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Research Article

Towards Sustainable Wastewater Treatment: Analyzing Specific Energy Consumption of Tehran Municipal Wastewater Treatment Plants using Key Performance Indicators

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Abstract
Due to rapid development of cities, number of municipal wastewater treatment plants (WWTP) has faced drastic growth in recent decades. Reviewing the literature indicates that WWTPs in urban areas are one of the essential energy consumers, and it is necessary to evaluate their energy consumption. In Tehran, the capital of Iran, the number of WWTPs has increased to meet the demands of its increasing population. Yet, the energy consumption of these WWTPs in Tehran has not been thoroughly examined. This research aims to measure and provide the specific energy consumption of Tehran WWTPs and bridge the research gap by providing precise measurements for three key performance indicators (KPIs): energy consumption per influent volume (kWh/m^3), per population-equivalent (kWh/PE-year), and per kilogram of Chemical Oxygen Demand removed (kWh/kg COD). The South Tehran Wastewater Treatment Plant (STWWTP), the largest WWTP in Tehran, demonstrated highest energy efficiency with consumption rates of 0.21 kWh/m^3 for influent volume, 16.75 kWh/PE-year, and 0.48 kWh/kg COD removed. Furthermore, the small-scale WWTPs of Tehran showed a significant variation in specific energy consumption. Zargandeh Wastewater Treatment Plant (ZWWTP) represented the poorest efficiency by consuming 96.34 kWh for each person under its service and 3.66 kWh per kg COD removed. In contrast, Ekbatan Wastewater Treatment Plant (EWWTP), among the small-scale WWTPs, demonstrated great energy efficiency with consumption rates of 33.15 kWh per capita and 0.52 kWh/m^3. However, this great variation in energy consumption of Tehran WWTPs needs further investigation, and strategies for improving the energy efficiency of these WWTPs are required.
Keywords: Wastewater treatment plant, Specific energy consumption, Sustainable city, Greenhouse gas emissions, Key performance indicators

Introduction

Scientists have indicated that the main strategy for mitigating the rate climate change is to reduce anthropogenic Greenhouse Gas emissions (GHG) (Songolzadeh et al., 2014; Yoro & Daramola, 2020). In recent decades, the exponential growth of urban populations and the rapid development

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of cities have led to a significant surge in the number of domestic wastewater treatment plants (WWTPs) (Qu et al., 2019; Sun et al., 2016). The treatment procedures used in municipal WWTPs include various energy-intensive stages, including effluent collection, conveyance, treatment processes, and the disposal of treated effluent (Christoforidou et al., 2020). This has resulted in municipal WWTPs becoming significant energy consumers. The energy consumption of municipal WWTPs is estimated to account for approximately 1% to 3% of a country's total electricity generation (US Department of Energy, 2014; Reinders et al., 2012).

Clearly, energy plays a crucial role in ensuring the effective and optimal functioning of a WWTP, with the secondary treatment processes serving as the main energy consumers. (Christoforidou et al., 2020). Worldwide, the treatment of wastewater is responsible for consuming nearly 200 TWh of energy, equivalent to approximately 1% of the total global energy consumption. What is even more alarming is the projected increase in future energy consumption, with estimates indicating a surge of 50-80% in different regions across the world (International Energy Agency, 2018).

Regrettably, many WWTPs, especially in developing countries, are getting their required energy from non-renewable resources, and this has caused enormous GHG emissions for energy demand of WWTPs. For example, Yerushalmi et al. (2013) conducted a study on a locomotive repair factory WWTP to estimate GHG emissions from different parts and showed that 80% of the total GHG emissions were associated with fossil fuel consumption for electricity production.

Furthermore, in order to quantify both direct and indirect GHG emissions from WWTPs in Shenzhen, Liao et al. (2020) conducted a comprehensive study on 26 WWTPs and developed a hybrid life cycle analysis model. They collected data from these WWTPs in Shenzhen, the third populous city in China, and measured their GHG emissions. They indicated that energy consumption of a WWTP is responsible for a substantial amount of GHG emissions, and type of treatment process highly affects the energy consumption. It was indicated that 65 to 75% of the total GHG emissions is related to the electricity use in the studied WWTPs.

Another motive behind measuring the specific energy consumption of a wastewater treatment plant (WWTP) is to ensure the sustainability of these treatment facilities. For example, Fighir et al. (2019) evaluated sustainability of four Italian and Romanian municipal WWTPs. They showed that in WWTPs that there is no biogas valorization, the main contribution in terms of GHG emissions is electricity consumption of the plant. In this study, the Italian WWTPs exhibited lower energy consumption and GHG emission (0.41 kg CO_2/kWh) compared to Romanian WWTPs (1.07 kg CO_2/kWh).

Also, introduction of more stringent and restrictive standards on the quality of water effluents has caused more energy demand for WWTPs (Di Fraia et al., 2018). For example, in the past years, China has enforced considerably stricter wastewater management rules. As a result, the amount of discharge COD and NH3-N from WWTPs reduced noticeably in the past years (Lu et al., 2019). However, the enhanced level of treatment has led to higher energy consumption. From 2008 to 2018, the average energy consumption intensity increased by 30%, and the total electricity consumption by WWTPs reached 19.73 billion kWh.

Therefore, detailed information on WWTPs' energy consumption is becoming increasingly important, and in many countries, comprehensive studies have been conducted on different WWTPs. For instance, in Greece, results of an analysis showed that WWTPs in Greece consume greatest proportion of their energy in secondary treatment (72%) and pretreatment (13%) stages. Only 8% is consumed for sludge management and 6% for tertiary treatment consumes 8% and tertiary treatment 6% (Christoforidou et al., 2020). This analysis showed that energy consumption per volume of treated wastewater differs with the size of the plant, being higher for smaller plants.

Also, for smaller plants the energy consumption per population-equivalent was measured to be higher (up to 245 kWh/PE-year) than larger plants which are characterized by energy consumption between 22 and 95 kWh/PE-year. As the importance of quantifying the specific energy consumption of WWTPs has been well-established, several studies have been carried out in different countries to measure the energy consumption of WWTPs and determine the proportion attributed to each facility. Table 1 provides an overview of studies that have examined the specific energy consumption of WWTPs in various countries.

Table 1. Specific energy consumption and main energy consumers in WWTPs in different countries (Maktabifard et al., 2018)

References	Specific energy consumption (kWh/m^3)	Location of the studied WWTP(s)	Percentage of different sectors			
			Aeration (%)	Sludge treatment (%)	Pumping (%)	Other (%)
Gans et al. (2007)	0.26	China (Beijing)	57	5	–	38
Nouri et al. (2006)	0.3	Iran (Tabriz)	77	7	11	7
Panepinto et al. (2016)	0.3	Italy (Turin)	51	29	–	20
Jonasson (2007)	0.32	Austria (Strass)	57	13	9	21
Mizuta and Shimada (2010)	0.32	Japan (Northern Kumamoto)	46	31	18	5
Gu et al. (2017)	0.37–1.6	Singapore	60	12	12	16
Wang et al. (2016)	0.43	USA (Sheboygan)	–	–	–	–
NEWRI (2009)	0.45	Singapore (Jurong)	–	–	–	–
Jonasson (2007)	0.48	Sweden (Stockholm)	48	14	9	29
Zaborowska et al. (2017)	0.48	Poland (Slupsk)	53	–	30	17
Trojanowicz and Karamus (2016)	0.67–1.11	Poland (Kronso)	–	–	–	–
Masłoń (2017)	0.87	Poland (Rzeszow)	–	–	–	–
Yeshi (2015)	0.89	Singapore (Changi)	13	9	24	54
Aymerich et al. (2015)	–	Spain (Girona)	42	31	20	7
Henriques and Catarino (2017)	–	Portuguese (different cities)	53	–	12	35
Marner et al. (2016)	–	Germany (different cities)	67	11	5	17

The energy consumption of a WWTP is influenced by several factors, as indicated by studies. These factors include the size of the plants, the type of treatment process and aeration system used, the age of the plant, the quality requirements for effluent, and the volume of influent, among others (Gu et al., 2017; Plappally, 2012; Bodik & Kubaska, 2013). Gurung et al. (2018) expressed that the average energy consumption at Finnish WWTPs is 0.49 kWh/m^3 and that total energy consumption of WWTPs in Finnish are positively correlated with sludge production and inflow rate; however, their analysis showed that the unit energy consumption reduces with an increase in plant capacity.

Nevertheless, there are still many cities in the world where comprehensive studies on their municipal WWTPs have not been carried out. Tehran city, ranked 25th in the list of most populous cities (Safaee & Nematipour 2021), involves seven WWTPs that are serving to a great portion of Tehran Citizens. Regrettably, the energy performance of these WWTPs has not been adequately studied. As energy consumption is a vital indicator for sustainability and plays a significant role in estimating and planning the reduction of greenhouse gas emissions, it is crucial to measure the exact energy consumption and present it using suitable units. The objective of this paper is to offer comprehensive information on the energy consumption of Tehran WWTPs, with a focus on identifying the major energy consumer sectors by breaking down the energy usage. Furthermore, this paper aims to assess the energy performance of each WWTP in Tehran by utilizing appropriate energy indicators.

Energy Performance Indicator

One of the most challenging issues for assessing energy consumption of WWTPs is choosing the right metric for reporting the energy performance of a WWTP. Typically, two energy Key Performance Indicators (KPIs) are employed based on the available data: 1) energy consumption per volume of treated wastewater or influent (kWh/m^3), and 2) energy consumption per population-equivalent (kWh/pe-year). When comparing the energy consumption in kWh/PE-year or kWh/m^3, the assumption is that pollutant concentrations in the influent (nitrogen and phosphorus, solids, organic matter) do not differ significantly between WWTPs. It is evident that this approach can cause several inaccuracies. Thus, a recommended approach is to report WWTPs' energy consumption per unit of pollutant removed (Longo et al., 2016).

In this regard, one of the most used energy indicators is unit energy consumption per kg Chemical Oxygen Demand (COD) removed (Li, Tang, and Gu 2021). Other units like kWh/kg $TSS_{removed}$, kWh/ kg $BOD_{removed}$ or kWh/kg $N_{removed}$ also have used by several authors in their studies (Bodik and Kubaska, 2013; Lackner et al., 2014; Pan et al., 2011; Pretel et al., 2016). The benefit of reporting the energy consumption per unit of pollutant removed relies on the fact that the removal process of nutrients and organic matter is a major contributor to energy consumption in WWTPs. However, it is crucial to acknowledge that in many cases, the utilization of these units to report energy performance may be constrained by the availability of data. Still, in this research, data on the precise amount of COD removed in six of the Tehran WWTPs in 2021 was collected, allowing for the energy performance of these six WWTPs to be reported in the unit of kWh/kg COD removed, along with other KPIs.

Materials and Methods

Study Area and Population

Tehran is the capital of Iran with an area of 620 square km^2 which is located in the northern part of the country (35.68°N, 51.38° E). Tehran city has a population of 8.5 million and a day-time population of more than 10 million people because of daily commuters. Currently, there are 7 operating wastewater treatment plants in Tehran that serve to a portion of Tehran population. To address the wastewater management needs of the population segment whose wastewater is not currently directed to treatment facilities, alternative approaches such as on-site treatment systems have been considered. For this study, based on the available data on WWTPs, six major WWTPs in Tehran were selected for investigation. Table 2 presents a comprehensive overview of each of these selected WWTPs.

Table 2. Details and collected information of the studied WWTPs

Name	Population served	design capacity (m^3/day)	Influent volume (m^3/day)	Process type	Kg COD removed in the study year (Kg/year)	Geographical coordinates
South Tehran Wastewater Treatment Plant (STWWTP)	3150000	675000	1025991	Conventional Activated Sludge (CAS)	108975634.1	35°34'16.4"N 51°26'27.2"E
Shahrak Gharb Wastewater Treatment Plant (SGWWTP)	145000	30000	31406	Conventional Activated Sludge (CAS)	4333085.82	35°44'52.1"N 51°22'07.2"E
Ekbatan Wastewater Treatment Plant (EWWTP)	85000	15000	10397	Anaerobic-anoxic-aerobic (A2O)	1297857.5	35°42'06.0"N 51°18'33.9"E
Zargandeh Wastewater Treatment Plant (ZWWTP)	30000	6480	5196	Contact Stabilization Activated Sludge (CSAS)	788960.6	35°46'01.0"N 51°26'14.6"E
Mahallati Wastewater Treatment Plant (MWWTP)	30000	4800	5266	Extended Aeration Activated Sludge (EAAS)	789978.9	35°48'02.3"N 51°30'22.6"E
Sahebgharanieh wastewater treatment plant (SWWTP)	7000	864	1698	Extended Aeration Activated Sludge (EAAS)	195847.3	35°48'08.7"N 51°28'29.4"E

Data Collection

In this paper, energy performance of the selected WWTPs in Tehran is presented in three units: per volume of influent (kWh/m^3), per population-equivalent (kWh/pe-year) and per kg COD removed (kWh/kg COD removed). Equations 1 to 3 were utilized for reporting the results based on the selected units, which required obtaining detailed information and data for the WWTPs. The Tehran Province Water and Wastewater Company (TPWWC) is the designated organization responsible for wastewater management in Tehran. It carries out the task of monitoring the performance of WWTPs within the province. All WWTPs in Tehran must give detailed reports on the quality and quantity of influent and effluent flow to TPWWC. In 2021, a comprehensive evaluation of energy consumption was carried out for all WWTPs in Tehran. In this evaluation, energy consumption of WWTPs was measured in two categories; the energy that is consumed in the buildings of the plants, and the energy consumption of the treatment facilities in each plant.

$$Energy\ consumption\ per\ unit\ of volume\ of\ influent\ wastewater \left[\frac{kWh}{m3}\right] = \frac{Daily\ Energy\ Cosnumption\ in\ the\ WWTP \left(\frac{kWh}{d}\right)}{Volume\ of\ influent\ \left(\frac{\mathrm{m3}}{d}\right)} \quad (1)$$

$$Energy\ consumption\ per\ unit\ of\ COD\ removed \left[\frac{kWh}{kg\ COD}\right] = \frac{Total\ Energy\ Cosnumption\ of\ the\ WWTP \left(\frac{kWh}{year}\right)}{COD\ removed\ \left(\frac{\mathrm{kg\ COD}}{year}\right)} \quad (2)$$

$$Energy\ consumption\ per\ population-equivalent\ served \left[\frac{kWh}{\mathrm{pe{-}year}}\right] = \frac{Total\ Energy\ Cosnumption\ of\ the\ WWTP \left(\frac{kWh}{year}\right)}{population{-}equivalent\ served\ (\mathrm{pe{-}year})} \quad (3)$$

After the calculation of the total energy consumption of each WWTP, KPIs are employed to showcase the performance of each individual WWTP. These KPIs provide valuable insights into the efficiency and sustainability of the WWTPs.

Results and Discussion

In Iran, the energy consumption of buildings exceeds the global average by more than 5.2 times. (Heidari et al., 2018). It is estimated that the average energy use intensity of office buildings in countries like Iran is around 350 kWh/m^2·year (Fathi & Kavoosi, 2021; Bagheri et al., 2013). This highlights the importance of conducting thorough evaluations of the performance of various building types in Iran in order to develop effective strategies for reducing energy consumption. However, there has been limited effort in assessing the energy performance of different building types in Iran.

The assessment of energy consumption specifically for the buildings within the WWTPs were also not exempt from this lack of proper evaluation in terms of energy consumption. This research paper aims to address this gap by conducting a meticulous evaluation of the total energy usage in the Tehran WWTPs. To ensure accuracy, a detailed analysis of the buildings within each WWTP was performed to identify the main energy consumers. As a result, the energy consumption of each WWTP is presented in three distinct categories: energy consumption in treatment facilities, energy consumption in buildings, and overall energy consumption.

South Tehran Wastewater Treatment Plant's Energy Consumption

STWWTP is located in an area of approximately 110 hectares in the south Rey city in the south of Tehran. STWWTP is distinguished as both the largest wastewater treatment plant in Iran and an example of sustainable WWTPs on a global scale. Due to biogas recovery and combined heat and power production, a significant proportion of the plant energy consumption is provided inside the site from renewable energy sources.

Treatment Facilities' Energy Consumption

Table 3 presents a detailed breakdown of the energy consumption of the key consumers within the treatment facilities of the STWWTP. The total energy consumption of STWWTP facilities is 143677.2 kWh/day. Based on the working hours of the treatment facilities in 2021, the major consumers and their respective energy consumption percentages are as follows: turbo blowers for aerobic process consumed 80657 kWh/day (56.1%), pumps for wastewater and sludge consumed 26489 kWh/year (18.4%), trickling filters consumed 11618.64 kWh/day (8.08%), anaerobic digesters consumed 3113.1 kWh/day (2.1%) and the other facilities consumed 21798 kWh/day (5.7%).

Table 3. Energy consumption of different treatment facilities and equipment in STWWTP

Name of the unit/facility/equipment	Energy consumption (kWh/day)	Proportion to the total energy consumption of facilities (%)
Turbo Blowers (for aeration)	80657.28	56.1
Pumping station (influent flow)	26399.7	18.37
Trickling filters	11618.6	8.08
Return sludge	7920.1	5.5
Potable water pumping	1039.9	0.72
Anaerobic digesters (six digesters)	3113.1	2.16
Chlorination	481.53	0.3
Boilers	154	0.1
Bar screens (course and fine)	2055.2	1.43
Odour control unit	515.59	0.35
Combined heat and power	779	0.5
Waste stabilization ponds	171.5	0.1
Other sectors/equipment	8280.2	5.7
Total consumption of treatment facilities	143677.2	100

Buildings' Energy Consumption

The buildings' energy consumption of STWWTP is divided and shown in Figure 1. Nearly 40.3% of the total consumption is related to the laboratory rooms and equipment, which is due to the large number of samples for different quality tests Heating and hot water usage account for 35.6% of the total electricity consumption. Cooling facilities in the building contribute approximately 11.9% of the total consumption, with the majority of the energy consumption attributed to a chiller with a real power of 70 kW. Offices and lighting are the minor energy consumers, accounting for 3.7% and 8.5% of the building's energy consumption of STWWTP, respectively.

Total Energy Consumption of South Tehran Wastewater Treatment Plant

The total energy consumption in STWWTP in 2021 is 52768215 kWh/year. However, due to the biogas recovery and combined heat and power production, a significant portion of the total energy consumption of STWWTP is provided on-site from renewable energy sources. In 2021, nearly 44 GW of energy was produced on-site at the plant from biogas recovery. Therefore, only 8,768,215 kWh per year was obtained from external sources.

Based on the operation of STWWTP in 2021, the energy consumption per volume of influent wastewater is 0.21 kWh/m^3, per population-equivalent served per year is 16.75 kWh/PE-year, and per kg COD removed is 0.48 kWh/kg COD removed.

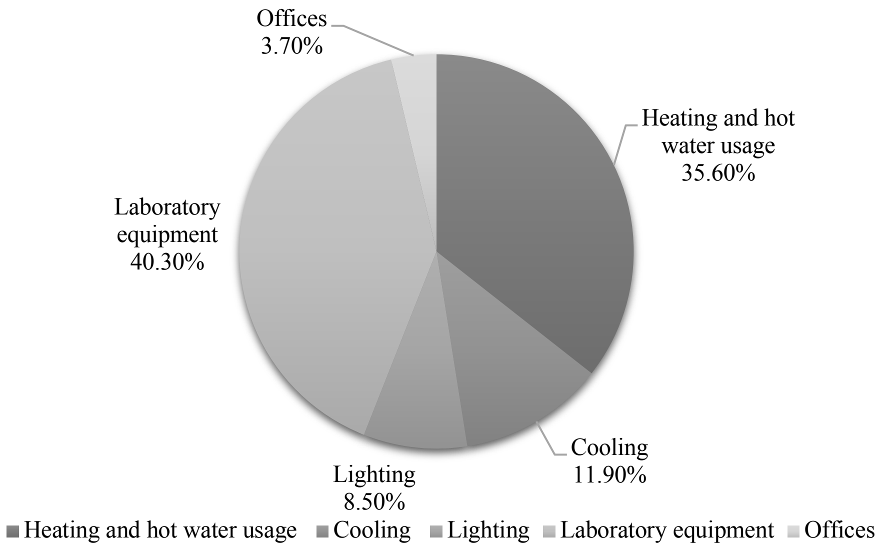

Figure 1. The total energy consumption of buildings in STWWTP (in 2021: 326037 kWh) and share of different parts

Shahrak Gharb Wastewater Treatment Plant

The design process and construction of the SGWWTP began in 1989, and by 1995, the plant was fully constructed and operational. Due to its proximity to Pardisan Park and Milad Tower, the treated water from the SGWWTP is used for the irrigation of green spaces in the vicinity of Milad Tower and Pardisan Park.

Treatment Facilities' Energy Consumption

Table 4 shows the energy consumption of the treatment facilities within the SGWWTP. The calculations consider the operational hours of the plant in 2021. It is evident from the table that the pumps and aeration blowers account for the majority of the energy consumed. Considering the average working hours of each equipment, the energy consumption of the treatment facilities in the SGWWTP amounts to 28184.6 kWh/day. On a daily average, the energy consumption of pump stations within the plant was 17754 kWh/day, aeration facilities consumed 6011.28 kWh/day, sludge management facilities accounted for 4070.9 kWh/day and other facilities consumed 348.5 kWh/day.

Buildings' Energy Consumption

Figure 2 provides a breakdown of the energy consumption of the buildings within the SGWWTP and the respective share of each component. On average, air conditioners in the buildings of the SGWWTP operate for approximately 960 hours per year. Most of these air conditioners have a higher power capacity than necessary for cooling the buildings. Accordingly, 42.75% of the total electricity consumption (84237.165 kWh/year) is consumed for the cooling of the buildings. The usage of 194 high-consumption fluorescent lamps (40W) in the buildings results in lighting being responsible for approximately a quarter of the total electricity consumption, amounting to 50660.5

kWh/year. Additionally, laboratory equipment and offices account for 28.43% of the buildings' energy consumption, while the remaining portion is attributed to heating systems.

Table 4. Energy consumption of different treatment facilities and equipment in SGWWTP

Name	Energy consumption (kWh/day)	Proportion to the total consumption of facilities (%)
Influent pumping	15737	55.83
Aeration	4981.68	17.67
Surrounding green space pumping (Milad tower+Pardisan park)	2016.94	7.15
Stabilization aeration	1029.6	3.65
Primary sludge	1306.8	4.63
Return sludge	2201.7	7.81
Sludge scraper bridge	348.5	1.23
Other sectors/equipment	562.38	1.99
Total consumption of treatment facilities	28184.6	100

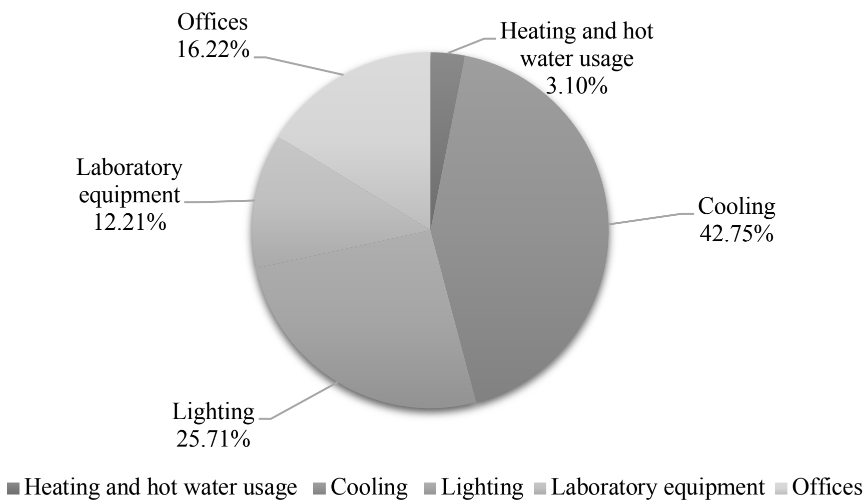

Figure 2. The total energy consumption of buildings in SGWWTP (in 2021: 197046 kWh) and share of different parts

Total Energy Consumption of Shahrak Gharb Wastewater Treatment Plant

The total energy consumption of the SGWWTP amounts to 10484425k kWh/year, with buildings being responsible for only 1.9% of the total consumption. The pumps are the major consumers, accounting for nearly 56% of the total energy usage as they handle the influent. Therefore, the energy consumption per volume of influent wastewater in SGWWTP is 1.01 kWh/m3, per population-equivalent served per year is 72.30 kWh/PE-year, and per kg COD removed is 2.42 kWh/kg COD removed.

Ekbatan Wastewater Treatment Plant

EWWTP is located in an area of approximately 70 hectares in the Ekbatan town and started its operation in 1984.

Treatment Facilities' Energy Consumption

Table 5 details the energy consumption of different facilities in the EWWTP. The data highlights that blowers and sand filters account for the highest energy consumption. However, it is important to note that in the EWWTP, there are three sand filters and five blowers, but they do not operate concurrently. The total energy consumption of the EWWTP treatment facilities is calculated at 6820.6 kWh/day. Considering the daily working hours of each equipment, snail pumps used for aeration consume more than one-third of the total energy consumed in the treatment facilities of the EWWTP.

Table 5. Energy consumption of different treatment facilities and equipment in EWWTP

Name	Energy consumption (kWh/day)	Proportion to the total energy consumption of facilities (%)
Snail pump for aeration	2650.56	38.86
Sand filters (pumps 1 & 2)	1734.48	25.43
Anoxic influent pump	145.728	2.13
Influent pumps	477.66	7.00
Sludge Dryer	512.42	7.51
Blowers	239	3.50
Other sectors/equipment	787.52	11.54
Total consumption of treatment facilities	6820.6	100

Buildings' Energy Consumption

Figure 3 illustrates the energy consumption of buildings within the EWWTP. An important aspect is that all WWTPs in Tehran send their test species to the EWWTP for quality testing. The presence of large laboratory rooms and equipment in the buildings of the EWWTP contributes significantly to the overall energy consumption. As a result, a substantial portion of the energy usage of buildings in this plant is allocated to laboratory operations. In the study year, the laboratories in the EWWTP consume approximately 224153 kWh/year. Cooling facilities (7407 kWh/year) and heating system (72571 kWh/year) are accounted for almost a quarter of the total consumption, whereas offices and lighting system only accounted for 3.4% of the total consumption.

Total Energy Consumption of Ekbatan Wastewater Treatment Plant

In 2021, the total energy consumption in the EWWTP amounted to 2818110. The plant buildings are responsible for 11.6% of the total energy consumption, owing to a large number of laboratory equipment in the buildings. Therefore, energy consumption per volume of influent wastewater in ETWWTP is 0.52 kWh/m^3, per population-equivalent served per year is 33.15 kWh/PE-year, and per kg COD removed is 2.17 kWh/kg COD removed.

Mahalati Wastewater Treatment Plant

The MWWTP, situated to the north of Tehran city and adjacent to Mahalati town, initiated its studies and implementation processes in 1982, and became operational in 2000.

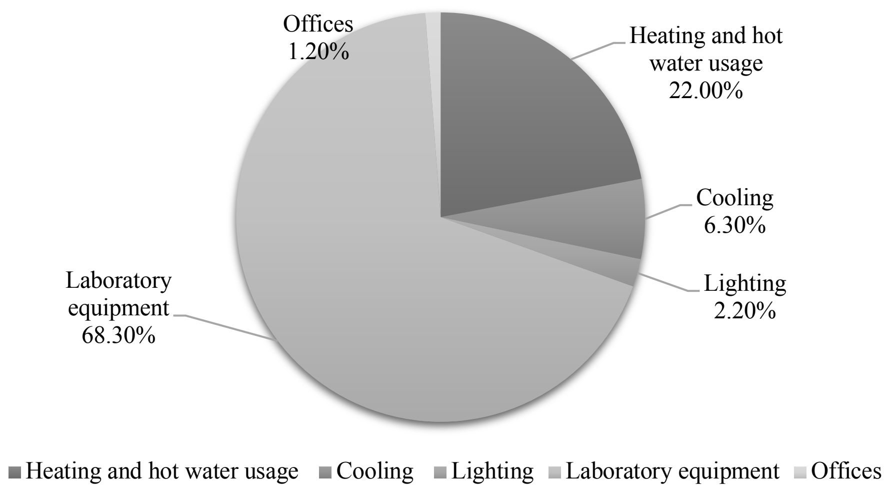

Figure 3. The total energy consumption of buildings in EWWTP (in 2021: 328445 kWh) and share of different parts

Treatment Facilities' Energy Consumption

Table 6 illustrates the daily average energy consumption of the treatment facilities at the MWWTP. Within this plant, there are three blowers, each operating for 8 hours per day. The combined energy consumption of all the blowers on an average day amounts to 2706 kWh/day. Additionally, the energy consumption for pumping the influent flow in the MWWTP is recorded as 2789 kWh/day. These two units contribute to more than 90% of the overall energy consumption of the treatment facilities. In 2021, the total energy consumption for the treatment facilities in the MWWTP was calculated to be 5990 kWh/day.

Buildings' Energy Consumption

Figure 4 provides a breakdown of the electricity consumption in the buildings of the MWWTP. The significant portion of the consumption, accounting for approximately three-quarters, is related to the utilization of high-energy electric heaters (2.4 kW) and boilers (10 kW) for heating and hot water systems. This heating-related consumption amounts to a considerable 40608 kWh per year. While, the cooling system is only responsible for 1.7% of the total consumption. Overall, the total energy consumption of the buildings at MWWTP amounts to 57098 kWh per year.

Total Energy Consumption of Mahalati Wastewater Treatment Plant

In 2021, the MWWTP had a total energy consumption of 2243448 kWh. The buildings within the MWWTP accounted for only 2.5% of the overall energy consumption. Based on the average operating hours of the plant during that year, the energy consumption per volume of influent wastewater in the STWWTP was measured at 1.28 kWh/m^3. For each population-equivalent served per year, the energy consumption amounted to 74.78 kWh/PE-year. Furthermore, the energy required to remove one kilogram of COD was calculated to be 2.80 kWh/kg COD removed.

Table 6. Energy consumption of different treatment facilities and equipment in MWWTP

Name	Energy consumption (kWh/day)	Proportion to the total energy consumption of facilities (%)
Influent pumping	2789.03	46.56
Blowers	2706	45.17
Return sludge	269.2	4.49
pre-aeration	144.93	2.41
Other sectors/equipment	80.1	1.33
Total consumption of treatment facilities	5990	100

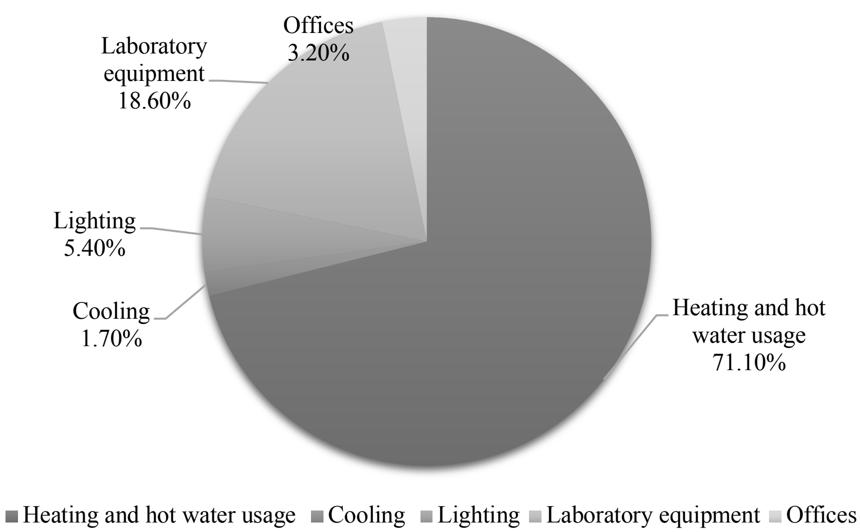

Figure 4. The total energy consumption of buildings in MWWTP (in 2021: 57098 kWh) and share of different parts

Zargandeh Wastewater Treatment Plant

The ZWWTP is situated in the northern region of Tehran city. The studies and executive operations for the facility were initiated in 1981, and it has been in service since 1987.

Treatment Facilities' Energy Consumption

Table 7 provides an overview of the primary energy consumers within the treatment facilities of ZWWTP. The influent pumping stations at ZWWTP have an energy consumption of 2827.44 kWh/day, while the aeration units consume 2592.21 kWh/day. Overall, the total energy consumption of the treatment facilities in ZWWTP amounts to 7842.4 kWh/day.

Buildings' Energy Consumption

Figure 5 provides a breakdown of the energy consumption within the buildings of ZWWTP. Cooling and heating systems are the primary energy consumers, accounting for 53.45% of the total energy usage. Within this category, cooling facilities alone contribute 33.6% of the overall energy consumption. Additionally, offices consume 18.8% of the energy, while laboratory equipment accounts for 22.84%. The smallest contribution to the energy consumption in the buildings is related to lighting, representing only 5.53% of the total.

Table 7. Energy consumption of different treatment facilities and equipment in ZWWTP

Name	Energy consumption (kWh/day)	Proportion to the total energy consumption of facilities (%)
Influent pumping station	2827.44	36.05
Blower + return sludge	2048.1	26.11
Aeration	2000.59	25.52
Surface Aerator	591.62	7.54
Secondary pumping	374.61	4.77
Total consumption of treatment facilities	7842.4	100

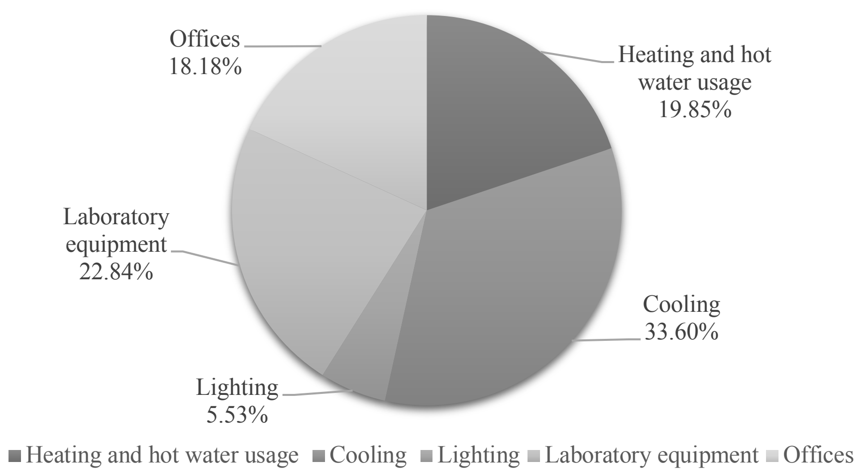

Figure 5. The total energy consumption of buildings in ZWWTP (in 2021: 27918 kWh) and share of different parts

Total Energy Consumption of Zargandeh Wastewater Treatment Plant

Based on the working hours of the buildings and treatment facilities of ZWWTP, the total energy consumption in 2021 was calculated to be 2890394 kWh/year. Thus, the energy consumption per volume of influent wastewater in ZWWTP is measured to be 1.22 kWh/m3. In terms of population-equivalent served per year, the energy consumption amounts to 96.34 kWh/PE-year. Finally, the energy consumption per kg of COD removed is calculated to be 3.66 kWh/kg COD removed.

Sahebgharanieh Wastewater Treatment Plant

SWWTP is the oldest wastewater treatment plant in Iran which is located in Pasdaran Street of Tehran City. Studies and executive operations began in 1942, and its operation started in 1960.

Treatment Facilities' Energy Consumption

In SWWTP, the blowers utilized for aeration tanks consume 388.87 kWh/day, while the pumps consume 390 kWh/day, as indicated in Table 8. The treated wastewater from SWWTP is employed for irrigating nearby urban green spaces, and this process requires a pump with a power rating of 6.5. The total energy consumption of the treatment facilities in SWWTP, based on the daily working hours of each equipment, is recorded as 831.1 kWh/day.

Table 8. Energy consumption of different treatment facilities and equipment in SWWTP

Name	Energy consumption (kWh/day)	Proportion to the total energy consumption of facilities (%)
Influent pumps	388.87	46.72
Blowers	390	46.87
Green space pumping	53.32	6.28
Total consumption of treatment facilities	832.19	100

Buildings' Energy Consumption

The energy consumption in the buildings of SWWTP amounted to 32650 kWh in 2021, as depicted in Figure 6. Surprisingly, a significant portion of the total consumption (52.93% or 17,267.2 kWh) is related to the offices, primarily due to the presence of outdated desktop computers and printers that consume high levels of power and remain operational even during off-hours. Moreover, laboratory equipment and lightings are responsible for 22.46 and 17.09% of the total energy consumption, respectively. Finally, in the buildings of SWWTP, only 7.5% of the total energy consumption is related to heating and cooling purposes throughout the year.

Total Energy Consumption of Sahebgharanieh Wastewater Treatment Plant

The total energy consumption at SWWTP was calculated to be 336399.35 kWh. Interestingly, the buildings within the plant accounted for 9.7% of the total consumption. This highlights the potential for significant energy reduction by effectively managing the energy consumption in the offices within the buildings. Overall, the energy consumption per volume of influent wastewater in SWWTP is calculated to be 1.07 kWh/m^3, per population-equivalent served per year is measured at 48.05 kWh/PE-year, and per kg COD removed is equal to 1.71 kWh/kg COD removed.

Overall Analysis

All the WWTPs investigated in this study, except for STWWTP, are classified as small-scale plants that serve to populations of less than 145,000 people. Yet, STWWTP is a large-scale plant specifically designed to serve the significant population of 3,150,000 people in Tehran.

As it has been indicated by several studied, one of the most influential factors that affects the energy efficiency of a WWTP is the size of the plant (Jafarinejad 2020; Dong et al. 2017; Panepinto et al. 2016; Maktabifard et al. 2018). These studies have shown that large-scale plants exhibit higher energy efficiency compared to smaller ones. Based on the three assessed KPIs in this paper, STWWTP displayed lower specific energy consumption values. This confirms the results of the previous studies on the influence of plants size (Haslinger et al., 2016; Bodik & Kubaska, 2013). Table 9 presents a summary of the KPIs measured for each of the WWTPs included in the study.

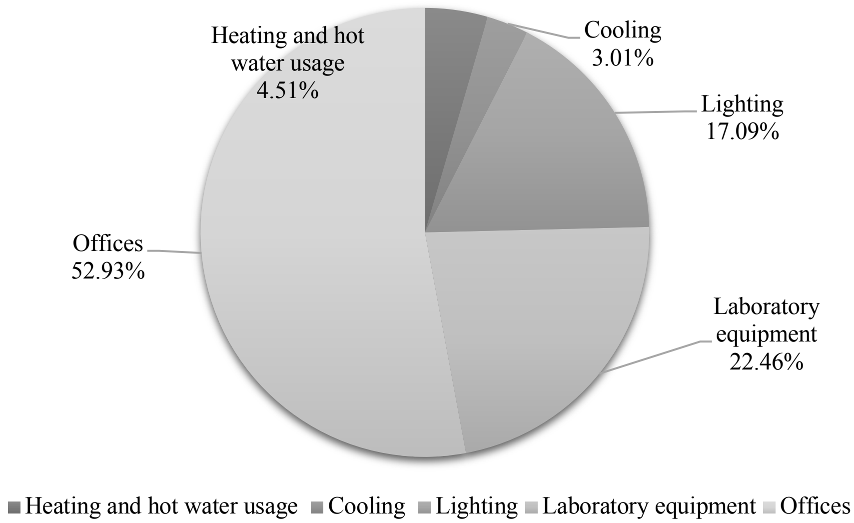

Figure 6. The total energy consumption of buildings in SWWTP (in 2021: 32650 kWh) and share of different parts

Table 9. Overall of the specific energy consumption of Tehran WWTPs in 2021

KPI	Unit's Name					
Specific Energy Consumption	STWWTP	SGWWTP	EWWTP	MWWTP	ZWWTP	SWWTP
Per volume (kWh/m^3)	0.21	1.01	0.52	1.28	1.22	1.07
Per capita (kWh/PE-year)	16.75	72.30	33.15	74.78	96.34	48.05
Per kg COD removed (kWh/kg COD)	0.48	2.42	2.17	2.80	3.66	1.71

Also, it has been indicated that smaller WWTPs typically show a larger variation in energy consumption compared to larger WWTPs (Niu et al., 2019). When examining the energy consumption of small-scale WWTPs in Tehran, it becomes evident that there is a considerable disparity in the energy usage among these facilities. In terms of energy consumption per capita and per kg COD removed, ZWWTP showed the lowest energy efficiency by consuming 96.34 kWh for each person under its service and 3.66 kWh per kg COD removed. Conversely, EWWTP showed the best performance by consuming only 33.15 kWh per capita and SWWTP had the greatest energy efficiency for COD removal by consuming only 1.71 kWh per kg COD removed. Also, EWWTP had the best efficiency in terms of energy consumption per influent volume with a consumption of 0.52 kWh/m^3.

MWWTP and SGWWTP exhibited high energy consumption per capita, consuming 74.78 kWh/PE-year and 72.30 kWh/PE-year served in 2021, respectively. Furthermore, MWWTP displayed the lowest energy efficiency among the WWTPs in terms of energy consumption per volume of influent, with a KPI of 1.28 kWh/m^3. It is crucial to emphasize that during the study year, both MWWTP and SGWWTP were operating beyond their design capacities. MWWTP received an influent flow that exceeded its design capacity by 9.7%, while SGWWTP experienced an overload of approximately 4.7%. Nevertheless, no precise relationship was identified between the loading condition of the WWTPs investigated in this study and their specific energy consumption.

By reviewing the literature, conflicting results on the relationship between loading conditions and specific energy consumption of WWTPs were found (Longo et al., 2018). Some authors concluded that the over-loaded or under-loaded conditions do not considerably affect the WWTP energy efficiency (Gómez et al., 2017), while others showed that loading condition affects the efficiency of a WWTP energy consumption (Guerrini et al., 2017; Niu et al., 2019; Lazic et al., 2019).

While the energy consumption of buildings within the WWTPs may not constitute a significant portion of the total energy consumption, there are several options available to enhance their energy efficiency. One simple and economically feasible solution, applicable to all buildings investigated in this study within Tehran WWTPs, is the implementation of green roofs. Extensive research has demonstrated the substantial potential of green roofs in improving building energy efficiency by mitigating the urban heat island effect and acting as an insulating layer (Shahmohammad et al., 2022; Castleton et al., 2010). Making green roofs by bio-based materials can improve their performance, reduce carbon footprint and improve the sustainability of green roofs. By using bio-based materials for green roof construction, their performance can be further enhanced, resulting in reduced carbon footprint and improved sustainability (Aghamohammadi & Shahmohammadi, 2023; Almeida et al., 2019).

Conclusion

In order to assess the eco-efficiency of WWTPs and develop effective strategies for enhancing their sustainability, it is essential to have precise data on their specific energy consumption. In the city of Tehran, there are seven major municipal wastewater treatment plants (WWTPs). Surprisingly, despite their significance, no study has been conducted to date that precisely assesses the energy consumption of these WWTPs. This paper aimed to address this research gap by comprehensively evaluating the energy consumption of Tehran WWTPs using suitable indicators to demonstrate their energy efficiency.

Energy consumption details of six out of the seven WWTPs in Tehran were collected and evaluated based on the available data, information, and authorized access. The energy consumption analysis of each WWTP in Tehran is divided into two categories: WWTPs' Buildings' Energy Consumption and treatment facilities' energy consumption. It was shown that, in Tehran WWTPs, the share of WWTPs' buildings from the total energy consumption is no more than 9.7%, and in most of them, it is negligible.

As the largest WWTP in Tehran, STWWTP showed the best energy efficiency among the others. Based on two indicators, ZWWTP had the poorest energy efficiency by consuming 96.34 kWh per population-equivalent served per year and 3.66 kWh per kg COD removed; regarding the energy consumption per volume of influent, MWWTP had the lowest energy efficiency (1.28 kWh/m^3). On the other hand, EWWTP showed the best performance regarding energy consumption per capita and per volume of influent (33.15 kWh/PE-year, 0.52 kWh/m^3), and SWWTP showed the greatest energy efficiency for COD removal (1.71 kWh/kg COD). Overall, a great variation between the specific energy consumption of the small-scale WWTPs was noticed.

Nevertheless, future studies are required for developing strategies to improve the energy efficiency of Tehran WWTPs. Improving energy efficiency would lead to reduced operational costs and a substantial decrease in GHG emissions. This paper provides detailed information on the primary consumers within each WWTP in Tehran, thereby aiding future researchers in identifying the most effective approaches to enhance energy efficiency in these facilities.

References

Aghamohammadi, N., & Shahmohammadi, M. (2023). Towards sustainable development goals and role of bio-based building materials. In Bio-Based Materials and Waste for Energy Generation and Resource Management (pp. 243-279). Elsevier.

Almeida, R., Simões, N., Tadeu, A., Palha, P., & Almeida, J. (2019). Thermal behaviour of a green roof containing insulation cork board. An experimental characterization using a bioclimatic chamber. Building and Environment, 160, 106179.

Aymerich, I., Rieger, L., Sobhani, R., Rosso, D., & Corominas, L. (2015). The difference between energy consumption and energy cost: modelling energy tariff structures for water resource recovery facilities. Water Research, 81, 113-123.

Bagheri, F., Mokarizadeh, V., & Jabbar, M. (2013). Developing energy performance label for office buildings in Iran. Energy and Buildings, 61, 116-124.

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

Castleton, H. F., Stovin, V., Beck, S. B., & Davison, J. B. (2010). Green roofs; building energy savings and the potential for retrofit. Energy and Buildings, 42(10), 1582-1591.

Christoforidou, P., Bariamis, G., Iosifidou, M., Nikolaidou, E., & Samaras, P. (2020). Energy benchmarking and optimization of wastewater treatment plants in Greece. Environmental Sciences Proceedings,

Di Fraia, S., Massarotti, N., & Vanoli, L. (2018). A novel energy assessment of urban wastewater treatment plants. Energy Conversion and Management, 163, 304-313.

Dong, X., Zhang, X., & Zeng, S. (2017). Measuring and explaining eco-efficiencies of wastewater treatment plants in China: An uncertainty analysis perspective. Water Research, 112, 195-207.

Fathi, S., & Kavoosi, A. (2021). Effect of electrochromic windows on energy consumption of high-rise office buildings in different climate regions of Iran. Solar Energy, 223, 132-149.

Fighir, D., Teodosiu, C., & Fiore, S. (2019). Environmental and Energy Assessment of Municipal Wastewater Treatment Plants in Italy and Romania: A Comparative Study. Water, 11(8).

Gans, N., Mobini, S., & Zhang, X. (2007). Appendix E. Mass and energy balances at the Gaobeidian wastewater treatment plant in Beijing, China.

Gómez, T., Gémar, G., Molinos-Senante, M., Sala-Garrido, R., & Caballero, R. (2017). Assessing the efficiency of wastewater treatment plants: A double-bootstrap approach. Journal of Cleaner Production, 164, 315-324.

Gu, Y., Li, Y., Li, X., Luo, P., Wang, H., Robinson, Z. P., Wang, X., Wu, J., & Li, F. (2017). The feasibility and challenges of energy self-sufficient wastewater treatment plants. Applied Energy, 204, 1463-1475.

Gu, Y., Li, Y., Li, X., Luo, P., Wang, H., Wang, X., Wu, J., & Li, F. (2017). Energy Self-sufficient Wastewater Treatment Plants: Feasibilities and Challenges. Energy Procedia, 105, 3741-3751.

Guerrini, A., Romano, G., & Indipendenza, A. (2017). Energy Efficiency Drivers in Wastewater Treatment Plants: A Double Bootstrap DEA Analysis. Sustainability, 9(7), 1126.

Gurung, K., Tang, W. Z., & Sillanpää, M. (2018). 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(3), 667-681.

Haslinger, J., Lindtner, S., & Krampe, J. (2016). Operating costs and energy demand of wastewater treatment plants in Austria: benchmarking results of the last 10 years. Water Science and Technology, 74(11), 2620-2626.

Heidari, F., Mahdavinejad, M., & Sotodeh, S. (2018). Renewable Energy and Smart Hybrid Strategies for High Performance Architecture and Planning in Case of Tehran, Iran. IOP Conference Series: Earth and Environmental Science, Henriques, J., & Catarino, J. (2017). Sustainable value–An energy efficiency indicator in wastewater treatment plants. Journal of Cleaner Production, 142, 323-330.

International Energy Agency (2018). World Energy Outlook 2018. International Energy Agency publications. Paris.

Jafarinejad, S. (2020). A framework for the design of the future energy-efficient, cost-effective, reliable, resilient, and sustainable full-scale wastewater treatment plants. Current Opinion in Environmental Science & Health, 13, 91-100.

Jonasson, M. (2007). Energy Benchmark for Wastewater Treatment Processes—A Comparison between Sweden and Austria. Department of Industrial Electrical Engineering and Automation, Lund University.

Lackner, S., Gilbert, E. M., Vlaeminck, S. E., Joss, A., Horn, H., & van Loosdrecht, M. C. M. (2014). Full-scale partial nitritation/anammox experiences – An application survey. Water Research, 55, 292-303.

Lazic, A., Henriksson, Å., & Baresel, C. (2019). Sustainable SBR Treatment: Treatment Efficiency, Energy, Carbon Footprint. International Journal of Water and Wastewater Treatment, 5(2).

Li, J., Tang, W. Z., & Gu, L. (2021). Energy efficiency assessment of China wastewater treatment plants by unit energy consumption per kg COD removed. Environmental Technology, 44(2), 278-292.

Liao, X., Tian, Y., Gan, Y., & Ji, J. (2020). Quantifying urban wastewater treatment sector's greenhouse gas emissions using a hybrid life cycle analysis method – An application on Shenzhen city in China. Science of the Total Environment, 745, 141176.

Longo, S., d'Antoni, B. M., Bongards, M., Chaparro, A., Cronrath, A., Fatone, F., Lema, J. M., Mauricio-Iglesias, M., Soares, A., & Hospido, A. (2016). Monitoring and diagnosis of energy consumption in wastewater treatment plants. A state of the art and proposals for improvement. Applied Energy, 179, 1251-1268.

Longo, S., Hospido, A., Lema, J. M., & Mauricio-Iglesias, M. (2018). A systematic methodology for the robust quantification of energy efficiency at wastewater treatment plants featuring Data Envelopment Analysis. Water Research, 141, 317-328.

Lu, J.-Y., Wang, X.-M., Liu, H.-Q., Yu, H.-Q., & Li, W.-W. (2019). Optimizing operation of municipal wastewater treatment plants in China: The remaining barriers and future implications. Environment International, 129, 273-278.

Maktabifard, M., Zaborowska, E., & Makinia, J. (2018). Achieving energy neutrality in wastewater treatment plants through energy savings and enhancing renewable energy production. Reviews in Environmental Science and Bio-Technology, 17(4), 655-689.

Marner, S., Schröter, D., & Jardin, N. (2016). Towards energy neutrality by optimising the activated sludge process of the WWTP Bochum-Ölbachtal. Water Science and Technology, 73(12), 3057-3063.

Masłoń, A. (2017). Analysis of energy consumption at the Rzeszów Wastewater Treatment Plant. International Conference on Advances in Energy Systems and Environmental Engineering, E3S Web Conferences, 22, 00115.

Mizuta, K., & Shimada, M. (2010). Benchmarking energy consumption in municipal wastewater treatment plants in Japan. Water Science and Technology, 62(10), 2256-2262.

NEWRI. (2009). Water & energy in the urban water cycle Improving energy efficiency in municipal wastewater treatment. In: Nanyang environment & water research institute in collabration with PUB Singapore & global water research coalition. pp 1–18.

Niu, K., Wu, J., Qi, L., & Niu, Q. (2019). Energy intensity of wastewater treatment plants and influencing factors in China. Science of The Total Environment, 670, 961-970.

Nouri, J., Jafarinia, M., Naddafi, K., Nabizadeh, R., Mahvi, A., & Nouri, N. (2006). Energy recovery from wastewater treatment plant. Pakistan Journal of Biological Sciences, 9(1), 3-6.

Pan, T., Zhu, X. D., & Ye, Y. P. (2011). Estimate of life-cycle greenhouse gas emissions from a vertical subsurface flow constructed wetland and conventional wastewater treatment plants: A case study in China. Ecological Engineering, 37(2), 248-254.

Panepinto, D., Fiore, S., Zappone, M., Genon, G., & Meucci, L. (2016). Evaluation of the energy efficiency of a large wastewater treatment plant in Italy. Applied Energy, 161, 404-411.

Plappally, A. (2012). Energy requirements for water production, treatment, end use, reclamation, and disposal. Renewable and Sustainable Energy Reviews, 16(7), 4818-4848.

Pretel, R., Robles, A., Ruano, M. V., Seco, A., & Ferrer, J. (2016). A plant-wide energy model for wastewater treatment plants: application to anaerobic membrane bioreactor technology. Environmental Technology, 37(18), 2298-2315.

Qu, J., Wang, H., Wang, K., Yu, G., Ke, B., Yu, H.-Q., Ren, H., Zheng, X., Li, J., Li, W.-W., Gao, S., & Gong, H. (2019). Municipal wastewater treatment in China: Development history and future perspectives. Frontiers of Environmental Science & Engineering, 13(6), 88.

Reinders, M., Greditgk-Hoffamnn, S., Risse, H., & Lange, M. (2012). Solution approaches for energy optimization in the water sector. IWA world congress on water, climate and energy, Dublin, Ireland,

Safaee, M. M., & Nematipour, N. (2021). Development of urban public spaces using urban underground spaces: a new method to improve quality of life (QOL) in Tehran metropolis. IOP Conference Series: Earth and Environmental Science,

Shahmohammad, M., Hosseinzadeh, M., Dvorak, B., Bordbar, F., Shahmohammadmirab, H., & Aghamohammadi, N. (2022). Sustainable green roofs: a comprehensive review of influential factors. Environmental Science and Pollution Research, 29(52), 78228-78254.

Songolzadeh, M., Soleimani, M., Takht Ravanchi, M., & Songolzadeh, R. (2014). Carbon Dioxide Separation from Flue Gases: A Technological Review Emphasizing Reduction in Greenhouse Gas Emissions. The Scientific World Journal, 2014, 828131.

Sun, Y., Chen, Z., Wu, G., Wu, Q., Zhang, F., Niu, Z., & Hu, H. Y. (2016). Characteristics of water quality of municipal wastewater treatment plants in China: implications for resources utilization and management. Journal of Cleaner Production, 131, 1-9.

Trojanowicz, K., & Karamus, Ł. (2016). Energetyczna utylizacja biogazu jako element gospodarki osadowej w oczyszczalni ścieków w Krośnie. Forum Eksploatatora, 4, 46-53.

US Department of Energy (2014). The Water-Energy Nexus: Challenges and Opportunities.

Wang, H., Yang, Y., Keller, A. A., Li, X., Feng, S., Dong, Y.-n., & Li, F. (2016). Comparative analysis of energy intensity and carbon emissions in wastewater treatment in USA, Germany, China and South Africa. Applied Energy, 184, 873-881.

Yerushalmi, L., Ashrafi, O., & Haghighat, F. (2013). Reductions in greenhouse gas (GHG) generation and energy consumption in wastewater treatment plants. Water Science and Technology, 67(5), 1159-1164.

Yeshi, C. (2015). Measured data based mass balance and energy efficiency of an 800,000 m3/day water reclamation plant in Singapore. 12th IWA specialised conference on design, operation and economics of large wastewater treatment plants. IWA, Prauge,

Yoro, K. O., & Daramola, M. O. (2020). Chapter 1 - CO2 emission sources, greenhouse gases, and the global warming effect. In M. R. Rahimpour, M. Farsi, & M. A. Makarem (Eds.), Advances in Carbon Capture (pp. 3-28). Woodhead Publishing.

Zaborowska, E., Czerwionka, K., & Makinia, J. (2017). Strategies for achieving energy neutrality in biological nutrient removal systems–a case study of the Slupsk WWTP (northern Poland). Water Science and Technology, 75(3), 727-740.