Wastewater treatment process impact on energy savings and greenhouse gas emissions

D. Mamais, C. Noutsopoulos, A. Dimopoulou, A. Stasinakis and T. D. Lekkas

ABSTRACT

The objective of this research was to assess the energy consumption of wastewater treatment plants (WWTPs), to apply a mathematical model to evaluate their carbon footprint, and to propose energy saving strategies that can be implemented to reduce both energy consumption and greenhouse gas (GHG) emissions in Greece. The survey was focused on 10 WWTPs in Greece with a treatment capacity ranging from 10,000 to 4,000,000 population equivalents (PE). Based on the results, annual specific energy consumption ranged from 15 to 86 kWh/PE. The highest energy consumer in all the WWTPs was aeration, accounting for 40–75% of total energy requirements. The annual GHG emissions varied significantly according to the treatment schemes employed and ranged between 61 and 161 $kgCO_{2e}$/PE. The highest values of CO_2 emissions were obtained in extended aeration systems and the lowest in conventional activated sludge systems. Key strategies that the wastewater industry could adopt to mitigate GHG emissions are identified and discussed. A case study is presented to demonstrate potential strategies for energy savings and GHG emission reduction. Given the results, it is postulated that the reduction of dissolved oxygen (DO) set points and sludge retention time can provide significant energy savings and decrease GHG emissions.

Key words | carbon footprint, control strategies, energy savings, greenhouse gas emissions, specific energy consumption, wastewater treatment

D. Mamais (corresponding author)
C. Noutsopoulos
A. Dimopoulou
Department of Water Resources and Environmental Engineering,
School of Civil Engineering, National Technical University of Athens,
5 Iroon Polytechniou, Zografou,
Athens 15780,
Greece
E-mail: *mamais@central.ntua.gr*

A. Stasinakis
Department of Environment,
University of the Aegean, University Hill,
Mytilene 81100,
Greece

T. D. Lekkas
EYDAP,
156 Oropou St.,
Athens 11146,
Greece

INTRODUCTION

Traditional municipal waste management in many European countries mostly addresses public health and environmental issues related to waste storage, treatment and disposal. As a result, in many cases municipal wastewater management has been practiced in a non-sustainable way, employing treatment schemes that exert a high energy demand, have a large carbon footprint and contribute significantly to climate change. In the USA, average annual specific energy consumption in wastewater treatment plants (WWTPs) is approximately 29 kWh/population equivalent (PE), ranging from 16 to 71 kWh/PE (Stillwell *et al.* 2010). In Europe annual specific energy consumption in WWTPs has been reported to range between 20 and 120 kWh/PE. As reported by Jonasson (2010) annual specific energy consumption from WWTPs in the UK, Sweden and Austria is approximately 38, 42 and 23 kWh/PE, respectively, whereas similar values have been reported by Balmer (2000) for five Nordic WWTPs (31–47.2 kWh/PE). Similarly, Krampe (2013) reported that the annual specific energy consumption of 11 WWTPs in South Australia ranged from 30 to 120 kWh/PE with an average value in the order of 60 kWh/PE. These values are comparable to the German Guide Manual, which sets an objective for energy optimization of approximately 20–30 kWh/PE, depending on the size of the WWTP (Krampe 2013). In most medium and large WWTPs that employ activated sludge systems for secondary treatment, aeration typically accounts for approximately 50–60% of all electricity consumption, followed by sludge treatment (15–25%) and secondary sedimentation including recirculation pumps (15%).

WWTPs have widely been recognized as one of the major sources of greenhouse gas emissions (GHG) in the water industry (US Environmental Protection Agency (US EPA) 1997). WWTPs directly produce carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) as a result of the treatment procedure and additionally contribute to

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CO_2 and CH_4 emissions through energy consumption. There are studies estimating GHG emissions from WWTPs (Cakir & Stenstrom 2005; Sahely *et al.* 2006). Reported values of GHG emissions from conventional activated sludge WWTPs with nutrient removal range from 0.9 to 2.2 $kgCO_{2e}/m^3$ (Flores-Alsina *et al.* 2011). Furthermore, Gustavsson & Tumlin (2013) report values of annual GHG emissions in the range of 7–108 $kgCO_{2e}$/PE for 16 Scandinavian WWTPs. According to the authors, the major contributor to GHG production was the emission of N_2O from wastewater treatment processes. In view of the above, the reduction of GHG emissions in a cost-efficient way without deteriorating effluent quality seems to be a great challenge for the operators of WWTPs. It has been shown that by implementing specific control strategies, a significant reduction of GHG emissions can be achieved (Flores-Alsina *et al.* 2011; Sweetapple *et al.* 2014).

The objectives of this research were to collect data on WWTP energy consumption, to develop a mathematical model to evaluate both onsite and off-site GHG emissions, and to propose energy saving strategies that can be implemented to reduce both energy consumption and GHG emissions in Greece. In order to achieve the above objectives operating and electricity consumption data from 10 WWTPs in Greece were collected. These WWTPs, with a treatment capacity ranging from 10,000 to 4,000,000 PE, employed various treatment schemes that included conventional activated sludge systems with anaerobic sludge digestion, extended aeration nutrient removal activated sludge systems and nutrient removal activated sludge systems with anaerobic sludge digestion. In addition, detailed energy analysis was conducted for the Psyttalia sewage treatment works (STW), the largest WWTP in Greece that serves the Greater Athens Area with a population of approximately 4 million people, in order to apply and evaluate relatively simple operational changes that can potentially achieve energy savings and GHG emission reduction, at a justifiable cost.

MATERIALS AND METHODS

Energy consumption and GHG emissions in WWTPs

Operational data were collected from 10 biological nutrient removal (BNR) WWTPs in Greece with a treatment capacity ranging from 15,000 to 4,000,000 PE. All WWTPs achieved the biochemical oxygen demand (BOD_5), total suspended solids (TSS) and total nitrogen (TN) effluent criteria established by the 91/271 EC Directive. Table S2 in the Supplementary Material (available online at http://www.iwaponline.com/wst/071/521.pdf) presents the treatment capacity, the average current loading and the type of treatment for both wastewater and sludge for each of the 10 WWTPs under consideration. The objectives of the survey were to provide data that would allow the evaluation of WWTP energy consumption in relation to treatment process and capacity, to identify the treatment stages that are the greater energy consumers and to assist in developing energy efficiency plans for WWTPs. For each WWTP the survey involved compiling data from each WWTP design study, drawings, utility bills and equipment inventory in order to develop an understanding of the wastewater and sludge treatment processes employed and the energy consumption at each treatment stage. In addition, operational data were collected that involved influent flows, influent chemical oxygen demand (COD), BOD_5, TSS, TN and total phosphorus (TP) loadings, sludge disposal, biogas reuse (if applicable) and effluent wastewater criteria. Operational data for each WWTP were collected for the summer and winter period. According to the survey, WWTPs were divided into the following two categories:

- Category 1 – WWTPs 1–5: This category includes small to medium size WWTPs with a treatment capacity ranging from 15,000 to 100,000 PE. All five WWTPs were extended aeration activated sludge systems with no primary treatment.
- Category 2 – WWTPs 6–10: Large WWTPs with a treatment capacity ranging from 100,000 to 4,000,000 PE with primary and secondary wastewater treatment. All five WWTPs that fell into this category employed anaerobic digestion for sludge treatment and biogas use for digestion heating. Additionally, one WWTP (WWTP 10) is currently using combined heat and power systems to produce heat and electricity from excess biogas.

GHG emission estimations included on-site and off-side production of CO_2, CH_4 and N_2O and the latter two were calculated in units of CO_2 equivalent, by multiplying by 23 and 296, respectively (IPCC 2001). The model applied to calculate GHG emissions was based on the comprehensive approach suggested by Bridle *et al.* (2008). A comprehensive description of this methodology can be found in Snip (2010), whilst a detailed description of the model is presented in the Supplementary Material to this paper (available online at http://www.iwaponline.com/wst/071/521.pdf). The major on-site GHG emissions considered were generated from (1) biological wastewater treatment, (2) sludge treatment and (3) biogas combustion for heating and electricity production. Off-site gas emissions considered were from energy consumption and sludge disposal. Off-site gas emissions from chemical consumption were considered negligible because no chemicals were employed for pH control and denitrification.

Case study of control strategies

The Psyttalia WWTP was chosen as a case study to evaluate the effect of operational parameters on energy consumption and GHG emissions. In August 2004, with the completion of Phase B, Psyttalia STW was upgraded to provide BNR for approximately 1,000,000 m^3/day average dry weather flow. According to the effluent requirements, the biological treatment stage was designed to ensure that an effluent quality of 25 mg/L for BOD_5 and 10 mg/L for total nitrogen is achieved. The constructed activated sludge unit consists of 12 bioreactors with a total volume of 298,140 m^3, followed by 64 rectangular final sedimentation tanks with a total surface area of 52,150 m^2. Each bioreactor tank is comprised of one anaerobic compartment, one anoxic compartment and four aerobic compartments, all with a net depth of 9.4 m. Psyttalia WWTP is already practicing energetic optimization by recovering electrical energy from anaerobic digestion biogas and by employing an energy efficient aeration system that includes fine bubble diffusion, variable frequency drive blowers and an automated dissolved oxygen (DO) monitoring and control system. During this study, additional energy efficiency improvements were evaluated for Psyttalia WWTP including operational measures such as optimization of sludge age and DO concentration set points in each aerobic compartment. The evaluation of each alternative energy saving practice was performed through the simulation of WWTP operation by GPS-X, a commercially available software (Hydromantis, Canada).

RESULTS AND DISCUSSION

Evaluation of specific energy consumption and GHG emissions in Greek WWTPs

The results of the evaluation of the specific energy consumption in the Greek WWTPs that took part in the survey are presented in Figure 1. The results show that average annual specific energy consumption ranged from 15 to 86 kWh/PE. Higher energy consumption, attributed to increased aeration demands due to higher endogenous respiration, was observed during summer with an average value of 42.3 kWh/PE versus a winter average value of 34.5 kWh/PE. Higher energy consumption was observed on average in Category 1 WWTPs (WWTPs 1–5), compared to conventional activated sludge WWTPs that employed anaerobic digestion for sludge treatment and used biogas for digestion heating (WWTPs 6–10). Average annual energy consumption by Category 1 WWTPs in Greece was approximately 44 versus 32 kWh/PE by Category 2 WWTPs. By comparing the two data sets (specific energy consumption for Categories 1 and 2) a p-value of 0.007 was calculated which represents an acceptable statistical significance. Psyttalia WWTP, the only WWTP that employed combined heat and power production from biogas, exhibited the lowest annual energy consumption at approximately 15 kWh/PE. In Category 1, the lowest specific energy consumption is exhibited by WWTPs 1 and 5. It is noteworthy that WWTP 1 is the only treatment plant of Category 1 that uses a diffusion system for aeration purposes, while WWTP 5 is the treatment plant operating at the lowest sludge age. The highest specific energy consumption was recorded for WWTPs 2, 3, 4 and 8. As illustrated in Table S2 (in the Supplementary Material), WWTP 2 is operating at the highest sludge age (52 d) of all the other WWTPs. Furthermore, WWTPs 3, 4 and 8 are the most energy consuming treatment plants as they exhibited the highest specific installed power among all the other WWTPs (38, 31 and 20 W/PE, respectively, versus the average value of 12 W/PE for the other WWTPs). The high specific energy consumptions of WWTPs 3, 4 and 8 are also correlated with the use of surface aeration systems and, in the case of WWTP 4, also with low treatment capacity. It should be noted that the low winter specific energy consumption of WWTP 3 is due to the increase of the organic loading of the treatment plant with high organic carbon liquid wastes from an industrial unit which results in an increase of the winter PE served by the treatment plant. According to the results, it is postulated that specific energy consumption decreases with increasing treatment

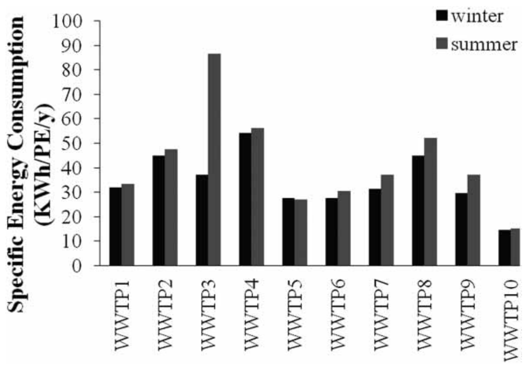

Figure 1 | Energy consumption by Greek WWTPs.

capacity. Such dependence is illustrated in Figure S1 in the Supplementary Material (available online at http://www.iwaponline.com/wst/071/521.pdf) and has been reported by several researchers (Mizuta & Shimada 2010; Krampe 2013). Moreover, specific energy consumption depends also on the type of aeration system, with WWTPs with diffusion systems exhibiting significantly lower energy consumption to treatment plants with surface aeration systems (26.5 versus 40 kWh/PE).

Figure S2 in the Supplementary Material (available online at http://www.iwaponline.com/wst/071/521.pdf) illustrates the distribution of energy consumption among the several wastewater and sludge treatment units for four representative WWTPs, while Figure 2 presents the contribution of aeration to the total energy consumption with respect to treatment capacity (Figure 2(a)) and the effect of the type of aeration (Figure 2(b)). Based on these data it is concluded that biological treatment accounts for more than 55% of the total energy consumption, with aeration being the basic consumer. Preliminary works and sludge treatment units are also significant energy consumers, accounting for approximately 11 and 8% of total WWTP energy consumption, respectively. The contribution of aeration to the total energy requirements depends on both the treatment capacity and the type of aeration, with the smaller WWTPs with surface aeration systems exhibiting higher energy consumption for aeration.

The results of the calculation of the GHG emissions from the surveyed Greek WWTPs are presented in Figure 3 and Figures S3–S6 in the Supplementary Material (available online at http://www.iwaponline.com/wst/071/521.pdf). According to the results, annual GHG emissions ranged from 61 to 161 $kgCO_{2e}$/PE. Comparable values of gas emissions have also been reported by others (Gustavsson & Tumlin 2013). Based on the data presented in Figure 3 and Figures S3–S5, GHG emissions are highly related to both system configuration (Figures S3 and S5) and treatment capacity (Figure 3). As shown in Figure S4, extended aeration WWTPs exhibited on average higher GHG emissions compared to conventional activated sludge systems. Average annual GHG emissions for Category 1 and 2 WWTPs were equal to 110 $kgCO_{2e}$/PE and 80 $kgCO_{2e}$/PE, respectively. By comparing the two data sets (annual GHG emission for Category 1 and 2) a p-value of 0.03 was calculated which represents an acceptable statistical significance. Figure S5 in the Supplementary Material shows that the primary contributor to the carbon footprint of the WWTPs was the direct GHG emissions due to wastewater treatment, which accounts for more than 45% of the total emissions (varying between 45 and 58%), with the exception of WWTPs 3 and 8 for which both direct, indirect and energy-related emissions are practically equally contributed to the carbon footprint. Among the surveyed treatment plants, a higher carbon footprint was calculated for WWTPs 2, 3, 4 and 5. The primary contributor to the carbon footprint of WWTP 2 was the direct on-site emissions from the higher aeration demands due to the high sludge age of the activated sludge system, whereas in the case of WWTP 5 the contribution of indirect emissions, due to increased sludge production, is appreciable as well. Based on these data it is postulated that, as the treatment capacity increases, the contribution of direct emissions decreases while the contribution of indirect emission increases. Furthermore, as presented in Figure S6 in the Supplementary Material, the contribution of indirect emissions to the total carbon footprint decreases with the increase of sludge age.

Psyttalia WWTP case study: evaluation of alternative control strategies

The Psyttalia WWTP was chosen as a case study to evaluate the effect of operational parameters on energy consumption

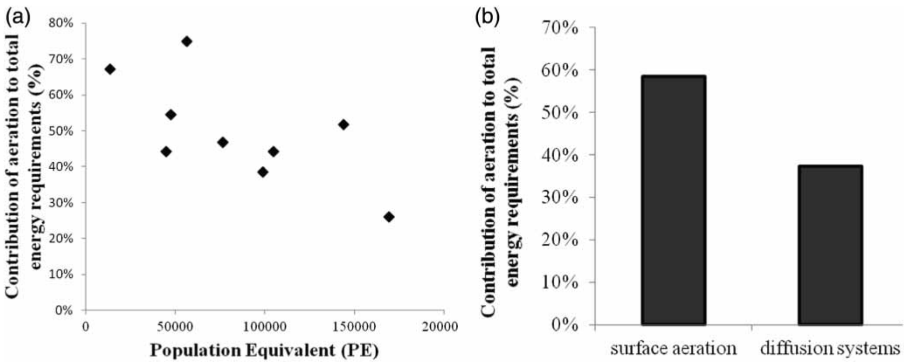

Figure 2 | (a) Contribution of aeration to the total energy requirements and (b) effect of type of aeration on energy consumption.

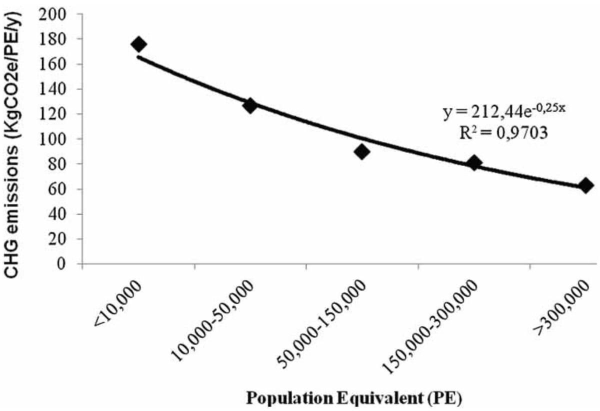

Figure 3 | Dependence of GHG emissions on the treatment capacity of the WWTPs.

and GHG emissions. Based on the results, biological wastewater treatment, primary treatment and sludge drying are the major energy consuming treatment stages that account for approximately 55, 15 and 10% of the total power consumption of Psyttalia WWTP. As a result, aeration and sludge treatment offer the greatest opportunities for energy savings. Therefore, energy efficiency improvements evaluated for Psyttalia WWTP included operational measures such as optimization of sludge age and oxygen concentration set points in each aerobic compartment. Currently, Psyttalia WWTP operates at DO set points for the four aerobic compartments of each bioreactor equal to 3.5, 3, 2.5 and 2 mg/L, respectively, and a sludge age equal to 8.4 d. It should be underlined that all scenarios considered achieved full compliance with Psyttalia WWTP effluent requirements. Scenarios A1–A4 evaluated the plant performance at lower DO set points for the four aerobic compartments than the existing ones. The DO set points were equal to: 3, 2.5, 1.5 and 1.5 mgO_2/L for Scenario A1; 2.5, 2.5, 1.5, 1.5 mgO_2/L for Scenario A2; 3.0, 2.5, 1.0, 0.5 mgO_2/L for Scenario A3; and 2.5, 2.5, 1.0, 0.5 mgO_2/L for Scenario A4. Scenario B involves the operation of the activated sludge unit at the lowest acceptable solids retention time (6.1 d), while Scenario C is a combination of Scenarios A3 and B. The results obtained for each alternative control strategy were evaluated with respect to the excess sludge produced and the energy savings in the whole WWTP. Based on the results (Table 1), it is anticipated that the decrease of the DO set points to lower values than those of the existing situation results in an appreciable profit of energy consumption in the order of 6–10.1% (annual energy savings between 1.400 and 2.900 MWh) of the total annual energy consumption for aeration purposes. Another possible practice is the operation of the activated sludge unit at its minimum allowable sludge age which results in an appreciable energy decrease in the order of 6.2% (Scenario B). In order to achieve further energy savings (in the order of 11.2%), a combined approach can be adopted (Scenario C) which enables a decrease of both DO set points and sludge age (energy savings in the order of 4.500 MWh on an annual basis). It should be mentioned that when adopting strategies of lower sludge age, the cost for the treatment and handling of the additional excess sludge produced should be considered as well.

Table 1 | Results of alternative scenarios for the decrease of energy consumption

Scenarios	Decrease in annual energy consumption of the aeration system (%)[a]	Total annual energy savings (MWh/year)
A1: DO set points 3, 2.5, 1.5 and 1.5 mg/L	6	1.440
A2: DO set points 2.5, 2.5, 1.5 and 1.5 mg/L	9	2.514
A3: DO set points 3, 2.5, 1.0 and 0.5 mg/L	7.1	1.814
A4: DO set points 2.5, 2.5, 1.0 and 0.5 mg/L	10.1	2.910
B: Sludge age 6.1 d and no change at current DO set points	6.2	3.700
C: Sludge age 6.7 d; DO set points 3, 2.5, 1.0 and 0.5 mg/L	11.2	4.500

[a]Comparisons are made with the zero scenario in which the set points of the four aerobic compartments were equal to 3.5, 3, 2.5 and 2 mg/L and sludge age was equal to 8.4 d.

CONCLUSIONS

Operational data collected from 10 BNR WWTPs in Greece with a treatment capacity ranging from 15,000 to 4,000,000 PE showed that average annual specific energy consumption in WWTPs in Greece is approximately 38 kWh/PE, ranging from 15 to 86 kWh/PE. Accordingly, the annual average GHG emissions in Greek WWTPs is of the order of 94 kCO_{2e}/PE, ranging from 61 to 161 $kgCO_{2e}$/PE. If the great number of WWTPs operating in the European Union with a total treatment capacity exceeding 400 million PE is considered, the energy savings and environmental benefits arising from efforts to decrease WWTP energy consumption could be very significant. Therefore it is vital to recommend specific control strategies for the mitigation of emissions and the reduction of energy consumption in WWTPs.

REFERENCES

Balmer, P. 2000 Operation costs and consumption of resources at Nordic nutrient removal plants. *Water Science and Technology* **41** (9), 273–279.

Bridle, T., Shaw, A., Cooper, S., Yap, K. C., Third, K. & Domurad, M. 2008 Estimation of greenhouse emissions from wastewater treatment plants. In: *Proceedings IWA World Water Congress and Exhibition*, 7–12 September 2008, Vienna, Austria. CD Rom. IWA Publishing, London, UK.

Cakir, F. Y. & Stenstrom, M. K. 2005 Greenhouse gas production: a comparison between aerobic and anaerobic treatment technology. *Water Research* **39** (17), 4197–4203.

Flores-Alsina, X., Corominas, L., Snip, L. & Vanrolleghem, P. A. 2011 Including greenhouse gas emissions during benchmarking of wastewater treatment plant control strategies. *Water Research* **45**, 4700–4710.

Gustavsson, D. J. I. & Tumlin, S. 2013 Carbon footprints of Scandinavian wastewater treatment plants. *Water Science and Technology* **68** (4), 887–893.

IPCC 2001. *Climate Change 2001: The Scientific Basis*. Cambridge University Press, Cambridge, UK.

Jonasson, M. 2010 Energy Benchmark for Wastewater Treatment Processes – A Comparison between Sweden and Austria. Masters Thesis, Innsbruck University, Austria.

Krampe, J. 2013 Energy benchmarking of South Australian WWTPs. *Water Science and Technology* **67** (9), 2059–2066.

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

Sahely, H. R., MacLean, H. L., Monteith, H. D. & Bagley, D. M. 2006 Comparison of on-site and upstream greenhouse gas emissions from Canadian municipal wastewater treatment facilities. *Journal of Environmental Engineering and Science* **5** (5), 405–415.

Snip, L. 2010 Quantifying the Greenhouse Gas Emissions of Wastewater Treatment Plants. PhD Thesis, Wageningen University, The Netherlands.

Stillwell, A. S., Hoppock, D. C. & Webber, M. E. 2010 Energy recovery from WWTPs in the United States: a case study of the energy–water nexus. *Sustainability* **2**, 945–962.

Sweetapple, C., Fu, G. & Butler, D. 2014 Multi-objective optimization of wastewater treatment plant control to reduce greenhouse gas emissions. *Water Research* **55**, 52–62.

US Environmental Protection Agency (US EPA) 1997 *Estimates of Global Greenhouse Gas Emissions from Industrial and Domestic Wastewater*. Report No. EPA-600/R-97–091. Office of Policy, Planning and Evaluation, US Environmental Protection Agency, Washington, DC.

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