which represents 60% of the overall WWTPs inflow in Slovakia. The largest WWTP in Slovakia is the one serving the capital city of Bratislava, with the treatment capacity of 1.05 mil. p.e. and the actual load of 360 000 p.e., which represents ca. 15% of the overall wastewater load and inflow, in Slovakia.

Statistical data from 68 municipal treatment plants were used to evaluate the energy intensity of WWTPs, in 2011. All monitored WWTPs were operated as conventional biological activated sludge system plants. The base for statistical evaluation were 51 largest Slovak plants (designed load capacity ranging from 5000 up to 1 050 000 p.e.) with the following technological configuration: mechanical pre-treatment, primary sedimentation tanks, activated sludge basins with secondary sedimentation tanks, anaerobic sludge treatment with biogas production and its utilisation (thermal and/or energy production). All large treatment plants are operated by thirteen water companies (most of them having the legal form of a municipally owned joint-stock companies), in Slovakia.

17 small WWTPs (designed capacity ranging from 500 up to 2500 p.e.) located mainly in Eastern Slovakia, were selected for comparison of energy intensity of large WWTPs. The selected small plants are also designed as biological activated sludge systems with extended aerobic sludge stabilisation systems without primary sedimentation tanks, and no biogas and energy production. The tested small WWTPs are operated by Ekoservis Slovakia, Ltd.

2.1. ENERGY CONSUMPTION OF WWTPS IN SLOVAKIA

In total, those 51 tested large plants consumed more than 105 GWh of energy, in 2011. From the evaluation point of view, the specific energy consumption data characterising the treatment plant efficiency are more significant. The specific energy consumption referred to the inflow (kWh/m^3) is the most commonly used parameter. In large plants in Slovakia, it was in the range of 0.145–1.422 kWh/m^3, with the average of 0.485 kWh/m^3 (see Fig. 1). The specific energy demand of Slovak WWTPs is comparable with that of other countries [2, 4, 7] despite the fact that the requirements on effluent parameters are stricter, in the Slovak Republic. The whole territory of the Slovak Republic is characterised as a sensitive area with the highest nutrient removal requirements, e.g. a WWTP with more than 100 000 p.e. is expected to reach the effluent N_{tot} < 10 mg/dm^3, etc.), which extremely increases the treatment process energy demand (full nitrification).

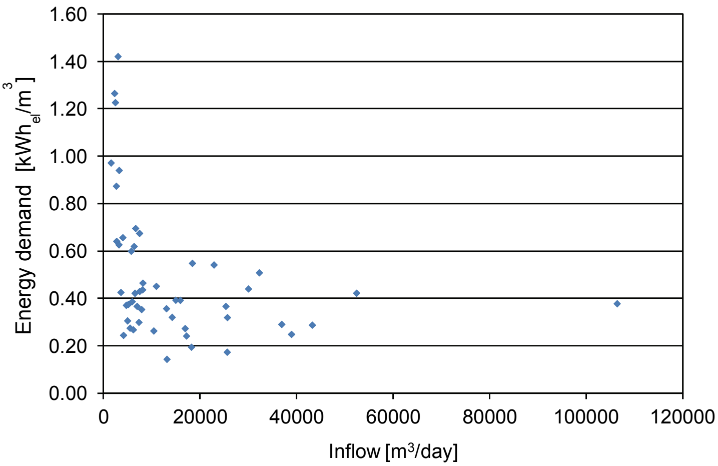

Fig. 1. Specific energy demand in 51 large municipal WWTPs in the Slovak Republic

The specific energy consumption normally decreases with the increasing inflow or load of WWTP. There are the thirteen smallest municipal plants (from the group of large WWTPs – Fig. 1) with the actual daily flow below 5000 m^3/day, which show also relatively high specific energy demand with the average of 0.768 kWh/m^3 (range of 0.264–1.422 kWh/m^3). This high specific energy demand probably results from many factors; firstly, from the age of the plant (15–25 years) and the low actual load in contrary to the designed load (ca 40%).

The tested group of 17 rural WWTPs with the inflow lower than 300 m^3/day represents a group with the highest specific energy consumption (Fig. 2). The average energy demand in the tested rural plants was 0.915 kWh/m^3, which is in agreement with high energy and operation costs of small plants with aerobic sludge stabilisation as shown in literature [2, 8]. Some plants in this group had extremely high energy consumption (higher than 1.5 kWh/m^3); on the other hand, there were also plants with energy demand comparable with large plants (<0.5 kWh/m^3). These differences depend also on many technical and technological factors (concentration of influent wastewater, depth of the activated sludge tank, aeration system, etc.).

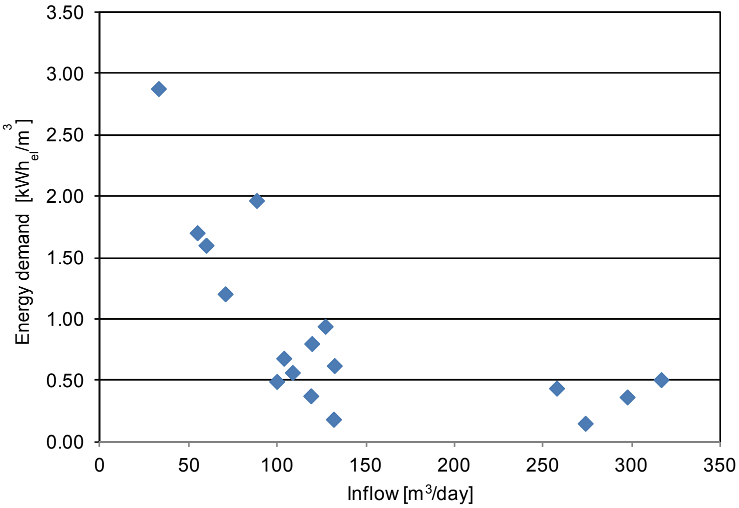

Fig. 2. Specific energy demand in 17 small municipal WWTPs in the Slovak Republic

It is obvious from Figure 3 that the larger plants show much more effective energy demands than small plants. The groups of plants with daily inflow above 5000 m^3/day have a relatively steady energy demand of 0.331–0.414 kWh/m^3.

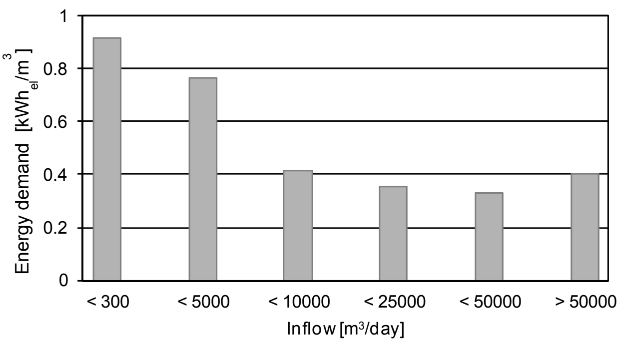

Fig. 3. Specific energy demand by daily inflow groups-

Specific energy demand increases also with the increasing influent pollution concentration (COD, BOD_5, nitrogen). Figure 4 shows the relation between influent

BOD_5 concentration in raw wastewater and specific energy demand in the large WWTPs. It can be seen from the measured data that increasing specific energy demand is also connected with higher BOD_5 concentration in raw wastewater. Firstly, all plants with diluted raw wastewater have a very low specific energy demand; WWTP Brezno – 0.14 kWh/m^3 with the influent BOD_5 concentration – 92 mg/dm^3, and WWTP Martin – 0.17 kWh/m^3 with influent BOD_5 concentration – 122 mg/dm^3.

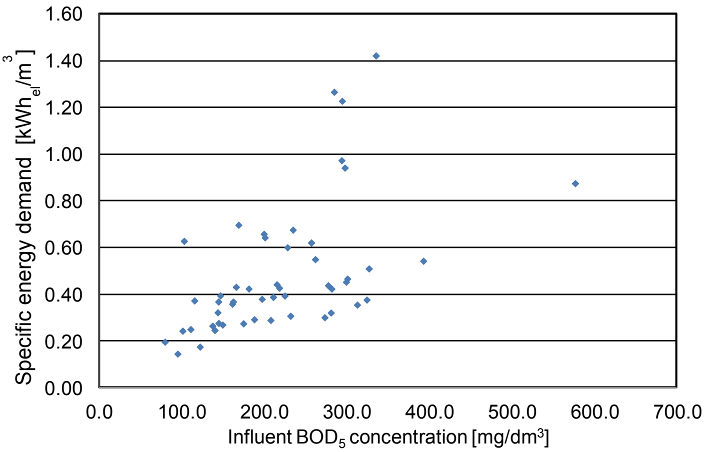

Fig. 4. Specific energy demand vs. influent BOD_5 concentration

Many others specific parameters can be used to express the energy demand efficiency of a WWTP. The average energy demand related to BOD_5 load represents the value of 2.27 kWh/kg BOD_5 (ranging from 1.10 up to 6.09 kWh/kg BOD_5), in Slovak plants. The largest Slovak WWTP Bratislava Central has a specific energy demand of 1.92 kWh/kg BOD_5. This specific parameter is comparable with other European metropolitan WWTPs, e.g. Prague – 1.5 kWh/kg BOD_5, Berlin – 1.8 kWh/kg BOD_5, Hague – 2.1 kWh/kg BOD_5; the only exception is Budapest-South – 0.95 kWh/kg BOD_5 [13].

2.2. HEAT CONSUMPTION OF SLOVAK WWTPs

Wastewater treatment plants with anaerobic fermentation and biogas production need thermal energy for heating digesters. Optimum temperature for anaerobic digestion processes ranges from 37 to 40 °C, but there are some plants with lower (WWTP Martin 33 °C) or higher (WWTP Bratislava 42 °C) operation temperature. Heating of raw sludge at digesters inflow represents more than 80–85% of total heat consumption in Slovak WWTPs; the rest is used for heating of offices, and washrooms and showers, and losses through the digester wall surface. Installation of combined heat and power (CHP) devices for energy production resulted in a considerable decrease in heat energy production from biogas. In winter, when the outdoor temperature drops below 0 °C, natural gas is necessary to be supplied to heat the anaerobic mesophilic processes.

Moreover, the high heat energy demand of digesters is caused by relatively low TS content in the sludge at the digesters input – 2.5–3.5%. These values indicate low efficiency of sludge thickening processes or low interest in thermal balances of digester reactors. The low TS content in influent sludge results in severe consequences such as high heat losses for raw sludge heating. The thermal balances of digestion process could be more efficient with higher raw sludge content (5–6%) at the digesters input.

2.3. ENERGY PRODUCTION FROM WASTEWATER

Energy production from wastewater (sludge) treatment has been commonly used in Slovakia, recently. The interest in biogas production and utilisation has been growing, and there is a lot of potential unused and available to maximize biogas production used for CHP energy or fuel (biomethane) production. The recent research data show that anaerobic digestion utilises only about 20% of the energy content of the sewage. By-products from sewage treatment combined with organic solid waste can provide a valuable source of energy, if managed and utilized effectively. About 1/3 of the chemical energy in biogas can be transformed into mechanical energy, the residual energy is heat that can be recycled and used for heating [1].

Energy production from biogas has been a challenge for Slovak WWTPs, recently. From 51 large WWTPs with controlled biogas production, only 23 have installed CHP devices with total installed output of 5.4 MW_{el}. Overall, 67.9 MWh_{el} were produced daily in all plants, i.e. by average only ca 12.4 hours of full CHP operation. The highest operation productivity of energy production was achieved in WWTP Trnava with more than 23.5 hours of full CHP operation, when expressed as annual average. Also, the specific energy production per produced m^3 of biogas was relatively low – 1.2 kWh_{el}/m^3, by average. There are some large plants with very low specific production of kWh_{el}, e.g. WWTP Poprad and WWTP Prešov – 0.2 kWh_{el}/m^3; and, on the other hand, there are some plants with high efficiency of energy production, e.g. WWTP Petržalka with 2.1 kWh_{el}/m^3 and WWTP Bratislava Central with 2.0 kWh_{el}/m^3, respectively.

Another interesting parameter of energy generation efficiency is the specific production of kWh_{el} per m^3 of treated wastewater. The average value of this parameter is 0.1 kWh_{el}/m^3 in the Slovak WWTPs, though there are plants where these values exceeded 0.25 kWh_{el}/m^3 (WWTP Bratislava Central, WWTP Trnava, etc.).

The latest efforts of European WWTPs are streamed to optimising their energy demand through regulation and control of electric devices, replacing outdated machines by new ones with low energy consumption, optimisation of sludge thickening, etc. On the other hand, increase of biogas production by utilisation of biodegradable waste contributes to significant increase of energy production. These trends in European municipal WWTPs lead to the increase of energy autarky of treatment processes. Some positive examples of WWTPs (e.g., Budapest-South) with nearly 100% of energy autarky, could be found in the recent literature [13].

As is obvious from the above data, the efficiency of energy production and its utilisation is relatively low in WWTPs in Slovakia. The relation between energy production and consumption (energy autarky), is ca. 25.6%. There are some plants with extremely low energy autarky (lower than 5% – absolutely no electricity generation efficiency), and there are examples with higher autarky – more than 50%. Energy autarky of WWTP Bratislava Central (66%), WWTP Trnava (64%), WWTP Martin (52%) operated without external biowastes dosing, are comparable with that of VEOLIA water plants with average autarky 49% [13].

3. TOWARDS WWTPs SUSTAINABILITY

Biological wastewater treatment plant is a facility for removal of mainly organic pollution from wastewater. In general, the treatment processes of a plant require a lot of energy nevertheless certain recent efforts to increase energy production from biogas, using heat pumps, etc. There are several measures that can be applied to improve energy balance in the Slovak WWTP, such as:

- *Aeration system optimisation.* Aeration as the main energy consumer in a WWTP which may be controlled by oxygen (or ammonia) concentration in activated sludge basins. Reducing the oxygen concentration below 1.5–2.0 mg/dm^3 clearly reduces the energy demand significantly, with no adverse impacts on the effluent quality.
- *Old devices replacement.* Mechanical and surface aerators, old pumps and mixers are characterised by high energy demand. New devices are equipped with modern energy saving regulators (frequency changers) enabling more effective operation.
- *Sludge thickening optimisation.* Actual low sludge concentrations dosed into digesters should be increased up to the acceptable value of 5–6%, which significantly
  - reduces the volume of processed sludge,
  - increases retention time in digesters,
  - increases specific biogas production from sludge,
  - enables one to use biodegradable waste.
- *Sludge heating.* It reduces the heat needed for sludge heating by recuperation of heat from effluent digested sludge. This measure could reasonably reduce the heat demand of digester operation.
- *Utilisation of biodegradable waste.* Digestion of biodegradable municipal or industrial waste can increase biogas and energy production. However, it is necessary to

ensure that external biowastes have no adverse effect on the anaerobic digestion process (high content of nitrogen or sulphur), nor these lower the reject water quality.

• *Utilisation of heat pumps.* Influent raw wastewater has a relatively high heat capacity, which could be utilised for digester heating.

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