Proof of concept for a new energy-positive wastewater treatment scheme
C. Remy, M. Boulestreau and B. Lesjean

ABSTRACT
For improved exploitation of the energy content present in the organic matter of raw sewage, an innovative concept for treatment of municipal wastewater is tested in pilot trials and assessed in energy balance and operational costs. The concept is based on a maximum extraction of organic matter into the sludge via coagulation, flocculation and microsieving (100 μm mesh size) to increase the energy recovery in anaerobic sludge digestion and decrease aeration demand for carbon mineralisation. Pilot trials with real wastewater yield an extraction of 70–80% of total chemical oxygen demand into the sludge while dosing 15–20 mg/L Al and 5–7 mg/L polymer with stable operation of the microsieve and effluent limits below 2–3 mg/L total phosphorus. Anaerobic digestion of the microsieve sludge results in high biogas yields of 600 NL/kg organic dry matter input (oDMin) compared to 430 NL/kg oDMin for mixed sludge from a conventional activated sludge process. The overall energy balance for a 100,000 population equivalent (PE) treatment plant (including biofilter for post-treatment with full nitrification and denitrification with external carbon source) shows that the new concept is an energy-positive treatment process with comparable effluent quality than conventional processes, even when including energy demand for chemicals production. Estimated operating costs for electricity and chemicals are in the same range for conventional activated sludge processes and the new concept.

Key words | advanced primary treatment, carbon footprint, energy balance, energy-positive wastewater treatment, microsieve

INTRODUCTION
Municipal raw sewage contains a high concentration of organic matter, which can be expressed in terms of the chemical oxygen demand (COD, in mg O₂/L). This organic matter contains some 4 kWh/kg COD as internal chemical energy (Heidrich et al. 2010). Assuming that municipal raw sewage carries 120 g COD per population equivalent (PE) and day (ATV 2000), the theoretical annual chemical energy potential of raw sewage is 175 kWh/PE. A comparison of this energy potential with the average power consumption of municipal wastewater treatment plants (WWTPs) using an activated sludge process (32–34 kWh/(PE*a) for treatment plants >10,000 PE (DWA 2013)) shows that the theoretical energy potential of raw sewage is five times greater than the power required for its treatment. This fundamental calculation suggests that it should be possible to develop an energy-positive WWTP, i.e. a plant for which energy recovery is greater than its energy consumption.

In the conventional activated sludge process, after mechanical cleaning and pre-treatment to separate out particulate matter, organic compounds are mineralised by microorganisms in the activated sludge tank or integrated in the biomass. This process and the biological nitrification of ammonium nitrogen both require considerable amounts of oxygen, and much energy is consumed by aeration in conventional WWTPs. By means of anaerobic stabilisation of the resulting sewage sludge, biogas can be generated from parts of the organic matter for use as a fuel in a combined heat and power (CHP) station so that part of the energy in the wastewater is recovered. Most of the generated heat is used directly, e.g. for heating anaerobic digesters or for central heating, so that only the generated electricity represents recovered energy which can be used externally. Typically, some 10–18 kWh/(PE*a) of electricity is produced from the biogas (MUNLV 1999), which can correspond to up to
70% of the power consumption of the plant. However, this level of recovery only represents 5–10% of the theoretical energy potential in untreated sewage.

Improved exploitation of energy present in raw wastewater has been explored by previous studies using enhanced primary treatment (e.g. Paulsrud et al. 2014) and combining it with improved anaerobic digestion (Jenicek et al. 2013), indicating that energy self-sufficient WWTPs are theoretically feasible without addition of external co-substrates (Schwarzenbeck et al. 2008) or favourable conditions in raw wastewater (Nowak et al. 2011). To increase the rate of energy recovery and at the same time to reduce the energy consumption for wastewater treatment, the CARISMO project tested a new concept for wastewater treatment in pilot scale using real sewage (KWB 2013).

The process is based on separating as much organic matter as possible by means of a low-energy filtration method, thus maximising the amount of sludge formed and reducing the carbon load for the subsequent stages of treatment (Figure 1). After mechanical pre-treatment of the raw sewage and grit removal, coagulants and flocculants are dosed followed by filtering in a drum microsieve (100 μm mesh) in order to separate out the particulate organic matter and the formed flocs. The generated sludge is passed through a decanting unit and then fed into an anaerobic digester where biogas is generated. The flocculation and microsieving and also the biogas generation from the resulting sludge were tested in the CARISMO project.

At the start of the project, the aim of the new process was to transfer more of the influent organic matter into the sludge (at least 60% of influent COD) and thus to achieve an increase in biogas yield by at least 50% related to the influent wastewater.

In addition to determining the technical viability, a further goal was to compare the overall energy consumption and associated greenhouse gas emissions of the new CARISMO concept with those for the activated sludge process in a conventional treatment plant. A mass and energy flow model was set up for the CARISMO concept on the basis of the results of the pilot tests. This model was then evaluated for a comprehensive energy balance of reference and CARISMO schemes, including downstream treatment for the elimination of the residual COD and nitrogen for comparable effluent quality with the reference process.

METHODS

The pilot tests were carried out using real raw sewage from the Stahnsdorf WWTP in Berlin. The mean influent quality for the Stahnsdorf plant shows a high concentration of suspended solids (SS) (mean: 508 mg/L), COD (1,038 mg/L), total phosphorus (TP = 14 mg/L) and total nitrogen (TN = 91 mg/L), indicating a low level of dilution of the raw wastewater. Owing to precipitation events and the differing influent qualities from urban areas, the values show

![Figure 1](https://iwaponline.com/wst/article-pdf/70/10/1709/470005/1709.pdf)
relatively large fluctuation. The samples of raw sewage for the pilot plant have been extracted after mechanical pre-treatment (8 mm rake screen and aerated grit trap).

On the basis of laboratory jar tests, coagulants and flocculants were selected for the pilot tests and optimum doses determined in order to maximise the retention of COD in the subsequent filtration while keeping the consumption of chemicals as low as possible. Polyaluminium chloride (PACl) showed slightly higher COD extraction than ferric chloride (FeCl₃) and was thus chosen as the coagulant. After extensive testing, the optimum dosing was defined as 15–20 mg/L aluminium (as PACl) and 5–7 mg/L polymer (active substance of a cationic polymer with high molecular weight) and used for the tests in the pilot plant.

The pilot plant was fed with 4.5–6 m³ raw sewage per hour. The manually controlled pilot plant was operated on workdays for eight hours and was cleaned once a week. Inline-dosing of PACl and coagulation in a 500 L tank with stirrer (G-value > 1,000 s⁻¹) was followed by inline-dosing of polymer and a further 500 L tank with stirrer (G-value ~100 s⁻¹) to form macroflocs (Figure 2). The flocculated raw sewage was then filtered in a drum sieve (Hydrotech, 100 μm mesh), with an automatic backwash with technical water at 5 bar (dilution of outflow < 2%). The collected sludge was decanted (~12 h) and then added to the anaerobic digester.

Sampling of influent and effluent was done automatically by a composite sampler (4–6 h mixed sample), and samples were analysed by cuvette tests (Hach Lange, Germany) after homogenisation in an Ultraturrax (IKA, Germany) or filtration on 1.6 μm glass microfibre filter (Whatman, New Jersey, USA). SS were analysed in the laboratory after filtration over 0.45 μm (DIN EN872).

The anaerobic digester (300 L) was automatically fed with sludge via a cooled buffer tank (15 L/d in four charges per day) and mixed by a recirculation pump. A heating jacket maintained a constant temperature of 35–38 °C in the reactor (mesophilic digestion). Regular samples were taken from the reactor inflow and outflow and analysed; the amount of biogas generated was registered continuously in a gas counter (Ritter), and the methane content was regularly checked with a gas sensor (Gas Sensor Innovation GmbH, Gänserndorf, Germany). Tracer tests with spiked lithium on the sludge showed a mean retention time of 16 days.

**RESULTS OF PILOT TRIALS**

The drum sieve could be operated without major operational problems throughout the 18 months of pilot testing and was effectively cleaned by the automatic backwash, so that chemical cleaning was only necessary twice over this period.
period. As expected, sieving always removed more than 95% of SS (Table 1). Only 4–26 mg/L SS could be measured in the effluent of the sieve. Increasing influent concentrations of SS resulted in a slight increase in effluent concentrations. At the same time, the microsieve removed 70–85% of organic matter measured as COD. The COD in the effluent was 130–280 mg/L O₂. More detailed investigations of COD revealed that 95% of particulate COD and 20% of the dissolved COD could be removed from raw sewage by the combination of flocculation and microsieving, indicating that the relative extraction of total COD increases with an increasing proportion of particulate COD which can be retained by the microsieve. The raw sewage in Stahnsdorf has a relatively high proportion of particulate COD (approximately 70–80% of total COD) compared to more diluted wastewater.

The process removed 70–90% of total phosphorus from the sludge, achieving an effluent concentration of 2–3 mg/L TP. 94% of the particulate phosphorus was removed, compared to 70% of the dissolved phosphorus. With further optimisation of the dosage of flocculation agent, it should be possible to achieve concentrations below 2 mg/L TP with this process. As expected, only some 20% of total nitrogen in the inflow was retained, which corresponds to the particulate proportion of nitrogen in the raw sewage. The effluent from the microsieve still contained 61 mg/L NH₄-N, which would have to be removed by further treatment.

For the downstream treatment, the denitrification potential of the remaining organic matter is important, because the conventional biological denitrification requires a readily available source of carbon. The denitrification potential is assessed by measuring the content of volatile fatty acids (VFA) in the effluent of the microsieve, because these VFA are regarded as being readily accessible as a carbon source for the denitrification. The microsieve effluent still contained 120 mg/L acetate-equivalents as VFA, which was available for subsequent denitrification. Kinetic denitrification tests also confirmed an existing denitrification potential of the microsieve effluent.

The backwash water with separated sludge accounted for 4–10% of the influent volume of the pilot plant. For an industrial-scale plant, experience suggests that maximum 4–6% backwash water and 1–2% total solids (TS) can be expected with conservative estimates. The sludge from the microsieve pilot had relatively low solid matter content (6–15 g/L), but this could be increased to 20–50 g/L solid matter within 12 h in the static thickener, thus providing a good starting concentration for the subsequent anaerobic treatment. The sludge volume index of the microsieve sludge was about 50 mL/g.

In the anaerobic reactor, relatively stable degradation rates were achieved for both the mixed sludge from the Stahnsdorf plant and the CARISMO sludge from the pilot plant, although there were some fluctuations in the degradation rate of organic matter due to small reactor volume and operational disturbances. Nevertheless, it was possible to determine the mass balances for the anaerobic reactor with sufficient accuracy for phosphorus (±3%) and COD (±11%). Specific biogas production for the different types of sludge could be determined from the balances of organic dry matter (oDM). For a 50% rate of degradation of oDM, the mixed sludge from the Stahnsdorf treatment plant provided a mean biogas yield of 450 NL/kg oDMₑ, which

### Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Influent</th>
<th>Effluent of drum filter</th>
<th>Relative elimination</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Min-max</td>
<td>Mean</td>
</tr>
<tr>
<td>Suspended solids (mg SS/L)</td>
<td>465</td>
<td>264–749</td>
<td>13</td>
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<tr>
<td>Total COD (mg O₂/L)</td>
<td>954</td>
<td>668–1,192</td>
<td>208</td>
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<tr>
<td>COD particulate (mg O₂/L)</td>
<td>711</td>
<td>509–876</td>
<td>20</td>
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<tr>
<td>COD soluble (mg O₂/L)</td>
<td>275</td>
<td>206–326</td>
<td>192</td>
</tr>
<tr>
<td>Total phosphorus (mg TP/L)</td>
<td>14.2</td>
<td>11.6–19.4</td>
<td>2.0</td>
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<tr>
<td>P particulate (mg P/L)</td>
<td>8.3</td>
<td>4.9–14.8</td>
<td>0.5</td>
</tr>
<tr>
<td>P soluble (mg PO₄-P/L)</td>
<td>7.6</td>
<td>4.6–9.4</td>
<td>1.8</td>
</tr>
<tr>
<td>Total nitrogen (mg TN/L)</td>
<td>90</td>
<td>73–111</td>
<td>75</td>
</tr>
<tr>
<td>NH₄-N (mg NH₄-N/L)</td>
<td>68</td>
<td>54–77</td>
<td>61</td>
</tr>
</tbody>
</table>

Mean values of composite samples (n = 16).
agreed well with the real operating data of the industrial-scale anaerobic treatment. For the ‘primary sludge’ from the CARISMO plant, a mean-specific biogas production of 600 NL/kg oDM_in was observed for a 56% oDM degradation rate, which can be attributed to the higher proportion of easily degradable organic matter in the raw sewage. The mean methane concentration for both types of sludge was approximately 60 vol.% CH₄.

**ENERGY BALANCE AND CARBON FOOTPRINT**

The results obtained with the pilot plant were transferred to a hypothetical WWTP for 100,000 PE in order to quantify the differences between a reference WWTP using the activated sludge process or using the CARISMO concept. The electricity and chemicals used for the wastewater treatment and anaerobic sludge digestion were set against the electricity produced from the CHP plant. To simplify the model, the dewatering and disposal of the sludge, return load from sludge dewatering, auxiliary demands and the necessary infrastructure were not included in the calculation.

The energy consumption is calculated in units ‘kWh_electric/m³ raw sewage’. In addition to the power consumption and the output of the CHP plant, chemicals are expressed ‘virtually’ in these units on the basis of the primary energy consumption for the production of the chemical and the primary energy input for the generation of one kWh of electricity in Germany. The datasets for the production of the chemicals (FeCl₃, PACl, polymer and methanol as external carbon source) are extracted from a database for life cycle assessment (Ecoinvent 2010). To calculate the global warming potential, the indirect greenhouse gas emissions from the production of electricity and chemicals are also derived from the database, accounting for the German electricity mix in 2011 (613 g CO₂-eq/kWh). Direct emissions from denitrification (0.6% of the removed N as N₂O for all processes (Wicht 1996)) and the use of methanol (fossil CO₂) are calculated from literature data. The global warming potentials of greenhouse gases are expressed over 100 years (IPCC 2007).

The quality of the raw sewage was defined in terms of the mean influent concentrations for the Stahnsdorf treatment plant (COD = 1,000 mg/L, TP = 15 mg/L and TN = 86 mg/L). Effluent specifications were based on the requirements of the German Wastewater Ordinance for Category 4 (<100,000 PE) as follows: COD = 100 mg/L, TN = 18 mg/L, TP = 2 mg/L (AbwV 2013). Extensive nitrification is also required (NH₄-N < 5 mg/L).

The assessment is based on a comparison of the simplified mass balance of the process chain for the reference WWTP and for the CARISMO concept. For the reference WWTP, a transfer of 60% of the influent COD into the sludge is assumed, compared to 73% for the CARISMO concept. A biofilter provides the subsequent treatment of the residual COD and the removal of nitrogen so that in addition to the aeration of the wastewater for COD reduction and nitrification, dosing of an external carbon source (methanol) is also necessary. In the biofilter, the residual COD will be mineralised or integrated in the excess sludge in equal parts. The biogas yield of the excess sludge is estimated at 336 NL/kg oDM_in (MUNLV 1999). For the denitrification in the biofilter, it is calculated that 56 mg/L methanol is required as carbon source, assuming 4.5 g COD/g NO₂-N (ATV 2000) for denitrification and taking into account the available carbon source after microsieving (120 mg/L Ac-eq). The energy and chemicals required for the reference WWTP are calculated on the basis of the oxygen balance in accordance with ATV (2000) in combination with values from the literature, for example for pumps and agitators (MUNLV 1999). A dose of 20 mg/L Fe is assumed for the chemical precipitation of phosphorus. For the CARISMO concept, the data are based on the pilot tests and the manufacturer’s data for energy consumption of microsieve and biofilter (Table 2). The biogas yield was estimated based on the results of pilot trials (for biofilter sludge as stated above).

The overall energy balance shows that the reference WWTP with an energy consumption of 0.6 kWh/m³ (including chemicals) and electricity production of 0.4 kWh/m³ has a net electricity demand of 0.14 kWh/m³ and a net energy demand of 0.2 kWh/m³ raw sewage (Figure 3). The electricity production corresponds to 74% of the plant’s own requirements, which is in the upper range for existing treatment plants. For a COD influent concentration of 1,000 mg/L, the electricity consumption is 24 kWh/(PE*a) compared to electricity production of 17.5 kWh/(PE*a). The relatively low consumption in the model of the reference WWTP is primarily due to the exclusion of the sludge dewatering (centrifuges) and the return load, which in particular for nitrogen can amount to 10–20% of the influent load, thus increasing further the electricity consumption in the activated sludge process.

In the CARISMO concept, the electricity consumption is 0.25 kWh/m³ or 11 kWh/(PE*a), which represents a reduction of 54% compared to the reference. Electricity is mainly consumed by the biofilter (aeration and pumps), while the microsieve itself only accounts for 0.01 kWh/m³. At the same time, the electricity generation is 81% higher.
(0.72 kWh/m³ or 32 kWh/(PE·a)) due to the increased extraction of COD. This is due both to the increased amount of organic sludge in CARISMO (+36% oDM) as well as the higher biogas yield per kilogram oDM in the anaerobic digester (+40% according to Table 2). Overall, the CARISMO concept shows a net electricity balance of 0.47 kWh/m³ raw sewage, producing 288% of the plant’s own requirements. However, considerable quantities of chemicals are used (PACl, polymer and methanol). Taking into account the energy consumption for the production of the chemicals, there is still a net energy gain of 0.17 kWh/m³ raw sewage, producing 288% of the plant’s own requirements. Nevertheless, the overall energy balance shows that even when including the energy demand for the chemicals used, the CARISMO concept represents an ‘energy-positive’ process for wastewater treatment with a comparable effluent quality to the reference WWTP and that it can therefore serve as a source of renewable energy.

Similarly, the assessment of related greenhouse gas emissions shows that the CARISMO concept performs better than the reference WWTP (Figure 4). For the latter, the model shows a net global warming potential of 0.27 kg CO₂-eq/m³ raw sewage (including the estimated emission of N₂O from denitrification). Owing to the increased electricity generation and the lower electricity consumption, the global warming potential of the

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Reference treatment plant with activated sludge process</th>
<th>CARISMO concept: flocculation + microsieve + biofilter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity for wastewater treatment (kWh/m³)</td>
<td>0.51a</td>
<td>0.01 (microsieve)</td>
</tr>
<tr>
<td>Electricity for thickener + anaerobic digester (kWh/m³ sludge)</td>
<td>3.3</td>
<td>3.3</td>
</tr>
<tr>
<td>Dosage Fe/Al (mg/L)</td>
<td>20 (Fe)</td>
<td>20 (Al)</td>
</tr>
<tr>
<td>Dosage polymer (mg/L)</td>
<td>7</td>
<td>56</td>
</tr>
<tr>
<td>Dosage methanol (mg/L)</td>
<td>430</td>
<td>600 (primary sludge)</td>
</tr>
<tr>
<td>Biogas yield (NL/kg oDM in)</td>
<td>336 (biofilter sludge)</td>
<td>336 (biofilter sludge)</td>
</tr>
<tr>
<td>Biogas quality (vol-% CH₄)</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Electrical efficiency of CHP (%)</td>
<td>38</td>
<td>38</td>
</tr>
</tbody>
</table>

*Efficiency of aeration and oxygen transfer: 550 Wh/kg O₂ for activated sludge, 450 Wh/kg O₂ for biofilter.

![Energy balances of reference WWTP and CARISMO concept.](https://iwaponline.com/wst/article-pdf/70/10/1709/470005/1709.pdf)
CARISMO concept is 0.06 kg CO₂-eq/m³ raw sewage even after including the N₂O emissions from denitrification in the biofilter and the fossil CO₂ released by the conversion of methanol (which is produced from natural gas). Thus the CARISMO concept may at least be designated as ‘CO₂-neutral’ wastewater treatment plant.

A first estimate shows comparable net operating costs for the reference WWTP and CARISMO concept (Figure 5). The electricity consumed and produced for internal consumption was priced at €0.13 kWh, while the excess power generated through the CARISMO concept could only be sold at €0.09 kWh (because it is currently ineligible for subsidies of renewable energy in Germany). Assuming typical commercial prices for chemicals, the CARISMO concept then has slightly higher operating expenditure, but this is offset to a large extent by the revenue from electricity sales. Overall, the increased expenditure on chemicals in the CARISMO concept does not lead to appreciable higher operating costs for electricity and chemicals.

CONCLUSIONS

The new concept for wastewater treatment described here is based on the increased separation of organic matter from raw sewage by flocculation and microsieving. Pilot tests showed the technical feasibility of the concept and the effectiveness in the removal of total COD (70–80%) and phosphorus (<2–5 mg/L in effluent) in relatively concentrated wastewater. As expected, the sludge shows a higher
specific biogas yield in anaerobic digestion than the mixed sludge from the conventional activated sludge process. Furthermore, an overall assessment of the energy consumption and greenhouse gas emissions revealed that the new CARISMO concept (including subsequent treatment in a biofilter to remove residual COD and nitrogen) offers advantages over a reference WWTP in terms of primary energy balance and carbon footprint. Even when taking into account the energy requirements for the production of the chemicals used (in particular, methanol as external carbon source), the CARISMO concept proves to offer an ‘energy-positive’ process for wastewater treatment reaching typical effluent standards for a 100,000 PE WWTP (COD = 100 mg/L, TN = 18 mg/L and TP = 2 mg/L). Net operating costs for electricity and chemicals are estimated to be comparable to conventional treatment processes. In view of the promising results of the pilot tests and the energy balance and the successful demonstration of the technical feasibility, plans are being prepared for the demonstration of the CARISMO concept as ‘energy positive’ and ‘CO2-neutral’ treatment scheme in a full-scale wastewater treatment plant.

The energy balance clearly shows that after extensive removal of organic carbon by microsieving, the subsequent removal of nitrogen accounts for a large part of the energy consumed. To minimise the dosage of external carbon source (methanol) required for biological denitrification, it might be possible to develop dynamic control strategies, e.g. with a nitrate probe in the effluent, or alternatively to filter part of the raw sewage without flocculation so that the dissolved COD remains available for the denitrification. In the future it may also be possible to combine the CARISMO concept with new low-energy methods for removing nitrogen without an external carbon source, e.g. by means of autotrophic deammonification, algal reactors or the removal of NH4 with an ion exchange process.

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