Sustainability assessment of advanced wastewater treatment technologies

ABSTRACT
As a consequence of the EU Water Framework Directive more focus is now on discharges of hazardous substances from wastewater treatment plants and sewers. Thus, many municipalities in Denmark may have to adopt to future advanced treatment technologies. This paper describes a holistic assessment, which includes technical, economical and environmental aspects. The technical and economical assessment is performed on 5 advanced treatment technologies: sand filtration, ozone treatment, UV exclusively for disinfection of pathogenic microorganisms, membrane bioreactor (MBR) and UV in combination with advanced oxidation. The technical assessment is based on 12 hazardous substances comprising heavy metals, organic pollutants, endocrine disruptors as well as pathogenic microorganisms. The environmental assessment is performed by life cycle assessment (LCA) comprising 9 of the specific hazardous substances and three advanced treatment methods; sand filtration, ozone treatment and MBR. The technical and economic assessment showed that UV solely for disinfection purposes or ozone treatment is the most advantageous advanced treatment methods if the demands are restricted to pathogenic microorganisms. In terms of sustainability, sand filtration is the most advantageous method based on the technical and environmental assessment due to the low energy consumption and high efficiency with regards to removal of heavy metals.

Key words | advanced wastewater treatment, life cycle assessment, MBR, ozone treatment, sand filtration, UV treatment

INTRODUCTION
In 2000 the EU Water Framework Directive (WFC) (2000/60/EF) came into force with the aim to protect and improve the quality of EU waters. It is expected that new environmental quality standards (EQS) for specific compounds and sum parameters will be formulated in a future daughter directive to the WFC. Effluents from wastewater treatment plants (WWTP), etc. must result in compliance with these EQS so this may entail new requirements for existing WWTP in the form of advanced wastewater treatment technologies.

There are many aspects that must be assessed before the optimal advanced treatment technology is chosen at a specific WWTP. These include technical, economic and environmental aspects which can play a major role in the selection process. All these aspects are included in the study described here, which is based on a Danish project on advanced treatment technologies for municipal wastewater (Clauson-Kaas et al. 2006). Another technical and economical assessment was conducted in a Dutch study (STOWA 2005).

The study also entails a tool for environmental assessment of various WWTP with specific outlet concentrations of selected hazardous substances. The tool can be used as a decision supporting tool in the screening process when
advanced wastewater treatment technologies are evaluated at a specific WWTP.

**METHODS**

A holistic assessment is performed including technical, economical and environmental aspects. The environmental pros, e.g., reduced emissions are weighed out against the matching cons, e.g., energy and resource consumption for building and operation of the selected advanced wastewater treatment technology.

The technical aspects of the chosen advanced wastewater treatment technologies are described using literature and knowledge of specific WWTP. The following advanced treatment technologies are screened:

- Sand filtration
- Ozone treatment
- UV treatment for disinfection purposes
- Membrane bioreactor (MBR)
- UV in combination with advanced oxidation.

The following hazardous compounds and pathogenic microorganisms are selected for this assessment:

- Organic hazardous substances; PAH, DEHP, nonylphenol and LAS
- Heavy metals: cadmium, lead and nickel
- Estrogens: 17α-ethinylestradiol (EE2) and 17β-estradiol (E2)
- Pathogenic micro organisms: *E. coli*, enterococci and coliforms.

The above mentioned hazardous compounds are selected due to the fact that they are covered by one or more of the following points:

- on the EU Water Framework Directive list of prioritized compounds (parliament and council decision 2455/2001/EF)
- are found in Danish municipal wastewater at environmental critical concentrations (The Danish Environmental Protection Agency 2005)
- show estrogenic or estrogenic-like activity in laboratory tests (Kjølholt & Stuer-Lauridsen 2004)
- are relevant as indicators according to the EU Bathing Water Directive.

The economic evaluation is performed using costs from actual WWTP with the specific advanced treatment technology or costs from suppliers. The cost estimations reflect the 2006 level for building and operation by:

- treatment of 50,000 m³ municipal wastewater per day
- a lifetime of the treatment technology of 20 years
- an interest rate of 5% p.a.

The environmental assessment is based on the EDIP LCA methodology (Wenzel et al. 1997; Hauschild et al. 1998; Wenzel 1998; Clauson-Kaas et al. 2000). The following model is used:

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Existing waste Water treatment Harmful substances in Improved treatment Harmful substances out Avoided or reduced emission
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The model is used for determining/calculating the potential environmental impacts of the selected advanced wastewater treatment technologies as a supplement to existing municipal wastewater treatment in traditional activated sludge WWTP.

The efficiency of the selected treatment technologies for removing specific hazardous compounds was estimated based on a literature study.

**RESULTS AND DISCUSSION**

**Technical aspects**

Sand filtration is a well known method for removal of particulate matter including heavy metals. Furthermore, up to 50% of pathogenic microorganisms are removed.

Ozone treatment is not used for treatment of household wastewater in Denmark. It is primarily used to remove hazardous compounds, estrogens, LAS, PAH, etc. in industrial wastewater. Ozone treatment cannot remove heavy metals (Huber et al. 2004).

UV for disinfection purposes does become more widespread at existing WWTP to e.g. fulfill demands in the EU Bathing Water Directive. The method is effective in removing pathogenic microorganisms.
MBR does show very high removal efficiencies on many hazardous compounds, e.g. heavy metals, estrogens, LAS as well as pathogenic microorganisms (van der Graaf et al. 1999).

UV in combination with advanced oxidation is a fairly new advanced treatment method. The method is at present tested in Hoersholm, Denmark, as a part of the EU LIFE project APOP (www.apop.dk). It is expected that this treatment method will gain positive treatment results due to the expected synergetic effect of advanced oxidation and UV treatment.

Economic estimates

The cost estimates have been made for the five selected advanced wastewater treatment technologies. The prices include investments and operation costs (Table 1).

UV for disinfection purposes and ozone followed by UV are the most feasible solutions. UV for disinfection purposes are restricted to the situations where demands only are set to removal of pathogenic microorganisms.

Sand filtration is the most economic feasible solution if removal of heavy metals is required.

Environmental aspects

The LCA assessment is made for sand filtration, ozone treatment and MBR. It includes heavy metals, endocrine disruptors (E2, EE2, PAH, DEHP, NPE) and the detergent LAS. Pathogenic microorganisms are not included in the assessment and therefore the advanced treatment methods UV for disinfection are not included in the environmental assessment. UV in combination with advanced oxidation is not assessed due to lack of data on treatment efficiency combined with corresponding use of resources from full scale tests.

The principles of LCA (EDIP) are used for estimation of induced and prevented potential environmental impacts (Wenzel et al. 1997).

The induced and the prevented potential environmental impacts must be weighed to evaluate the total impacts of the selected potential environmental impact of the advanced treatment method (EC 2003). This is illustrated for sand filtration in Figure 1.

The length of the bar, e.g. for global warming is calculated as the sum of greenhouse gases in CO2-equivalents (mostly from power consumption) emitted from the improved treatment process normalized to 1 m3 of treated wastewater and a global proxy-scenario. When this proxy-scenario is based on politically target emission levels (e.g. set by international conventions for global warming) the corresponding figure is said to be targeted or weighted. Currently, the figure for 1 Person Equivalent Targeted (PET) = 9.570 kg CO2- eq./person/year covering all sources based on all human activities (including industry, heating, cooling, agriculture, traffic, etc.) as average for the entire global population.

For a given treatment scenario the induced global warming impact may be 5,750 kg CO2-eq./day for the additional advanced treatment of 50,000 m3/day, which corresponds 0.12 kg CO2-eq./m3. Normalized to the other sources, this corresponds 0.12 kg CO2-eq./m3 divided by 9.570 kg CO2-eq. /year * PET which equals 12 μPET * year/m3.

Similarly for the prevented impacts, the focus is on ecotoxicity as a main motivation for reducing discharges of harmful substances. The length of the bar is calculated as the removed ecotoxicity per m3 by the improved treatment process normalized to a national proxy-scenario for ecotoxicity equivalents emitted from all other sources in the country per person.

The induced and prevented potential environmental impacts for MBR are shown in Figure 2.

The induced and prevented potential environmental impacts for ozonation are shown in Figure 3.

The results of the environmental assessment for sand filtration show that the induced potential environmental

<table>
<thead>
<tr>
<th>Treatment method</th>
<th>Costs [Euro cents/m3 treated wastewater]</th>
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</thead>
<tbody>
<tr>
<td>Sand filtration</td>
<td>4.6</td>
</tr>
<tr>
<td>Ozone treatment</td>
<td>2.6</td>
</tr>
<tr>
<td>UV for disinfection purposes (traditional)</td>
<td>1.6</td>
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<tr>
<td>UV in combination with advanced oxidation</td>
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<tr>
<td>– Ozone followed by UV (new process)</td>
<td>1.6</td>
</tr>
<tr>
<td>– UV and ozone</td>
<td>4.0</td>
</tr>
<tr>
<td>– UV and hydrogen peroxide</td>
<td>6.8</td>
</tr>
<tr>
<td>MBR</td>
<td>8.6</td>
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</tbody>
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impacts are lower than the prevented. For ozone treatment and MBR the induced potential environmental impacts are higher than the prevented potential environmental impacts. This is the case due to the relatively high energy consumption for the ozone treatment and MBR.

The environmental assessment has been extended with a sensitivity analysis where the most critical assumptions have been tested:

- Variations in the content of hazardous compounds in the wastewater (STOWA 2001)
- Variations in the treatment efficiency of the selected treatment technologies
- Changes in the method for estimating ecotoxicity, i.e. Predicted No Effect
- Concentration (PNEC) (Larsen 2004)
- Including more hazardous substances than the ones selected.

Figure 1 | The induced and prevented potential environmental impacts from sand filtration in weighted and normalized impact potentials.

Figure 2 | The induced and prevented potential environmental impacts from MBR in weighted and normalized impact potentials. It is assumed that 0.4 kWh/m³ is used for differential pressure and fouling control.

Figure 3 | The induced and prevented potential environmental impacts from ozonation in weighted and normalized impact potentials. 8 mg O₃/l dosage is assumed to be used.
The sensitivity analysis shows that including more hazardous substances (Zn, Cu, Hg and Cr are also assumed to be removed) changes the result considerably. It is especially evident with sand filtration, where the difference between the prevented and the induced potential environmental impacts become even larger. This indication is not as clear for ozone treatment and MBR.

In this assessment it is assumed that the sludge is dewatered and incinerated. If this assumption must be changed to reflect a specific WWTP with disposal of sludge at agricultural land, the conclusions can change due to the potential environmental impact of heavy metals from the sludge. This scenario is not investigated further.

CONCLUSION

Based on the results from this study, UV for disinfection and ozone treatment are the most feasible solutions if the water quality demands only influences the discharge of pathogenic microorganisms. It is, however, recommended that occupational health and safety aspects are assessed before these two advanced wastewater treatment technologies are chosen.

Sand filtration has the most advantageous technical and environmental aspects based on the assumptions made in this assessment. This is the case if water quality demands affects the discharge of various hazardous substances including heavy metals, pathogenic microorganisms, etc.

UV in combination with advanced oxidation comprises a number of advanced treatment technologies, which are space-saving and economically advantageous. Before a holistic assessment of this category of advanced treatment technology can be performed, more data must be collected on treatment efficiencies, energy consumption, resource consumption, occupational health and safety aspects and other pros and cons.

MBR has a relatively high energy consumption related to urban wastewater treatment, which results in larger potential environmental impacts and costs compared to ozone treatment and sand filtration.

PERSPECTIVES

Sustainable wastewater management is not only a matter of introducing ever more stringent effluent standards by legislation followed by implementation of utilities—the challenge is to balance the achievable environmental benefits with the corresponding induced drawbacks from energy and resource requirements. Furthermore, the technology must also comply with technical and economical demands.

This project illustrates the practical use of a LCA-based decision supporting tool for environmental assessment of the three selected treatment technologies at site-specific outlet concentrations. Thus, any existing WWTP can use the tool to assess future prevented or induced potential environmental impacts by introducing sand filtration, ozone treatment or MBR.

Similar to the recent Dutch study, this study has identified data gaps for the assessment. Relatively few data from full-scale studies are available in the peer-reviewed literature combining advanced treatment technology and corresponding removal efficiency at field conditions for WFD-relevant hazardous substances including operating conditions (energy and resource requirements e.g. chemicals dosage, etc.)

Further technical developments of treatment technologies may improve the efficiencies so the assessments performed in this study should be considered as scenarios which continuously may be updated and tailored to specific sites. Furthermore, developments in the LCA methods may change the sustainability balance. On the one hand, inclusion of more hazardous substances in the future will give weight to the environmental benefits. On the other hand, inclusion of more emission sources in the proxy-scenarios, e.g. corrosion-related storm water pollutants such as heavy metals, will count the other way. Finally, new data on toxicological impacts may go either way. Improved data in all the mentioned areas will contribute to more justified assessments.

It is the hope of the authors that evaluation of the sustainability balance may become a widely used discipline both for environmental regulators, researchers and for wastewater utilities.

ACKNOWLEDGEMENTS

The study was conducted by COWI, Institute of Product Development (DTU) and Henrik Wenzel ApS and financed.
by a joint grant from the Danish Water and Wastewater Association, the Danish Environmental Protection Agency, Lynettefaellesskabet and Avedoere Wastewater Services. Furthermore, Helle Strandbæk (the Municipality of Aalborg) and Henrik Rasmus Andersen (DTU, Orbicon and representative for the Municipality of Hørsholm’s APOP project) has contributed to the report by providing data, discussions of content and progress including commenting the draft version of the report.

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