Energy requirements for waste water treatment

K. Svardal and H. Kroiss

ABSTRACT

The actual mathematical models describing global climate closely link the detected increase in global temperature to anthropogenic activity. The only energy source we can rely on in a long perspective is solar irradiation which is in the order of 10,000 kW/inhabitant. The actual primary power consumption (mainly based on fossil resources) in the developed countries is in the range of 5 to 10 kW/inhabitant. The total power contained in our nutrition is in the range of 0.11 kW/inhabitant. The organic pollution of domestic waste water corresponds to ~0.018 kW/inhabitant. The nutrients contained in the waste water can also be converted into energy equivalents replacing market fertiliser production. This energy equivalent is in the range of 0.009 kW/inhabitant. Hence waste water will never be a relevant source of energy as long as our primary energy consumption is in the range of several kW/inhabitant. The annual mean primary power demand of conventional municipal waste water treatment with nutrient removal is in the range of 0.003–0.015 kW/inhabitant. In principle it is already possible to reduce this value for external energy supply to zero. Such plants should be connected to an electrical grid in order to keep investment costs low. Peak energy demand will be supported from the grid and surplus electric energy from the plant can be is fed to the grid. Zero 'carbon footprint' will not be affected by this solution. Energy minimisation must never negatively affect treatment efficiency because water quality conservation is more important for sustainable development than the possible reduction in energy demand. This argument is strongly supported by economical considerations as the fixed costs for waste water infrastructure are dominant.

Key words | energy requirement, wastewater treatment

K. Svardal (corresponding author)
H. Kroiss
Institute of Water Quality,
Resource and Waste Management,
Vienna University of Technology,
Karlsplatz 13/226,
1040 Vienna,
Austria
E-mail: *svardal@iwag.tuwien.ac.at*

INTRODUCTION

Actual discussion on the relationship between human activity and the environment is dominated by energy and climate change (carbon footprint). Fundamental dependence of economic development and social welfare on fossil fuel imports becomes increasingly relevant for the large global economies (US, EU, East Asia, China and India).

Political relevance is closely linked to the increasing consciousness that fossil fuel represents a limited resource even there is enough fuel for the next 50 years.

Changes in environmental policy (consciousness) need about 30 years until they become really effective: Primary energy consumption (6 kW/person) in our countries is about 60 times higher than our food consumption (0.1 kW/person). Food production consumes >1,000 m^3 of water/person/year which is >1,000 times our drinking requirement (1 m^3/a) and >20 times our waste water production.

Water and waste water treatment technology can secure water supply for everybody on the globe but not for food supply. Waste water reuse will not solve the global food problem; even it can help in some regions.

Highly efficient waste water treatment is a basic requirement for water quality management in all regions, with increasing importance with decreasing water availability and increasing population density. Minimisation of energy requirement for waste water treatment is an important goal but has a lower priority than the human and environmental health which is closely related to efficient water quality management. Waste water will neither solve the food nor the energy problem, but a better resource management will have to consider the complex relationships.

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Reference parameters and general theoretical basis

Within the development of suitable process indicators for waste water treatment (Lindtner & Zessner 2003, Lindtner *et al.* 2004, Lindtner & Svardal 2008) have analysed many parameters in regard to their sensitivity for energy and cost-comparisons. The mean annual COD-load of the waste water inflow to the treatment plants turned out to be the most suitable for several reasons. It can be defined as population equivalent for COD: $PE_{COD} = 110$ g COD/PE/d which corresponds to the internationally agreed value of 60 g BOD/PE/d. In this way a direct relationship to the waste water producers can be established. This reference parameter is also suitable for comparisons of energy-requirement-data, because the most relevant energy-consumption for biological waste water treatment plants is depending on the organic pollution load and not on sewage flow in m^3 (Briscoe 1995).

In this paper the following reference parameters and units are used:

- 1 inhabitant (p)
- time: 1 year (a)
- Pollution load: Population Equivalent (PE)
  - 110 g COD/d; (equivalent to 60 g BOD_5/d), 40 kg COD/a
- Energy: J, kWh
- Power: W

For a majority of larger municipal treatment plants (>50,000 inhabitants) operational data show a relationship between inhabitants (p) and the mean yearly COD pollution load (PE) in the range of 2. This relationship is used in this paper for the comparison of statistical data related to inhabitants with waste water related data related to population equivalents (PE).

Energy content of waste water

In many publications waste water is considered as a potential energy source (Logan 2005; Van Lier 2007). It is therefore important to quantify this potential and relate it to the overall energy consumption of the inhabitants in order to show its relevance. Waste water contains energy in form of organic material and as heat. The energy equivalent of the nutrients can be related to the energy demand for production of market fertiliser substituting the nutrient loads in waste water.

The COD of the waste water can be interpreted as an energy parameter (J, kWh) considering that the oxygen demand for complete oxidation of organic pollution can directly be linked to the energy content. Nearly all organic compounds of waste water have a calorific value between 13 and 15 kJ/g COD. In this paper a value of 14 kJ/g COD will be used.

Table 1 | Primary energy content of municipal waste water compounds

	Annual load (kg/PE/a)	Energy equivalent (kWh/PE/a)	Power (W/PE)
COD	40	156	18
Nitrogen	3.3	36	4
Phosphorus	0.5	5	0.6
Total	–	197	22.5

The calculation of the energy equivalent of the nutrients is based on the state of the art technology for fertilizer production. For the production of nitrogen fertilizer from atmospheric nitrogen about 11 kWh/kg N are required. Zessner (1999) reports for phosphorus fertilizer a value of 10 kWh/kg P (UBA 2008).

A detailed analysis of large Austrian municipal treatment plant influents (Lindtner & Zessner 2003) resulted in following average values for nitrogen and phosphorus loads related to PE (110 g COD/PE/d): for nitrogen 9 g N/PE/d (3.3 kg N/PE/a) and for phosphorus 1.45 g P/PE/d (0.5 kg P/PE/a). The data in Table 1 are based on these default values. Fertiliser production is mainly based on fossil energy such as natural gas or liquid fuels and not on electric power.

For hot water production in central Europe ~100 W/p are used and result in an increased waste water temperature. Only a small portion of this energy (approximately 5%) can economically be exploited under favourable conditions by heat pumps (Schmid 2007) e.g. for district heating. Priority should be given to hot water production by direct use of solar irradiation.

In order to demonstrate the relevance of energy demand for waste water treatment Table 2 contains some actual

Table 2 | Comparative data about actual primary energy consumption of one inhabitant in developed countries

Total primary energy input	>6,000 W/p
Food production	>200 W/p
Electronic information system	>200 W/p
Traffic, transport	>1,000 W/p
Nutrition, food	~110 W/p
Waste water treatment with nutrient removal by conventional mechanical biological treatment (activated sludge process)	0 to 15 W/p

data about the energy consumption in developed countries. On the basis of these values it can be concluded that reduction of energy consumption by waste water treatment achieved on the expense of lower waste water treatment efficiency should be strictly avoided. It also shows that waste water will not be a relevant source of energy for our civilization. These arguments do not excuse inefficient energy management at waste water treatment plants.

RELATIONSHIP BETWEEN TREATMENT EFFICIENCY REQUIREMENTS, SLUDGE TREATMENT TECHNOLOGY AND ENERGY DEMAND OF TREATMENT PLANTS

General statements and assumptions

Although energy costs are not dominant for total waste water treatment costs the question to which extent treatment efficiency requirements influence the energy demand, is of some interest. The design of activated sludge treatment plants, the most commonly used waste water treatment process, is based on the sludge age, which determines the treatment efficiency at the temperature range in the aeration tank. The actual treatment efficiency is also depending on aeration control and the sludge settling and thickening properties.

Energy consumption for waste water treatment is primarily depending on the oxygen demand but also on the aeration efficiency and the quality of the aeration control. The total oxygen demand is composed of 3 components:

- OUC oxygen demand for the oxidation of carbonaceous compounds
- OUDN oxygen demand for the oxidation of ammonia to molecular nitrogen removed from the waste water by nitrification/denitrification (1.7 g O_2/g N-DN)
- OUN oxygen demand for the oxidation of ammonia to nitrate, which is contained in the effluent (4.3 g O_2/g NO_3-N_e)

The calculation of the annual mean of OUC (kg O_2/PE/d) and the COD contained in the excess sludge is based on Figure 1. This diagram is derived from sound full scale experience and is in agreement with model calculation results (ASM 1, Henze *et al.* 1987) for conventional municipal waste water. The influence of temperature variations on oxygen demand is relevant for the changes during the day and the seasons but not for the yearly mean, as the yield coefficient is nearly independent from the temperature. A annual mean temperature of ~15 °C was assumed which is representative for moderate climatic conditions in Europe.

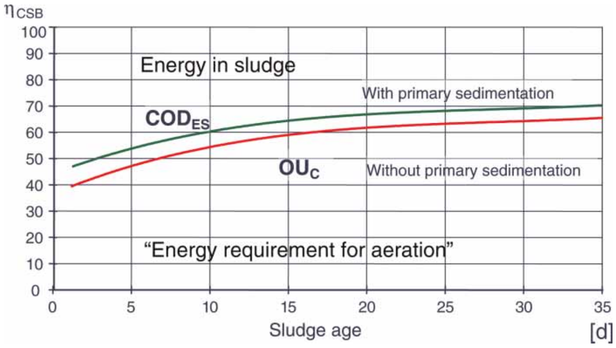

Figure 1 | COD (Energy) balance concept: Removed COD load (100%) = OUC + COD in the excess sludge (COD_{ES})

For the energy balance calculations for different process configurations the assumptions contained in Table 3 have been made. They are representative for normal municipal waste water and have been derived from literature (Nowak *et al.* 1996) as well as from operational data of treatment plants. The values reported apply to moderate climatic conditions.

The COD of anaerobically stabilised sludge can be as low as ~25 g COD/PE under favourable conditions (retention time >> 20 days, excellent mixing conditions, temperature between 37 and 39 °C, very efficient screening) The assumption of 30 g COD/PE/d avoids therefore an overestimation of the methane production potential. Theoretical methane production during sludge digestion was calculated as 0.35 NL (at 101.325 kPa, 0 °C) CH_4 per g COD degraded. The assumptions for COD and N-content of aerobically stabilised sludge are based on investigations by Nowak *et al.* (1996).

Aeration efficiency under operational conditions can vary in a broad range of values as process benchmarking

Table 3 | Assumptions made for energy requirement calculations for different process configurations

Yearly mean temperature in aeration tank	°C	15
COD of anaerobically stabilised sludge	g/PE/d	30
COD of simultaneously aerobically stabilised sludge, optimisation for N-removal	g/PE/d	34
COD of simultaneously aerobically stabilised sludge, optimisation for stabilization	g/PE/d	30
Aeration efficiency under operational conditions, conventional/efficient new equipment	kg O_2/kWh	1.7/2.2

results from Austrian plants have shown. The assumptions made for this publication are representative for efficient aeration systems.

Process configurations

Table 4 shows 5 process configurations investigated in detail. 4 different treatment efficiency requirements are combined with 4 different process configurations. For processes 1 to 3 treatment plants with a capacity >100.000 PE were assumed while processes 4 and 5 are representative for small plants (~5.000 PE). Phosphorus removal has little influence on energy requirements and has been therefore neglected.

Process 1 was chosen as the probably most common treatment efficiency requirement worldwide and allows to demonstrate the influence of advanced treatment efficiency requirements (process configurations 2 to 5) on energy demand. Processes 2 and 3 were selected to demonstrate the actual possibilities to minimise energy consumption for large waste water treatment plants by efficient process design and equipment selection as demonstrated at the Vienna Main Treatment Plant (Wandl *et al*. 2009) and the AIZ Plant in Austria (Wett 2006). For the processes 1 to 3 a COD/N ratio of 110/9 was assumed based on the analysis of large municipal treatment plant influent composition (Lindtner & Zessner 2003).

Process 4 represents the most common configuration for treatment plants with a capacity <20,000 PE. Aeration control is optimised for nitrogen removal.

Process 5 represents the worst case for energy consumption, as full nitrification and no denitrification was assumed which will not happen in practice even when aeration is optimised for aerobic sludge stabilisation. In many cases such an operation would result in a pH drop due to high nitrate concentrations followed by a breakdown of nitrification. For process 4 and 5 a COD/N ratio of 110/11 was assumed as it is typical for domestic sewage without important influence of industry and trade.

Table 4 | Process configurations for energy balances

Process	Treatment efficiency requirements	Process configuration	Sludge age (d)
1	EU-requirements for normal areas (BOD-removal only)	1 step activated sludge process with primary sedimentation and anaerobic sludge digestion	4
2	EU-requirements for sensitive areas, >75% N-removal, full nitrification for $T > 8\,^{\circ}\mathrm{C}$, [a]	1 activated sludge process with primary sedimentation and anaerobic sludge digestion, conventional equipment	15
3	EU-requirements for sensitive areas, >75% N-removal, full nitrification for $T > 8\,^{\circ}\mathrm{C}$, [a]	2 step activated sludge process with primary sedimentation, sludge digestion. Efficient new equipment and deammonification for sludge liquor	1.5/8
4	Simultaneous aerobic sludge stabilisation with N-removal efficiency >80%	1 step activated sludge process with intermittent aeration, no primary sedimentation	25
5	Simultaneous aerobic sludge stabilisation, no denitrification, (theoretical case)	1 step activated sludge process without primary sedimentation	25

[a] Minimum requirements according to the Austrian effluent standards for municipal waste water treatment (1.AEVkA 1996).

COD and energy balances for the different process configurations (Tables 5–9)

Table 5 | Process configuration 1, COD and energy balance

COD influent	110 g/PE/d
COD primary sedimentation *(COD removal efficiency 30%)*	77 g/PE/d
COD content primary sludge: 110 − 77 =	33 g/PE/d
COD effluent	11 g/PE/d
COD removal aeration tank: 77 − 11 =	66 g/PE/d
OUC = 50% of COD removal (Figure 1)	33 g/PE/d
COD–ES = 50% of COD removal	33 g/PE/d
COD content of digested sludge	30 g/PE/d
COD raw sludge: PS + ES = 33 + 33 =	66 g/PE/d
COD Biogas (methane) 66 − 30 =	36 g/PE/d

Aeration efficiency: αSAE = 1.7 kg O_2/kWh; Oxygen saturation $c_s = 10$ mg/l, DO = 2 mg/l
Aeration energy requirement: $(33/1.7) * 10/8 = 24.3$ Wh/PE/d
Methane production: 36 g COD/PE/d $*$ 0.35 NL CH_4/g COD = 12.6 NL CH_4/d; Electrical conversion efficiency of gas engine: 3 kWh/Nm^3 CH_4
Energy balance: $24.3 - 12.6 * 3 = -13.5$ Wh/PE/d (−0.56 W/PE)

Table 6 | Process configuration 2, COD and energy balance

COD influent (9 g N/PE/d)	110 g/PE/d
COD primary effluent *(COD removal efficiency 20%)*	87 g/PE/d
COD Primary sludge	23 g/PE/d
COD effluent	9 g/PE/d
COD-removal aeration tank: 87 – 9 =	78 g/PE/d
OUC 65% of COD removal (Figure 1)	51 g/PE/d
COD–ES (2 g N/PE/d)	27 g/PE/d
OUN = (9 – 2 – 5.6) * 4.3 =	6 g/PE/d
OUDN = 5.6 * 1.7 =	10 g/PE/d
COD content of digested sludge	30 g/PE/d
COD raw sludge: 23 + 27 =	50 g/PE/d
COD biogas: 50 – 30 =	20 g/PE/d

Aeration efficiency: αSAE = 1.7 kg O_2/kWh; DO aerobic zones = 1.5 mg/l

OU_{total} = 51 + 6 + 10 = 67 g/PE/d; aeration energy: 67/1.7 * (10/8.5) = 46.4 Wh/PE/d

Methane production: 20 g COD/PE/d * 0.35 NL CH_4/g COD = 7.0 NL CH_4/d, Electrical conversion efficiency of gas engine: 3 kWh/Nm^3 CH_4

Energy balance: 46.4 – 7.0 * 3 = +25.4 Wh/PE/d; (+1.06 W/PE)

Table 7 | Process configuration 3, COD and energy balance

COD influent (9 g N/PE/d)	110 g/PE/d
COD primary effluent *(COD removal efficiency 30%)*	77 g/PE/d
COD primary sludge	33 g/PE/d
COD effluent:	9 g/PE/d
COD removal in aeration tank:	68 g/PE/d
OUC 50% of COD removal	34 g/PE/d
COD–ES (3.5 g N/PE/d)	34 g/PE/d
COD raw sludge: (3.5 g N/PE/d): 33 + 34 =	68 g/PE/d
OUDN: (denitrified N-load 3.7 g N/PE/d): 3.7 * 1.7 =	6.3 g/PE/d
OUN = (9 – 3.5 – 3.7) * 4.3 =	7.7 g/PE/d
COD content of digested sludge	30 g/PE/d
reject water treatment (WETT 2006) 1.5 g N/PE/d * 1.05	1.6 g/PE/d
COD biogas: 68 – 30 =	38 g/PE/d

Aeration efficiency: αSAE = 2.2 kg O_2/kWh; DO aerobic zones = 1.5 mg/l

OU_{total} = 34 + 7.7 + 6.3 + 1.6 = 49.6 g/PE/d; Aeration energy: (49.6/2.2) * 10/8.5 = 26.5

Methane production: 38 g COD/PE/d * 0.35 NL CH_4/g COD = 13.3 NL CH_4/d; Electrical conversion efficiency of gas engine: 4 kWh/Nm^3 CH_4

Energy balance: 26.5 – 13.3 * 4 = –26.7 Wh/PE/d; (–1.1 W/PE)

Table 8 | Process configuration 4, COD and energy balance

COD influent (11 g N/PE/d)	110 g/PE/d
COD effluent:	9 g/PE/d
COD removal in aeration tank	101 g/PEd
OUC 66% of COD removal (Figure 1)	67 g/PE/d
COD stabilised sludge (2.3 g N/PE/d)	34 g/PE/d
OUDN: N-removal 7 g N/PE/d: 7 * 1.7 =	11.9 g/PE/d
OUN: (NO_3-N in effluent: 11 – 2.3 – 7 = 1.7 g N/PE/d): 1.7 * 4.3 =	7.3 g/PE/d

Aeration efficiency: αSAE = 1.7 kg O_2/kWh; DO in aerobic zones = 1.0 mg/l

OU_{totalt} = : 67 + 7.3 + 11.9 = 86 g O_2/PE/d;

Energy balance: Aeration energy: (86/1.7) 10/9 = +56.2 Wh/PE/d (+2.3 W/PE)

Table 9 | Process configuration 5, COD and energy balance

COD-influent (11 g N/PE/d)	110 g/PE/d
COD effluent:	9 g/PE/d
COD removal in aeration tank:	101 g/PE/d
OUC 68% of COD removal (Figure 1)	69 g/PE/d
COD stabilised sludge (2 g N/PE/d)	30 g/PE/d
OUN (nitrate effluent 11 – 2 = 9): 9 * 4.3 g O_2/g N =	38.7 g/PE/d
OU_{total}: 69 + 38.7 =	107.7 g/PE/d

Aeration efficiency: αSAE = 1.7 kg O_2/kWh; DO in aeration tank = 1.2 mg/l

Energy balance: Aeration energy: (107.7/1.7) * 10/8.8 = +72 kWh/PE/d (+3.0 W/PE)

From the results of the COD and energy balances (Table 10 and Figure 2) the following can be drawn:

- Higher treatment efficiency requirements (nutrient removal instead of BOD removal only) result in an increase of energy requirements for large treatment

Table 10 | Comparison of calculation results

	Dim	1	2	3	4	5
Aeration efficiency αSAE	kgO_2/kWh	*1.7*	*1.7*	*2.2*	*1.7*	*1.7*
Mean DO in aerobic zones	mg/L	*2*	*1.5*	*1.5*	*1*	*1.2*
η_{el} *gas engine*	%	*25*	*25*	*37*	–	–
Power demands for aeration	W/PE	1.0	1.9	1.1	2.3	3.0
Other power demand[a]	W/PE	0.7	0.7	0.9	0.7	0.6
Total power demand	W/PE	1.7	2.6	2.0	3.1	3.6
El. power from biogas	W/PE	1.6	0.9	2.1	0	0
Total external power demand	W/PE	0.2	1.7	−0.1	3.1	3.6
External energy demand	kWh/PE/a	2	15	−1	27	32

[a] Derived from the results of the Austrian Benchmarking system http://www.abwasser-benchmarking.at

It represents an average value which can be achieved under favourable conditions. Specific local situation and sludge treatment can result in additional energy requirements of up to 1.6 W/PE (~15 kWh/PE/a).

plants but can be compensated by optimal process and modern equipment selection (compare processes 1, 2 and 3)

- For small treatment plants (<20,000 PE) it is not economical to minimise the demand for external energy by applying sludge digestion and gas engines as the investment costs are dominant as compared to the energy costs. Optimisation of energy demand by maximising denitrification results in lower stabilisation quality of the sludge which has to be considered for sludge handling and disposal
- Large treatment plants can be operated energy self sufficient on annual perspective even when high nutrient removal and nitrification efficiency is required. From an economic point of view it cannot be recommended to make treatment plants self supplying with electrical energy but to connect them to large electrical grids able to equalise the strong variations in energy demand over time at the treatment plants.

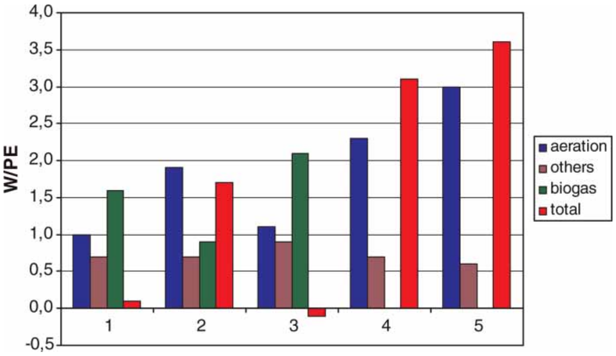

Figure 2 | Comparison of mean yearly power demand for the 5 process configurations related to the mean COD pollution load in the influent expressed as population equivalent (PE_{110}).

CONCLUSIONS

- Total energy equivalent of waste water pollution is ~22.5 W/PE (~45 W/inhabitant), which is <0.5% of actual primary energy consumption in developed countries
- Energy from waste water will never be relevant for solving the energy crisis.
- The yearly mean of total electric energy demand for aeration at WWTP > 50,000 PE with nutrient removal can be reduced to less than 20 kWh/PE/a (<2.3 W/PE).
- Electric energy production from biogas can be increased by:
  - ○ Increasing energy [COD-] content of raw sludge by using primary sedimentation, 2-stage biol. treatment systems
  - ○ Increasing the efficiency of the conversion of gas to electric energy
  - ○ Optimisation of the operation of anaerobic digestion: feeding, temperature, mixing, etc.. The application of sludge disintegration technologies (DWA 2009) should be evaluated in every single case through an energy balance.
- It is possible to reduce the 'carbon footprint' of waste water treatment with nutrient removal to zero on a yearly basis.
- The size of the plant (<50,000 PE, >100,000 PE) has important impact on process selection and minimum external energy demand.
- Treatment efficiency has no dominant effect on energy demand and on operational costs, fixed costs are dominant
- Efficient waste water treatment is indispensible for water quality management and is more relevant for sustainable development than energy minimisation. This does not excuse wasting of energy at waste water treatment plants.

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