Using the Life Cycle Assessment Methodology for a Comprehensive Evaluation of Energy Demand in Wastewater Treatment

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Abstract
Previously, the analysis of energy demand for wastewater treatment was often limited to one-dimensional analyses of electricity demand. However, a comprehensive analysis requires the inclusion of all different contributions to energy demand, such as the energy required to produce chemicals (e.g. coagulants and flocculants) and transport sludge, and the additional fuels needed to dry sewage sludge. System boundaries must be expanded to include upstream and downstream processes in order to capture all relevant contributions to energy demand. Additionally, a comprehensive analysis accounts for secondary products of wastewater treatment: the production of electricity from digester gas, the recycling of nutrients and water to agriculture, and the substitution of fossil fuels in sludge co-incineration. The Life Cycle Assessment (LCA) methodology defined in ISO 14040/44 is a suitable tool for this task. With it, all different primary and secondary energy demands can be quantified and assessed using consistent indicators, complemented by an assessment of other environmental impacts such as the greenhouse effect.

Keywords: Wastewater treatment, municipal, energy, energy balance, energy consumption, sewage treatment plant, life cycle assessment, balancing group, primary energy, global warming potential

1. Introduction
Social and political demands for the sustainable use of energy resources have prompted the water industry to step up energy-saving efforts. In addition to the high costs of electricity and other energy carriers, companies in the water industry are increasingly responding to the heightened environmental awareness of their customers. In water resources management, it was found that energy demand for wastewater treatment plants (WWTPs) constitutes a major share of the overall energy consumption. Some of this energy can be recovered by exploiting the energy potentials of wastewater, for example, by generating electricity and heat from digester gas (biogas) at combined heat and power (CHP) plants. Given favourable conditions for water quality and optimized water management, the medium-term goal of becoming an energy-neutral or even energy-positive wastewater treatment plant seems feasible and appropriate (Haberkern et al 2008).
Previously, the analysis of energy demand for wastewater treatment was often limited to analysis of the electricity and heating demands of wastewater treatment plants and to the production of these energy carriers by the conversion of digester gas into electricity. The energy balance is thus calculated by subtracting total electricity consumption from total electricity production at a wastewater treatment plant. In most cases, 100% of the heat required for heat digesters and operations buildings at combined heat and power plants is produced in-house. According to the above definition, wastewater treatment plants with balanced electricity and heat requirements are referred to as “energy neutral”, and those with a surplus of generated electricity and heat are classified as “energy-positive”. An energy-positive WWTP can supply its surplus power and heat to other consumers.

According to the traditional approach, the energy balance is estimated solely based on the electricity and heat balance. However, a comprehensive energy consumption analysis requires the inclusion of all known forms of energy consumption and production in the sense of a holistic approach. Besides the direct consumption of electricity and heat associated with operating a wastewater treatment plant, indirect consumption also occurs due to upstream and downstream processes such as:

- Production and supply of chemicals, such as coagulants and flocculants for sludge dewatering;
- Transportation of sewage sludge for disposal;
- Heating of sludge digesters, drying of sewage sludge and auxiliary firing during mono-combustion of sewage sludge using fossil energy carriers such as natural gas or fuel oil.

These forms of indirect energy consumption are not captured in traditional energy analyses based on the electricity balance. Strictly speaking, such an electricity balance can demonstrate electricity-neutrality but not energy-neutrality. If processes for the recycling of nutrients from wastewater and sewage sludge and for thermal energy recovery from sewage sludge combustion are in place, indirect energy-saving potentials such as the following should also be taken into account:

- Substitution of mineral fertilizers (nitrogen, phosphorus, potassium) by recycling nutrients in sewage sludge to agriculture or by producing fertilizer products (recovery of phosphorus from sewage sludge ash, recovery of phosphorus as MAP);
- Substitution of fossil fuels with thermal energy recovered from sewage sludge combustion (e.g. co-incineration of sludge in cement and power plants).

The total energy balance of a sewage plant should include all direct and indirect contributions to energy consumption and the energetic contribution of all products. The comprehensive energy neutrality of a sewage plant for all forms of energy can then be captured and analyzed accordingly. In principle, the methodology described here allows the examiner to expand the total energy balance for wastewater treatment to include energy expenditures for wastewater transport (pumping stations) and the construction of infrastructure (WWTPs and sewer systems). However, this article will focus on the operational energy balance of a model WWTP in order to elucidate the underlying analytical approach.

2. The Life Cycle Assessment approach
An appropriate methodological approach to comprehensive Life Cycle Assessment can be found in the LCA principles and guidelines outlined in the ISO 14040/44 standards, which
have been used for years to evaluate the environmental impact of products (Klöpffer and Grahl 2009). This standardized method of Life Cycle Assessment allows for the extension of system boundaries to include all important points:

- The inclusion of all relevant processes, such as upstream and downstream processes (production of chemicals, transportation of sewage sludge, etc.),
- Quantitative assessment of all variables in terms of a common functional unit;
- Extension of the system boundaries as needed to include secondary functions such as nutrient recycling or sewage sludge combustion for the substitution of fossil fuels.

When such an approach is taken, all relevant energy forms and processes can be depicted and captured in the analysis. In addition to evaluating the consumption of energy resources, the LCA approach also allows for analysis of other environmental indicators, such as the emission of harmful greenhouse gases like carbon dioxide from fossil energy carriers (“carbon footprint”). The Life Cycle Assessment methodology will be described and illustrated below based on calculations of total energy consumption and greenhouse gas (GHG) effects for a model wastewater treatment plant.

3. Methods

The Life Cycle Assessment methods used here follow the methodologies defined in the ISO 14040/44 standards (ISO 14040 2006; ISO 14044 2006). Accordingly, the LCA procedure is divided into four phases:

1. Goal and scope definition
2. Inventory analysis
3. Impact assessment
4. Interpretation

The individual phases will be explained and illustrated based on a model WWTP below.

1. Goal and scope definition

The primary function of the process system “wastewater treatment plant” is to purify wastewater to the required effluent quality. Different reference values can be used to relate the data to the functional units of the process system. The volume of treated wastewater (consumption per cubic meter of wastewater) is an obvious choice as a reference value, but does not take the variable pollution of wastewater into account. The use of organic load as the reference value for the energy analysis makes it possible to compensate for differences in wastewater quality in the scope of the assessment. The population equivalent (p.e.) according to ATV A 131, expressed as organic matter load per year (p.e.\_COD = 120 g COD/p.e.*d (ATV 2000)), is a suitable functional unit.

The system boundaries of the Life Cycle Assessment are set so as to encompass all internal processes within the model WWTP as well as all relevant upstream and downstream processes, including inputs related to the provision of electricity, heat, chemicals and additional fuels and those required for sewage sludge disposal (Figure 1). Secondary functions of wastewater treatment plants – in particular, the production of electricity and heat from digester gas, the recycling of nutrients to agriculture, and the production of biofuels for the replacement of fossil fuels – are also captured in the analysis by expanding the system boundaries to include secondary products.
2. Inventory analysis
An inventory analysis includes the consumption data for all processes within the system boundaries. The initial inventory analysis should cover all wastewater treatment processes at the investigated WWTP, including sludge treatment and sludge disposal. Data must be collected for all inputs and outputs associated with these processes, including the electricity and heat demand and the consumption of chemicals and additional fuels. Likewise, the transport distances for sludge disposal must also be determined.

Inventory analyses should be performed using Life Cycle Assessment software specifically designed for steady-state (static) modelling of material and energy flows within a wastewater treatment plant, e.g. Umberto® software (IFU and IFEU 2005). The software facilitates visualization of the overall wastewater treatment process, including the many different flows associated with it. This simplifies the analysis and presentation of results. In many cases, interdependencies and correlations become clear while setting up the model, thus improving process understanding for all persons involved.

Once the inventory analysis has been set up, energy consumption rates associated with the supply of operational resources (electricity, heat, chemicals and fuels) can be accessed from a process database containing averaged data sets for these parameters. The model calculations below were made using the Ecoinvent database (Ecoinvent 2007), which provides data on the primary energy demand and greenhouse effect of various products (Table 1).

Greenhouse gas emissions credits were awarded for the following secondary products of wastewater treatment when calculating the energy balance:

- Electricity and heat produced from digester gas in CHP plants
- Material recovery from sewage sludge: Plant nutrients in fertilizer products or sewage sludge (nitrogen, phosphorus and potassium)
- Thermal energy recovered from sewage sludge combustion: Energy gain and substitution of fossil fuels (e.g. lignite and hard coal) with biofuels.
Table 1: Primary energy demand and greenhouse effect of selected processes of wastewater treatment

<table>
<thead>
<tr>
<th>Consumption of</th>
<th>Primary energy [MJ]</th>
<th>Greenhouse effect [kg CO₂-eq]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity, 1 MWh, German mix 2010</td>
<td>10180</td>
<td>628</td>
</tr>
<tr>
<td>Heat, 1 MWh, from natural gas burner (η = 85%)</td>
<td>4450</td>
<td>255</td>
</tr>
<tr>
<td>Natural gas, 1 MWh heating value</td>
<td>3780</td>
<td>217</td>
</tr>
<tr>
<td>FeCl₃ (40%), 1000 kg</td>
<td>2740</td>
<td>183</td>
</tr>
<tr>
<td>Polymers (active substance), 1000kg</td>
<td>62910</td>
<td>2193</td>
</tr>
<tr>
<td>MgCl₂ (30%), 1000 kg</td>
<td>1365</td>
<td>77.5</td>
</tr>
<tr>
<td>Transport by truck (16-32t), 1000 tkm</td>
<td>1900</td>
<td>134</td>
</tr>
</tbody>
</table>

Source: Calculations based on Ecoinvent 2007

Material recovery is crucially determined by the plant availability of nutrients contained in the sewage sludge, which may be limited (Table 2). The amount of thermal energy recovered from sewage sludge combustion is largely determined by the calorific value of the sludge which, in turn, is dependent on the organic dry matter content of the sludge. The calorific value is expressed as the lower heating value (LHV), which can be calculated as a function of dry matter content (DMC) and loss on ignition (Table 3).

Table 2: Credits for secondary products of wastewater treatment

<table>
<thead>
<tr>
<th>Credits for substitution of:</th>
<th>Primary energy [MJ]</th>
<th>Greenhouse effect [kg CO₂-eq]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mineral fertilizer nitrogen, 1000 kg as N</td>
<td>-48900</td>
<td>-7500</td>
</tr>
<tr>
<td>Mineral fertilizer phosphorus, 1000 kg as P</td>
<td>-40000</td>
<td>-2700</td>
</tr>
<tr>
<td>Mineral fertilizer potassium, 1000 kg as K</td>
<td>-12500</td>
<td>-800</td>
</tr>
<tr>
<td>Lignite, 1000 kg (LHV = 8650 MJ/kg)</td>
<td>-10100</td>
<td>-970</td>
</tr>
<tr>
<td>Hard coal, 1000 kg (LHV = 26500 MJ/kg)</td>
<td>-30000</td>
<td>-2950</td>
</tr>
</tbody>
</table>

Source: Calculations based on data from Ecoinvent 2007 and Remy 2010

Table 3: Lower heating value (LHV) of sewage sludge as a function of dry matter content (DMC) and loss on ignition (LOI)

<table>
<thead>
<tr>
<th>Lower heating value [MJ/kg]</th>
<th>Loss on ignition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40%</td>
</tr>
<tr>
<td>DMC = 25%</td>
<td>0.33</td>
</tr>
<tr>
<td>DMC = 30%</td>
<td>0.9</td>
</tr>
<tr>
<td>DMC = 40%</td>
<td>2.0</td>
</tr>
<tr>
<td>DMC = 90%</td>
<td>7.5</td>
</tr>
</tbody>
</table>

Source: Calculations based on IFEU 2002
Assumption: LHV (organic DMC) = 22 MJ/kg organic DMC
3. Impact assessment
To perform an impact assessment, the inventory results are first classified into impact
categories and appropriate category indicators are defined. In this study, cumulative energy
demand (CED) for non-renewable resources was defined according to the VDI guidelines of
the German Association of Engineers (VDI 1997). CED is a measure of the primary energy
consumption of fossil fuels and nuclear fuels (excluding renewable energy sources) and is
expressed in megajoules (MJ). Global warming potential (GWP) is another important
environmental indicator describing the emission of climate-active gases that contribute to the
greenhouse effect (e.g. CO₂ from fossil sources, CH₄, N₂O and other trace gases). The global
warming potential of these emissions was expressed in CO₂ equivalents (CO₂-eq), the
internationally recognized characterization factors recommended by the Intergovernmental
Panel on Climate Change (IPCC 2007).

In impact assessments, environmental impacts (consumption of primary energy and emission
of greenhouse gases) are weighted against savings effects of secondary products (avoidance
of energy consumption and emissions by substitution of other products, such as electricity,
mineral fertilizers and fossil fuels). These secondary products make “negative” contributions
to the environmental impact of a WWTP and thus taken into the balance sheet as GHG
emissions credits. The actual total energy consumption of wastewater treatment can be
described by this method, which takes all forms of energy consumption and all secondary
products of wastewater treatment into account.

4. Interpretation
The last phase of life cycle assessment is analysis and interpretation of the results in terms of
the focus defined in the goal and scope. Analysis of the contribution of each individual
process at a wastewater treatment plant provides insight into the major consumers and the
forms of energy consumption. Sensitivity analyses can be performed to additionally check the
effects of specific inventory data or assumptions. The data collection process can then be
refined or specific supplementary measurements performed as needed.

4. Example of a comprehensive energy analysis
The LCA procedure will be illustrated briefly based on the example of an energy-optimized
model WWTP with a capacity of 100,000 p.e. (MUNLV 1999). Electricity, heat and chemical
demands were estimated, and these figures were used as inputs for the LCA (Table 4).
Greenhouse gas credits were awarded for electricity and heat obtained from the digester gas
utilization at the CHP plant and for thermal energy recovered from sewage sludge
combustion. Regarding sludge disposal, calculations were made assuming the co-incineration
of sewage sludge at a lignite power plant and that the sludge was transported a distance of
200 km for disposal. In addition, the calorific value of the sludge (25% DMC) was assumed to
be 0.8 MJ/kg.
Table 4: Daily material and energy consumption and greenhouse gas credits for a model wastewater treatment plant with a capacity of 100,000 population equivalents

<table>
<thead>
<tr>
<th>Material and energy consumption</th>
<th>WWTP</th>
<th>Sludge treatment</th>
<th>Sludge disposal</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Consumption</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity kWh</td>
<td>5562</td>
<td>733</td>
<td></td>
</tr>
<tr>
<td>Heat kWh</td>
<td>4000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flocculant (FeCl$_3$) kg</td>
<td>1000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polymers kg</td>
<td>75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transport km</td>
<td></td>
<td>200</td>
<td></td>
</tr>
<tr>
<td><strong>Credits</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity kWh</td>
<td>5115</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat kWh</td>
<td>8767</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Substitution of lignite kg</td>
<td></td>
<td>2312</td>
<td></td>
</tr>
</tbody>
</table>

*Source: MUNLV 1999 and own estimates*

The determined consumption rates and credits can be converted into primary energy using the data in Tables 1 and 2. Thus, the model WWTP had an annual total primary energy consumption of 352 MJ/(p.e. COD*year), including consumption for sludge treatment and disposal (Figure 2). On the other side, the sum of credits (outputs) for electricity and heat from the CHP plant and for sludge incineration in the power plant was -418 MJ/(p.e. COD*year). When calculating the heat balance, one should bear in mind that only a portion of the heat can be effectively utilized by the WWTP. Because surplus heat can only be used at nearby sites, it must be released in the environment in many cases. After deducting unused surplus heat from the credit side, the credits for surplus heat decrease to -340 MJ/(p.e. COD*year). Calculated under the above assumptions, the primary energy balance for the model WWTP was only 12 MJ/(p.e. COD*year). Hence, the model plant comes very close to the goal of energy-neutrality.

When calculating the greenhouse effect, both indirect (consumption related to electricity, chemicals and transportation) and direct emissions of greenhouse gases must taken into account. Nitrous oxide (N$_2$O), which develops in sludge digesters due to incomplete denitrification, is a major greenhouse gas. Because of its high greenhouse potential (300 kg CO$_2$-eq), N$_2$O can considerably add to the greenhouse effect of a wastewater treatment plant. Direct process emissions for the model plant were estimated using blanket factors for emissions in order to emphasize their impact.

The global warming potential of the model WWTP was estimated at 31 kg CO$_2$-eq/(p.e. COD*year) for direct and indirect emissions (Figure 3). GHG emissions credits for secondary products amounted to -24 kg CO$_2$-eq/(p.e. COD*year), yielding a net GHG emissions balance of 7 kg CO$_2$-eq/(p.e. COD*year). Thus, the total greenhouse gas emissions from the model WWTP amount to approximately 700 tons CO$_2$-eq per year although the plant had a
good energy balance. The contribution from direct process emissions to the greenhouse effect was substantial: 9.1 kg CO$_2$-eq/(p.e.*COD*year) N$_2$O from the sludge digester. This should always be taken into account in comparable situations.

Figure 2: Primary energy demand per population equivalent and year for a model WWTP with a capacity of 100,000 p.e.

Figure 3: Greenhouse effect per population equivalent and year for a model WWTP with a capacity of 100,000 p.e.
5. Outlook
This paper describes a comprehensive Life Cycle Assessment approach to estimating the energy demand of wastewater treatment. Building on the LCA guidelines and principles defined in ISO 14040/44, this method systematically accounts for all contributions to the consumption of primary energy. In addition to analyzing electricity and heat demand and other conventional variables, the comprehensive inventory approach also accounts for indirect energy demand from chemicals consumption, transportation, and so forth through the use of impact category indicators. With this approach, the system boundaries can be expanded to ensure that the analysis includes secondary products of wastewater treatment, such as electricity, heat, nutrients and biofuels recovered from wastewater treatment plants. The approach makes it possible to evaluate and compare different process options in terms of their effects on wastewater treatment plants, which is important, especially against the background of increasing demands for the recovery of energy and nutrients from wastewater and sewage sludge. New concepts for energy-neutral and energy-positive sewage plants can be assessed by this comprehensive approach. The shifting of environmental impacts due to the introduction of new technologies can be identified by extending the analysis to other environmental impacts, such as the greenhouse gas emissions profile (“carbon footprint”) of wastewater treatment plants. For example, equipping a WWTP with a tertiary filtration stage would improve effluent quality but would also result in increased energy consumption and greenhouse gas emissions. In principle, the LCA approach is also an appropriate method for comparing different wastewater treatment systems (centralized or decentralized, etc.) in a consistent manner. Thus, a suitable tool is available for the investigation of current and future questions relating to sustainability issues in urban water management.

References


