REPORT

Cicerostr. 24
D-10709 Berlin
Germany
Tel +49 (0)30 536 53 800
Fax +49 (0)30 536 53 888
www.kompetenz-wasser.de

Final version, **Date: 19.02.2013**

Executive summary

Project: CoDiGreen

Optimisation of energy and nutrient recovery in wastewater treatment schemes

by Christian Remy and Boris Lesjean
Kompetenzzentrum Wasser Berlin gGmbH
Cicerostr. 24, 10709 Berlin

Preparation of this report was financed through funds provided by
Veolia Water and Berliner Wasserbetriebe

Berlin, Germany

2012

Important Legal Notice

Disclaimer: The information in this publication was considered technically sound by the consensus of persons engaged in the development and approval of the document at the time it was developed. KWB disclaims liability to the full extent for any personal injury, property, or other damages of any nature whatsoever, whether special, indirect, consequential, or compensatory, directly or indirectly resulting from the publication, use of application, or reliance on this document. KWB disclaims and makes no guaranty or warranty, expressed or implied, as to the accuracy or completeness of any information published herein. It is expressly pointed out that the information and results given in this publication may be out of date due to subsequent modifications. In addition, KWB disclaims and makes no warranty that the information in this document will fulfil any of your particular purposes or needs. The disclaimer on hand neither seeks to restrict nor to exclude KWB's liability against all relevant national statutory provisions.

Wichtiger rechtlicher Hinweis

Haftungsausschluss: Die in dieser Publikation bereitgestellte Information wurde zum Zeitpunkt der Erstellung im Konsens mit den bei Entwicklung und Anfertigung des Dokumentes beteiligten Personen als technisch einwandfrei befunden. KWB schließt vollumfänglich die Haftung für jegliche Personen-, Sach- oder sonstige Schäden aus, ungeachtet ob diese speziell, indirekt, nachfolgend oder kompensatorisch, mittelbar oder unmittelbar sind oder direkt oder indirekt von dieser Publikation, einer Anwendung oder dem Vertrauen in dieses Dokument herrühren. KWB übernimmt keine Garantie und macht keine Zusicherungen ausdrücklicher oder stillschweigender Art bezüglich der Richtigkeit oder Vollständigkeit jeglicher Information hierin. Es wird ausdrücklich darauf hingewiesen, dass die in der Publikation gegebenen Informationen und Ergebnisse aufgrund nachfolgender Änderungen nicht mehr aktuell sein können. Weiterhin lehnt KWB die Haftung ab und übernimmt keine Garantie, dass die in diesem Dokument enthaltenen Informationen der Erfüllung Ihrer besonderen Zwecke oder Ansprüche dienlich sind. Mit der vorliegenden Haftungsausschlussklausel wird weder bezweckt, die Haftung der KWB entgegen den einschlägigen nationalen Rechtsvorschriften einzuschränken noch sie in Fällen auszuschließen, in denen ein Ausschluss nach diesen Rechtsvorschriften nicht möglich ist.

Colofon

Title
Executive summary – project CoDiGreen.
Optimisation of energy and nutrient recovery in wastewater treatment schemes

Project Acronym: CoDiGreen

Authors
Christian Remy, Kompetenzzentrum Wasser Berlin gGmbH
Boris Lesjean, Kompetenzzentrum Wasser Berlin gGmbH

Quality Assurance
Jan Waschnewski, Berliner Wasserbetriebe
Christoph Siemers, Stadtentwässerung Braunschweig
Prof. Thomas Dockhorn, TU Braunschweig

Publication / Dissemination approved by technical committee members:
Regina Gnirss, Berliner Wasserbetriebe
Christine Mesek, Stadtentwässerung Braunschweig
Bernhard Teiser, Abwasserverband Braunschweig
Andreas Hartmann, Kompetenzzentrum Wasser Berlin
Norbert Dichtl, ISWW der TU Braunschweig
Christophe Sardet, Veolia Wasser
Emmanuelle Trouvé, Veolia Eau

Deliverable number
D 1.1

Final version ☒
Date: 19.02.2013

Abstract (English)

The research project CoDiGreen (2010-2012) targets the optimisation of energy and nutrient recovery in the wastewater treatment schemes of Braunschweig and Berlin. Therefore, pilot experiments are conducted to test the effect of addition of co-substrates (grass silage, topinambur) and the thermal hydrolysis of excess sludge on the biogas yield of anaerobic digestion. In addition, co-digestion of grass silage is also tested in a full-scale digestor of the wastewater treatment plant (WWTP) Braunschweig-Steinhof. Beside the experimental part, the environmental footprint of the wastewater treatment scheme in Braunschweig and the sludge treatment line in WWTP Berlin-Waßmannsdorf is analysed with Life Cycle Assessment (LCA) to identify potentials for optimisation and assess selected technical options in their effects on the environmental profile. Finally, a market review of the concept of agricultural reuse of effluent and sludge in Braunschweig is conducted to get an overview of the market situation, and a risk assessment is initiated to identify potential risks associated with this practice.

The results of the pilot experiments show that both the addition of co-substrates and thermal hydrolysis can substantially increase the biogas yield and quality (CH_4 content) during mesophilic digestion (HRT = 20d). Methane yields can be increased by 10%, 9% and 13% for thermal hydrolysis of excess sludge, addition of grass silage (+10% TS), and the combination of both (if the methane yield is only related to the VS of the sludge, the increase was 10%, 31% and 38%). A two-step digestion with intermediate hydrolysis ("DLD") yields +19% CH_4. No exceedance of legal requirements for inorganic and organic pollutants can be detected, whereas lab-analysis indicate positive impacts on sludge dewaterability and polymer demand for dewatering.

For a full scale realisation of co-digestion it can be estimated that a 100.000 PE WWTP would require approximately 30 ha of extensively cultivated area to add +10% VS of grass substrate. However, the promising results of co-digestion with grass cannot be confirmed in full-scale trials, where only -8% of biogas yield can be measured (+2% if related to the VS of the sludge only). Even though the technical feasibility of grass addition can be shown, operational difficulties (fibre size, hydraulic mixing, low HRT) seem to prevent the realisation of the maximum potential of grass addition in full-scale.

The environmental assessment of the systems in Berlin and Braunschweig reveals a high degree of energy production in both systems, lowering associated impacts of carbon footprint and other environmental impacts. However, potentials for optimisation are identified in terms of energy production and nutrient recovery, and recommendations for the future testing of technical options are given based on the scenario analysis within the LCA. Environmental benefits of the reuse approach in Braunschweig are quantified and relate mostly to the lower discharge of nutrients and other pollutants into surface waters. The normalised environmental profile underlines the primary functions of wastewater treatment (= protection of surface waters), which should not be compromised while optimising energy demand and carbon footprint.

The risk assessment of the Braunschweig system follows the HACCP concept and quantifies risks for human health associated with pathogens and heavy metal input into agricultural soils, as well as ecological risks from heavy metal emission into the environment. Potential risks of agricultural reuse are successfully identified (viruses, Cadmium for humans, Zinc for ecosystems) based on quantitative modelling of fate and exposure, and results should now be validated by extended monitoring of these substances.

Finally, recommendations for system optimisation are given to increase energy and nutrient recovery in the wastewater schemes of Berlin and Braunschweig and lower the environmental footprint and risk associated with their operation.

Abstract (German)

Das Forschungsprojekt CoDiGreen (2010-2012) zielt auf eine Optimierung der Rückgewinnung von Energie und Nährstoffen in der Abwasserbehandlung in Braunschweig und Berlin. Dafür werden in Pilotversuchen die Auswirkungen einer Zugabe von Co-Substraten (Grassilage, Topinambur) und einer thermischen Druckhydrolyse des Überschussschlamms auf den Biogasertrag der Faulung untersucht. Zusätzlich wird die Co-Vergärung von Grassilage im großtechnischen Maßstab in einem Faulturm des Klärwerks Braunschweig-Steinhof getestet. Neben dem experimentellen Teil wird über eine Ökobilanz der ökologische Fußabdruck des Abwassersystems in Braunschweig und der Schlammbehandlung im Klärwerk Berlin-Waßmannsdorf analysiert, um Optimierungspotential zu erfassen und anhand ausgewählter Szenarien zu bewerten. Abschließend werden vergleichbare Konzepte der landwirtschaftlichen Wiederverwendung von Klarwasser und Schlamm in einer Marktstudie ermittelt und über eine Risikobewertung potentielle Gefahren dieses Systems identifiziert.

Die Pilotversuche zeigen, dass sowohl die Zugabe von Co-Substraten als auch die thermische Hydrolyse einen substantiellen Gewinn an Biogasmenge und –qualität (CH_4-Gehalt) in einer mesophilen Faulung (Verweilzeit: 20d) ermöglichen kann. Die Methanerträge können um 10%, 9% und 13% durch thermische Hydrolyse von Überschussschlamm, Zugabe von Grassilage (+10% TS) und eine Kombination beider Maßnahmen gesteigert werden (sofern der Methanertrag lediglich auf den oTR des zugeführten Schlamms bezogen wird, betrug die Steigerung 10%, 31% und 38%). Eine zweistufige Faulung mit zwischengeschalteter Hydrolyse („DLD“) erbringt +19% CH_4. Für anorganische und organische Schadstoffe werden dabei vorgeschriebene Grenzwerte der aktuellen Klärschlammverordnung nicht überschritten. Weiter zeigen Laboranalysen einen positiven Effekt auf die Entwässerbarkeit des Schlamms und den Bedarf an Polymeren. Leider können die vielversprechenden Ergebnisse der Co-Vergärung mit Gras in der Großtechnik nicht bestätigt werden.

Für eine großtechnische Realisierung einer Co-Vergärung lässt sich abschätzen, dass für 100.000 EW ca. 30 ha extensiv bewirtschafteter Fläche erforderlich sind, um 10% oTR an Gras in Bezug zum oTR des Rohschlamms zu erzeugen. Leider können die vielversprechenden Ergebnisse der Co-Vergärung mit Gras in der Großtechnik nicht bestätigt werden, in der nur -8% Biogasertrag gemessen werden (+2% wenn der Methanertrag lediglich auf den oTR des zugeführten Schlamms bezogen wird). Obwohl die technische Machbarkeit der Graszugabe gezeigt werden kann, scheinen betriebliche Probleme (Größe der Fasern, hydraulische Durchmischung, niedrige Verweilzeit) die Umsetzung des maximalen Potentials der Graszugabe in der Großtechnik zu verhindern.

Die Bewertung der Umweltwirkungen der Systeme in Berlin und Braunschweig zeigt eine hohe Eigenenergieerzeugung in beiden Systemen, so dass dadurch der Treibhauseffekt und andere relevante Umweltwirkungen vermindert werden. Dennoch kann noch Optimierungspotential bei der Energie- und Nährstoffrückgewinnung aufgezeigt werden, zu dessen Erschließung auf der Grundlage einer Szenarienanalyse Empfehlungen

formuliert werden. Die Umweltvorteile der Wiederverwendung in Braunschweig zeigen sich vor allem in einer verminderten Emission von Nähr- und Schadstoffen in die Gewässer. Die Normalisierung der Umweltwirkungen unterstreicht die Bedeutung der Primärfunktion der Kläranlage (= Schutz der Oberflächengewässer), die durch Optimierung von Energiebedarf und Treibhausgasemissionen nicht eingeschränkt werden sollte.

Die Risikobewertung der Braunschweiger Systems folgt dem HACCP-Konzept und quantifiziert Risiken für die menschliche Gesundheit durch Krankheitserreger und Schwermetalle in der Landwirtschaft und ökologische Risiken durch Schwermetalle. Potentielle Risiken der Wiederverwendung werden auf Grundlage quantitativer Modelle von Umweltverhalten und Exposition identifiziert (Viren, Cadmium für Menschen, Zink für Ökosystem) und sollten durch entsprechende Messprogramme überwacht werden.

Schließlich werden basierend auf den Projektergebnissen Empfehlungen zur Optimierung der Energie- und Nährstoffrückgewinnung in der Abwasserbehandlung in Berlin und Braunschweig formuliert, um letztlich die negative Umweltwirkungen zu minimieren und potentielle Risiken im Betrieb zu vermeiden.

Abstract (French)

Le projet de recherche CoDiGreen (2010-2012) a pour but l'optimisation énergétique et la récupération de nutriments dans les systèmes d'assainissement de Braunschweig et Berlin. Pour cette raison, des expériences en pilote sont effectuées pour tester l'effet de l'addition de co-substrats (herbe ensilée, topinambour) et de l'hydrolyse thermique sur le rendement en biogaz de la digestion anaérobie. De plus, la co-digestion de l'herbe ensilée est testée à grande échelle dans un digesteur de la station d'épuration (STEP) de Braunschweig-Steinhof. A côté de la partie expérimentale, l'empreinte environnementale du système d'assainissement de Braunschweig et de la filière de traitement des boues de la STEP Berlin-Waßmansdorf est évaluée par l'Analyse du Cycle de Vie (ACV) pour identifier les potentiels d'optimisation et déterminer les effets de certaines options techniques sur le profil environnemental. Finalement, une étude de marché sur les concepts de réutilisation des effluents et boues de Braunschweig pour l'agriculture est réalisée pour obtenir une vue d'ensemble de la situation du marché, et une évaluation des risques est initiée pour identifier les risques potentiels associés avec cette pratique.

Les résultats des expériences en pilote montrent qu'à la fois l'addition de co-substrats et l'hydrolyse thermique peuvent substantiellement augmenter le rendement et la qualité du biogaz (teneur en CH4) pendant la digestion mésophile (TDS = 20 j). Les taux de méthane peuvent être améliorés de 10%, 9% et 13% pour l'hydrolyse thermique de la boue en excès, l'ajout d'herbe ensilée (+10% TS), et la combinaison des deux (si le taux de méthane est relié seulement à la MV de la boue, l'augmentation atteint 10%, 31% et 38%). Une digestion en deux étapes avec hydrolyse intermédiaire (« DLD ») produit +19% CH4. Pas de dépassement des impératifs légaux de polluants inorganiques et organiques ne peut être détecté, tandis que les analyses en laboratoire indiquent des impacts positifs sur la déshydratabilité des boues et sur la demande en polymère pour la déshydratation.

Pour une réalisation à grande échelle de la co-digestion, il peut être estimé qu'une STEP de 100 000 EH nécessiterait environ 30 ha de surface cultivée de manière extensive pour un ajout de 10% de MV en substrat herbe. Cependant, les résultats prometteurs de la co-digestion avec de l'herbe ne peut être confirmé dans des essais à grande échelle, où seulement -8% du rendement du biogaz peut être mesuré (+2% si relié seulement au MV de la boue). Même si la faisabilité technique de l'addition d'herbe peut être demontrée, les difficultés opérationnelles semblent empêcher la réalisation du potentiel maximum de l'addition d'herbe à grande échelle.

L'évaluation environnementale des systèmes de Berlin et de Braunschweig révèlent un haut degré de production énergétique dans les deux systèmes, diminuant les impacts associés à l'empreinte carbone et aux autres impacts environnementaux. En outre, les potentiels d'optimisation sont identifiés en termes de production énergétique et de récupération des nutriments, et les recommandations d'options techniques pour les futurs essais sont effectuées, basées sur l'analyse de scénario inclus dans l'ACV. Les

bénéfices environnementaux de l'approche « reuse » in Braunschweig sont quantifiés et liés surtout au faible renvoi de nutriments et autres polluants dans les eaux de surface. Le profil environnemental normalisé souligne les fonctions primaires du traitement des eaux (=protection des eaux de surface), qui ne doivent pas être compromis lors de l'optimisation de la demande énergétique et de l'empreinte carbone.

L'évaluation des risques du système de Braunschweig suit le concept HACCP et quantifie les risques pour la santé humaine associée à l'introduction des pathogènes et des métaux lourds dans les sols agraires, ainsi que les risques d'émission des métaux lourds dans l'environnement. Les risques potentiels du « reuse » dans l'agriculture sont identifiés (virus, Cadmium pour les humains, Zinc pour les écosystèmes) basé sur un modèle quantitatif du devenir et de l'exposition de ces substances, et les résultats devraient maintenant être validés par une surveillance étendue de ces substances.

Finalement, les recommandations pour l'optimisation du système sont émises pour augmenter le rendement énergétique et la récupération des nutriments dans les systèmes d'assainissement de Berlin et Braunschweig et pour diminuer l'empreinte environnementale et les risques associés à leur opération.

Acknowledgements

The research project CoDiGreen (2010-2012) was financed by Veolia Water and Berliner Wasserbetriebe. This report is based on results of studies performed by the following project team (below in alphabetical order):

- Thomas Dockhorn (ISWW)
- Karsten Fülling (ISWW)
- Sonia Graja (VERI)
- Daniel Klein (ISWW)
- Boris Lesjean (KWB)
- Robert Mieske (ISWW)
- Christian Remy (KWB)
- Wolfgang Seis (KWB)
- Christoph Siemers (SE/BS)
- Jan Waschnewski (BWB)

The full list of publications produced within the project is available in Chapter 8. The publications are available for download on the KWB website www.kompetenz-wasser.de

The supervision of the CoDiGreen research project was performed by Berlin Centre of Competence for Water (KWB).

Table of Contents

List of Figures

List of Tables

Acronyms

CHP	-	Combined heat and power plant
COD	-	Chemical oxygen demand
DLD	-	“Digestiion / Lysis / Digestion”
DS	-	Dry solids
HACCP	-	Hazard Analysis and Critical Control Points
IMP	-	Intensive Monitoring Phase
LCA	-	Life Cycle Assessment
LD	-	“Lysis / Digestion”
ORC	-	Organic Rankine Cycle
PE	-	Population equivalent
RTD	-	Retention Time Distribution
SE/BS	-	Stadtentwässerung Braunschweig (Wastewater utility of Braunschweig)
TS	-	Total solids
VS	-	Volatile solids
WHO	-	World Health Organisation
WWTP	-	Wastewater treatment Plant

Chapter 1
Introduction

The European "Energy Package" aims at reducing the carbon emission while increasing the share of renewable energy in the grid mix and reducing the overall energy demand. Reduction target of 20% up to 40% by 2020 on 1990 level is considered throughout all industrial sectors. For urban water schemes, wastewater treatment is identified as the activity with highest potential regarding energy saving.

In Berlin, the city council targets to reduce the overall energy demand by 40% of 2000 level by 2020. This target applies also to Berliner Wasserbetriebe (BWB), who have to identify the best strategies to optimize the energy requirement of the urban water system and/or to produce and use renewable energy in order to reduce greenhouse gas emissions. The standardized method of Life Cycle Assessment (LCA) can be used to assess the energy and carbon footprint of the WWTPs, and an integrated LCA modelling of the complete plant (both wastewater and sludge handling systems) could be used to assess the optimisation potential to reduce the overall environmental footprint of the system.

The city of Braunschweig implements another sanitation concept which enables the WWTP to be quasi energy self-sufficient (Figure 1). On the "Klärwerk Steinhof" (KWS), the reuse of treated wastewaster and digested sludge in agriculture has been implemented for decades through (i) the irrigation the farmland with treated wastewater (2/3 of flow) to grow food and energy crops recycled in a biogas plant; (ii) the complete utilisation of thermophilic digested sludge as certified fertiliser in agriculture and (iii) the use of infiltration fields and stabilisation ponds as tertiary biological treatment step (receiving 1/3 of flow).

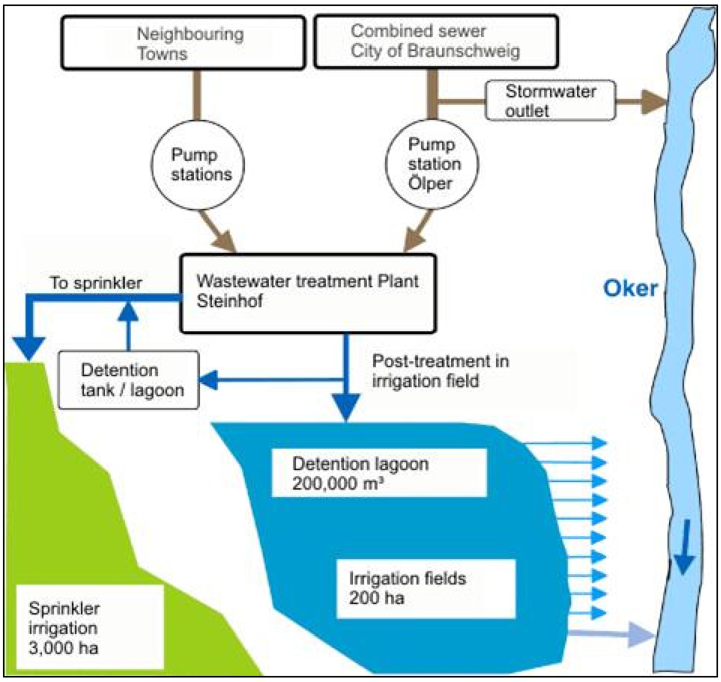

Figure 1: Simplified representation of the Braunschweig sanitation scheme.

Today the KWS produces about 2/3 of its energy requirement with the thermophilic sludge digester, and has a neutral energy balance considering the biogas delivered by the landfill and by the biogas plant using organic waste from households. However, the biogas production from landfill has been decreasing in the past years, and the second source of external biogas is bound to contracts that may be terminated. The plant operator (SE|BS) is therefore interested to investigate any other option that would reduce the energy dependency of the WWTP.

The goal of the 2-year project "CoDiGreen" was to investigate options to optimise the energy efficiency of the wastewater systems in Berlin and in Braunschweig and to reduce their energy dependency to external energy sources while improving the agricultural nutrients recovery. The following activities were performed:

1. Market review for wastewater systems with reuse of effluent and sludge, combined with growing of energy crops (CHAPTER 2)
2. Perform laboratory assessment and assess performances of different co-substrates and thermal disintegration of excess sludge before digestion (CHAPTER 3)
3. Perform full-scale trials with one digester of the WWTP Steinhof in Braunschweig to assess the performance of co-digestion of grass silage grown on infiltration fields (CHAPTER 4)
4. Perform an assessment of energy balance and carbon footprint of the sludge treatment of WWTP Wassmannsdorf (Berlin) and assess the environmental footprint of the wastewater scheme of Braunschweig using the methodology of LCA, and identify optimisation scenarios to reduce the energy dependency of the systems and increase nutrients recovery in Braunschweig (CHAPTER 5)
5. Initiate an environmental and health risk assessment of the wastewater scheme in Braunschweig with extensive reuse of effluent and sludge (CHAPTER 6)

Finally, conclusion and recommendations are drawn from the results of this study to identify promising measures for optimisation for the systems in Berlin and Braunschweig (CHAPTER 7). A list of publications is amended to this report (CHAPTER 8).

Chapter 2
Market review (KWB)

The market review shall provide an overview of relevant European activities in the wastewater sector combining the three distinct features of the wastewater scheme in Braunschweig:

1. the reuse of **sewage sludge** in agriculture
2. the reuse of **purified effluent** in agriculture
3. the growing of **energy crops** on farmlands irrigated with effluent and sludge

In the market review, relevant scientific and professional literature of the water sector and the internet were systematically screened for available information on wastewater systems featuring all three aspects of the Braunschweig system. In general, many references were found combining two of the three aspects of Braunschweig (i.e. reuse of sludge and effluent, reuse of sludge and energy crops), as reuse of sludge and effluent are common practice in central and southern European countries (e.g. France, Spain, Italy). However, the explicit combination of effluent and sludge reuse with growing of energy crops was only reported for very few systems which are described in detail below.

Existing systems in Germany

For Germany, only one other large-scale implementation of the Braunschweig approach could be identified, which is operated in the near-by city of **Wolfsburg**. Both systems have been set up in comparable historical and technical context during the 1950s. Similar to Braunschweig, the Wolfsburg area has the same features which favour the implementation of agricultural reuse of effluent and sludge:

- substantial climatic water deficit of the agriculture (>100 mm/a)
- limited amount of groundwater resources for irrigation
- sandy soils with low hydraulic buffer capacity which can infiltrate substantial amounts of irrigation water
- even terrain with sufficiently low groundwater table (>1.5m) for uniform infiltration of irrigation water
- low population density in the agricultural area
- optimum design of farmland for efficient operation of irrigation machinery

The Wolfsburg system treats municipal wastewater of 170,000 inhabitant equivalents with low industrial contribution in a conventional wastewater treatment plant. In contrast to the Braunschweig system, 100% of the effluent is distributed to farmlands (1500 ha) during summer without enhanced nitrogen removal via denitrification in the WWTP. On the farmlands, 300ha of maize are cultivated and digested in a biogas plant at the WWTP as energy crops, providing heat and electricity for the WWTP. In winter, effluent is denitrified and infiltrated locally to recharge groundwater resources. Sewage sludge is directly dewatered (no digestion) and dried by CHP off-gas heat during the whole year prior to its incineration in a nearby power plant. More details of the Wolfsburg system can be found in the appendix.

Existing systems in Europe

Comparable large-scale systems of effluent and sludge reuse in agriculture combined with energy crop cultivation in other European countries are not explicitly reported in relevant literature. Many systems are in operation where effluent and sludge are used in agriculture, but it was difficult to acquire information on the type of crops that are grown on the respective agricultural fields. Distinct information on the systematic combination of all three features of the Braunschweig system could be found for the following systems:

- **Enköpping (Sweden):** 20,000 inhabitants, 200ha of willow (short-rotation crop for energy production via incineration in CHP plant) is grown on fields irrigated with WWTP effluent (~ 200,000 m^3/a) and sludge. For nitrogen recovery, sludge liquor (10000 m^3/a) is also applied in agriculture.
- **BioPros (EU project 2005-2008)**: this research project provided guidelines for the safe application of wastewater and sludge for high efficient biomass production in short-rotation plantations (www.biopros.info).
- **WaterRenew (England)**: this research project tested the irrigation of short-rotation crops (willow, eucalyptus) with WWTP effluent and sludge to recover water and nutrients (field testing at 5 small sites across UK).

As a conclusion of the market review, the wastewater schemes of Braunschweig (350000 pe) and Wolfsburg (170000 pe) could be identified as the only full-scale systems of agricultural reuse of effluent and sludge combined with the cultivation of energy crops. In the EU context, a smaller system is in operation in Enköpping (Sweden) using short-rotation plantations as energy crops. All other activities in this field are either small-scale systems in the rural context (<100 pe) or research projects investigating the applicability of this concept in field sites, with an increasing number of projects in the last decade.

Chapter 3

Pilot-scale trials of co-digestion and thermal hydrolysis (ISWW)

The objective of this work package was to quantify the impact of co-digestion and the thermal hydrolysis process (THP) on the biogas yield and the degradation of volatile solids in pilot-scale experiments. Furthermore, inorganic and organic pollutants were measured to identify possible effects of co-digestion or TDH on sludge quality. Finally, dewatering properties of the digested sludge and the resulting return loads from sludge liquor were investigated.

The tests in pilot scale were carried out in two test series, each consisting of an adaption period and an intensive monitoring program (IMP) of four weeks. In the test series, different co-substrates were added: ensiled grass cut to 3mm fibres and topinambur greens. The thermal disintegration was implemented as a pre-treatment (lysis + digestion = LD configuration) as well as integrated between two digestion steps (digestion + lysis + digestion = DLD). The anaerobic digestion has been carried out in parallel with four lab-scale digesters (Figure 2) with a gross volume of 40 litres each in a container with mesophilic conditions (38°C). Thermal disintegration of sludge was realized in a lab-scale thermal hydrolysis plant at a temperature of 160°C with corresponding pressures for 30 minutes. Digestor performance was characterized by mass balances for COD, TC, N and P which could be closed with reasonable accuracy (input-output difference <10%).

Figure 2: Lab-scale digestors (40L) for pilot trials of co-digestion and equipment for thermal hydrolysis

Effects of co-digestion and thermal hydrolysis on biogas yield and quality

The reference digestor was operated with 50% primary and 50% excess sludge from WWTP Braunschweig with a HRT of 20d at mesophilic conditions. For the reference, a biogas yield of 528-575 L/kg VS_{input} with a CH_4 content of 64-66% was measured. The results show that thermal hydrolysis can increase the CH_4 yield by 10% in LD configuration and 19% in DLD configuration (Table 1). Co-digestion of ensiled grass with (+10% TS of co-substrate) reached an increase of 9% in CH_4 yield (31% if related to the

VS of the sludge only), whereas the combination of hydrolysis and grass addition resulted in a 13% increase in CH_4 yield (38% if related to the VS of the sludge only). For the DLD configuration, a maximum degradation of 76% of VS_{input} was reached. Concerning the kinetics of biogas production, no adverse effects of co-substrate addition could be observed in a daily profile of biogas production after feeding the reactors.

Table 1: Increase in biogas and CH_4 yield by co-digestion and thermal hydrolysis in pilot-scale trials

Scenario	Process	Increase in biogas yield	Increase in CH_4 yield
"LD"	PS + ES(160°C)	+8%	+10%
"DLD"	D + 160°C + D	+18%	+19%
Co-digestion	PS + ES + 10% Grass	+2% (+23%*)	+9% (+31%*)
"LD" + CoDi	PS + (ES + 10% Grass)160°C	+5% (+27%*)	+13% (+38%*)

PS: primary sludge, ES: excess sludge, D: digestion, HRT: 20d at 38°C

**related to the VS of the sludge only*

Organic and inorganic pollutants

A defined set of organic pollutants (AOX, nonylphenols, DEHP, PAH_{16}, dioxins, furans, PCB, PFT) were analyzed in grab samples to identify adverse effects of hydrolysis or co-substrate in digested sludge. Selected pollutants (NP, DEHP, PAH_{16}) showed a slight increase after thermal hydrolysis, but finally all pollutants were well below current legal limits for sewage sludge application in agriculture. 15 pharmaceutical compounds were analysed in one sample series from the raw water and the effluent from the four reactors. Ten compounds were detected above the quantification limits (5-10 ng/gTS) and the three compounds diclophenac, carbamacepine and metoprolol were found in most samples with concentrations above 100 ng/gTS and up to 500 ng/gTS. It is however to be noted that in many cases the recovery rates were not satisfying (26 to 228%!) and that propanolol was in the range 8-27 ng/gTS the sole compound that showed always satisfying recovery rates (75-125%).

For inorganic pollutants, heavy metals were transferred to the dissolved phase by thermal hydrolysis and reached higher concentrations related to dry matter after digestion, which is caused by higher degradation of volatile solids after hydrolysis. Again, no exceedance of current legal standards could be detected for heavy metals and organic micropollutants.

Dewaterability and return liquor

The dissolved phase of reactor outputs was sampled for COD, N and P to determine possible influences of thermal hydrolysis and co-substrates on return loads from sludge dewatering. For thermal hydrolysis, COD concentrations were considerably increased in the sludge liquor (+100-120% for LD, +400% for DLD configuration), whereas N and P content remained relatively constant. Tests for biodegradability (adjusted Zahn-Wellens test for 72h) revealed that refractory COD is increased by 110-140% for LD and 250% for DLD configuration. The addition of co-substrates had an effect on COD loads (+50%), but no adverse effect was detected for N and P.

Dewaterability of digested sludge was assessed with thermo-gravimetric analysis (TR(A)) of digestor effluent, determining a theoretical amount of free water that should be removable by mechanical dewatering. TR(A) results suggest that dewaterability of reference sludge (TR(A) = 20-24%) can be considerably increased by both grass addition (TR(A) = 31%) and thermal hydrolysis (TR(A) = 33-40%).

Chapter 4

Full-scale trials of co-digestion (ISWW, SE/BS, AVB)

The full-scale trials of co-digestion have been performed using the three existing digesters of the WWTP of Braunschweig from Nov 2010 until Aug 2011 (IMP: June 13-July 31). All three digesters have been cooled down from thermophilic to mesophilic conditions (38°C) prior to the trials to assure the comparability to the pilot-scale trials. The grass for co-digestion was harvested on fallow lands of the former sewage fields close to the WWTP and ensiled in silage tubes for at least 6 weeks before dosing.

All digesters were fed with the same raw sludge (mix of primary and excess sludge) by a time-controlled feeding unit. Corresponding to the size of the digesters, they received 20% (digester 1) and 40% (digester 2 and 3) of the total raw sludge quantity. Digester 1 was additionally fed with ensiled grass, adding 5-10% additional TS to digester 1 which corresponds to a quantity of fresh substrate of 600 – 1,000 kg/day (TS_{grass} = 55%, VS_{grass} = 90% of TS). Digester 2 received no co-substrates and was used as reference, while digester 3 additionally received grease which was already used as co-substrate before (Table 2). Standard parameters were measured at least weekly to characterize the input and output sludge, while flows and biogas production were recorded continually.

Table 2: Operating conditions of digesters in full-scale trials

Digester	Volume	**HRT* mean** (min – max) [d]	**HRT (20d-mean) during IMP**	**Type of substrate**	**Proportion of co-substrate during IMP, mean values**	
					%TS	**%Volume**
1	2,100 m³	**17.5** (14.9 - 21.4)	16.5	Raw sludge + ensiled grass	9	15.3**
2	4,450 m³	**21.8** (18.6 - 26.4)	20.5	Raw sludge only	-	-
3	4,450 m³	**20.3** (17.5 - 23.9)	19.2	Raw sludge + grease	1.9	5.9

* during the trial period (20d mean values)

** including flush water (0.9% additional volume of grass without flush water)

Harvesting, silage and dosing of grass

Grass was harvested in June (11 t/ha) and Sep 2010 (5 t/ha) with subsequent cutting, drying/swathing and shredding before putting into silage tubes. Shredding resulted in fibres of 2-3cm (expected: 8mm), which may negatively affect the kinetics of degradation in the digestion process due to lower surface area for bacterial attack. During the trials, no negative effect (e.g. mould) on grass quality could be detected in silage tubes. Feeding of the digestor was done with a Quickmix (Vogelsang GmbH) feeding device for biogas plants with a storage bunker above (agricultural mixer/feeder of 12 m³). The storage was daily loaded by a wheel loader from the silage tubes. Once a day, 600-1000kg of grass silage was then added into the digester feeding pipe, using 15-20m³ of WWTP effluent for flushing. Occasionally, grass formed a floating layer in digester 1, but in general no operational problems were encountered during the trials period. In winter, isolating housing was provided for the feeding equipment to prevent freezing.

Effects of co-substrates on biogas yield and quality

In general, mass balances of the digesters could be closed for COD, N and P with reasonable accuracy (<10% difference between in- and output). The volumetric loading of the digesters was increased from 1.76 kg VS/(m³*d) for the reference digester to 2.04 kg VS/(m³*d) with grass addition. Due to the flush water used for co-substrate feeding, digester 1 has a reduced HRT of 16.5d during the IMP. All digesters were operated in stable conditions during the IMP with low organic acid content (<100 mg/L HAc_{eq}).

The addition of grass silage increased the relative biogas production by only 2% (related to the VS of the sludge only) during the IMP phase (Table 3). The large potential of grass silage as a co-substrate which was detected in pilot trials (+23% gas production) could not be confirmed in full-scale. Reasons for the low effect of grass addition in full-scale may be seen in the lower HRT of the digestion process (due to flush water), poor mixing conditions of grass in the digestor or insufficient shredding of grass silage, resulting in larger fibres which could only partially be degraded in the available HRT (see discussion in Chapter 7). However, limited accuracy of gas measurement or mass balancing may also contribute to the low calculated biogas yield of co-digestion.

For a full scale realisation of co-digestion it can be estimated that a 100.000 PE WWTP would require approximately about 30 ha of extensively cultivated area (grass yield 7 tVS/ha*a) to add 10% VS of grass substrate (2700 tVS/100.000 EW assumed).

Table 3: Specific gas yields of reference and co-digestion during IMP of full-scale trials

Reactor	**HRT**	**CH_4 content**	**Specific gas yield**	**Increase by Co-Digestion**	**VS degradation**
	[d]	[%]	[NL/kg VS_{input}]*	[%]	[%]
Digester 1 (+ 10% TS grass)	16.5	61.8	589	2	45
Digester 2 (reference)	20.5	62.5	578	-	48
Digester 3 (+ grease)	19.2	63.7	565	-2	45.4

* related to VS sludge

Organic and inorganic pollutants

No negative effect of grass addition could be detected on organic and inorganic compounds, and the output sludge was well below legal limits of the sewage sludge ordinance during the full trials period.

Dewaterability and return liquor

No increase in dissolved COD, N or P could be detected for the liquid phase of the digested sludge from co-digestion. As in pilot trials, it was not possible to increase N content of the liquor with grass addition for possible N recovery, which was expected to be a possible side effect of grass addition. Dewaterability tests via TR(A) analysis revealed no clear effect of grass addition on free water content of the digested sludge. The promising results of pilot trials (significant increase in TR(A)) could not be reproduced.

Chapter 5

Life Cycle Assessment (KWB, BWB, SE/BS)

LCA study of the wastewater scheme in Braunschweig

This work package analyses the environmental footprint of the Braunschweig wastewater scheme using the methodology of Life Cycle Assessment. All relevant processes of wastewater treatment and disposal are modelled in a substance flow model based on available full-scale data (year 2010) complemented by literature data to calculate aggregated emissions and resource demand of the system (Figure 3). Products of the system (i.e. electricity from biogas combustion, nutrients, and irrigation water) are accounted with credits for the respective substituted products. Beside the status quo of the Braunschweig system in 2010, a set of optimisation scenarios are assessed in their effects on the environmental footprint which target an enhanced recovery of energy and nutrients.

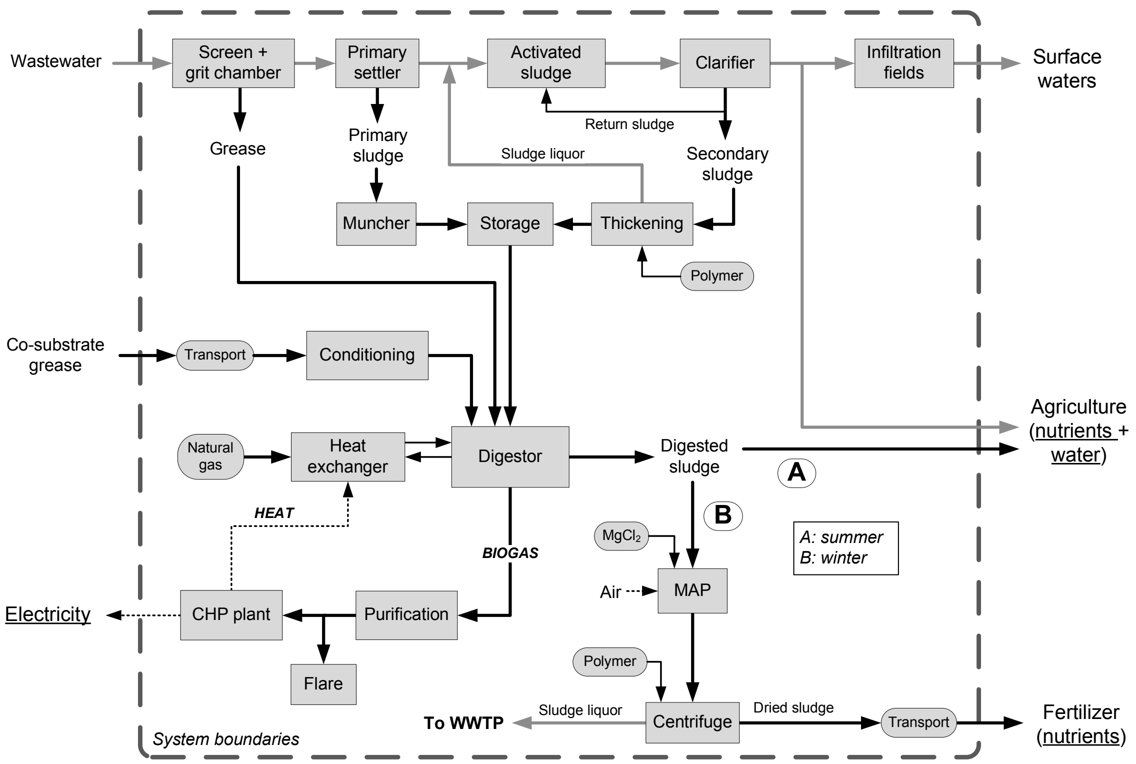

Figure 3: Scope of LCA study of wastewater treatment scheme in Braunschweig 2010 (secondary products are underlined)

The energetic balance of the system is comparatively good, as 79% of the cumulative energy demand can be offset by secondary products, mainly biogas (58%) and fertilizer substitution (14%). The optimisation of nutrient and especially water management offers considerable potential for improving the energy balance, the latter due to the high demand of electricity for pumping the water to the fields. The net carbon footprint of the system amounts to 10 kg CO_2-eq/(PE_{COD}*a) and is mainly caused by energy-related processes, augmented by direct emissions of N_2O and CH_4 in the activated sludge process. Nutrient emissions in surface waters are relatively low (29 g P and 80 g N/(PE_{COD}*a)) due to the transfer of nutrients to agriculture and the polishing effect of the infiltration fields. While effects on human toxicity are small after normalisation, Cu and Zn emissions to aquatic and terrestrial ecosystems lead to a substantial impact in ecotoxicity (organic substances not accounted). Normalisation of the environmental footprint reveals the primary function of the wastewater treatment plant, i.e. the protection of surface waters from inorganic and organic pollutants and excessive nutrient input (Figure 4). Whereas the quantitative contribution of the system is high for eutrophication and ecotoxicity, energy consumption and correlated indicators such as carbon footprint, acidification and human toxicity have only a minor share to the total environmental impacts in Germany. Consequently, the optimisation of the latter environmental impacts should only be pursued if the primary functions and related impacts on surface waters are not compromised by these measures.

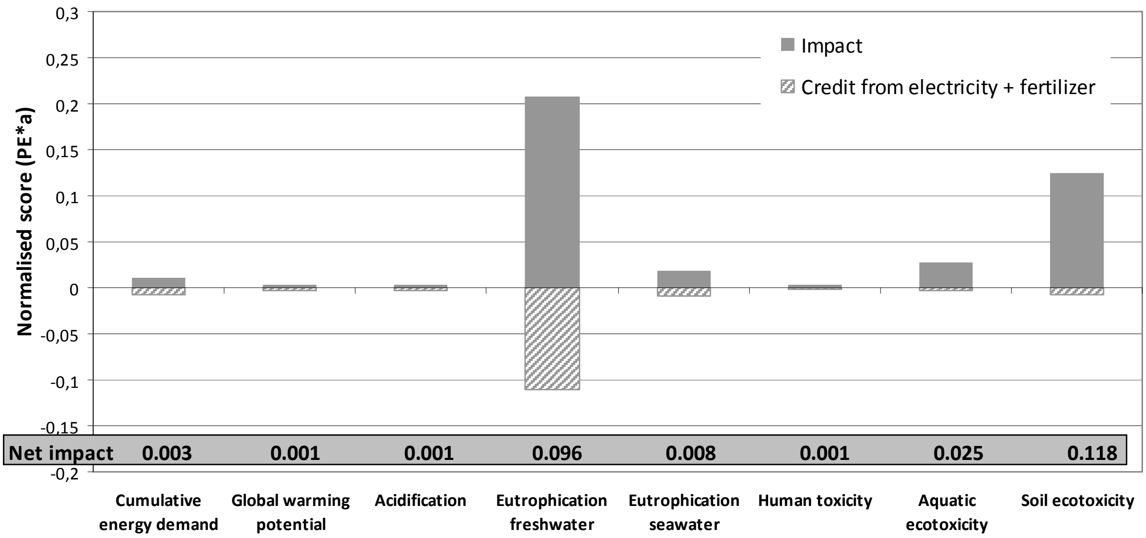

Figure 4: Normalised environmental profile of the Braunschweig wastewater scheme in relation to total environmental impacts in Germany

In scenario analysis, both the addition of co-substrates and the thermal hydrolysis of sludge for improving the anaerobic degradation into biogas have a substantial positive effect on the energy balance and carbon footprint without impairing other environmental impacts. Based on the results of the pilot trials in CoDiGreen, the current energy demand can be reduced up to 80% by a combination of adding ensiled grass into the digestor and hydrolysis of excess sludge (potentials have to be verified in full-scale trials). A two-step digestion process with intermediate dewatering and hydrolysis (DLD configuration with EXELYS™) seems promising in terms of energy benefits and carbon footprint. The recovery of nitrogen or phosphorus from the sludge liquor of dewatering does not result in major benefits in the environmental profile (in case of NH3 stripping with high NaOH requirement), whereas the implementation of an ORC process for energy recovery from excess heat can be fully recommended from an environmental point of view.

The methodology and results of this LCA have been successfully reviewed and certified to be in line with requirements of ISO 14040/44 (critical review by Prof. Matthias Finkbeiner of TU Berlin, Department of Sustainable Engineering).

LCA study of sludge treatment in WWTP Berlin-Waßmannsdorf

In this study, the goal of BWB was to demonstrate the suitability of the LCA method for system analysis, analysing the process for sludge treatment and disposal at the WWTP Berlin-Waßmannsdorf with a predefined focus on the total cumulative energy demand and the carbon footprint of the system. In addition to the characterization of the status quo in 2009, several measures for an energetic optimization of the system have been evaluated in their effects on the energy balance and greenhouse gas emissions. The process model of the system encompasses all relevant processes of sludge treatment and disposal, including the supply of electricity and chemicals, transport and incineration of the sludge, and treatment of sludge liquor which is recycled back to the WWTP inlet. Products recovered during sludge treatment (biogas from anaerobic digestion and MAP fertilizer) and disposal in incineration (electricity or substitution of fossil fuels) are accounted by credits for the respective substituted products.

Overall, sludge treatment and disposal in Berlin-Waßmannsdorf is an energy-positive process, recovering a net amount of energy of 162 MJ per population equivalent and year (PE*a). This is mainly due to the biogas generated in anaerobic digestion and the substitution of fossil fuels in co-incineration. Similarly, the carbon footprint of the process reveals an amount of 11.6 kg CO_2-eq/(PE*a) as avoided emissions, thus indicating the environmental benefits of energy recovery from sewage sludge. However, process emissions of the powerful greenhouse gases CH_4 and N_2O are estimated based on generic emission factors from literature, and can have a distinct influence on the overall carbon footprint. This underlines the necessity to support the results of this LCA with primary data from monitoring of emissions on-site.

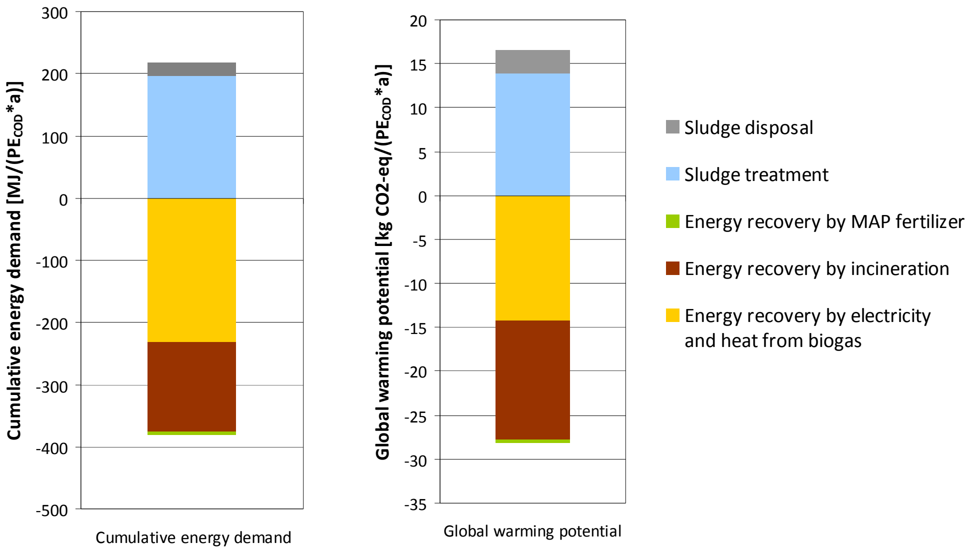

Figure 5: Cumulative energy demand and carbon footprint of sludge treatment and disposal in Waßmannsdorf 2009

The evaluation of optimization measures shows that the different routes for sludge disposal differ heavily in their environmental profile and reveal potentials for optimisation, especially in mono-incineration of sewage sludge. Some measures are beneficial for both energy and carbon footprint, while others can decrease energy demand, but may potentially increase the emission of powerful greenhouse gases such as N_2O (treatment of sludge liquor by deammonification).

Chapter 6

Risk Assessment (KWB, AVB)

In this work package, a risk assessment of the wastewater scheme in Braunschweig was initiated following the methodology of Water Safety Plans for the drinking water sector (HACCP concept). As a first step towards an overall risk-based management approach, the following issues of potential risk are analysed:

- Risk for human health due to pathogens in effluent used for agricultural irrigation
- Risk for human health due to input of heavy metals into agricultural soil
- Risk for terrestrial and aquatic ecosystems due to input of heavy metals in surface waters and agricultural soil

After hazard identification and characterization, risk assessment was conducted for risks associated with pathogens and heavy metals contained in WWTP effluent and sludge. Other risks of potential concern (e.g. organic pollutants, nitrate to groundwater) are not considered in the scope of this study.

<u>Risks for human health due to pathogens</u>

For this part, quantitative microbial risk assessment (QMRA) was conducted according to the WHO procedures. After identification of relevant pathogens, literature information was collected for all relevant parts of the system and used to characterize WWTP influent and effluent in terms of pathogen content. Scenarios for microbial risks are conducted for fieldworkers, nearby residents and children ingesting soil using a 1000 trial Monte Carlo Simulation. As a tolerable value of risk, an additional disease burden of 1 µDALY is set following the current WHO guidelines for wastewater reuse. This corresponds to an additional risk of a light gastroenteritis of 1:1000.

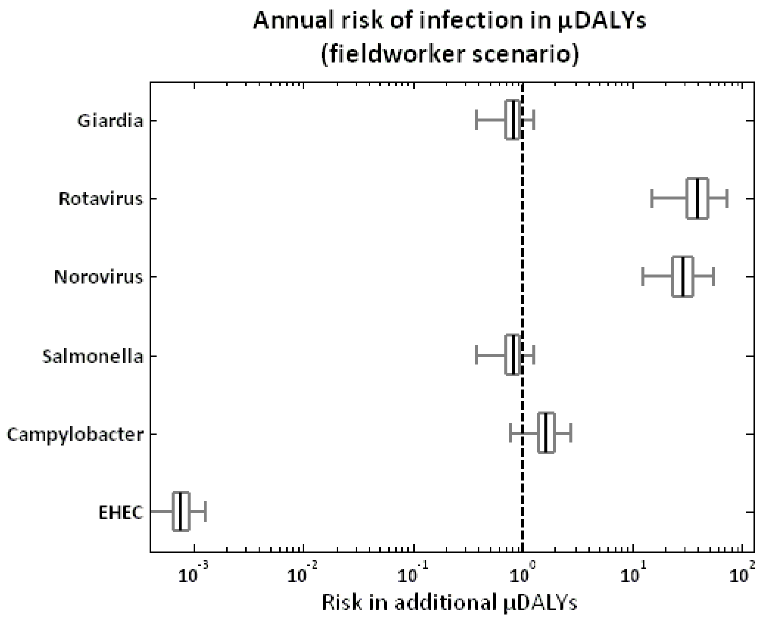

Figure 6: Annual risk of infection for the fieldworker scenario (dotted line is WHO standard = 1 µDALY; existing risk of infection with rotavirus and norovirus is 110 and 14 µDALY per person and year in Germany)

Acceptable risks of infection defined by WHO guidelines were substantially exceeded by viruses (Norovirus and Rotavirus) in the scenarios for fieldworkers (Figure 6) and playing children. The additional risk of infection approached the “background” existing risk in Germany of respectively 110 and 14 µDALY per person and year for rotavirus and norovirus. Based on the model results an additional reduction of 1.5log units is recommended for viruses to comply with the WHO guideline value. However, these results are only calculated based on literature values and should be validated with regular monitoring of WWTP effluent and sludge for selected pathogens.

Risk for human health and ecosystems due to heavy metals

For heavy metals, potential impacts on the terrestrial and aquatic ecosystems as well as on human health are assessed using the methods outlined in the *European Union Technical Guidance Document on Risk Assessment*. Tolerable limits of heavy metal concentration in soil are derived from acceptable daily intake levels for humans, whereas tolerable limits for ecotoxicity are derived from predicted no-effect concentrations (PNEC) of ecotoxicity tests.

For human consumption, the accumulation of Cadmium in wheat proved to be of highest concern in risk assessment. Based on predicted soil-plant transfer ratios, acceptable soil concentrations for Cadmium could be derived (0.5-0.8 mg Cd/kg TS) and compared to predicted values for agricultural soil in Braunschweig. Model results show slightly decreasing soli concentrations. These results include however large uncertainties due to a high variation in input data that could not be verified through monitoring results for Cd in soil (Figure 7). Therefore a close monitoring of Cd is recommended in the future for the agricultural area in Braunschweig, in particular on the parcels showing the highest soil concentrations.

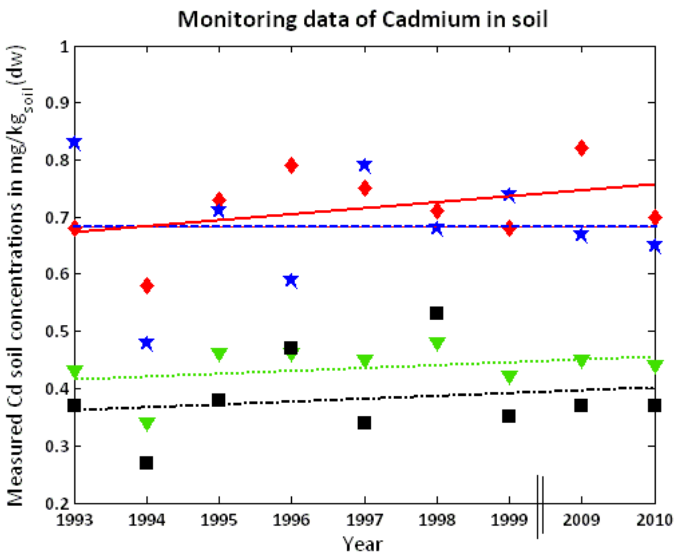

Figure 7: Monitoring data of different areas in Braunschweig irrigated with WWTP effluent and sludge

For ecotoxicity, no relevant risks for aquatic or terrestrial ecosystems could be detected, according to the State of the Art. Again, the model predictions of heavy metal accumulation should be validated by close monitoring of heavy metal concentrations in soil and mass balances of the agricultural fields to detect any potential risks at an early stage.

Chapter 7
Conclusion and outlook

Pilot and full-scale trials of co-digestion and thermal hydrolysis

Pilot trials of digestion in lab reactors show promising results for increasing CH_4 yield of the digestion process for both co-digestion of grass silage (+31% related to VS of sludge only) and thermal hydrolysis (+10-20% related to VS of sludge only , depending on configuration). The experimental results can be validated by high precision of relevant mass balances. No critical accumulation or evolution of inorganic and organic pollutants is detected during the trials. Thermo-gravimetric analysis indicates a positive effect of both options on dewaterability of the digested sludge. Return loads of COD in sludge liquor tend to increase for both co-digestion and thermal hydrolysis, the latter forming refractory COD due to high temperatures in hydrolysis.

Full-scale trials of co-digestion with grass silage at the WWTP Braunschweig show that the technical realisation of grass addition is feasible with reasonable efforts. However, the promising lab results for a substantial increase in biogas yield cannot be reproduced in full-scale. Despite a TS addition of +10% of grass silage, only a marginal increase in biogas production (+2%) can be measured compared to a reference digestor. Possible reasons are identified as follows:

- Shortening of hydraulic retention time in digestor by addition of flush water to feed grass into the digestor
- Insufficient chopping of grass silage in full-scale (2-3cm) delaying biological degradation of the fibres
- Poor hydraulic mixing in the reactor → separation of grass silage and sludge (formation of grass layer?) → formation of deposits/dead zones with grass silage, low effective hydraulic retention time

After a thorough interpretation of the experimental data (TS + VS reduction), a difference between pilot and full scale trials could be attributed to poor hydrodynamics and phase separation between grass silage and sludge (hydrodynamics and phase separation were not investigated but may have a high impact on gas production) . Also the addition of flush water and a larger fibre size are contributing to the lower effectiveness observed in full-scale. Beside the technical aspects, it is to assume that the different sampling strategies (1-2 samples/week in full-scale, compared to the complete assessment of all substrate batches in lab-scale) also had an influence on the accuracy and the comparability of the results.

Finally, a high potential of co-digestion and thermal hydrolysis is identified in pilot trials to increase biogas yield and improve the energy balance and carbon footprint of the wastewater scheme in Braunschweig. Existing barriers to implementation have been encountered in full-scale trials and the respective needs in future R&D have been identified (Table 4). An economic analysis is recommended to estimate costs and economic benefits of co-digestion with grass silage, including harvesting, silage, personnel expenditure at the WWTP and sludge disposal costs.

Table 4: Potential and barriers for implementation and resulting needs in R&D

Topic	Potential for CH_4 increase	Barriers to implementation	R&D needs
Status quo	?	- improve mixing in digestors	- RTD analysis
Co-Digestion (+10% TS grass)	+31%	- fibre size - hydrodynamics in full-scale digestor - feeding/mixing grass with sludge	- pilot trials with different size of grass - RTD analysis - system analysis
DLD (Exelys™)	+19%	- impact on dewaterability - energy balance / process scheme - centrate: refractory COD	- demo plant based on Hilerod (results of Krüger), data available - liquor treatment
DLD + Co-digestion (+10% TS grass)	> 38%?	- not assessed	- pilot trials

Environmental footprinting with Life Cycle Assessment in Berlin + Braunschweig

The methodology of Life Cycle Assessment is successfully applied to assess the environmental footprint of the wastewater scheme in Braunschweig and the sludge treatment line in Berlin-Waßmannsdorf. In addition to an inventory of the status quo of both systems to identify the sub-processes with high impacts for the environment, a set of optimisation measures is analysed to reveal promising options to reduce the environmental footprint. For the sludge treatment line in Berlin, it can be concluded that digestion of sludge and subsequent incineration generates considerable credits in energy balance and carbon footprint for the WWTP due to electricity and heat generation from biogas and substitution of fossil fuels in co-incineration.

Environmental benefits of the reuse approach in Braunschweig are quantified and relate mostly to the lower discharge of nutrients and other pollutants into surface waters. The LCA results indicate the importance to maintain the primary function of the WWTP (protection of surface waters) before optimisation of secondary issues such as energy demand and carbon footprint. The methodology of LCA used in the Braunschweig study is certified by an external expert to be in line with the requirements of ISO 14040/44 (“critical review”).

Risk assessment of the Braunschweig reuse system

Adopting the methodology of Water Safety Plans for the sanitation sector, a risk assessment is initiated following the HACCP concept. Using state-of-the-art models for risk estimation, potential risks of the Braunschweig approach for human health and the environment are quantified for both hygienic risks (pathogens) and chemical risks (heavy metals). Building upon available system data amended by assumptions from literature, the results of the study should now be validated with extended monitoring of selected issues of concern, e.g. content of pathogenic viruses in WWTP effluent and accumulation of Cd in agricultural soil.

Recommendations for system optimisation

Based on the results of the research project CoDiGreen, recommendation can be derived for the optimisation of the wastewater schemes in Braunschweig and Berlin.

For the Braunschweig system, the following actions are recommended:

- Implementation of DLD demo plant with EXELYS™ process
- Implementation of an Organic Rankine Cycle (ORC) process for conversion of excess heat into electricity
- Analysis of hydraulic mixing performance in existing full-scale digestors
- Pilot trials to confirm and overcome barriers in co-digestion of grass silage (fibre size, mixing in digestor)
- Full-scale trials of co-digestion with grass under thermophilic conditions
- Economic assessment of co-digestion and scenarios to identify potentials and restrictions
- Investigations to identify and quantify the influence of co-digestion and thermal hydrolysis on sludge dewaterability
- Monitoring of potential risks from agricultural reuse: sampling of WWTP influent, effluent and sludge for pathogenic viruses for one year, regular soil sampling of representative farmland for Cd content + setup of mass balances

For the Berlin system, the following actions are recommended:

- Extension of LCA study to include entire WWTP to assess side effects of measures in sludge treatment line
- Complement of existing analysis of energy balance and carbon footprint with other environmental indicators (e.g. human and eco-toxicity) for a comprehensive assessment of optimisation measures
- Optimization of mono-incineration facility in terms of energy balance (pre-drying of digested sludge?) and N_2O emissions
- Extended use of co-substrates in digestion with close monitoring of side-effects (dewaterability, liquor)
- Target the utilization of excess heat, e.g. with Organic Rankine Cycle process.

Chapter 8
Publication list

Conference presentations + papers

Klein D (2011): Improving biogas production on wastewater treatment plants by co-digestion of grass. Presentation at conference “Progress in Biogas”, 30 Mar-1 Apr, Stuttgart, Germany

Mieske R, Fülling K, Dockhorn T, and Dichtl N (2011): Influence of thermal disintegration in terms of biogas production and sludge properties in co-fermentation. Presentation at symposium “ReWater 2011”, 21-22 Nov 2011, Braunschweig, Germany.

Remy C, Lesjean B, and Waschnewski J (2011): Sustainable sewage treatment plant of the future: identifying global warming and energy optimization potentials with Life Cycle Assessment. Presentation at IWA conference “Cities of the Future”, 22-25 May 2011, Stockholm, Sweden, paper accepted for peer review in *Water Science & Technology*

Remy C, Lesjean B, and Siemers C (2011): Evaluation and optimisation of the environmental footprint of the Braunschweig sanitation concept with Life Cycle Assessment. Presentation at symposium “ReWater 2011”, 21-22 Nov 2011, Braunschweig, Germany.

Remy C and Siemers C (2012): Environmental assessment of the Braunschweig system of agricultural reuse of effluent with Life Cycle Assessment. Presentation to be held at conference “45. Essener Tagung 2012”, 14-16 Mar 2012, Essen, Germany.

Remy C, Siemers C, and Lesjean B (2012): Assessing the environmental sustainability of agricultural reuse of WWTP effluent and biosolids in Braunschweig/Germany with Life Cycle Assessment. Presentation to be held at conference “IWA World Congress on Water, Climate and Energy”, 14-18 May 2012, Dublin, Ireland.

Project deliverable reports

D 1.1 B. Lesjean and C. Remy “Optimisation of energy and nutrient recovery in wastewater treatment schemes – Executive Summary of Project CoDiGreen”

D 2.2 C. Remy: “LCA study in Berlin-Waßmannsdorf”

D 2.4 C. Remy: “LCA study of Braunschweig system”

D 2.6 W. Seis: “Risk assessment of the wastewater-reuse strategy of Braunschweig” (diploma thesis)

D 3.3+3.5: T. Dockhorn, D. Klein, K. Fülling and R. Mieske: “Optimisation of energy and nutrient recovery in wastewater treatment schemes: pilot and full-scale trials”

All reports are available for download in www.kompetenz-wasser.de

Appendix A

Information from a visit to Wolfsburg WWTP (19 Jan 2011) by B. Lesjean + C. Remy

Contact: Marc Stueben, marc.stueben@web.wolfsburg.de, Tel. +49 5361 281220

System layout in Wolfsburg

- **Collection of wastewater** from Wolfsburg city + smaller municipalities (total: 170000 person equivalents), separate sewer (no stormwater), low industrial contribution
- **Pumping** of wastewater to WWTP (~ 10 km)
- **Wastewater treatment:**
  - Mechanical treatment (rake + grit chamber)
  - No primary treatment
  - 6 tanks for activated sludge (Bio-P + nitrification/denitrification in cascading tanks), no nitrogen removal in summer (maximizing N recovery in agriculture)
  - clarifier
- **Sludge treatment** (only excess sludge!):
  - Sludge thickening in static thickeners
  - Dewatering in centrifuges → DM = 20%
  - Drying → DM > 90%
  - Sludge to power plant (VW)
- **Effluent discharge:**
  - Buffering in pond system (~ 1-2d as volume buffer)
  - Pumping to agricultural irrigation system
  - In winter: groundwater recharge
  - Hydraulic peak loads → surface waters (river Aller)
- **Agriculture**
  - Management of irrigation system by WEB (~ 1500 ha)
  - System of pressure pipes for distribution
  - In case of water scarcity (summer): additional pumping of groundwater
- **Biogas plant**
  - Feed: only maize (~ 700 ha)
  - Stable full-time operation
  - Electricity → 17 Mio kWh/a to grid (payment via EEG)
  - Heat → sludge drying

WWTP operation

- Influent: ~ 8 Mio m³/a, ca. 170000 person equivalents,
- COD removal continuously, effluent limit: < 20 mg/L to avoid wastewater charges (discharge to irrigation and groundwater recharge is (legally) equal to discharge to surface waters, however the limits have to be guaranteed in monitoring wells above groundwater table = polishing effect of soil passage can be accounted)
- Phosphorus removal continuously but only in winter (effluent limit: 1 mg/L) via Bio-P (Fe precipitation as backup). In summer: no removal. P demand in agriculture is met to 100% (accumulated P in soil from 70 years of spreading raw wastewater)

- Nitrogen removal only in winter (limit: 18 mg/L N_{total}, 5 mg/L NH_4 (?)), very good denitrification with effluent levels < 5 mg/L, in summer: no nitrogen removal to maximize N transfer to agriculture
- Sludge (~ 10 t DM/d, no anaerobic stabilization in digestior) has to be dewatered (centrifuge + polymers), dried (belt drier with heat from biogas plant) and incinerated (power plant of VW) due to concerns of consumers (food industry) → no recycling of P in sludge! This could be changed in the future (composting? application to agriculture?)
- Normally, no direct discharge into surface waters (river Aller), only in case of hydraulic peak loads, in total < 10% of volume
- Total electricity demand of 10-11 Mio kWh (incl. pumping, WWTP, irrigation), biogas plant yields 17 Mio kWh → self-sufficient system

Agricultural reuse of effluent

- Two irrigation areas for spreading of wastewater (Brackstedt + Jembke), ~ 1500 ha
- Total discharge to agriculture ~ 6 Mio m³/a (= 390 mm, ~ 40 mm per month)
- Farmers are obliged to accept wastewater for irrigation (sometimes more than they need)
- Fee for farmers: ~ 45 Euro/ha*a for irrigation
- WEB operates irrigation system (piping system, machinery, staff of 15)
- Daily control of weather condition (own weather station)
- Fields are partially operated with drainage system to prevent flooding
- WEB has to guarantee that groundwater is not affected by irrigation
- In case of water shortage for irrigation (dry spring + summer), recharged groundwater can be partially recovered to fill this gap
- If fields are removed from irrigation system (housing developments, road construction etc), equivalent alternative fields are prepared:
    - Installation of infrastructure for irrigation (piping, field roads for heavy machinery)
    - Investigation of soil properties
    - Monitoring wells
- WEB has to manage prevention against transport of aerosols by wind (30 ha of hedges) if settlements, roads etc, are nearby

Groundwater recharge

- Recharge area of 300 ha (mostly forest) with large trenches infiltrating into gravel layer
- Two groundwater layers separated by impermeable barrier → no hydraulic connection between aquifers (lower aquifer is used for drinking water production!)
- Recharge of groundwater in upper aquifer with purified wastewater in winter (~ 1.800.000 m3/a)
- Recovery of recharged groundwater for irrigation possible (dry summer), but in average < 0.6 Mio m³ annual surplus in groundwater → continuous replenishment of groundwater resources!
- Recovery wells are in direction of natural groundwater flow, minimum retention time in soil > few months
- Close monitoring of groundwater quantity and quality with many observation wells
- Modelling of groundwater flow with hydrodynamic models

Costs

- In total, 0.63 Euro/m³ for wastewater treatment incl. spreading (not collection + sewers!)
- 0.18 Euro/m³ for spreading (infrastructure + pumping costs + maintenance)