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Project CoDiGreen

Work package 2:

LCA study of Braunschweig wastewater scheme

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Abstract (English)

The present study 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. 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. The scenarios include the addition of different co-substrates, thermal hydrolysis of sludge in various configurations, nutrient recovery for nitrogen and phosphorus, and utilization of excess heat via an Organic Rankine Cycle (ORC).

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 to German conditions, 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. 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 per inhabitants in Germany. Consequently, the optimisation of the latter environmental impacts should only be pursued if the primary function of the sewage treatment and related impacts on surface waters are not compromised by these measures.

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, whereas the implementation of an ORC process for energy recovery from excess heat can be fully recommended from an environmental point of view.

Abstract (German)

Die vorliegende Studie bestimmt und analysiert den ökologischen Fußabdruck des Braunschweiger Abwassersystems mit der Methodik der Ökobilanz (Life Cycle Assessment). Alle relevanten Prozesse der Abwasserbehandlung werden basierend auf Daten aus dem Anlagenbetrieb in 2010 in einem Stoffstrommodell abgebildet, um daraus den Ressourcenverbrauch und die aggregierten Emissionen zu berechnen. Produkte des Systems (Strom aus Biogas, Nährstoffe, Wasser zur Bewässerung) werden über Gutschriften für die entsprechend ersetzten Industrieprodukte angerechnet. Neben der Erfassung der aktuellen Umweltwirkungen werden zudem Szenarien zur Optimierung der Energie- und Nährstoffrückgewinnung in ihren Auswirkungen auf den ökologischen Fußabdruck analysiert. Dies umfasst die Zugabe von Co-Substraten, thermische Hydrolyse des Schlamms in verschiedenen Konfigurationen, die vermehrte Rückgewinnung von Stickstoff und Phosphor sowie die Nutzung von Abwärme über einen Organic Rankine Cycle (ORC).

Die Energiebilanz des Braunschweiger Systems ist vergleichsweise gut, da 79% des kumulierten Energieaufwands durch Sekundärprodukte ausgeglichen werden kann, vor allem durch Biogas (58%) und Substitution von Mineraldünger (14%). Die Optimierung von Nährstoff- und vor allem Wassermanagement bietet hier noch erhebliches Potential zur Verbesserung der Energiebilanz, letzteres bedingt durch den hohen Stromverbrauch zum Verteilen des Klarwassers in der Landwirtschaft. Der CO_2-Fußabdruck des Systems beträgt netto 10 kg CO_2-eq/(EW_{CSB}*a) und wird überwiegend durch energetische Prozesse verursacht, ergänzt durch direkte Emissionen von N_2O und CH_4 aus dem Belebungsverfahren. Die Emission von Nährstoffen in Oberflächengewässer ist relativ gering (29 g P bzw. 80 g N/(EW_{CSB}*a)), da Nährstoffe in die Landwirtschaft umgeleitet oder im Rieselfeld weitgehend entfernt werden. Während die Wirkungen in der Humantoxizität nach der Normalisierung auf die gesamten Emissionen in Deutschland gering sind, verursachen die Emissionen von Cu und Zn in aquatische und terrestrische Ökosysteme merkliche Effekte im Bereich der Ökotoxizität (organische Stoffe wurden hier nicht berücksichtigt). Die Normalisierung des ökologischen Fußabdrucks verdeutlicht die Primärfunktion der Abwasserreinigung, nämlich den Schutz der Oberflächengewässer vor organischen und anorganischen Schadstoffen und überhöhtem Nährstoffeintrag. Während der quantitative Beitrag des Systems zur Eutrophierung und Ökotoxizität hoch ist, liefern Energieverbrauch und damit korrelierende Indikatoren (CO_2-Fußabdruck, Versauerung, Humantoxizität) nur einen geringen Beitrag zu den gesamten Umweltwirkungen pro Einwohner in Deutschland. Als Konsequenz sollten letztere Indikatoren nur durch solche Maßnahmen optimiert werden, die die Primärfunktion der Kläranlage (= Gewässerschutz) nicht verschlechtern.

Die Szenarioanalyse zeigt, dass sowohl die Zugabe von Co-Substraten als auch die thermische Hydrolyse einen substantiellen Beitrag zur Verbesserung der energetischen Bilanz und des CO_2-Fußabdrucks bewirken, ohne andere negative Umweltwirkungen auszulösen. Basierend auf Ergebnissen der Pilotversuche in CoDiGreen kann der momentane Energieverbrauch durch die Kombination aus der Zugabe von Grassilage und einer thermischen Hydrolyse des Überschussschlamms um bis zu 80% gesenkt werden. Vielversprechend ist auch ein zweistufiger Prozess mit Entwässerung vor der Hydrolyse (DLD mit EXELYS™). Während die vermehrte Rückgewinnung von Stickstoff und Phosphor nicht zu merklichen Verbesserungen des Umweltprofils führt, kann eine Abwärmenutzung über einen ORC-Prozess uneingeschränkt empfohlen werden.

Abstract (French)

Cette étude analyse l'empreinte environnementale du système d'assainissement de Braunschweig utilisant la méthode de l'Analyse du Cycle de Vie. Tous les procédés relevant du traitement et de l'élimination des eaux usées sont simulés dans un modèle de flux de matières basé sur les données disponibles à grande échelle (année 2010) et complété par des données de la littérature pour calculer les émissions agrégées et les demandes en ressources du système. Les produits du système (électricité générée lors de la combustion du biogaz, nutriments, et eau pour l'irrigation) sont imputés de crédits correspondant au produit industriel substitué respectif. En plus de l'évaluation du système de Braunschweig en 2010, une série de scénarios, qui ciblent des taux de récupération de l'énergie et des nutriments améliorés, est évaluée pour optimiser les impacts sur l'empreinte environnementale. Les scénarios incluent l'addition de différents co-substrats, l'hydrolyse thermique de la boue dans différentes configurations, la récupération du phosphore et de l'azote, et l'utilisation de la chaleur en excès par le cycle organique de Rankine (COR).

La balance énergétique du système est comparativement bonne, 79% de la demande énergétique cumulative peut être compensée par des produits secondaires, principalement biogaz (58 %) et fertilisants de substitutions (14%). L'optimisation des nutriments et de la gestion de l'eau offre un potentiel considérable pour améliorer la balance énergétique, étant donné la haute demande en énergie pour pomper l'eau dans les champs. L'empreinte carbone nette du système s'élève à 10 kg CO_2-eq/(PE_{COD}*a) et est principalement causée par la demande en énergie, augmentée par l'émission directe de N_2O et CH_4 dans le procédé boue activée. Les émissions de nutriments dans les eaux de surface sont relativement basses (29 g P et 80 g N/(PE_{COD}*a)) dues au transfert de nutriments en agriculture et à l'effet de polissage des champs d'infiltration. Alors que les effets sur la toxicité de l'homme sont réduits après normalisation des impacts à l'échelle de l'Allemagne, les émissions de cuivre et de zinc dans les écosystèmes aquatiques et terrestres causent un impact sensible sur l'écotoxicité (substances organiques non prises en compte). La normalisation de l'empreinte environnementale révèle la fonction primaire des stations d'épuration, à savoir la protection des eaux de surface des polluants organiques et inorganiques et l'introduction excessive de nutriments. Tandis que la contribution du système est haute pour l'eutrophication et l'écotoxicité, la consommation énergétique et les indicateurs corrélés tel que l'empreinte carbone, l'acidification et la toxicité de l'homme ont seulement une part mineure sur l'empreinte environnementale totale par habitants en Allemagne. En conséquence, l'optimisation des impacts secondaires tels que la demande en énergie ou l'empreinte carbone devraient seulement être effectué si la fonction primaire de l'épuration et ses impacts sur les eaux de surface ne sont pas compromis par ses mesures.

L'analyse des scénarios montre que tant l'addition de co-substrats que l'hydrolyse thermique de la boue pour améliorer la dégradation anaérobique en biogaz ont un effet positif substantiel sur la balance énergétique et l'empreinte carbone sans détériorer les autres impacts environnementaux. Basés sur les résultats des essais pilotes dans CoDiGreen, la demande en énergie actuelle peut être réduite jusqu'à 80% en combinant l'addition d'herbe ensilée dans le digesteur et l'hydrolyse de la boue en excès (potentiels à vérifier avec des essais à grande échelle). Un procédé de digestion en 2 étapes avec une déshydratation intermédiaire et une hydrolyse (configuration DLD avec EXELYS^{TM}) semble prometteur en termes de bénéfice énergétique et d'empreinte carbone. La récupération de l'azote et du phosphore de la boue ne présentent pas de bénéfices environnementaux majeurs, mais l'implémentation d'un procédé COR pour récupérer de l'énergie de la chaleur en excès est vivement recommandé d'un point de vue environnemental.

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The substance flow model of the process is based on a variety of data collected from the full-scale plant in Braunschweig Steinhof. Additionally, the approach of the study and the results have been discussed in detail with the project team of CoDiGreen. In particular, the following persons are thanked for their support and for interesting discussions: Prof. Thomas Dockhorn, Daniel Klein, Robert Mieske, and Karsten Fülling. The help of Daniel Mutz as co-worker for the UMBERTO™ model is greatly appreciated.

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Acronyms

AVB	-	Abwasserverband Braunschweig (Wastewater association Braunschweig)
BS	-	Braunschweig
CED	-	Cumulative energy demand
CFC	-	Chlorofluorocarbon
CHP	-	Combined heat and power plant
COD	-	Chemical oxygen demand
DS	-	Dry solids
GJ	-	Gigajoule
GHG	-	Greenhouse gas
GWP	-	Global warming potential
IPCC	-	Intergovernmental Panel on Climate Change
ISO	-	International Organisation for Standardisation
LCA	-	Life Cycle Assessment
MAP	-	Magnesium-Ammonium-Phosphate
MJ	-	Megajoule
oDM	-	Organic dry matter
ORC	-	Organic Rankine Cycle
PAH	-	Polychlorinated aromatic hydrocarbons
PCB	-	Polychlorinated biphenyls
PCDD	-	Polychlorinated dibenzodioxins
PCDF	-	Polychlorinated dibenzofurans
PE	-	Population equivalent
SE/BS	-	Stadtentwässerung Braunschweig (Wastewater utility of Braunschweig)
TS	-	Total solids
UBA	-	Umweltbundesamt (German Federal Environment Agency)
WWTP	-	Wastewater treatment plant

Chapter 1

Introduction and layout of the study

The treatment and disposal of municipal wastewater has developed into a complex process nowadays. In addition to the primary functions of a wastewater treatment plant (WWTP), i.e. the protection of receiving surface waters against negative influences of organic and inorganic pollutants and excessive nutrient input, modern wastewater treatment plants target the recovery of valuable resources from the wastewater. In particular, energy and plant nutrients (phosphorus and nitrogen) can be recovered by technical processes to utilize the potentially exploitable content of the wastewater and close energy and material cycles of society.

However, the purification of the wastewater and the recovery of energy and nutrients require the input of higher amounts of energy (mainly electricity) and chemicals and generate higher volumes of sewage sludge, which is a sink for organic and inorganic pollutants in the wastewater and has to be disposed of. Energy recovery from sewage sludge is mainly based on anaerobic digestion of the sludge, producing biogas which can be converted into electricity and heat in combined heat and power (CHP) plants on-site. Nutrient recovery can either be reached by agricultural application of the stabilized sludge on farmland or by extraction of nutrients from sludge or highly concentrated side-streams (e.g. liquor from sludge dewatering) by specific process steps. While the disposal of sludge in agriculture is practiced in many small and medium-scale WWTPs, nutrient recovery in large WWTPs is mainly based on sophisticated technologies to extract P and N from sludge, liquors or ashes of sludge incineration.

The wastewater treatment scheme of the city of Braunschweig treats and disposes the municipal wastewater from around 350000 inhabitants. Historically, the system is based on the spreading of treated wastewater (= effluent) and sludge in agriculture through a fixed system of pumping stations and pipes, delivering water and nutrients to 3000 ha of farmland near the WWTP (Eggers 2008). The continuous operation of the system since 1954 is a well-managed example of agricultural reuse of WWTP effluent and sludge in a highly industrialized country, a practice which is more and more recommended by experts worldwide to overcome local problems of water scarcity and close local water and nutrient cycles. Thus, the Braunschweig wastewater scheme is a fairly unique system in the German context where possible future options for wastewater treatment and disposal can be studied in detail.

However, the overall benefits of this approach in mitigating potential impacts on the environment still have to be verified in a holistic and comprehensive analysis of the system. The implementation of agricultural reuse is associated with additional demand for energy and resources, and both effluent and sludge contain a variety of organic and inorganic substances which may be potentially harmful for humans or eco-systems. Hence, the key questions to be answered are related to the overall environmental footprint of the Braunschweig system: does the agricultural reuse of WWTP effluent and sludge lead to lower environmental impacts of wastewater treatment if referenced to a conventional system? How can these benefits and potential drawbacks of agricultural reuse be identified and – if possible – quantified? And how can we optimize the wastewater scheme in Braunschweig to maximize its environmental benefits and minimize potential drawbacks?

A suitable tool for the holistic and comprehensive analysis of the potential environmental impacts of a technical process is the method of Life Cycle Assessment (LCA). Following a standardized methodology (ISO 14040/44), LCA quantifies potential environmental impacts over the whole life cycle of a process, i.e. including all relevant upstream or downstream processes which are directly related to the product system. By aggregating all flows of resources or emissions into the environment, the total sum of resource demand and emissions is calculated and evaluated with a set of scientifically-derived environmental indicators describing specific issues of environmental concern, e.g. impacts on global warming, eutrophication or ecotoxicity. Thus, relative contributions of sub-processes or specific life cycle stages as well as potential trade-offs in environmental impacts can be identified and characterized in a quantitative approach to provide decision support for the implementation of measures for system optimization.

Within the research project “CoDiGreen” (2010-2012) managed by the Berlin Centre of Competence for Water (KWB), the Braunschweig wastewater scheme is assessed in its environmental footprint via the methodology of LCA. In particular, the following tasks of interest are addressed:

1. Characterize quantitatively the environmental footprint[1] of the existing system of wastewater management and disposal in Braunschweig
2. Reference the Braunschweig wastewater scheme to a conventional system of wastewater treatment and disposal (= no agricultural reuse of effluent) to identify specific benefits and drawbacks of the reuse approach in Braunschweig
3. Identify promising measures for optimisation of the environmental footprint of the Braunschweig wastewater scheme, based on the experimental results of the research project “CoDiGreen”

Therefore, a Life Cycle Assessment of the Braunschweig wastewater scheme is conducted according to the methodology defined in ISO 14040/44 (ISO 14040 2006; ISO 14044 2006). This report contains the single steps of the LCA and is structured as follows:

- Definition of goal and scope (chapter 2)
- Life cycle inventory (chapter 3)
- Life cycle impact assessment (chapter 4)
- Interpretation and conclusions (chapter 4 + 5)

To comply with the ISO standard 14040, a critical review of the applied LCA methodology is conducted by Prof. Dr. Matthias Finkbeiner (TU Berlin, Department of Sustainable Engineering). The review includes the definitions of the study (“goal and scope”) and the methodological approach as well as the conclusions drawn from the analysis. The verification of life cycle inventory data is explicitly excluded from the review. The review statement is attached at the end of this document.

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[1] Environmental footprint is used here as a synonym for LCA

Chapter 2
Definition of goal and scope

2.1 Goal and target group

The goal of this Life Cycle Assessment is to assess the environmental impacts of the Braunschweig wastewater scheme and identify potentials for lowering its environmental footprint. This includes the analysis of the status quo of the Braunschweig system in the year 2010 as well as different scenarios for optimisation, based on the results of the research project “CoDiGreen”. The scope of the study encompasses the wastewater treatment plant Braunschweig-Steinhof, the infiltration fields, and the delivery of purified effluent and sewage sludge to agriculture for irrigation purposes. Regarding the environmental impacts, the study has a focus on energetic aspects and emissions into the environment. The primary target group of this study consists of operators and decision-makers within the wastewater utility (Stadtentwässerung Braunschweig), Veolia Water as the operating company, and researchers within the scientific community related to water and wastewater management. Additionally, results of this study will be utilized to inform institutional staff and the interested public on the environmental impacts associated with the operation of the wastewater treatment scheme in Braunschweig. The results of this study are not intended to be used in comparative assertions intended to be disclosed to the public.

2.2 Function and functional unit

The function of the system under review is the **treatment and disposal of municipal wastewater in the wastewater treatment scheme at Braunschweig-Steinhof (WWTP BS) to reach the legally required emission levels (AbwV 2004)**. Additionally, secondary functions of the system (recovery of energy, nutrients and water) are influencing the results of this study (cf. 2.4).

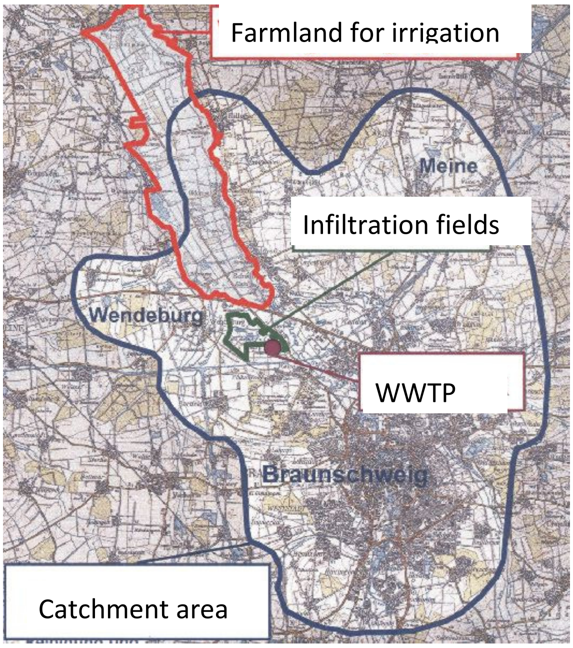


Figure 1: Map of Braunschweig wastewater scheme

The wastewater of the city of Braunschweig and surrounding communities is delivered by pumping stations to the WWTP at Steinhof (~ 10 km north-west of the city centre, see Figure 1). Here, the wastewater is treated for the removal of suspended solids, organic matter, and nutrients N and P in a conventional activated sludge process with nutrient removal. Part of the purified effluent from the process is then spread on historic infiltration fields (220 ha, in operation for more than 100a) for polishing prior to its discharge to surface waters via the Aue-Oker canal. The remaining part of the effluent is pumped to a dedicated agricultural area where it is spread on agricultural fields (= agricultural reuse of purified effluent). Sewage sludge is stabilised via anaerobic digestion and then added to the effluent during spring and summer (Mar-Sep) to recycle the contained nutrients to agriculture. During winter and a short summer period (4 weeks), stabilised sludge is dewatered and stored on-site before it is applied to agricultural fields in the greater Braunschweig area (outside the agricultural area for spray irrigation). All activities related to the reuse of effluent and sludge in agriculture are operated by the Braunschweig wastewater association ("Abwasserverband Braunschweig") in cooperation with local farmers. The system for agricultural reuse is in operation since 1954 and has been upgraded with a full-scale biological WWTP in 1979 (Eggers 2008).

The functional unit of this LCA relates the function of the system to the total annual organic load of the WWTP, representing the amount of pollution (= organics) that arrives at the WWTP. A common unit in wastewater treatment is the organic load per "population equivalent", which is defined as the amount of 120 g chemical oxygen demand (COD) per person and day (120 g COD/(pe*d), ATV 2000). Consequently, the functional unit of this study is defined as follows:

Functional unit:	Treatment and disposal of municipal wastewater originating from one population equivalent (PE_{COD}) per year → Unit: $(PE_{COD}*a)^{-1}$

On average, it is calculated that the WWTP BS-Steinhof receives a wastewater load of 350000 PE_{COD} per year, of which 280000 PE are from inhabitants of Braunschweig and 70000 PE are from industries (SE/BS 2010). Hence, the total annual environmental impacts are divided by the factor of 350000 to end up with the annual environmental impacts per population equivalent and year.

2.3 Reference input flows

The reference input flow is defined as the annual amount of wastewater that arrives at WWTP BS. The volume and composition of this input flow is compiled from regular measurements of quantity and quality of influent (Table 1). Representative sampling of influent wastewater in a WWTP is a difficult task due to the high variability of inflow volume and quality and the sampling location and procedure. Influent sampling at WWTP Steinhof is done ahead of the primary sedimentation stage, after mechanical treatment and after addition of return flows from sludge dewatering (Figure 2).

In mechanical treatment, coarse material (larger particles, grit, and grease) is removed from the wastewater by screening, grit chamber and grease trap. While screenings and grit are disposed after washing (e.g. in road construction), grease from mechanical treatment is pumped to anaerobic sludge digestion for stabilisation and biogas production. The removal of screenings and grit has no influence on the plant operation, but grease generates some biogas in digestion. Hence, grease is accounted to the wastewater influent, while screenings and grit are neglected here. The quantity of grease is measured (429 t/a), and the quality of grease is estimated from literature (ATV 1998), assuming a dry matter content of 8% and annual loads of 28 t COD, 0.4 t N, and 0.4 t P.

Additionally, the internal return flow from sludge dewatering is added in front of the sampling point, so that this flow has to be subtracted from the influent flow measured at the sampling point. The respective quantity and quality of the return flow from dewatering are described in chapter 3.1.2.

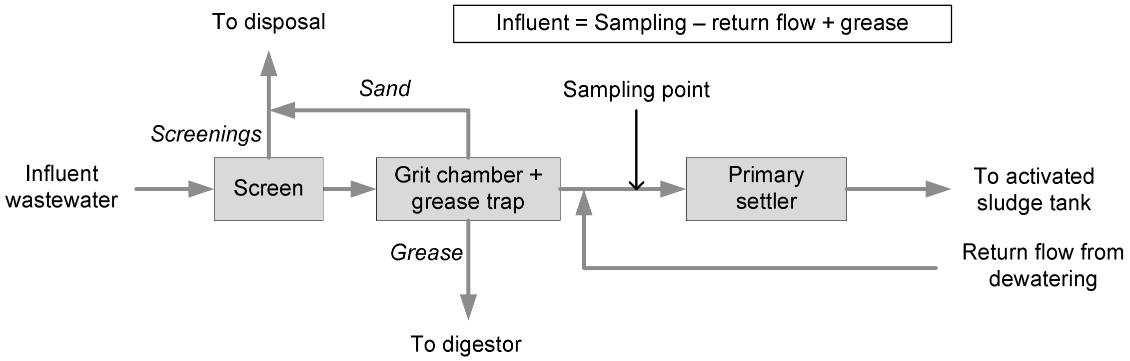


Figure 2: Definition of influent wastewater quantity and quality

Table 1: Reference input flow: quantity and quality of influent wastewater at WWTP Braunschweig-Steinhof in 2010

Parameter	**Mean load per functional unit (PE_{COD}*a)**		**Total annual mean load**		**Annual mean concentration**	
Volume	64.2	*m³*	22.5	*Mio m³/a*		
Dry matter	26.3	*kg*	9196	*t/a*	409	*mg/L*
COD	62	*kg*	21965	*t/a*	966	*mg/L*
Nitrogen	4.3	*kg*	1497	*t/a*	67	*mg/L*
Phosphorus	0.7	*kg*	239	*t/a*	11	*mg/L*
Potassium	1.3	*kg*	465	*t/a*	21	*mg/L*
Cadmium	0.13	*g*	46	*kg/a*	2.1	*µg/L*
Chromium	0.8	*g*	279	*kg/a*	12.4	*µg/L*
Copper	6.1	*g*	2118	*kg/a*	94.3	*µg/L*
Nickel	0.7	*g*	256	*kg/a*	11.4	*µg/L*
Lead	1.5	*g*	512	*kg/a*	22.8	*µg/L*
Mercury	0.02	*g*	6	*kg/a*	0.3	*µg/L*
Zinc	18	*g*	6307	*kg/a*	280.9	*µg/L*

Source: SE/BS 2010

2.4 System expansion

Primarily, the wastewater treatment scheme in Braunschweig fulfils the function of handling and disposal of municipal wastewater. That includes treatment and discharge of purified effluent in infiltration fields or agriculture and anaerobic digestion of sewage sludge prior to its disposal in agriculture. Within these process steps, valuable secondary products can be recovered from the effluent and sludge:

- Biogas with high methane content is generated during anaerobic digestion, which is combusted on-site in combined heat and power (CHP) plants to generate heat and electricity for the plant. Thus, the WWTP can satisfy a major part of its own electricity and heat demand. A direct substitution of natural gas is not considered due to additional processes required prior to the feeding of biogas into the gas grid (purification, enrichment of CH_4 content).
- Purified effluent and stabilised sludge are spread on agricultural farmland. Thus, the water itself and plant nutrients (nitrogen and phosphorus) are delivered to agriculture. Depending on the respective plant availability and substitution potential, these products can substitute irrigation with groundwater and mineral N and P fertilizer.

In this LCA, the secondary products of the Braunschweig wastewater scheme are accounted for by subtracting the environmental impacts of substituted products (electricity, phosphorus and nitrogen mineral fertilizer, or electricity for groundwater pumping) (Table 2). This approach is called “avoided burden” and can be used in LCA to account for secondary functions of processes (Curran 2007). In fact, farmers receiving the effluent and sludge from WWTP BS do apply less groundwater and mineral fertilizer than without the reuse system.

Table 2: Secondary products of wastewater scheme in Braunschweig and their respective substituted products

Secondary products of sludge handling	**Equivalent products accounted as “avoided burden”**
Electricity from biogas combustion	Grid electricity
Heat from biogas combustion	Credits for heat used on-site (“heat utilized”) No credits for excess heat
Nitrogen and phosphorus in effluent and sewage sludge	Mineral nitrogen and phosphorus fertilizer
Water for irrigation	Grid electricity used for pumping of groundwater (up to 100mm/ha*a)

For electricity, the substituted amount of grid electricity is directly calculated as the amount of electricity generated during biogas combustion. Heat generated in CHP plant is either utilized on-site for digester heating and other purposes or is emitted to the environment as excess heat. Hence, heat is not accounted for in the system expansion.

Nutrients in effluent and sewage sludge are accounted with respect to their plant availability and their substitution potential (Table 3). Plant availability depends on the chemical form of the nutrient and is particularly important for phosphorus. The substitution potential relates to the temporal aspects of supply and demand, being an important factor for the substitution of mineral nitrogen fertilizer.

Table 3: Plant availability, substitution potential and effective substitution of nitrogen and phosphorus delivered by Braunschweig wastewater scheme

Nutrient	Plant availability	Substitution potential	Effective substitution
Phosphorus in sludge	80%	100%	80%
Phosphorus in effluent	80%	100%	80%
Nitrogen in sludge (summer)	100%	40%	40%
Nitrogen in sludge (winter)	100%	100%	100%
Nitrogen in effluent	100%	40%	40%

Plant availability and substitution potential of phosphorus

Phosphorus is mainly transferred to sewage sludge during wastewater treatment, and its plant availability is heavily depending on the mode of P elimination: while P in sludge from biological P elimination is readily plant-available, the plant availability of P eliminated by chemical precipitation with ferric salts is known to be limited due to the strong chemical fixation in the precipitates (Coker and Carlton-Smith 1986; Suntheim 2001; IME 2005). At WWTP BS, a mixed mode of P elimination is applied, with biological P elimination and some chemical precipitation with FeCl2. Hence, a limited plant availability for P in sludge of 80% is assumed in this study to reflect the effects of a partial chemical P elimination. Residual P in the WWTP effluent is in dissolved form and is assumed 100% plant-available. Regarding the substitution potential, excess P accumulates in the soil in mineral form (= forming a pool of available nutrient), so that plants can over time access the full amount of P.

Plant availability and substitution potential of nitrogen

For nitrogen, plant availability of N in sludge and effluent is set to be 100% due to its predominant form of inorganic nitrogen (ATV 1996). The fraction of organic-bound nitrogen is assumed to be small, and this slow-releasing nitrogen can be plant-available as well. For the substitution potential, the balance of seasonal supply and demand for nitrogen is essential: nitrogen demand is primarily during the growing season, while excess nitrogen supply during times without demand is quickly denitrified and lost for fertilizer substitution. Unfortunately, the supply of nitrogen with effluent and sludge in the agricultural reuse system is evenly distributed throughout the year, whereas the nitrogen demand is mainly in spring time (Figure 3). Resulting from a rough mass balance, the substitution potential of N in effluent and sludge is estimated to 40% in this study. However, nitrogen contained in dewatered sludge (winter operation) is stored on-site and can be specifically applied during times of nitrogen demand, leading to a substitution potential of 100%.

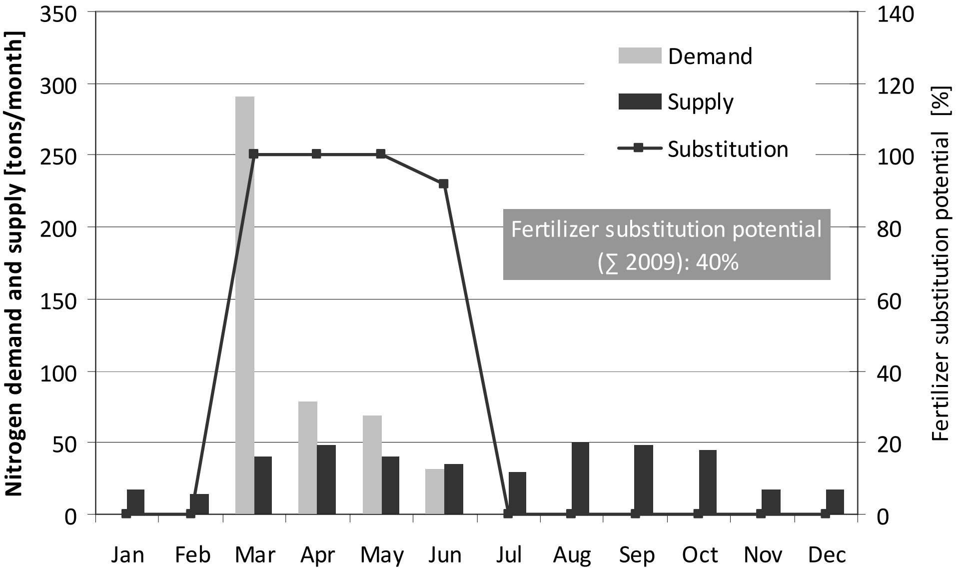


Figure 3: Seasonal variation of nitrogen demand and supply during agricultural reuse in Braunschweig

Substitution of groundwater pumping for irrigation

The continuous supply of irrigation water with the reuse of purified WWTP effluent enables the growing of crops on the sandy soils in the Braunschweig area despite the climatic water deficit (Eggers 2008). However, the effective amount of water required for irrigation is smaller than the actual applied volume: while the farmers would actually need an average amount of 80-150 mm/(ha*a) for plant growth depending on climatic variability (AVB 2011), the wastewater association delivers more than 400 mm/(ha*a) to the farmlands. This fact is due to the historic development of the Braunschweig system and its specific boundary conditions with a small natural receiving water (river Oker): a large part of the WWTP effluent has to be delivered to “soil treatment” for an additional polishing to mitigate negative effects in hydraulic stress and water quality in the river Oker. Consequently, the reuse system is not optimised for the needs of the farmers in terms of nutrients and water supply, but rather serves as an additional treatment step in a historical perspective.

Therefore, the amount of groundwater irrigation that is effectively substituted by reused effluent is set equivalent to the water demand of the farmers, i.e. to 100 mm/(ha*a) on average. All water that is spread on farmlands in excess of this volume does not effectively substitute another product. Is has to be noted here that benefits from additional recharge of the local groundwater resources is not accounted in this study. A future assessment of the water footprint of this system could bring more insight into the benefits of groundwater recharge, but this aspect is out of the scope of this study.

2.5 Description of the investigated scenarios

The baseline scenario of this LCA represents the status quo of the wastewater scheme in Braunschweig in the year 2010. A scenario for a hypothetical “conventional” wastewater treatment scheme (= no agricultural reuse of effluent) is set up to identify the specific effects of the wastewater reuse in Braunschweig on the environmental impacts of the system. Furthermore, a variety of optimisation measures for the existing system are described in optimisation scenarios, based on the results of pilot and full-scale experiments in CoDiGreen (KWB 2010) and internal studies of the operators (Table 4). All scenarios are briefly described in the following chapters, whereas the process data can be found in Chapter 3.

2.5.1 Baseline scenario

The baseline scenario represents the status quo of wastewater treatment and disposal in the WWTP Braunschweig-Steinhof in 2010. It consists of mechanical treatment, primary sedimentation, activated sludge process and final clarifier, infiltration fields, the irrigation system for delivery of effluent and sludge (in summer) to farmland, anaerobic sludge stabilisation in digestors, biogas electrification in combined heat and power (CHP) plants and seasonal sludge dewatering and storage on-site (Figure 4). In addition to the wastewater-derived sludge, a small amount of external co-substrate (grease) is converted to biogas, using free digestor capacity for the disposal of food waste to improve biogas production.

Wastewater treatment

Influent wastewater is treated by screening, grit separator and grease trap to remove coarse material, inorganics (grit) and floating grease. More suspended solids are removed in primary sedimentation, where primary sludge is separated by gravity from the wastewater. In the activated sludge tank, wastewater is mixed with recycled microbial sludge and aerated for the mineralisation or incorporation of organic matter by microbes. Nitrogen is partially converted to N_2 via nitrification and denitrification, whereas phosphorus is eliminated via excess uptake by specialized microbes (= biological P elimination) or chemical precipitation with addition of $FeCl_2$ (= chemical P elimination). Purified effluent is separated from activated sludge in final clarifiers. Activated sludge is recycled to the aeration tank, and a fraction of it (secondary or excess sludge) is separated and thickened in centrifuges to increase its solids content prior to stabilisation. Sludge water from thickening is directly recycled to the aeration tank.

Table 4: List of scenarios for LCA of wastewater scheme in Braunschweig

Scenario name	Scenario type	Definition
BS2010	Baseline	Existing process of wastewater treatment and disposal in the year 2010
BS2010_conv	Baseline conventional	Hypothetical conventional system without infiltration fields and effluent reuse
CoSub_Grass10	Cosubstrate grass	Addition of grass (+10% DS) as cosubstrate (results of pilot experiments)
CoSub_Grass12	Cosubstrate grass	Addition of grass (+12% DS) as cosubstrate (results of full-scale experiments)
CoSub_Topi10	Cosubstrate topinambur	Addition of topinambur (+10% DS) as cosubstrate (results of pilot experiments)
Hyd_LD	Thermal hydrolysis	Hydrolysis of excess sludge (results of pilot experiments)
Hyd_LDgrass	Thermal hydrolysis + cosubstrate grass	Hydrolysis of excess sludge + addition of grass (+10% DS) (results of pilot experiments)
Hyd_DLD	Thermal hydrolysis in DLD config.	Two step digestion process with intermediate hydrolysis of primary + excess sludge
Hyd_DLDexe	Thermal hydrolysis in DLD with exelys™	Two step digestion process with intermediate hydrolysis of thickened primary + excess sludge (Exelys™ process)
NH3stripp	NH_3 stripping in sludge liquor	Stripping of NH_3 in sludge liquor of dewatering + recovery of N fertilizer
MAP	MAP recovery in sludge liquor	Precipitation of MAP in sludge liquor of dewatering + recovery of P/N fertilizer
CoSub_ORC	Cosubstrate grass + Organic rankine cycle	Addition of grass (+12% DS) and utilisation of excess heat for ORC process (100kW)
CoSub_ORC_PS	Grass + ORC + primary sludge thickening	Addition of grass (+12% DS), thickening of primary sludge and ORC process (100kW)

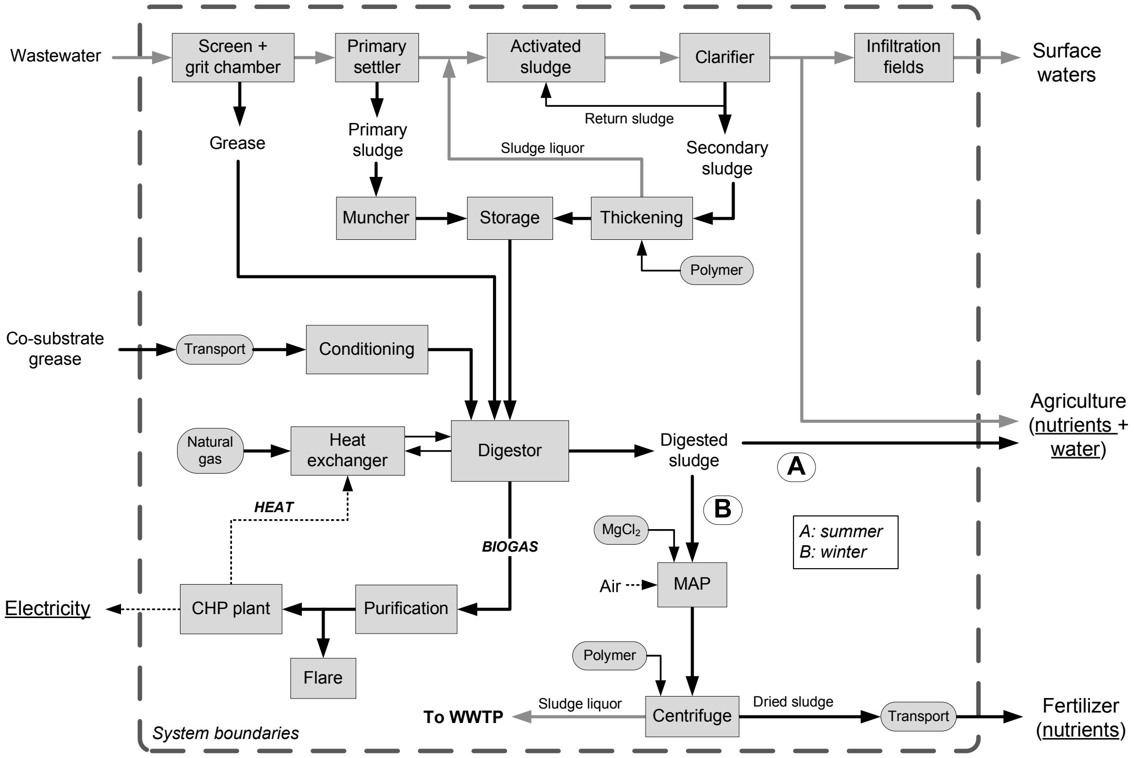


Figure 4: Scope of LCA study of wastewater treatment scheme in Braunschweig 2010 (secondary products are underlined)

Effluent discharge to infiltration fields

Part of the purified effluent is pumped to the historic infiltration fields adjacent to the WWTP site, where the effluent is further polished by soil passage and hydraulic peak loads (= heavy rain events) can be levelled off in large ponds and meanders (Figure 5). The drainage of the infiltration fields is then discharged into the Aue-Oker canal, finally carrying the water to the river Oker. During the passage of the infiltration fields, quantity and quality of the effluent can be altered due to evaporation/precipitation in ponds or interaction with the soil ecosystem. However, the sampling point for the legal discharge limits is located after the infiltration fields, prior to discharge into Aue-Oker canal.

Figure 5: Meander system of infiltration fields

Sludge digestion, dewatering and disposal

Primary sludge and thickened excess sludge are mixed prior to anaerobic stabilisation in digestors. Digestors are usually operated in thermophilic mode (55°C), but in 2010 they have been changed to mesophilic operation (38°C) for the full-scale experiments in CoDiGreen. Digestor heating is provided by excess heat from biogas combustion in CHP plants. During cold winter months, natural gas from the grid is used to amend the heat from the CHP plants. Grease from mechanical treatment and external co-substrates (grease as food waste) is added into the digestion process, providing a hydraulic retention time of 21d in the digestors. In summer, digested sludge is directly added to the effluent which is delivered to agricultural irrigation (see below). During winter operation (Nov – Mar), digested sludge is dewatered in centrifuges with the addition of polymers. Prior to dewatering, $MgCl_2$ is added to precipitate magnesium-ammonium phosphate (MAP) to transfer dissolved PO_4 into sludge. Sludge liquor which is heavily loaded with nitrogen is recycled to the influent of the WWTP. Dewatered sludge is stored on-site in a roofed storage depot before it is transported and applied to farmlands in the surroundings in late summer.

Biogas utilization

Biogas from all digestors is collected and purified in an activated carbon filter where H_2S in the biogas is eliminated. Purified biogas is dried, stored and combusted in CHP plants to generate electricity and heat. Each biogas process has an emergency flare, which is tested with a small amount of biogas regularly. The electricity of the CHP plants is mostly used on-site, while the heat (off-gas and cooling water) is used on-site for digestor heating and other minor purposes (hot water, buildings, etc.). Excess heat is emitted into the environment.

Agricultural reuse of effluent and sludge

A large part of the WWTP effluent and the digested sludge in summer operation (Mar-Sep) is directly discharged to a gravity sewer which delivers the mixture to the agricultural fields of AVB. There, four large pumping stations are operated to deliver the effluent to the irrigation system which has been in operation since 1954, using a system of 100 km of pipes and 900 discharge points to distribute the water to the fields. From the discharge points, large spray irrigation machinery is fed with irrigation water and spreads the effluent and sludge on the agricultural fields (Figure 6). High safety standards are applied to minimize hygienic hazards to the population and food consumers: The growing of crops for raw or direct consumption is forbidden, and irrigation has to be stopped at least four weeks before the crops are finally harvested (Eggers 2008). Crops for food processing include corn, sugar beets, potatoes, and maize (= energy crops for biogas plants).

Figure 6: Irrigation machinery for spreading of reused effluent

2.5.2 Hypothetical conventional system

This scenario describes a hypothetical conventional wastewater system without infiltration fields as polishing system and without reuse of effluent in agriculture. For this scenario, it is assumed that the total effluent of the WWTP is directly discharged to surface water, and digested sludge is dewatered throughout the entire year before its application in agriculture. Energy demand for aeration of wastewater in the activated sludge process is adjusted due to the higher return load of nitrogen in sludge liquor.

2.5.3 Addition of co-substrates

If the capacity of the digestors exceeds the required capacity for the digestion of sewage sludge in reasonable retention times, additional biogenic substrates can be dosed into the digestor to increase the production of biogas (MUNLV 2001). The list of possible co-substrates includes substrates from different origins such food waste (e.g. fats, food scraps) and agricultural substrates (e.g. grass, topinambur or other energy crops). Grass is readily available in Braunschweig as it grows naturally on 30 ha of infiltration fields owned by the WWTP utility. This grass can be harvested, shredded into smaller fibres, and stabilised by a silage process (fermentation) to make the carbon content accessible in the digestion process. An alternative energy crop is topinambur which is actually grown on a small area within the infiltration fields. Within the research project CoDiGreen, the suitability of both ensiled grass and topinambur greens as co-substrate for digestion is tested in pilot and full-scale experiments. The results of these experiments (biogas quantity and quality, influence on the process of sludge dewatering) directly feed into the scenarios of this LCA.

The addition of co-substrates introduces an additional source of energy into the Braunschweig system. Thus, it has to be stressed that the scenarios of this LCA only focus on the improvement of the Braunschweig system, i.e. by making use of co-substrates available on-site (no farming or fertilizer addition required) and by using free digestor capacity of the plant. The scenarios do not necessarily look into the best possible use of the co-substrates, as these could also be used for energy production in an external biogas plant.

2.5.4 Sludge pre-treatment by thermal hydrolysis

Typically, the degradability of organic matter in excess sludge is limited in anaerobic digestion. This sludge contains large fractions of microbial cells or microbial compounds that are not readily biodegradable, mainly because the organic matter is not hydrolyzed (= dissolved in the water phase). Different processes based on thermal, chemical or biological processes are available to increase the hydrolysis of organic compounds and improve the degradability of the organic matter (Müller et al. 2005). A promising approach is the thermal hydrolysis of sludge by steam injection: sludge is preheated before steam is added to the sludge, reaching high temperatures (160°C) and pressures (> 5 bar) for a certain time. After hydrolysis, sludge is depressurized and excess heat is recycled to sludge preheating. In a subsequent digestion process, hydrolyzed organic matter is converted into biogas.

The effects of thermal hydrolysis on biogas yields and the down-stream process of sludge dewatering are investigated in pilot-scale experiments within CoDiGreen. Hence, the scenarios are based on results of these pilot trials and thus show potential benefits which have to be confirmed in full-scale application. In total, four different configurations for thermal hydrolysis are considered (Figure 7):

1. Thermal hydrolysis of thickened excess sludge prior to digestion
2. The combination of thermal hydrolysis of excess sludge and the addition of grass as co-substrate (+10% DS)

3. A two-step digestion process with intermediate thermal hydrolysis (“digestion – lysis –digestion” = DLD configuration), having a comparable total hydraulic retention time (21d) than the existing digestion process. This scenario is only of theoretical interest due to the high volume of sludge to be hydrolyzed and the corresponding high demand for external fuels (cf. 3.3.2) impairing the energy balance. However, it is based on the experimental results of pilot trials in CoDiGreen and thus used for internal reference.
4. A two-step digestion process with intermediate thermal hydrolysis, based on the patented EXELYS™ process where sludge is dewatered after the first digestor to minimize water content (and thus steam demand) in the hydrolysis stage. This scenario is based on estimated design values of the supplier (Krueger 2011).

A decisive feature for the energetic benefit of thermal hydrolysis is how to meet the steam demand of the process. If steam can be provided via using excess heat from the CHP plant, the process is energetically beneficial. In case of high demand of external fuels (natural gas) for steam production, the energetic benefits of additional biogas production can be quickly offset. In this LCA study, the heat balance of thermal hydrolysis is estimated based on design studies and in cooperation with the WWTP operators. It has to be noted here that the final energy balance of a hydrolysis process in full-scale can be different to the results of this study. However, other benefits of thermal hydrolysis include the decrease of solids in digested sludge, thus lowering the costs for its disposal.

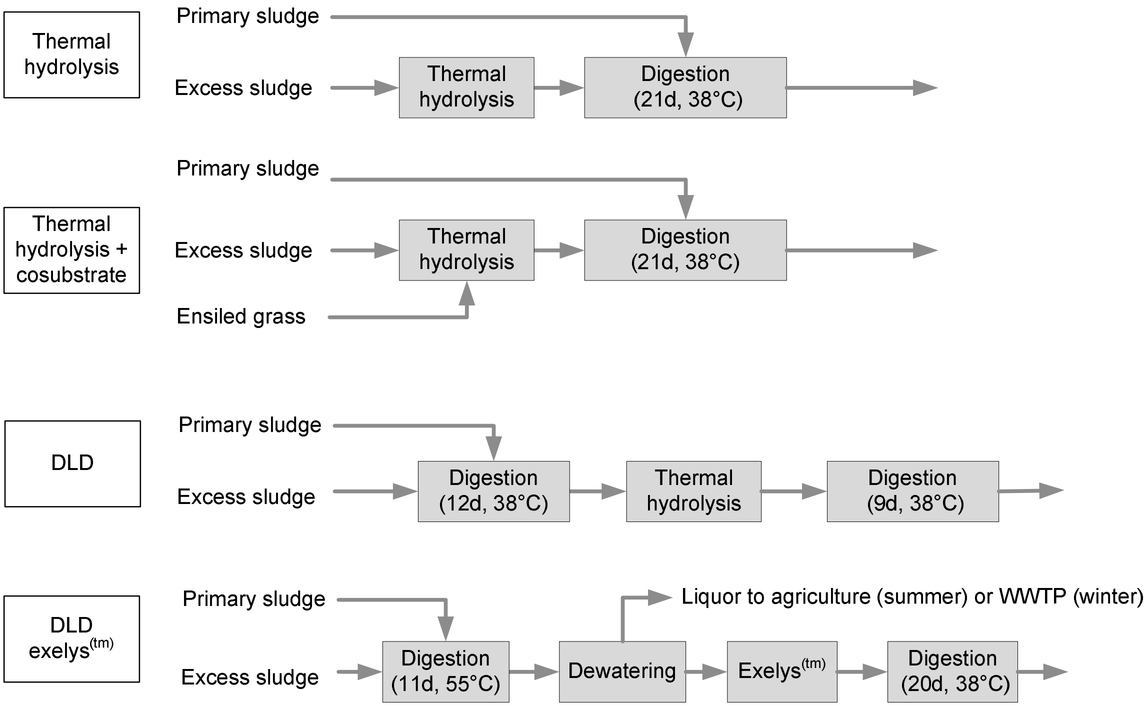


Figure 7: Different layouts for scenarios with thermal hydrolysis

2.5.5 Nutrient recovery from sludge liquor

Sludge liquor from dewatering contains high loads of nitrogen and phosphorus which are recycled to the influent of the WWTP, thus increasing the nutrient load and causing additional demand for energy and chemicals. The recovery of nitrogen and phosphorus from the sludge liquor as fertilizer products would increase the substitution potential for mineral fertilizers and decrease this additional burden to the treatment process. In particular, this LCA considers NH3 stripping for nitrogen recovery and MAP precipitation for phosphorus recovery. Both scenarios are based on design values and data from other full-scale applications and have not been tested in Braunschweig yet.

NH_3 stripping

In this scenario, sludge liquor from dewatering is treated in a stripping process to separate nitrogen in the form of gaseous NH_3, ending up with the final fertilizer product of an ammonium sulphate solution $(NH_4)_2SO_4$. The stripping process is a well-known technical process where sludge liquor is sprayed in a counter-current flow of air which is then recycled into a solution of sulphuric acid to re-dissolve NH_3. Liquor is heated and its pH elevated prior to stripping to maintain a high efficiency of the process. Full-scale plants for NH_3 stripping are successfully in operation for sludge liquor treatment in medium to large-scale WWTPs (DWA 2005).

MAP precipitation

For the recovery of phosphorus, the existing MAP precipitation (in digested sludge) would be relocated to the treatment of the sludge liquor, thus generating a higher product quality of MAP without major impurities from sludge. Due to the similar nature of the process in sludge or liquor, energy demand of the MAP process and dosing of $MgCl_2$ would essentially be equal to the amount currently used in Braunschweig today. No additional chemicals are required due to the favourable pH for MAP precipitation in the sludge liquor (pH = 7.8). However, existing positive effects of MAP precipitation in sludge prior to dewatering on the performance of the dewatering process would be missing, assuming a less efficient dewatering and higher amounts of sludge to be disposed of.

2.5.6 Utilization of excess heat with Organic Rankine Cycle

Excess heat from the CHP plants can be utilized in an energy conversion process based on the organic rankine cycle (ORC). In this process, heat is converted into electricity by evaporating an organic fluid with low vaporization temperature. This fluid is then fed to a turbine for electricity generation, before it is re-condensed to enter the cycle again. The ORC process has a relatively low efficiency (net conversion of 14-18% of heat to electricity), but allows the utilization of low-grade heat. The process has no emissions and thus is environmentally beneficial, especially for the conversion of waste heat to electricity which would normally be emitted to the environment without usage.

In this LCA, two different scenarios for the implementation of an ORC process are considered based on definitions of the operators:

1. Addition of grass as co-substrate (equivalent to scenario CoSub_Grass12) and using an ORC engine of 100kW electrical output
2. Addition of grass as co-substrate (equivalent to scenario CoSub_Grass12), employing additional thickening of primary sludge and using an ORC engine of 100kW electrical output

The latter scenario considers the implementation of a thickening stage for the primary sludge, which will reduce its water content and volume and thus the heating demand of the following digestor. Consequently, more excess heat will be available for the ORC process. In general, the excess heat which can be effectively utilized for the ORC process is calculated with a predicted heat balance of the WWTP (PFI 2010).

2.6 System boundaries

This LCA includes all processes that are required for the treatment and disposal of municipal wastewater in the WWTP Braunschweig-Steinhof (Figure 4), starting from the raw wastewater until the discharge of treated effluent to the Aue-Oker canal or the reuse in agriculture.

The following definitions specify the system boundaries of this LCA:

- For all processes, this LCA is restricted to the impacts caused by process operation. All infrastructure or capital equipment is excluded from the assessment. It has been shown that the impact of WWTP infrastructure is likely to be negligible (<5%) in conventional sanitation systems compared to the impacts from its operation, especially if the wastewater transport (i.e. the sewer network) is excluded in the assessment (Remy 2010). This is mainly due to the long lifetimes of wastewater infrastructure (~ 30-50a (LAWA 2005)), resulting in a low annual impact. It has to be noted here that screening studies come to a different conclusion and recommend including the infrastructure in LCAs of wastewater treatment (Frischknecht et al. 2007). Although the required distribution system for transporting the effluent to the spray irrigation in Braunschweig may imply substantial environmental impacts during its construction, the impact on the overall operation is estimated to be small. Comparing the size of the distribution system (100km of pipes) to the size of the Braunschweig sewer system (1300km (SE/BS 2010)), it is obvious that impacts from construction of the distribution system should be significantly smaller than those associated with the sewer system itself.
- The production and transport of electricity, natural gas and chemicals required for the process is included.
- Operational expenses for maintenance of the system are excluded.
- The infiltration fields are considered as additional treatment step of the technical system, thus being a part of the system under investigation. Polished effluent that is drained from infiltration fields and discharged into surface waters (Aue-Oker canal) and atmospheric emissions from infiltration fields (= nitrogenous gases from denitrification, evaporated water) are accounted as emissions into the environment.

- For agricultural reuse, pumping of effluent and sludge to agriculture is considered in this LCA. Input of nutrients and heavy metals into soil are considered as emissions to agricultural soils. Atmospheric emissions of agricultural reuse (e.g. nitrogenous gases) are estimated to be comparable for mineral and secondary fertilizers and are thus excluded from this assessment.
- For dewatered sludge from winter operation, storage and transport to agricultural fields is included in the assessment.
- For external co-substrates (grease), it is assumed that they are waste from other processes. Thus, environmental impacts associated with their production, processing, collection etc. is allocated to the primary function (e.g. in the food industry). This allocation can be supported by the economic value, because food producers are charged a fee for the disposal of their waste in the WWTP. However, transport of co-substrates from the point of collection to the WWTP is included in this LCA.
- For grass silage as co-substrate, environmental impacts of production on-site, harvesting and silage process are included in this LCA. However, grass is supposed to grow naturally on infiltration fields without further addition of fertilizers or water (= no impacts of production).

Cut-off criteria

No explicit cut-off criterion is defined for this LCA. For the foreground system, the demand for electricity and natural gas for heating are considered together with chemicals consumed in relevant amounts (>1 t/a). All other chemicals or operating supplies (e.g. for maintenance) are cut-off in this LCA. For the disposal, further treatment of screenings and grit eliminated in mechanical treatment has been neglected in this LCA. It is estimated that the aggregated share of all substances which are cut-off from this LCA will not exceed 5% of the total input or output mass into the system. For the background system, cut-off criteria are defined in the documentation of each dataset.

Considered elementary flows

For the process model of sludge handling and treatment, the following material flows are included in this LCA:

- Volume (or weight for co-substrates)
- Dry matter
- COD
- Nitrogen
- Phosphorus
- Potassium
- Heavy metals (Cd, Cr, Cu, Ni, Pb, Hg, Zn)

Organic pollutants are explicitly excluded from this LCA due to the lack of regular monitoring data for the different flows. Only a small selection of these substances (PAH, PCD, PCDD/PCDF) are monitored in the sludge of the WWTP by grab sampling, so that conclusive load balances cannot be set up for the entire WWTP. Consequently, it was decided to exclude these substances from this LCA together with the WWTP operators. For emerging organic micropollutants in the wastewater (e.g. pharmaceuticals), characterisation factors for impact assessment are currently in preparation (Larsen et al. 2009). However, the exclusion of organic pollutants is clearly a limitation of the present approach and might underestimate the impacts in human and ecotoxicity from the application of sewage sludge to agriculture. It has to be noted though that the sewage sludge of Braunschweig is well below the legal limits for sewage sludge application in agriculture (AbfKlärV 1992) for all relevant organic and inorganic pollutants (SE/BS 2010).

For the environmental impacts assessed in this study, the following direct emissions (= on-site emissions of the WWTP) are relevant:

- Global warming potential: CO_2 from fossil sources, CH_4, and N_2O
- Acidification: SO_2, NH_3, NO_x
- Eutrophication of freshwaters: P to surface waters, P to agricultural soil
- Eutrophication of seawaters: N to surface waters, N to agricultural soil
- Human toxicity: Heavy metals to surface waters and agricultural soil
- Freshwater aquatic ecotoxicity: Heavy metals to surfaces waters and agricultural soil
- Terrestrial ecotoxicity: Heavy metals to surfaces waters and agricultural soil

For the indirect environmental impacts (= from background processes, e.g. electricity production, transport, production of chemicals or fertilizers), all relevant resource demand and emissions from the respective datasets are accounted in this LCA. For further information, full reports of the datasets are available elsewhere (Ecoinvent 2007).

Geographical and temporal scope

The geographical and temporal scope of the foreground system is limited to the specific boundary conditions of the WWTP of Braunschweig-Steinhof for the reference year 2010. As each WWTP has specific conditions of influent quality and process layout, the results are not directly transferable to other WWTPs, even though the results may help to understand the specific impacts of agricultural reuse of WWTP effluent for the environmental profile. For the background system, the geographical and temporal scope is set for the period of 2000-2010 in Germany, relating to the availability of most recent datasets. Some datasets are only available as European average.

2.7 Data quality

Data quality requirements

This LCA should provide a general picture of the environmental footprint of the Braunschweig wastewater scheme. Thus, primary data of the foreground system should be as recent as possible and relate to the existing system in Braunschweig. For the background system, most recent data reflecting German conditions should be used if possible, but can be amended by European or World average datasets if necessary. The technology of the WWTP and reuse scheme relates to the specific system in Braunschweig, whereas background processes (e.g. electricity or chemical production) can be assessed as a technology mix of Germany or Europe.

The precision of the primary data as well as the completeness of the inventory depends on the available data from WWTP operation. It is evident that a WWTP is a dynamic biological process with high daily and seasonal variability of input flows and pollutant loads. If possible, data of continuous sampling of inputs and outputs is used to generate annual mean values for WWTP operation. For atmospheric emissions of the activated sludge process and CHP plant, generic emission factors have to be used due to lack of sampling data.

The representativeness is assessed to be high, as primary data from the operators of the WWTP Braunschweig is used for this LCA. Concerning the consistency of the methodological approach, all parts of the system which are included in this LCA are assessed with a comparable method. Certainly, the cut-off of certain parts of the system (e.g. infrastructure, emissions of during agricultural reuse of effluent and sludge compared to mineral fertilizer, treatment of grit + screenings) has an influence the results of this LCA.

In general, the documentation of the most relevant inventory data should allow the reproduction of the results of this LCA fairly good. However, not all inventory data is listed in this study due to the complexity of the WWTP process: intermediate flows within the system are not completely characterized in the inventory. Nevertheless, the relevant inputs (electricity and chemicals) and outputs (effluent and sludge) of the foreground system are documented in detail and should provide reasonable reproducibility of the results.

Uncertainty of the data and assumptions is not reported in this LCA. In general, the uncertainty of primary data for WWTP operation is determined by sampling procedures and frequency and is estimated not to exceed ±10% for the main input and output flows. The modelling of the biological process and the calculation of related process emissions is based on generic emission factors and thus affected by a higher uncertainty (cf. 4.6.2 for sensitivity analysis). For energy input and output and material demand, data is based on information of the WWTP purchasing management and thus is supposed to be of high accuracy.

Description of the data sources

The primary data for the process model has been collected in close cooperation with the operators of the WWTP Braunschweig-Steinhof and the wastewater association:

- Substance flow data for 2010 is based on regular self-monitoring of quality and quantity of WWTP influent and effluent (daily 24h-composite samples), sludges and liquors (weekly grab samples). Data was extracted from the internal data management system of SE/BS. However, a WWTP is a dynamic biological process, and sludge quality and quantity may vary with weather conditions, process operations or simply in the sequence of seasons. Hence, it is difficult to obtain a closed balance and thus a conclusive picture of the “average” annual operation of such a facility, even if monitoring data is readily available. Finally, all input data for this LCA has been validated and all inconsistencies have been solved in cooperation with the operating staff of the WWTP.

- Data for the demand of electricity, heat, natural gas, and chemicals of each process is provided by the WWTP operators. For electricity, monitoring data is sometimes available for larger sub-parts of the system, so that allocation of the electricity demand to specific processes has been estimated according to generic energy data (MUNLV 1999). The total sum of electricity demand in each sub-part of the process model equals the reported electricity demand.
- The distribution of effluent and sludge to infiltration fields or agricultural reuse is defined by the effective disposal routes in 2010.
- For transport distances of dewatered sludge, external co-substrates, and chemicals, best estimates are used which have been validated by WWTP operators.
- Data for direct emissions of biological processes in the activated sludge process and in infiltration fields (e.g. from denitrification) are estimated with generic emission factors based on literature due to lack of primary data.

Background data for transport processes and the production of electricity, natural gas, chemicals and fertilizer is extracted from the database ecoinvent v2.1 (Ecoinvent 2007) as documented in the inventory, representing average German or European conditions.

2.8 Allocation

For the primary function of the foreground system, no allocation is required due to the nature of the input flows (= wastewater). For the external co-substrates (grease), environmental impacts are allocated to the upstream functions (e.g. food production) and are thus excluded in this LCA, considering the digestion of co-substrates as waste treatment. This assumption is supported by the economic value of the co-substrates, because the suppliers of fats and grease have to pay for the disposal of their waste in the WWTP. Only the transport of co-substrates to the WWTP is included within this LCA.

For the background system, allocation procedures are documented in the respective datasets.

2.9 Indicators of Life Cycle Impact Assessment

This LCA uses a midpoint-oriented approach for impact assessment, based on the Dutch LCIA method ReCiPe 2008 (Goedkoop et al. 2009). This impact assessment method is a well-established, internationally accepted impact method for LCA in industrialized countries. Its indicators describe the main impacts of environmental concern for societies in Western Europe. The use of midpoint indicators gives a detailed picture of the relevant issues in each category of environmental impact and thus supports the goal of this LCA study in tracking the important areas of environmental concern affected by the operation of a WWTP. This method is amended by the cumulative energy demand, a well-established energy indicator on the inventory level. In total, 8 indicators are used for the impact assessment (Table 5).

Table 5: Indicators for Life Cycle Impact Assessment

Indicator	**Abbr**	**Unit**	**Remarks**	**Source**
Cumulative energy demand	CED	*MJ*	Non-renewable energy resources (fossil + nuclear)	VDI 1997
Global warming potential	GWP	*kg* CO_2*-eq*	Time horizon: 100a	IPCC 2007
Acidification potential	AP	*kg* SO_2*-eq*	Time horizon: 100a	ReCiPe 2008
Eutrophication potential for freshwaters	EPfresh	*kg P-eq*	Accounts only P emissions	ReCiPe 2008
Eutrophication potential for seawaters	EPsea	*kg N-eq*	Accounts only N emissions	ReCiPe 2008
Human toxicity potential	HTP	*kg DCB-eq*	Time horizon: 100a	ReCiPe 2008
Freshwater aquatic ecotoxicity potential	FAETP	*kg DCB-eq*	Time horizon: 100a	ReCiPe 2008
Terrestrial ecotoxicity potential	TETP	*kg DCB-eq*	Time horizon: 100a	ReCiPe 2008

The following environmental impacts usually assessed within ReCiPe 2008 are explicitly excluded in this LCA:

- *Mineral resource depletion* is not assessed due to the exclusion of infrastructure in this LCA and according to results of previous studies (Remy 2010). In general, inorganic chemicals for the WWTP operation ($FeCl_3$, $MgCl_2$, lime) are not composed of rare minerals. Recovery of phosphorus from wastewater and substitution of raw phosphate ore may develop into a substantial benefit of the reuse system in the future.

- *Fossil fuel depletion* is mainly represented by the cumulative energy demand of non-renewable resources.
- *Ozone depletion* is caused by certain halogenated gases which are not specifically emitted in the wastewater scheme.
- *Emission of particulate matter* (PM10) and *ozone forming substances* (NMVOC) is not assessed due to the lack of primary data of the foreground system. These substances are mainly emitted in combustion processes and may be relevant for the electrification of biogas in the CHP plant.
- *Ionising radiation* mainly relates to the use of nuclear fuels in power plants, an issue that is not in the focus of this LCA.
- *Land use* is an impact category which could be relevant for the Braunschweig system. However, the agricultural fields used for the disposal of effluent and sludge have been operated as farmland before the construction of the irrigation system (Eggers 2008). Thus, no change in land use ("transformation") was inflicted by the wastewater scheme, and the impact would be related to land occupation of agriculture in general. Hence, this impact is allocated to the production of food and not to the wastewater reuse system.
- *Freshwater use and consumption* ("water footprint") is excluded from this LCA, even though the agricultural reuse of WWTP effluent substitutes the use of groundwater for irrigation and thus relieves the pressure on local water resources. However, different methods for water footprinting are currently discussed in the scientific community (Berger and Finkbeiner 2010), and adequate inventory data for many processes was not available during the setup of this study. It is explicitly recommended to complement this study with a well-based assessment of the water footprint in the future to properly reflect this important feature of agricultural reuse of WWTP effluent in the environmental profile.

2.10 Optional elements of Life Cycle impact assessment

Grouping and weighting have not been used in this study. Normalisation is done in relation to the total environmental impacts in Germany 2007 in the respective impact categories (Table 6). Normalisation factors are calculated based on LCIA characterization factors and available information on resource use and emission data of Germany. For toxicity data, normalisation may be biased by an incomplete inventory of environmental pollutants. However, normalisation data includes heavy metals which are the only group of pollutants considered as direct emissions in this LCA.

Table 6: Normalisation factors for Germany 2007

Indicator	**Unit**	**Factors for Germany (2007)**	**Sources for emission data**
Cumulative energy demand	*MJ/(pe*a)*	137934 (fossil) 18575 (nuclear)	*BMWi 2009*
Global warming potential	*kg CO_2-eq/(pe*a*	11840	*UBA 2010*
Acidification potential	*kg SO_2-eq/(pe*a)*	33.3	*UBA 2010*
Eutrophication of freshwaters	*kg P-eq/(pe*a)*	0.3	*UBA 2010*
Eutrophication of seawaters	*kg N-eq/(pe*a)*	9.7	*UBA 2010*
Human toxicity potential	*kg DCB-eq/(pe*a)*	265.3	*UBA 2010 (data for 2003/2005)*
Freshwater aquatic ecotoxicity potential	*kg DCB-eq/(pe*a)*	1.89	*UBA 2010 (data for 2003/2005)*
Terrestrial ecotoxicity potential	*kg DCB-eq/(pe*a)*	1.65	*UBA 2010 (data for 2003/2005)*

2.11 Interpretation

Identification of the significant issues based on the results of the Life cycle inventory and impact assessment phases of the LCA

Interpretation of the results of this LCA is based on the midpoint indicator results of the status quo for 2010 (baseline scenario). For the baseline scenario, allocation of the impacts on the different process steps is shown to reveal the contribution of the specific processes to the overall environmental impact (“contribution analysis”). Indicator results are normalised to reveal the quantitative contribution of the Braunschweig system in relation to the total environmental impacts in Germany 2007. The baseline scenario is further referenced to a hypothetical conventional WWTP (= no agricultural reuse of effluent, no infiltration fields) to identify the specific benefits and drawbacks of the reuse approach in Braunschweig. For the optimization scenarios, the relative change in impacts compared to the baseline scenario is reported to visualize the potential effects of the specific measure on the overall environmental footprint of the wastewater scheme.

Evaluation considering completeness, sensitivity and consistency checks

Sensitivity analysis is conducted for important assumptions of the study, mainly related to system expansion (accounting of nutrients and irrigation water from agricultural reuse), background datasets of life cycle inventory (power mix and fertilizer production) and generic emission factors of the WWTP process. Completeness of the LCA and consistency of the approach is qualitatively discussed in the interpretation to reveal potential biases of the methodology and related results.

Conclusions, limitations, and recommendations

Finally, conclusions are drawn from the impact assessment phase of the study concerning the environmental footprint of the existing system, its specific benefits and drawbacks with reference to a conventional WWTP, and potential measures for improvement of the environmental profile. Limitations of the methodology in terms of system boundaries, selected indicators, and data quality of the inventory are critically discussed to give information about potential short-comings of this LCA. Finally, recommendations are given both for improving the environmental profile of the Braunschweig system and for the methodology of future LCA studies in Braunschweig.

2.12 Critical review

To comply with the ISO standard 14040, a critical review of the applied LCA methodology is conducted by Prof. Dr. Matthias Finkbeiner (TU Berlin, Department of Sustainable Engineering). The review includes the definitions of the study ("goal and scope") and the methodological approach as well as the conclusions drawn from the analysis. The verification of life cycle inventory data is explicitly excluded from the review. The review statement is attached at the end of this document.

2.13 Reporting

All relevant information of this LCA is provided in a written report to the primary target group of this LCA. This report describes the goal and scope definitions, summarizes the most relevant primary data of the Life cycle inventory, and presents results of the impact assessment along with a critical discussion of the conclusions and limitations of this study. Furthermore, a short summary of the study will be part of the final wrap-up report of the research project CoDiGreen.

Chapter 3

Life Cycle Inventory

3.1 Operation of wastewater treatment plant in Braunschweig-Steinhof

The existing process of wastewater handling and disposal at WWTP Braunschweig-Steinhof includes mechanical and biological treatment, anaerobic stabilisation of sludge, discharge of the effluent to infiltration fields, pumping of effluent and stabilised sludge to agriculture. In winter, sludge is dewatered and stored prior to its disposal in agriculture (Figure 4). This chapter summarizes all relevant data used for the process model of this LCA ("Life Cycle Inventory"). The process model is set up using the LCA software UMBERTO® (IFU and IFEU 2005) (see Appendix A for screenshot).

3.1.1 Wastewater treatment

Mechanical treatment and primary sedimentation

Influent wastewater arrives at the WWTP underground in large gravity pipes. It is lifted by spiral pumps (~ 50 Wh/m^3) prior to the removal of coarse material (screening), grit (grit chamber) and floating grease (grease trap). The annual amount of these materials is 319 tons of screenings, 395 tons of grit, and 430 m^3 of grease. While screenings and grit are disposed in landfills (impact of disposal neglected in this LCA), grease is pumped to the digestion unit for biogas production. Influent wastewater flows by gravity to primary sedimentation, where suspended organic matter settles by gravity and is transferred to primary sludge. Before the sedimentation tank, return liquor from sludge dewatering is added to the wastewater flow. The partial elimination of total solids, COD, N and P is calculated based on influent and effluent sampling of primary sedimentation stage (Table 7). Transfer of heavy metals is calculated from sampling of primary sludge. Dry matter content of primary sludge is difficult to measure due to high variability, but is estimated to 4% DS. Energy demand for sludge pumping and scraper are estimated to 5 Wh/m^3 influent wastewater (MUNLV 1999).

Table 7: Process data for primary sedimentation

		Influent	**Effluent**	**Elimination ratio [%]**
Total solids	*mg/L*	413	249	40
COD	*mg/L*	937	574	39
N	*mg/L*	70	63	10
P	*mg/L*	11.2	9.4	16
Heavy metals				5-32

Aeration tank and final clarifier

Wastewater from primary sedimentation flows to the activated sludge stage, where it is mixed with return activated sludge. The activated sludge process is operated with anaerobic, anoxic and aerated zones to enable biological P elimination, nitrification and denitrification. Sludge age is estimated to 11-12d in annual mean, and sludge production is calculated based on ATV model of A131, assuming a wastewater temperature of 14.5°C and a yield coefficient of 0.95 g biomass/g eliminated carbon (ATV 2000). Removal ratios for COD, N, P and heavy metals are calculated based on influent and effluent samples (Table 8). Activated sludge is separated by gravity in final clarifiers (0.68% DS), from where it is recycled to the influent of the activated sludge tank. Chemical dosing of $FeCl_2$ (713 t/a of 10% $FeCl_2$ solution) supports P elimination by chemical precipitation and prevents the generation of H_2S in subsequent digestion of sludge. Electricity demand for aeration (6669000 kWh/a) is taken from electric meters.

CO_2 emissions from microbial mineralisation of organic matter are of biogenic origin and thus not relevant for this LCA. Other direct emissions of the activated sludge process are estimated based on generic emission factors from literature: for NH_3 and N_2O, emission factors of 0.45 and 0.6% of influent N load are estimated (Bardtke et al. 1994; Wicht 1996). The emission factor of N_2O from biological nitrification and denitrification is a subject for intensive research currently, and a high variability of this factor (0.01-15%) has been detected for many activated sludge plants depending on operational conditions (Kampschreur et al. 2009; Foley et al. 2010; Ahn et al. 2010). Hence, the influence of a variation of this emission factor will be analysed in sensitivity analysis.

Table 8: Process data for activated sludge tank

		Influent to activated sludge tank	**WWTP effluent**	**Elimination ratio [%]**
Total solids	*mg/L*	249	9	96
COD	*mg/L*	574	43	93
N	*mg/L*	63	10	84
P	*mg/L*	9.4	1	89
Heavy metals				68-94

Electricity demand of the WWTP

For some process steps, the specific demand for electricity is monitored and can be allocated to the respective processes (e.g. aeration, dewatering, digestor mixing). Electricity demand of other processes is estimated based on specific data from literature (MUNLV 1999). However, the overall total electricity demand of the WWTP is monitored by the operators and amounts to 12.9 Mio kWh in 2010. Hence, the remaining electricity demand which cannot be allocated to specific processes is allocated to the WWTP operation in general, so that the total electricity demand of the WWTP is properly considered in this LCA.

3.1.2 Sludge digestion and dewatering

Thickening of excess sludge

Excess sludge from activated sludge is thickened in decanters with the addition of polymers as flocculants (0.5 g/kg DS). Decanters require 1.1 kWh/m³ of digested sludge, including pumping of liquors to the WWTP inlet. Excess sludge is thickened from 0.86% to 6.6% dry matter content, producing sludge liquor of 2000 m³/d which is recycled to the activated sludge tank (quality estimated to be comparable to WWTP effluent (Table 8)).

Digestion

Primary and excess sludge are mixed in a storage tank before the mixed sludge is fed into the anaerobic digestion tanks. Here, sludge is stabilised by microbial activity at mesophilic conditions (38°C) during the trials period. Heating of the digestors requires 28.7 kWh/m³ sludge of thermal energy, which is delivered by waste heat from the CHP units. During cold winter months, additional natural gas is used for heating (247300 m³ in 2010). Emissions of natural gas burner are estimated to be comparable to CHP plant emissions (see below), but generate fossil CO_2. Mixing of the digestors and pumping of sludge needs 2.9 kWh/m³ sludge of electricity.

During a retention time of 21d, organic matter of the sludge is degraded (58%) and converted into biogas (425 L/kg oDM_{input}, 63% CH_4). For external co-substrates and grease from mechanical treatment, a biogas yield of 800 and 750 L/kg oDM is assumed. In total, 4476400 m³ of biogas (63% CH_4) are produced in anaerobic digestion in 2011.

Biogas purification and combustion in CHP plants

Biogas from digestion is purified in activated carbon filters (35 Wh/m³ biogas) and fed to CHP plants, where it is converted into electricity and heat with electrical and thermal efficiencies of 36.7 and 40%, respectively. This corresponds to an annual production of 10.3 Mio kWh of electricity and 11.2 kWh of heat. A small amount of annual biogas volume (0.23%) is used to test the emergency flare of the system. Emission factors of flare and CHP plants are calculated based on literature (Ronchetti et al. 2002) and are documented in detail elsewhere (Remy 2010).

Dewatering, storage and disposal of digested sludge

Digested sludge (510 m³/d, 2.6% DS) is either mixed with WWTP effluent and pumped to agriculture (summer operation, 48% of total sludge volume) or dewatered and stored on-site (winter operation, 52% of total sludge volume). Prior to dewatering, Mg (1 kg/m³ sludge of 30% $MgCl_2$ solution) is added and sludge is aerated (0.2 kWh/m³ sludge) to enable the precipitation of magnesium-ammonium phosphate (MAP, “struvite”), thus preventing operational problems and limiting dissolved P in sludge waters. Aerated sludge is then dewatered in high performance decanters with the addition of polymers as flocculants (25.7 g/kg DS). Decanters require 4.4 kWh/m³ of digested sludge, including pumping of liquors to the WWTP inlet. Sludge is dewatered to 28.1% DS, producing sludge liquor of 464 m³/d ([TS]= 4330 mg/L, [COD]=1220 mg/L, [N]=1330 mg/L, [P]=248 mg/L). After dewatering, limestone is added to the dewatered sludge (122 g/kg DS) for stabilisation. Dewatered sludge is stored on-site (= no emissions accounted) until the transport to nearby agricultural fields for disposal in late summer.

3.1.3 Discharge of effluent to infiltration fields

A part of the WWTP effluent (9960000 m^3 or 45% of total) is fed by pumping to infiltration fields. Hydraulic peak loads are levelled off in large ponds and meandering river-like systems. Thereafter, the water is infiltrated into the soil by gravity, where the effluent is polished in a natural filtration step by physico-chemical (filtration + adsorption) or biological (nitrification/denitrification) processes. Depending on weather conditions, evaporation of water or raining on infiltration fields can alter the volume of the effluent considerably. Infiltration fields are drained by a piping system, and the collected polished effluent is finally discharged to surface waters via the Aue-Oker canal. Both quantity and quality of the WWTP effluent are altered during the passage of the infiltration fields (e.g. by rain or evaporation), usually improving the quality of the effluent (Table 9). However, accumulated phosphorus from historic application of untreated wastewater on the fields sometimes leads to an additional increase of P load after infiltration, especially in low-flow conditions of summer where oxygen depletion favours the re-dissolution of soil phosphorus and hydraulic peak loads may wash out particulate P (SE/BS 2010).

Table 9: Quantity and quality of WWTP effluent polished in infiltration fields

		WWTP effluent to infiltration fields	**Discharge from infiltration fields to Aue-Oker canal**
Volume	*Mio m^3*	9.96	12.65
TS	*mg/L*	9	11.5
COD	*mg/L*	43	36
N	*mg/L*	10	6.3
P	*mg/L*	1	0.8
Cd	*µg/L*	0.1	0.4*
Cr	*µg/L*	2.3	2.1
Cu	*µg/L*	7.6	6
Ni	*µg/L*	3.2	7*
Pb	*µg/L*	2.2	4*
Hg	*µg/L*	0.2	0.2
Zn	*µg/L*	16.6	18.2

**Higher concentrations in water discharged into the canal can be caused by different limits of quantification (LOQ) of sampling!*

3.1.4 Pumping of effluent and stabilised sludge to agriculture

The remaining part of the WWTP effluent (12.4 Mio m³/a or 55%) and the stabilised sludge in summer operation are mixed and delivered to the area of agricultural irrigation by gravity (~ 10 km). There, the mixture is distributed to four large pumping stations where it is fed into the irrigation system. Pumping of the effluent and sludge requires 0.37 kWh/m³ to deliver a pressure of ~ 5 bar in the system. The final spreading of the water and sludge by mobile irrigation machinery is operated only by using the system pressure and does not need any additional energy.

In case of high water demand of agriculture (e.g. in hot summer periods), effluent from the infiltration fields can be diverted to agricultural reuse by an additional pumping station near the discharge point to Aue-Oker canal.

3.2 Hypothetical conventional WWTP

For the scenario of the hypothetical conventional WWTP without infiltration fields and agricultural reuse, the following assumptions are taken into account:

- The total volume of WWTP effluent is directly discharged to surface waters, considering the quality and quantity of the existing process (Table 9).
- Stabilised sludge is dewatered throughout the whole year, stored on-site and applied in agriculture with substitution potentials of 100%/80% for N/P.
- Higher return loads from dewatering are recycled to the aeration tank, especially for COD and nitrogen. Hence, energy demand for aeration and recycling is estimated to rise by 10% due to higher oxygen demand for COD and N removal, resulting in a total energy demand of 7335900 kWh/a for aeration.
- All other process parameters are kept constant.

3.3 Measures for optimisation

3.3.1 Addition of co-substrates

These scenarios evaluate the addition of organic co-substrates into the digestion process: either grass silage or topinambur greens. The respective type and amount of co-substrates added in each scenario, the corresponding biogas yields and total increase in methane production are based on the results of pilot and full-scale experiments in CoDiGreen (Table 10). Allocation of gas yields between co-substrates and mixed sludge is estimated, as only the total sum of gas yield has been measured in the experiments. It has to be noted that biogas yields vary heavily between pilot (513 L/kg oDM_{in}) and full-scale experiments (317 L/kg oDM_{in}) with ensiled grass, presumably due to incomplete digestion of grass in the full-scale process. Possible reasons are the insufficient shredding of the ensiled grass (pilot: 1-2mm by hand, full-scale: 1-2 cm by agricultural machinery), difficulties in mixing of grass in full-scale digestors, or reduced retention time in the digestor due to flush water (15m³/d) used for pumping the grass into the digestion tank. Thus, results of pilot experiments

(CoSub_Gras10 and CoSub_Topi) should be seen as a maximum potential for additional biogas yield with co-substrates under optimized conditions, whereas full-scale results (CoSub_Gras12) show the actual biogas yield that could be realized in full-scale.

Table 10: Process data for scenarios with addition of co-substrates

Scenario		**CoSub_Gras10**	**CoSub_Gras12**	**CoSub_Topi10**
Type of co-substrate		Ensiled grass	Ensiled grass	Topinambur greens
Dosing on top of mixed sludge		+10% DS	+12% DS	+10% DS
Weight	*t/a*	3850	4620	2265
Organic dry matter	*t/a*	1820	2184	1820
Effect on gas production				
Specific gas yield of co-substrate*	*L/kg oDM_{in}*	513	317	376
Specific gas yield of mixed sludge*	*L/kg oDM_{in}*	474	410	474
Methane content	*% CH_4*	67	63	64
Relative increase in total CH_4 yield		+30%	+5%	+21%
Effect on dewatering				
COD load in liquor		+50%	+50%	+10%
Final DS	%	30	28	30
Source		*Pilot*	*Full-scale*	*Pilot*

** allocation of gas yield to co-substrate or mixed sludge estimated*

The digestion of co-substrates leads to a higher COD load in liquor from sludge dewatering. Based on results of pilot experiments, COD in sludge liquor is increased by 50% with ensiled grass (pilot + full-scale) or 10% by topinambur. Additionally, better efficiency of dewatering has been detected in pilot experiments via specific measurements (TR(A) method), which is attributed to the fibre structure of the co-substrates. This effect is considered by increasing the DS content of dewatered sludge from 28% to 30% for the scenarios based on pilot-scale experiments (CoSub_Gras10 and CoSub_Topi10).

3.3.2 Thermal hydrolysis

In these scenarios, sludge from WWTP is pre-treated by thermal hydrolysis (= addition of steam) to improve its degradability in anaerobic digestion and increase the gas yield. Four different scenarios are considered for thermal hydrolysis with different configurations of the process (cf. 2.5.4). The process data of three scenarios is based on results of pilot experiments in CoDiGreen, whereas the fourth scenario is based on assumptions from the supplier of this specific process (Table 11).

The demand of external fuels is a decisive parameter for the energy balance of thermal hydrolysis. In general, heat is internally recycled in the process by heat recovery from sludge leaving the hydrolysis unit. Additional heat is provided by the addition of steam into the sludge. For hydrolysis of excess sludge (190 m^3/d) or dewatered mixed sludge (73 m^3/d in Exelys™ process), it is assumed that 100% of steam demand is produced by off-gas heat from CHP plants, and no external fuels are required for the hydrolysis. For the hydrolysis of both primary and excess sludge (458 m^3/d in scenario Hyd_DLD), 50% of steam demand has to be generated with external fuels (natural gas). Hence, the latter scenario has an impaired energy balance and is only of theoretical interest in this study. In all scenarios of thermal hydrolysis, heating of digestors is provided by hot sludge from hydrolysis or additional heat from CHP plants.

Table 11: Process data for scenarios with thermal hydrolysis

Scenario		**Hyd_LD**	**Hyd_LDgrass**	**Hyd_DLD**	**Hyd_DLDexe**
Configuration		Hydrolysis of excess sludge	Addition of grass + hydrolysis of excess sludge	Two-stage digestion + intermediate hydrolysis	Two-stage digestion + intermediate dewatering and lysis (Exelys™)
Steam demand	*L/m³*	150	150	150	200
Steam production by CHP off-heat	%	100	100	50	100
Effect on gas production					
Relative increase in total gas volume		+8%	+26%	+24%	+27%
Methane content	*% CH_4*	64	68	63	63
Relative increase in total CH_4 yield		+10%	+36%	+24%	+27%
Effect on dewatering					
COD load in liquor		+130%	+200%	+400%	+185%
Final DS	%	30	32	30	30
Source		*Pilot*	*Pilot*	*Pilot*	*Krueger 2011*

Thermal hydrolysis has an effect on downstream dewatering of digested sludge, increasing both COD loads in liquor (= generating non-biodegradable or “hard” COD due to high temperatures) and dewaterability (= final DS content) of sludge. These effects are accounted in this LCA based on results of pilot experiments (Table 11). Polymer demand for dewatering is assumed to be comparable to the existing process (25.7 g/kg DS). Electricity demand for pumping and mixing in the hydrolysis reactor is estimated to 1.8 kWh/m³ for all scenarios (DWA 2009).

For the Exelys™ process, the following assumptions are made based on supplier info (Krueger 2011):

- intermediate dewatering is done in a decanter (4 kWh/m³) with the addition of polymer (7 g/kg DS), reaching a DS content of 23% prior to hydrolysis
- quality of sludge liquor from Exelys™ is assumed to be comparable to the full-scale process in Braunschweig ([COD]= 1200 mg/L, [N]= 1325 mg/L, [P]=250 mg/L)
- sludge liquor is either recycled to the WWTP inlet in winter or added to the irrigation water in summer
- final dewatering after the two-stage digestion is done with a belt press (4.3 kWh/m³) with the addition of polymer (8 g/kg DS), reaching a final DS of 30%

3.3.3 NH_3 stripping in sludge liquor

For this scenario, sludge liquor from dewatering is treated in a stripping process to recover the nitrogen as a fertilizer product. Nitrogen-rich liquor is sprayed in a counter-current air flow to strip nitrogen in the form of NH_3, which is then redissolved in an acid solution, recovering ammonium sulphate ($(NH_4)_2SO_4$) as a final product. All process data is estimated from literature (DWA 2005). The process has no direct emissions on-site.

Sludge liquor is heated from 40°C to 70°C (5 kWh/m³ with heat recovery, provided by off-gas heat of CHP plant), and its pH is elevated (4 kg NaOH (50%) per kg N_{in}) to increase the efficiency of the stripping process. In total, 90% of nitrogen is removed from sludge liquor and recovered as liquid fertilizer. Electricity demand for air blowers and pumping is estimated to 1.6 kWh/m³ liquor. Stripped NH_3 is recovered in acid solution (3.8 kg H_2SO_4 (96%) per kg N_{in}) to produce liquid ammonium sulphate $(NH_4)_2SO_4$ (38%). This solution can directly be used for fertilizing with a 100% plant availability of nitrogen. Remaining sludge liquor is recycled to the WWTP inlet after recovering the heat internally.

3.3.4 MAP precipitation in sludge liquor

In the MAP scenario, struvite is precipitated in the sludge liquor by addition of 1.8 kg $MgCl_2$ (30%) per m³ of liquor. Thus, 70% of the P load in liquor are precipitated in the form of MAP (NH_4MgPO_4) and then eliminated from the liquor as MAP crystals. Separated MAP has a low content of impurities and can be directly used as fertilizer, assuming 100% plant availability of its phosphorus and nitrogen content. Electricity demand for pumping and mixing in the process is estimated to 0.2 kWh/m³. With MAP precipitation in sludge liquor, positive effects of MAP precipitation in digested sludge (= existing configuration) on subsequent sludge dewatering would be missing. Hence, it is assumed that final DS after dewatering will decrease from 28% to 26% with in the MAP scenario, and polymer demand will increase from 25.7 to 27.7 g/kg DS (SE/BS 2010).

3.3.5 Organic Rankine Cycle

In these scenarios, excess heat of the CHP plants is converted to electricity via an organic rankine cycle. The decisive parameters determining the energetic benefits of the ORC process are the specific amount of excess heat which is available for the ORC, the size of the ORC unit, and its prospective hours of operation during the year. Due to high seasonal variation of heat demand in the WWTP (digestor heating, facility heating only in winter), the operating hours for the ORC process depend on the internal heat balance of the WWTP. For the existing WWTP process, the available amount of excess heat does not allow a cost-efficient operation of an ORC process yet. Hence, two scenarios for ORC implementation have been developed in consultation with the operators, based on economic calculations of the cost-efficiency of an ORC installation (SE/BS 2010):

- scenario CoSub_ORC: Addition of co-substrate grass (= scenario CoSub_Gras12) and ORC process (100kW)
- scenario CoSub_ORC_PS: Addition of co-substrate grass (= scenario CoSub_Gras12), thickening of primary sludge and ORC process (100 kW)

Whereas the first scenario builds upon the results of scenario CoSub_Gras12, the second scenario considers a modification of the WWTP process which has been investigated in an internal study: primary sludge is thickened prior to digestion, reducing its volume by 33% and increasing its DS content (4% → 6%). Thus, less heat is required for digestor heating, and more excess heat is available for the ORC process (Table 12). DS content of primary sludge can be increased by gravity in static thickeners without major energy demand (additional pumping is neglected here). For the ORC process itself, no chemical demand during operation or on-site emissions are considered in this LCA. Impacts would arise from the infrastructure, but this is excluded in this LCA.

Table 12: Process data for ORC scenarios

Scenario		**CoSub_ORC**	**CoSub_ORC_PS**
WWTP process data based on scenario		CoSub_Gras12	CoSub_Gras12 + thickening of primary sludge
Excess heat of CHP plant	*kW*	930	1040
Electrical power of ORC process	*kW*	100	100
Operating hours*	*h/a*	6000	7000
Electricity production from ORC	*kWh/a*	600000	700000

** calculated based on heat balance of WWTP (PFI 2010)*

3.4 Background processes

3.4.1 Electricity supply

The electricity mix is based on the German gross production mix of electricity for 2009 (BMWi 2009). Electricity from other sources than listed in Table 13 (“miscellaneous” = 5% of power mix) is accounted as 50% wind power (= renewable energy) and 50% hard coal (fossil energy). Datasets for electricity production are compiled from ecoinvent database (Ecoinvent 2007). A loss of 1.8% of electricity is assumed during grid transport for medium voltage.

Table 13: Electricity mix used in this LCA

Energy type	Assumed power mix [%]	Ecoinvent module
Nuclear	22.6	Electricity, nuclear, at power plant [GER]
Hard coal	20.8	Electricity, hard coal, at power plant [GER]
Lignite	24.5	Electricity, lignite, at power plant [GER]
Natural gas	12.9	Electricity, natural gas, at power plant [GER]
Oil	2.1	Electricity, oil, at power plant [GER]
Wind	8.7	Electricity, at wind power plant [RER]
Hydro	3.2	Electricity, hydropower, at power plant [GER]
Biogas	4.2	Electricity, at cogen with biogas engine, allocation exergy [CH]
Photovoltaic	1	Electricity, production mix photovoltaic, at plant [GER]

Source: BMWi 2009 (miscellaneous sources allocated to hard coal (+2.5%) and wind power (+2.4%))

3.4.2 Transport by truck

Truck transport is modelled with the dataset “transport, lorry 16-32t, EURO4 [RER]” from the ecoinvent database (without infrastructure). It includes all direct and indirect emissions associated with the operation of the vehicle (Ecoinvent 2007). Transport distances for collection of external co-substrates (50 km), sludge disposal to agriculture (15 km), and supply of chemicals (220 km for $FeCl_2$/$MgCl_2$/NaOH/H_2SO_4, 1100 km for polymers, 50 km for limestone) are estimated in cooperation with the operators of the WWTP Braunschweig.

3.4.3 Supply of fuels and chemicals

The production of chemicals and natural gas is modelled with datasets from ecoinvent (Ecoinvent 2007). For some chemicals, datasets are generated based on own assumptions for production processes due to lack of datasets in ecoinvent (Table 14). The production of $FeCl_2$ is assumed from waste acids. The production of polymers for water treatment (mainly polyacrylamide) is modelled with its precursor acrylonitrile. $MgCl_2$ is produced by evaporating concentrated waste brines from salt production.

Table 14: Life cycle data for chemicals production and natural gas

Chemical	Dataset	Remarks
$FeCl_2$ (10%)	Based on production from waste acid	300km truck transport of waste acid + 0.6 kWh/t $FeCl_2$ (10%) for cleaning
Polymer	Modelled as: acrylonitrile from Sohio process, at plant [RER]	Acrylonitrile is precursor of polyacrylamide
$MgCl_2$ (30%)	Based on evaporation of waste brines from salt production	305 kWh E_{therm} for 1m³ of $MgCl_2$ (30%)
Limestone	Limestone, milled, loose, at plant [CH]	
NaOH (50%)	Sodium hydroxide, 50% in H_2O, production mix, at plant [RER]	
H_2SO_4 (96%)	Sulphuric acid, liquid, at plant [RER]	
Natural gas	Natural gas, high pressure, at consumer [DE]	Heating value = 39 MJ/m³

3.4.4 Production of industrial nitrogen and phosphorus fertilizer

The production of industrial nitrogen and phosphorus fertilizer is calculated with datasets generated from Umberto® (IFU and IFEU 2005). Ecoinvent datasets for fertilizer production basically relate to the same primary sources and do not include heavy metals contained in mineral fertilizers (cf. 4.6.2). Basic inventories for fertilizer products are adopted from literature (Patyk and Reinhardt 1997) and amended with emissions to surface waters from other sources (Gaillard et al. 1997). Heavy metal content of mineral N and P fertilizers is calculated based on market shares and specific metal content of fertilizer products (Hackenberg and Wegener 1999; Drescher-Hartung et al. 2001). Details of the datasets are documented elsewhere (Remy 2010). A transport of 300km by truck is assumed for the delivery of the fertilizer from the production site to Braunschweig.

3.5 Selected results of Life Cycle Inventory

3.5.1 Balance of demand and production of electricity and heat

As first information on the energetic balance of the Braunschweig wastewater scheme and of the effect of the optimisation scenarios, a balance of the demand and production of electricity and heat is calculated for each scenario of this LCA (Table 15). The electricity demand of the baseline scenario amounts to 50 kWh/(PE_{COD}*a) and is offset by a production of 29.4 kWh/(PE_{COD}*a) in biogas combustion. Hence, the baseline scenario has a theoretical self-sufficiency of 59% for the electricity demand. This self-sufficiency can be increased up to 80% with co-substrate addition and thermal hydrolysis (scenario Hyd_LDgrass), based on the results of the pilot experiments in CoDiGreen.

Table 15: Balance of demand and production of electricity and heat

*[kWh/PE_{COD}*a]*	**Baseline**	**CoSub_Gras10**	**CoSub_Gras12**	**CoSub_Topi10**	**Hyd_LD**	**Hyd_LDgrass**	**Hyd_DLD**	**Hyd_DLDexe**	**NH3stripp**	**MAP**	**CoSub_ORC**	**CoSub_ORC_PS**
Electricity demand	49.9	50.0	50.0	50.0	50.2	50.4	51.0	50.3	49.1	49.8	50.0	49.5
Aeration	19.1	19.1	19.1	19.1	19.1	19.1	19.1	19.1	18.6	19.1	19.1	19.1
Sludge treatment	5.9	6.0	6.0	6.0	6.2	6.4	7.0	6.3	5.6	5.8	6.0	5.5
Auxiliary WWTP	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2
Spray irrigigation	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.8	14.7	14.7	14.7	14.7
Electricity production	29.4	38.2	30.8	35.5	32.4	40.4	36.5	37.3	29.4	29.4	32.5	32.8
CHP plant	29.4	38.2	30.8	35.5	32.4	40.4	36.5	37.3	29.4	29.4	30.8	30.8
ORC											1.7	2.0
Net electricity balance	**20.4**	**11.9**	**19.2**	**14.5**	**17.9**	**10.4**	**14.5**	**13.0**	**19.7**	**20.4**	**17.4**	**16.7**
Heat demand digestor	15.3	15.6	15.7	15.5	0	0	15.6	16.9	11.4	15.2	15.7	13.0
Heat demand hydrolysis					26.5	29.0	37.3	15.7				
Heat production CHP plant	32.1	41.6	33.6	38.8	35.3	43.6	39.8	40.7	38.1	32.1	33.6	33.6

The heat demand of the digestors and of thermal hydrolysis of sludge can be met by the heat produced by the CHP plant (off-gas and cooling water), except for scenario Hyd_DLD where extra fuel is required due to the high amount of sludge to be treated (cf. Table 11).

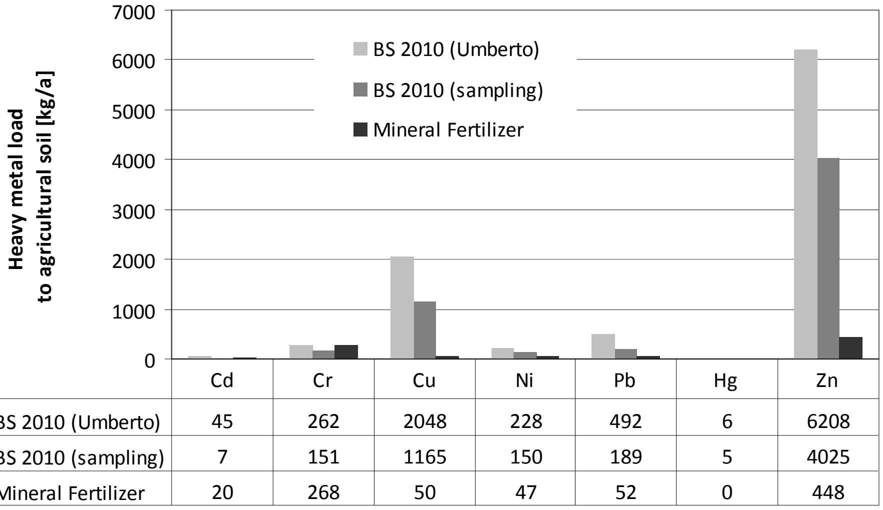
3.5.2 Heavy metal loads to agricultural soil

Due to their low concentrations, trace pollutants such as heavy metals are difficult to quantify precisely in load balances in a WWTP. Primary data of regular sampling can be impaired with relatively high variance, resulting from sampling procedures, sample preparation, or insufficient limits of quantification. Thus, heavy metal balances in a WWTP are difficult to close, even though heavy metals cannot be degraded or metabolized in the biological process due to their chemically persistent nature.

For this LCA, it is assumed that heavy metal loads in the WWTP influent and effluent represent the flows with the highest accuracy, because they are sampled with a high frequency and using a mixed sample (daily 24h-composite samples). Sampling in wastewater sludge is done in weekly grab samples, and sample preparation can be difficult in the sludge matrix. Consequently, heavy metal balances are artificially closed by assuming that influent and effluent loads in the WWTP are measured properly, while the remaining heavy metals will end up in the wastewater sludge (influent = effluent + sludge).

The calculated heavy metal loads (= based on influent data) are substantially higher (+120-640%) than the loads based on effluent and sludge sampling in the WWTP (Figure 8). For some heavy metals (Cd, Pb, Ni), this discrepancy can be explained be insufficient limits of quantification in the influent sampling, leading to an overestimation of the mean influent concentrations as they are below the limit of quantification (SE/BS 2010).

In this study, the calculated loads will be used for impact assessment despite the higher uncertainty in the respective data. Compared to an average mineral fertilizer with equivalent nutrient content, digested sludge and effluent have a high content of Cu, Zn, Ni, Pb and Hg, whereas they decrease the loads of Cd/Cr based on the sampling data.



	Cd	Cr	Cu	Ni	Pb	Hg	Zn
■ BS 2010 (Umberto)	45	262	2048	228	492	6	6208
■ BS 2010 (sampling)	7	151	1165	150	189	5	4025
■ Mineral Fertilizer	20	268	50	47	52	0	448

Figure 8: Heavy metals to agricultural soil: comparison of calculated loads (Umberto), sludge analysis (sampling) and mineral fertilizer with equivalent nutrient content

Chapter 4

Life Cycle Impact Assessment

4.1 Environmental impacts of wastewater scheme in Braunschweig in 2010

For evaluating the environmental impacts of the Braunschweig wastewater system, the total indicator results are analysed with a contribution analysis, showing the contribution of the different stages (WWTP, sludge treatment and disposal (in winter), operation of infiltration fields, and agricultural irrigation) and the different types of energy consumption (electricity, heat, chemicals, transports, credits for substitution of fertilizer or electricity production). Thus, decisive parts of the system can be identified that have a high influence on the respective environmental impact, revealing potential targets for optimization measures.

4.1.1 Cumulative energy demand

In total, the gross cumulative energy demand of the wastewater scheme in Braunschweig amounts to 584 MJ/(PE_{COD}*a). The wastewater treatment process itself consumes 50% of this energy, mainly in the form of electricity (Figure 9). Sludge treatment contributes with 25% to energy demand for electricity, heating of digestors, and polymer for sludge dewatering. While the infiltration fields have only a small demand of electricity (low pumping head), the pumping of effluent into the distribution system for agricultural reuse consumes 22% of the total energy demand for delivering the system pressure (5 bar).

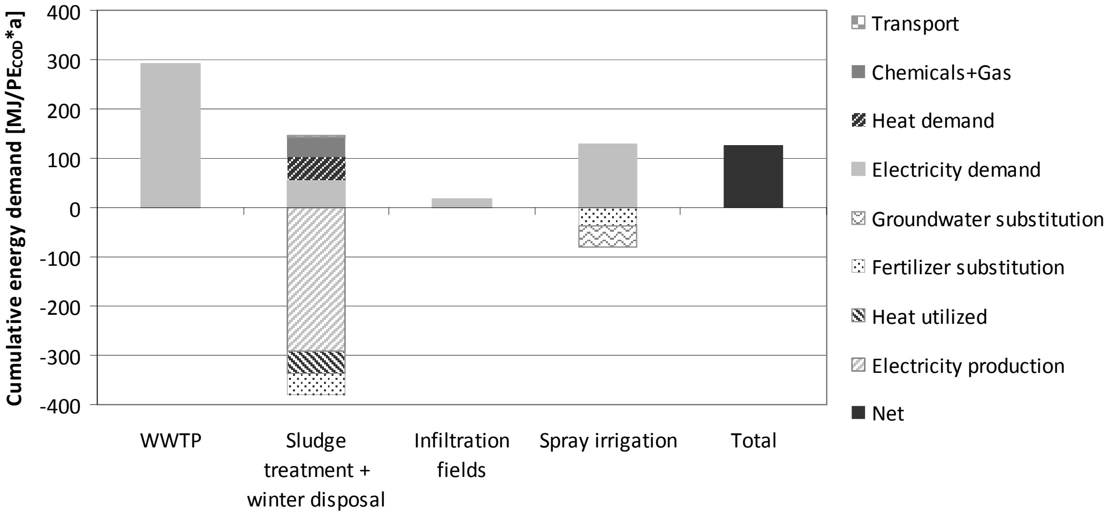


Figure 9: Cumulative energy demand of wastewater scheme in Braunschweig 2010

The credits for substitution of grid electricity, mineral fertilizer or groundwater pumping are accounted with 459 MJ/(PE_{COD}*a) for the Braunschweig system. The main part of these credits (73%) is generated from biogas combustion generating electricity and heat, so that the sludge treatment itself is energetically beneficial. The substitution of mineral fertilizer by nutrients in sludge and effluent has a credit of 82 MJ/(PE_{COD}*a) (18%), whereas the substituted groundwater pumping contributes only 41 MJ/(PE_{COD}*a) (9%). Overall, the recovery of energy and nutrients in sludge treatment is energetically more beneficial than the recovery of water and nutrients in agricultural reuse. However, it has to be kept in mind that the substitution potential for reused nitrogen (40%) and water (25%) is limited in Braunschweig (cf. 2.4), revealing major potentials for system optimization by improving the efficiency of water and nutrient management according to the needs of the farmers. Currently, the agricultural reuse of effluent is energetically unfavourable due to the limited accountability of water and nutrients.

The net energy demand of the Braunschweig system amounts to 126 MJ/(PE_{COD}*a), so that 79% of the initial cumulative energy demand are compensated by secondary products of the system. The influence of varying assumptions for the substitution potential of reused water and nutrients is further investigated in sensitivity analysis.

4.1.2 Carbon footprint

The gross carbon footprint of the wastewater system in Braunschweig amounts to 43 kg CO_2-eq/(PE_{COD}*a). 55% of the carbon footprint is generated in the WWTP process, mostly due to electricity demand (42%) and on-site process emissions of N_2O and CH_4 from the biological process (Figure 10). Sludge treatment contributes 23% of the carbon footprint due to electricity and heat demand, chemicals and on-site emissions of CH_4 (from CHP plant) and fossil CO_2 (digestor heating with natural gas in cold winter months). Pumping to agricultural reuse and infiltration fields generates another 19% and 3%, respectively.

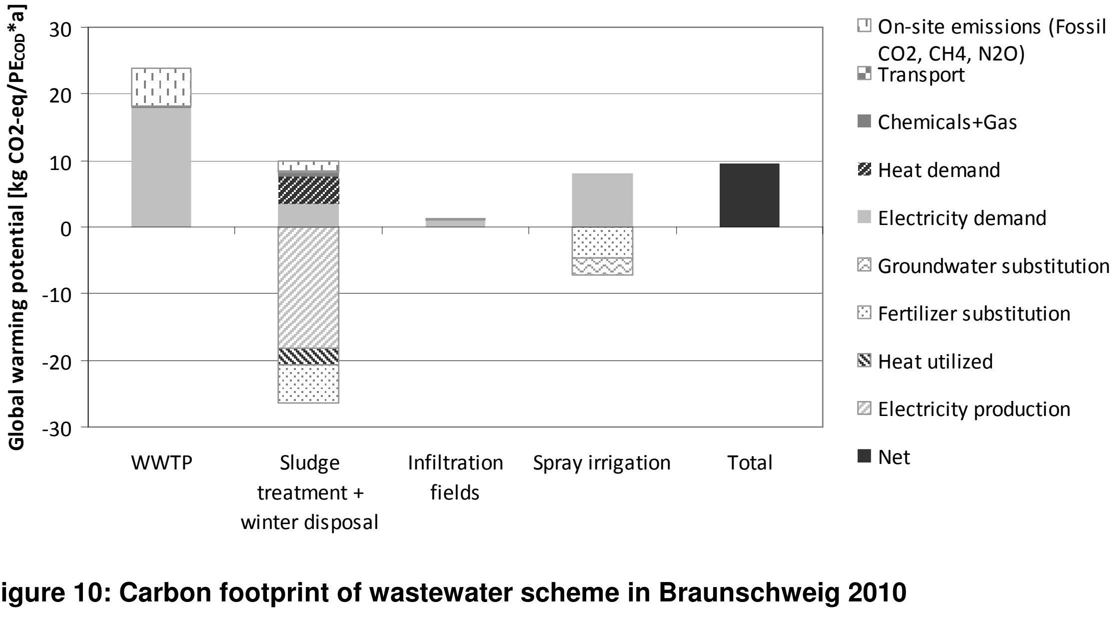


Figure 10: Carbon footprint of wastewater scheme in Braunschweig 2010

Credits for secondary products add up to 34 kg CO_2-eq/(PE_{COD}*a), with contributions of 61%, 31%, and 8% for electricity and heat, nutrients, and groundwater pumping. For the carbon footprint, nutrient recovery plays a more important role than for the cumulative energy demand due to N_2O emissions during the production of nitrogen fertilizer. Hence, agricultural reuse is almost neutral in carbon footprint due to credits for fertilizer substitution. In total, the net carbon footprint of the Braunschweig system amounts to 10 kg CO_2-eq/(PE_{COD}*a), so that 78% of the initial carbon footprint can be compensated by secondary products. For sensitivity analysis, assumptions for substitution potentials of water/nutrients and generic emission factors of the biological process (N_2O, CH_4) are investigated in their influence on the overall results.

4.1.3 Acidification

The gross acidification potential of the Braunschweig system amounts to 110 g SO_2-eq/(PE_{COD}*a), mostly due to on-site emissions of acidifying gases in biological wastewater treatment (51% by NH_3) and indirect emissions of electricity production (33% by SO_2) (Figure 11). The direct NH_3 emissions of the WWTP process occur during aeration of raw wastewater and are estimated with a generic emission factor in this LCA. These emissions cannot be completely avoided (no off-gas cleaning possible with open tanks) and can only be mitigated by precise control of the aeration regime and other process conditions. Substituted products generate credits of 80 g SO_2-eq/(PE_{COD}*a), with a high contribution of fertilizer substitution. In total, the net acidification potential of the Braunschweig system adds up to 30 g SO_2-eq/(PE_{COD}*a). Sensitivity analysis will reveal the influence of the generic emission factor for NH_3 from the biological WWTP process on the overall results.

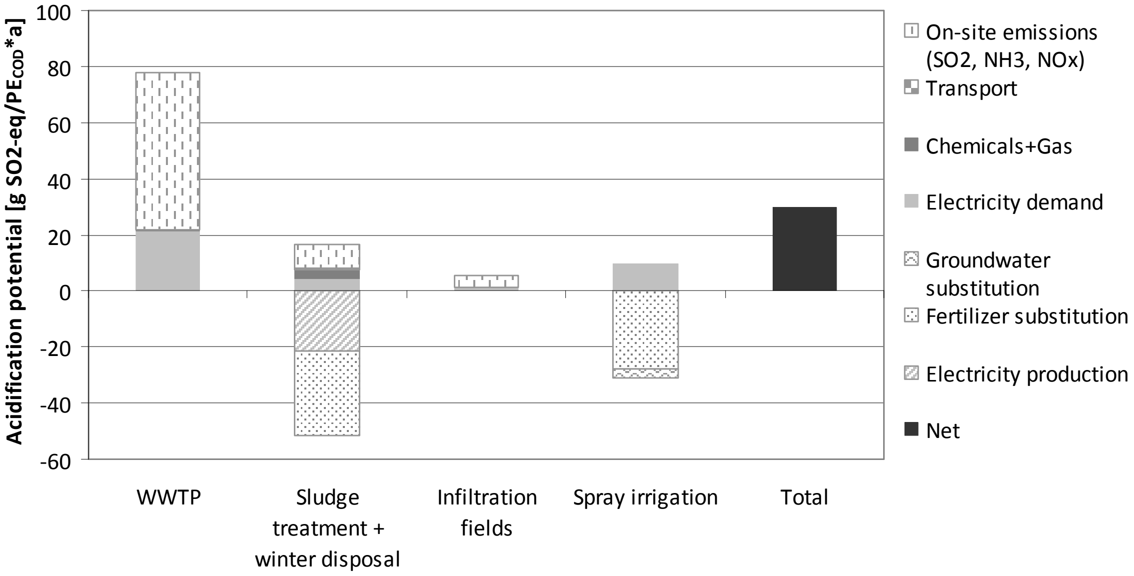


Figure 11: Acidification potential of wastewater scheme in Braunschweig 2010

4.1.4 Eutrophication of freshwaters and seawaters

Direct or indirect emissions of P into surface waters are responsible for the eutrophication of freshwaters. In the corresponding indicator, the gross eutrophication potential of freshwaters adds up to 62 g P-eq/(PE_{COD}*a) for the Braunschweig system, where the effluent of the infiltration fields to surface waters contributes to 47% and the input of P into agricultural soil another 47% (Figure 12). The latter is completely compensated by fertilizer substitution, as both variants (reuse or mineral fertilizer) transfer a comparable load of P to agricultural soils. Electricity production or substitution plays only a minor role in this impact category.

The decisive influence of this impact is the direct emissions of the WWTP, which is closely related to its primary function (i.e. the protection of surface waters). In Braunschweig, the infiltration fields used for effluent polishing play an important role in P control: while they can improve the effluent quality (usually in winter), it is also possible that phosphorus bound in the soil is re-dissolved during oxygen-depleted conditions in summer or mobilized in form of particulate P during hydraulic peak load events. However, P emissions of the WWTP are regulated by authorities and are thus closely monitored by the operators, targeting the minimisation of P emissions to surface waters. Finally, the net eutrophication potential of freshwaters amounts to 29 g P-eq/(PE_{COD}*a).

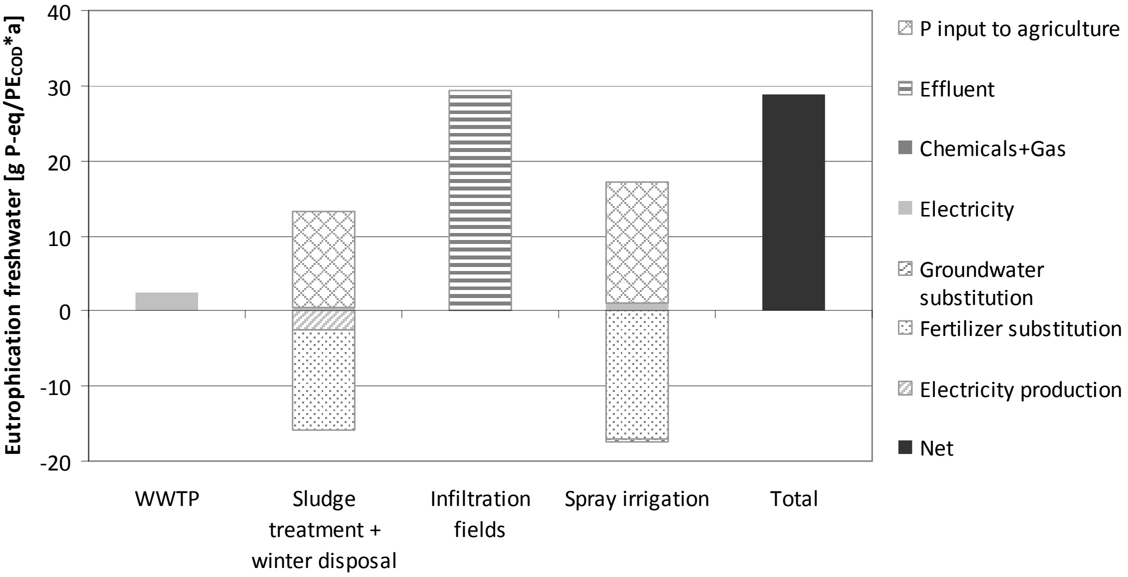


Figure 12: Eutrophication potential for freshwaters of wastewater scheme in Braunschweig 2010

The other nutrient of concern is nitrogen, causing the eutrophication of seawaters by transfer of N via river systems into the oceans. For the Braunschweig system, the gross eutrophication potential for seawaters amounts to 173 g N-eq/(PE_{COD}*a). 45% of the total impact is caused by direct emissions of nitrogen from the infiltration fields, while 49% is accounted for nitrogen input into agricultural soils (Figure 13). In analogy to the P emissions, N emissions to agricultural soil are completely compensated with avoided impacts from mineral fertilizer production and application.

Direct nitrogen emissions into surface waters are strictly regulated by the authorities, requiring regular monitoring and process control to minimize negative effects in the environment. Nitrogen can be eliminated by biological processes (denitrification), so that effluent polishing in infiltration fields has a positive effect on the effluent quality due to enhanced nitrogen removal in soil passage (cf. Table 9). Hence, the Braunschweig system has a low effluent concentration for nitrogen (6 mg/L) in comparison with other large-scale WWTPs. Overall, the net eutrophication potential of seawaters adds up to 80 g N-eq/(PE_{COD}*a) for the Braunschweig system.

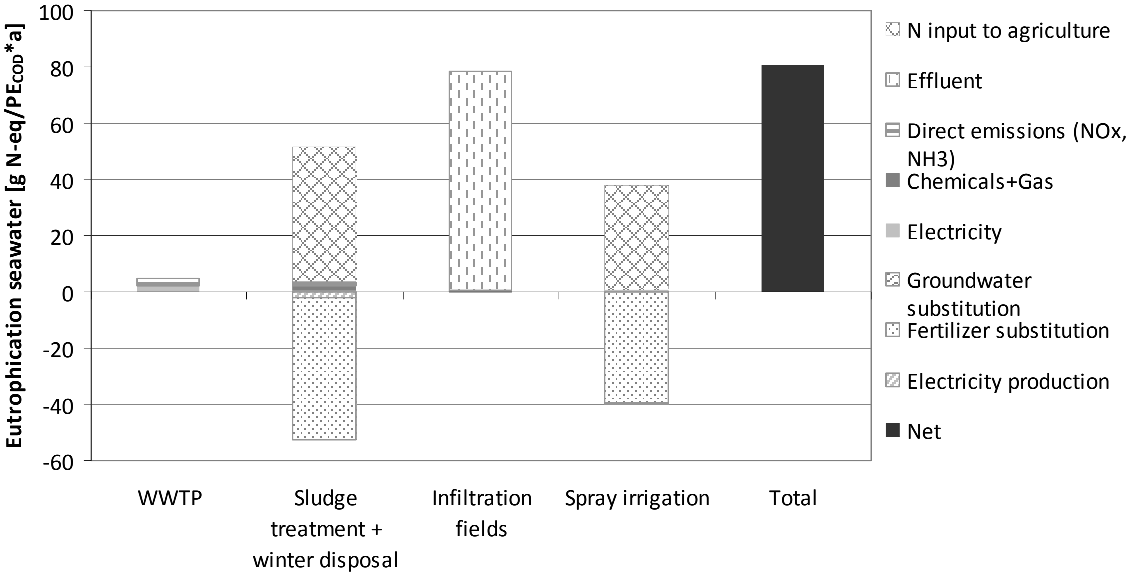


Figure 13: Eutrophication potential for seawaters of wastewater scheme in Braunschweig 2010

4.1.5 Human toxicity

For human toxicity, the impact assessment calculates a gross human toxicity potential of 708 g DCB-eq/(PE$_{COD}$*a), mainly caused by indirect emissions during electricity production (68%) and heavy metal input to agricultural soil (30%). The contribution of heavy metal input to farmland describes the potential risk of negative effects on humans through transfer of heavy metals to food and further on to consumers. This issue is of potential concern in the Braunschweig reuse scheme, and consequently the close monitoring of heavy metal concentrations in soil and crops is required by the authorities. It has to be noted here that organic pollutants are explicitly excluded from this LCA (cf. 2.6). Additionally, a risk assessment study is carried out in the project “CoDiGreen” to identify and mitigate potential hazards for humans in the reuse scheme (KWB 2010).

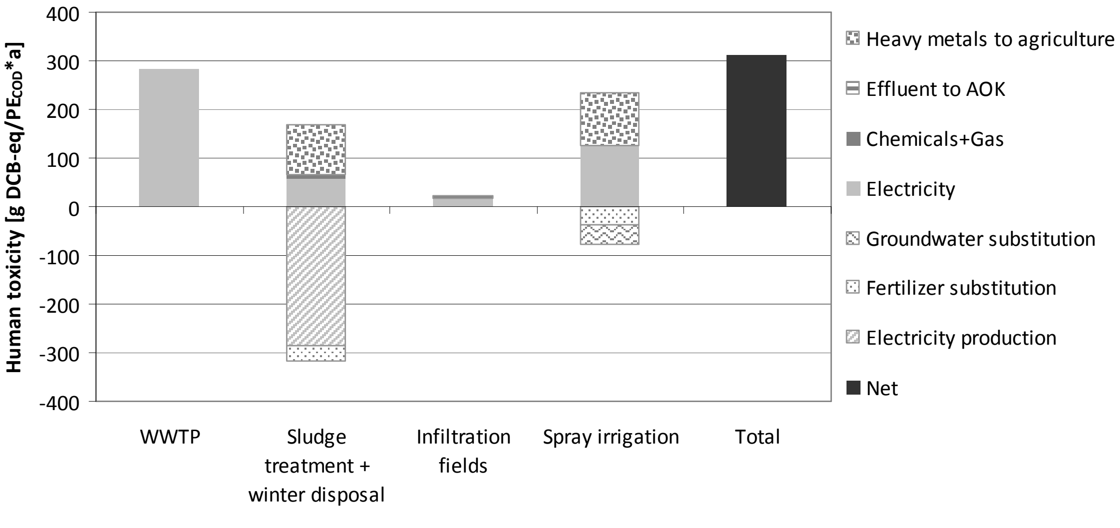


Figure 14: Human toxicity potential of wastewater scheme in Braunschweig 2010

The indirect emissions from electricity supply are mostly compensated by credits for electricity production from biogas. Credits for substitution of mineral fertilizer are substantially smaller than impacts from reuse of water and sludge, revealing the higher content of heavy metals in effluent and sludge, compared to mineral fertilizer (cf. Figure 8). In total, credits for human toxicity amount to 395 g DCB-eq(/PE_{COD}*a), resulting in a net human toxicity potential of 313 g DCB-eq/(PE_{COD}*a) for the Braunschweig system.

4.1.6 Aquatic and terrestrial ecotoxicity

Ecotoxicity in aquatic ecosystems is mainly caused by direct emissions of heavy metals to surface waters (via effluent of infiltration fields) or by indirect emissions of heavy metals to agricultural soil, followed by their transfer to surface waters via groundwater. For the Braunschweig system, the gross freshwater aquatic ecotoxicity potential is calculated to 53 g DCB-eq/(PE_{COD}*a), with contributions of effluent from infiltration fields (58%) and reused water and sludge in agriculture (40%) (Figure 15). It has to be noted here that the ecotoxicity assessment of effluent and sludge is limited to inorganic heavy metals and excludes organic pollutants (cf. 2.6). However, both effluent and sludge contain a variety of organic pollutants (polycyclic aromatic hydrocarbons, endocrine disruptors, pharmaceuticals, etc) which are not evaluated in this LCA, thus showing an important limitation of the approach of this study.

Credits for substitution of electricity and nutrients are small, accounting for only 6 g DCB-eq/(PE_{COD}*a). The low heavy metal content of mineral fertilizer in comparison to the reuse of water and sludge (cf. Figure 8) is responsible for this effect, once again stressing potential ecotoxicity hazards by increased emission of heavy metals to agricultural soils. The net freshwater aquatic ecotoxicity potential for the Braunschweig system amounts to 47 g DCB-eq/(PE_{COD}*a).

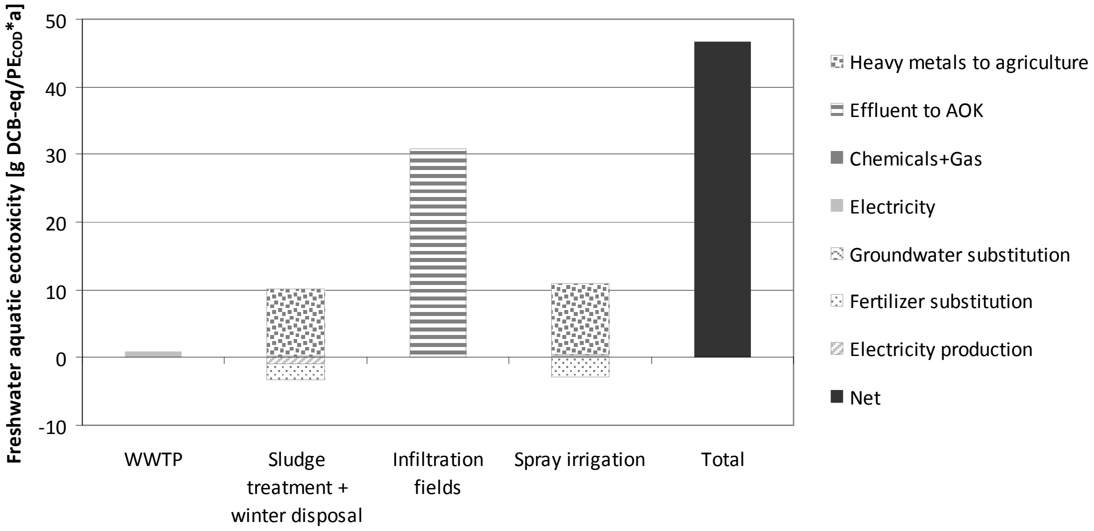


Figure 15: Freshwater aquatic ecotoxicity potential of wastewater scheme in Braunschweig 2010

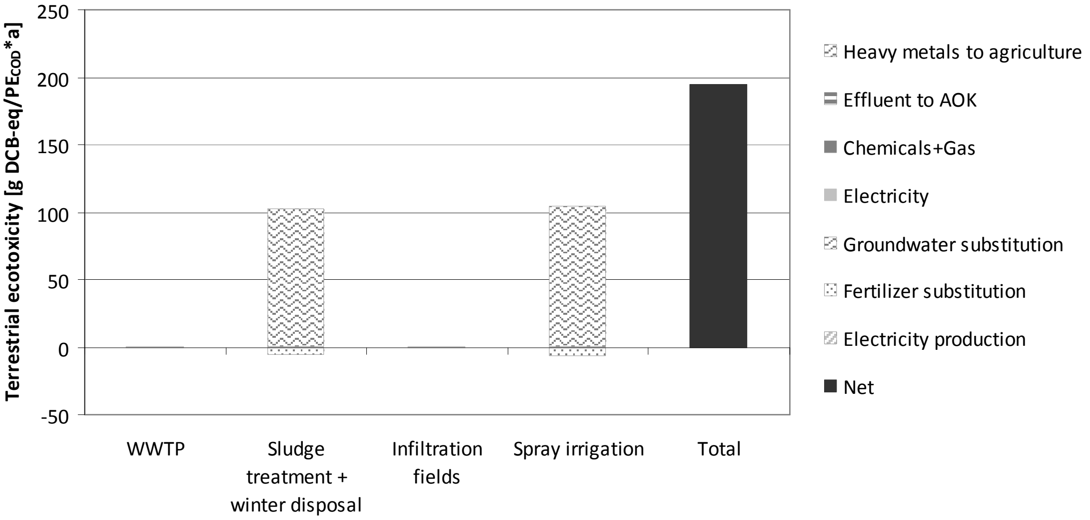


Figure 16: Terrestrial ecotoxicity potential of wastewater scheme in Braunschweig 2010

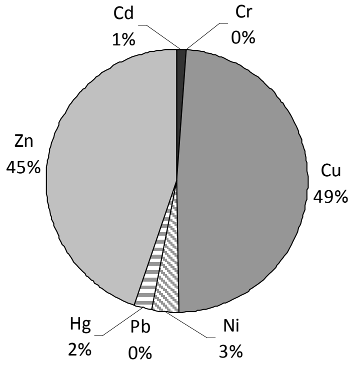


Figure 17: Contribution of heavy metals emitted to soil to terrestrial ecotoxicity potential

Comparable results are obtained for the terrestrial ecotoxicity: the gross terrestrial ecotoxicity potential amounts to 206 g DCB-eq/(PE_{COD}*a), with 99% contribution of the direct input of heavy metals to agricultural soils via reused water and sludge (Figure 16). Effluent from the infiltration fields has a negligible influence in this impact category (<1%), because the transfer of heavy metals from surface waters to soil is less distinctive than vice versa. Again, credits for mineral fertilizer substitution are small (12 g DCB-eq/(PE_{COD}*a) due to the low heavy metal content of industrial fertilizer compared to that of reused water and sludge. A deeper analysis of the contributing heavy metals shows the high influence of Cu and Zn for this impact category (Figure 17). Both metals are typically found in wastewater in high concentrations, because they are heavily used in pipe installations (Cu) and surface coatings (Zn). Hence, they finally end up in the wastewater sludge and cause high ecotoxicity impact scores during sludge application in agriculture due to their high loads (cf. Figure 8) and relatively high characterisation factors. For the Braunschweig system, a net terrestrial ecotoxicity potential of 194 g DCB-eq/(PE_{COD}*a) is calculated in this study.

4.2 Normalisation

All indicator results for the baseline scenario are normalised to the total environmental impacts in Germany 2007. The normalised scores for the different indicators are between 0.003 and 0.2 PE*a for the impacts only and 0.001-0.1 PE*a for the net impacts, showing a large variation in the relative contribution of the different categories of environmental impact (Figure 18).

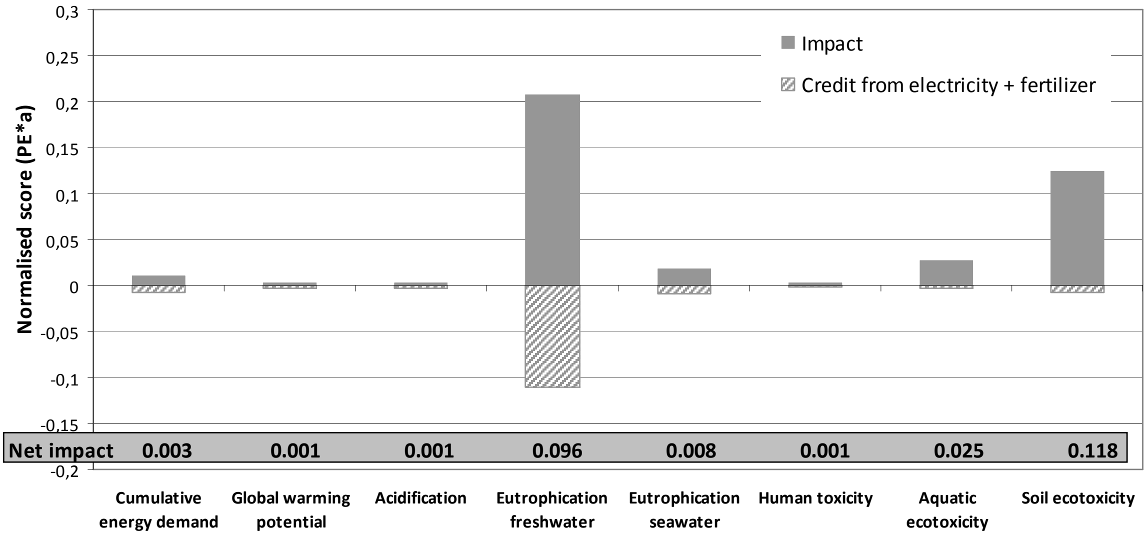


Figure 18: Normalisation of environmental impacts of the wastewater scheme in Braunschweig 2010 to total environmental impacts in Germany

Two groups of indicators can be distinguished after normalisation:

1. Indicators with high net contribution (>0.005 PE*a): eutrophication of freshwaters and seawaters, aquatic and terrestrial ecotoxicity potential
2. Indicators with small net contribution (<0.005 PE*a): cumulative energy demand, global warming potential, acidification potential, and human toxicity potential

The first group of indicators is strongly correlated to the primary function of the WWTP, i.e. the protection of surface waters from excessive input of pollutants. These indicators are mainly influenced by direct emissions of the WWTP into surface waters (nutrients in case of eutrophication, heavy metals in case of aquatic ecotoxicity) and consequently have a high relative contribution after normalisation. Due to the reuse of effluent and sludge in agriculture and the related input of heavy metals into agricultural soils, the Braunschweig system also has a relatively high impact in terrestrial ecotoxicity. A careful monitoring of negative effects caused by heavy metal transfer to agricultural soils is recommended to ensure that environmental impacts on terrestrial ecosystems are as small as possible. For humans, toxicity of heavy metals spread on farmland seems to be of less quantitative importance with respect to the small normalised score of human toxicity potential. Nevertheless, both agricultural soils and crop products are monitored closely by operators and authorities to identify possible accumulation of heavy metals in soil or plants and to prevent any possible danger to human health at an early stage.

The second group of indicators is mainly determined by resource demand or emissions of indirect processes (energy supply, chemicals), partially amended by specific gaseous process emissions on-site (N_2O and NH_3 from aeration, CH_4 from CHP plant). They can be influenced by a reduction in energy or chemicals demand or by process optimisation to avoid unnecessary emissions during aeration or CHP plant operation.

In other words, the normalisation of the environmental indicators reveals the quantitative importance of maintaining and improving the primary function of the WWTP (= protection of surface waters) and shows the impact of agricultural reuse of effluent and sludge on terrestrial ecosystems. Impacts related to the energy and chemicals which are required to maintain the primary function are quantitatively small after normalisation. Hence, the optimisation of these indicators (cumulative energy demand, carbon footprint) should be carefully monitored not to compromise the primary function of the WWTP, i.e. by deteriorating the effluent quality. It should be noted that the normalisation results show just the quantitative contribution and cannot be interpreted in the sense of a qualitative importance which would require grouping and weighting of the indicator results.

4.3 Reference to conventional WWTP

The environmental impacts of the Braunschweig wastewater scheme are referenced to a hypothetical WWTP using a conventional way of effluent discharge, i.e. the direct discharge into surface waters (= no infiltration fields, no agricultural reuse of water). Sludge is disposed in agriculture in both variants. Thus, the specific effects of the Braunschweig reuse system on the environmental profile are revealed (Figure 20):

- The environmental impacts of effluent discharge (eutrophication via nutrient emissions, aquatic ecotoxicity via heavy metals) are substantially smaller in the Braunschweig reuse system. That effect is mainly caused by the diversion of a major part of nutrients and heavy metals to agriculture (= not into surface waters) and secondly by the polishing effect of the infiltration fields (further reduction of nitrogen and phosphorus in the effluent prior to discharge into the river).
- The ecotoxic effects on terrestrial ecosystems are comparable between both systems due to the identical way of sludge disposal in agriculture. Most heavy metals are bound in the wastewater sludge, so that both scenarios have comparable impacts in terrestrial ecotoxicity. This impact could only be decreased by thermal disposal of sludge and subsequent deposition in a landfill.
- Energy demand and related indicators (cumulative energy demand, global warming potential) are higher in the Braunschweig reuse system.

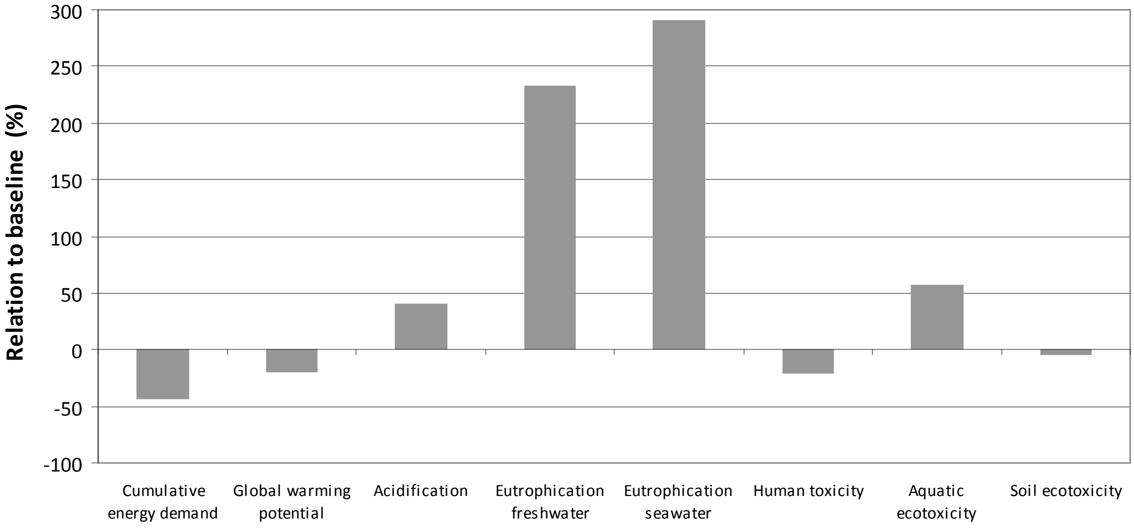
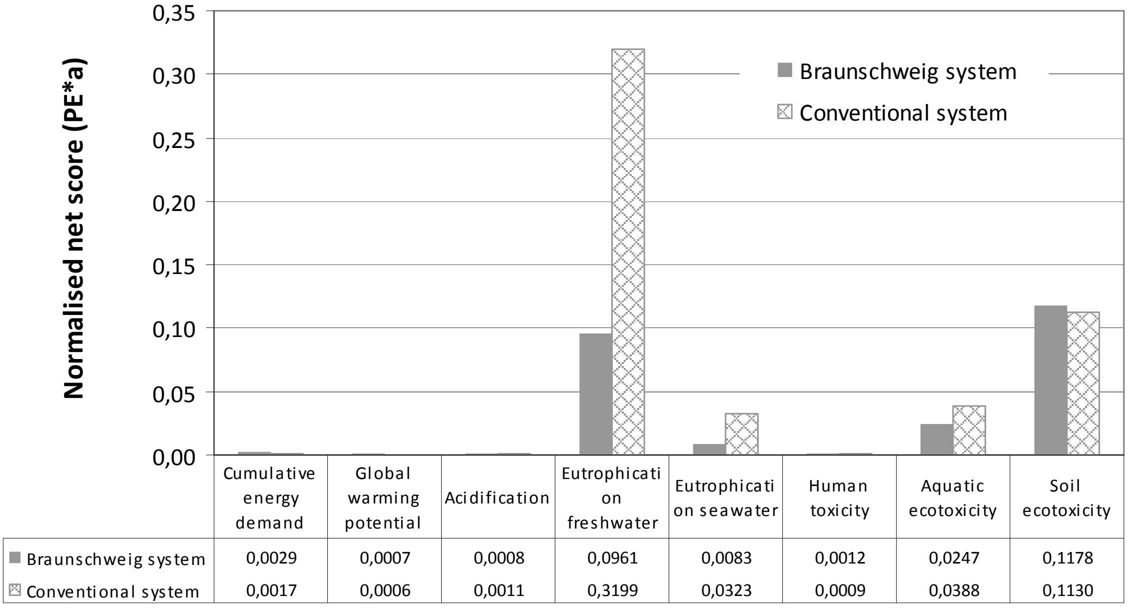


Figure 19: Environmental profile of the conventional system in relation to baseline



	Cumulative energy demand	Global warming potential	Acidification	Eutrophication freshwater	Eutrophication seawater	Human toxicity	Aquatic ecotoxicity	Soil ecotoxicity
■ Braunschweig system	0,0029	0,0007	0,0008	0,0961	0,0083	0,0012	0,0247	0,1178
⊠ Conventional system	0,0017	0,0006	0,0011	0,3199	0,0323	0,0009	0,0388	0,1130

Figure 20: Comparison of normalised environmental impacts of Braunschweig wastewater reuse scheme and hypothetical conventional system

Overall, the Braunschweig system has obviously environmental benefits regarding the primary functions of a WWTP with high quantitative importance (Figure 20): the emissions of nutrients and heavy metals in surface waters are lower than in a conventional system of direct effluent discharge. Additionally, the reuse of effluent in agriculture does not substantially increase the ecotoxicity on terrestrial ecosystems if compared to a system with agricultural disposal of sludge. However, the energy balance of the Braunschweig system and the resulting carbon footprint are inferior to a conventional system, mainly due to high amounts of electricity required for pumping the effluent to the distribution system in agriculture. Here, the over-irrigation of the farmland beyond the actual demand for irrigation water leads to an inferior energy balance of agricultural reuse in this LCA, as only 25% of the reused water is actually accounted as valuable product (cf. 2.4). Hence, 75% of the water is delivered to the fields without actually substituting groundwater pumping, impairing the energetic balance of the Braunschweig system.

The historic reason behind the excessive supply of water to agriculture is the small surface water (river Oker) available for receiving the discharge of the WWTP. For the protection of this sensible river from hydraulic peak loads or excessive pollutant inputs, land application of wastewater was established in Braunschweig during the 1950s. Thus, the amount of water delivered to the fields does not match the actual demand for irrigation, but is rather oriented on the amount of water that can be directly discharged to the river system. Taking into account the positive impacts of effluent reuse in agriculture on the direct impacts to the river (eutrophication, aquatic ecotoxicity), the higher energy demand and carbon footprint of the Braunschweig system may be justified as a trade-off to improved river quality. However, an optimised system of agricultural reuse with closer matching of water supply and demand would have a better energy balance than the existing Braunschweig system. Finally, optimisation of water management related to the needs of the farmers would be advisable in Braunschweig to overcome this energetic handicap, even though it would only affect the environmental balance (accounting of substituted groundwater) and not the actual energy demand for pumping. Another possibility would be the discharge of more water via infiltration fields into the river, but this could lead to higher nutrient and pollutant loads in the aquatic system.

4.4 Environmental impacts of optimization measures

The following chapter describes the environmental impacts of different measures for system optimisation. For all optimisation scenarios, selected indicators are presented with a relative contribution analysis, showing the change in the respective environmental impact compared to the baseline scenario. Thus, relevant environmental effects of the optimisation measures can be identified and assigned to underlying operational issues, e.g. electricity demand, chemicals demand, biogas production etc. Additionally, relative environmental profiles are calculated showing the impact of a certain measure on all categories of environmental impacts. Profiles are useful to determine trade-offs between different environmental effects and reveal potential drawbacks of optimisation measures. Finally, relative and normalised impacts of all optimisation measures are compared to identify most promising measures and give a conclusive picture on the potential improvement of the environmental footprint of the Braunschweig wastewater scheme.

4.4.1 Co-substrates

The addition of organic co-substrates (ensiled grass, topinambur greens) into the digestion process leads to a substantial increase in the biogas production and consequently in the credit for electricity production. This has a positive effect on both cumulative energy demand and carbon footprint of the Braunschweig system, reducing the existing net energy demand by 12-69% (Figure 21) and the carbon footprint by 14-66% (Figure 22).

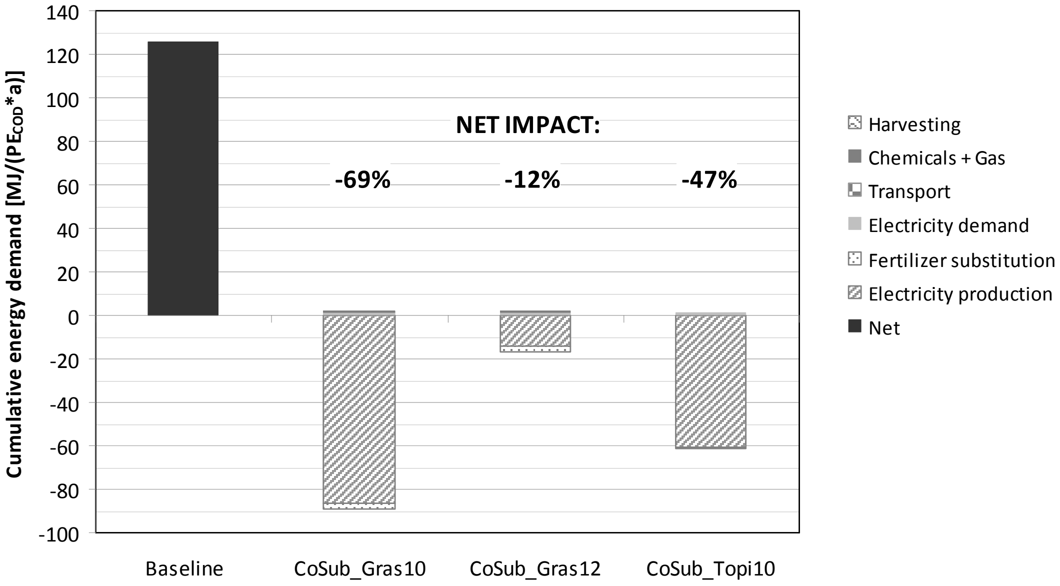


Figure 21: Change in cumulative energy demand due to addition of co-substrates

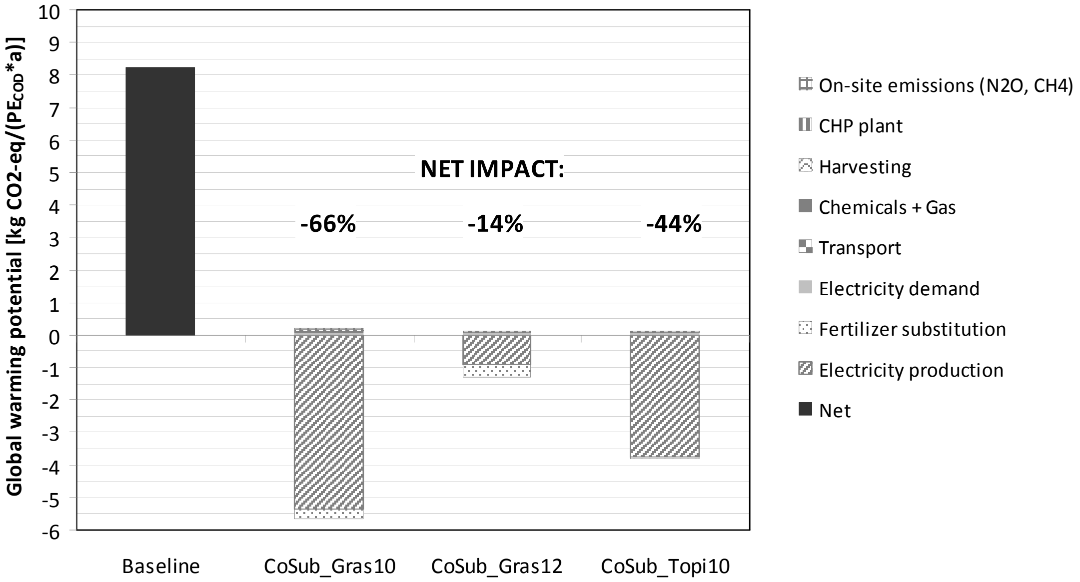


Figure 22: Change in carbon footprint due to addition of co-substrates

Both effects are mainly due to the additional electricity production from biogas, whereas the additional nutrients delivered by the co-substrates and the respective increase in fertilizer substitution have only a minor impact. The latter effect is no double-counting of nutrients, because the co-substrates grow on nutrients which are delivered by WWTP effluent to infiltration fields and consequently would be lost for recovery. With the input of co-substrates from infiltration fields into the digestors, more nutrients enter the route to agricultural reuse (through disposal of digester residuals of co-substrate digestion in agriculture) so that the overall recovery of nutrients from wastewater is improved. Further impacts from harvesting, sludge transport or chemicals are negligible in relation to the benefits from biogas production.

The addition of co-substrates decreases the net acidification potential by 8-21%, mainly due to avoided emissions during the production of electricity and fertilizers (Figure 23). Additional impacts are generated by emissions from CHP plant during biogas combustion, but these emissions are completely offset by the benefits from the substituted products. For human toxicity, net benefits of co-substrate addition amount to 3-25% (Figure 24) due to the increase in substituted electricity. Additional input of heavy metals from co-substrates into agricultural soil contributes only a minor impact in human toxicity.

For the co-substrate scenarios, it has to be kept in mind that the results for scenarios CoSub_Gras10 and CoSub_Topi10 are based on the results of pilot-scale experiments in CoDiGreen, which could not yet be verified in full-scale. The scenario CoSub_Gras12 represents the effects of co-substrate addition which could be observed in the full-scale plant, leaving a high potential for improvement in relation to the lab-scale results. This fact is discussed in detail in the report of the experimental results.

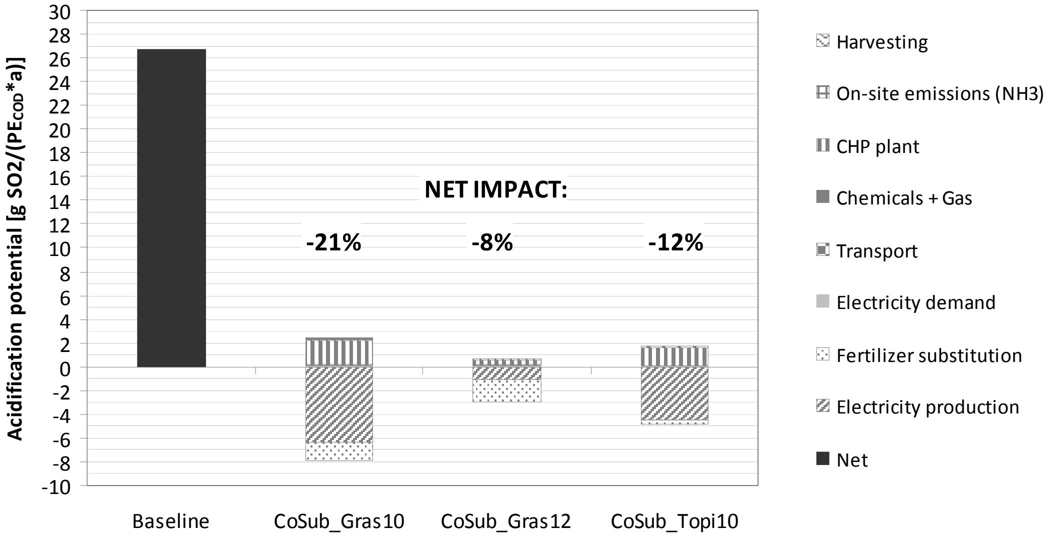


Figure 23: Change in acidification due to addition of co-substrates

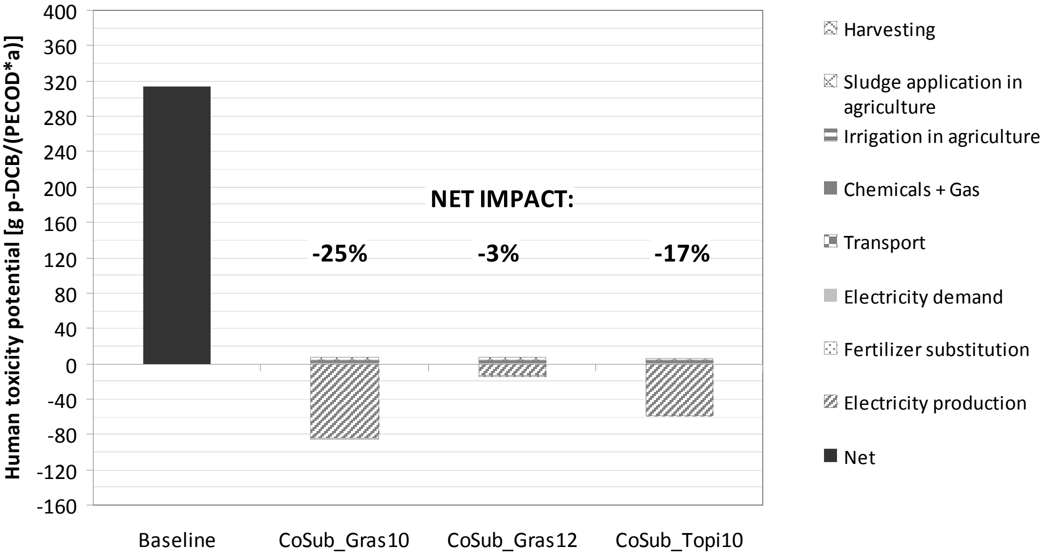


Figure 24: Change in human toxicity due to addition of co-substrates

The overall environmental profile of co-substrate addition shows a substantial improvement in many impact categories for the exemplary scenario CoSub_Gras10 (Figure 25). Only in aquatic and soil ecotoxicity, the additional heavy metal content in co-substrates leads to a small increase in heavy metal input into the soil. However, the increase in ecotoxicity potential is marginal for both aquatic (+0.2%) and terrestrial ecosystems (+1.3%).

In summary, it can be concluded that the addition of organic co-substrates into the digestion process leads to an overall improvement of the environmental profile of the Braunschweig wastewater scheme. Major improvements originate from the enhanced production of electricity from biogas, with minor contributions of the additional nutrients substituting mineral fertilizer. Additional impacts from emissions during biogas combustion are offset by benefits from electricity substitution. Finally, co-substrates have a low content of heavy metals, so that the additional input of heavy metals into the agricultural system leads only to a minor increase of ecotoxicity.

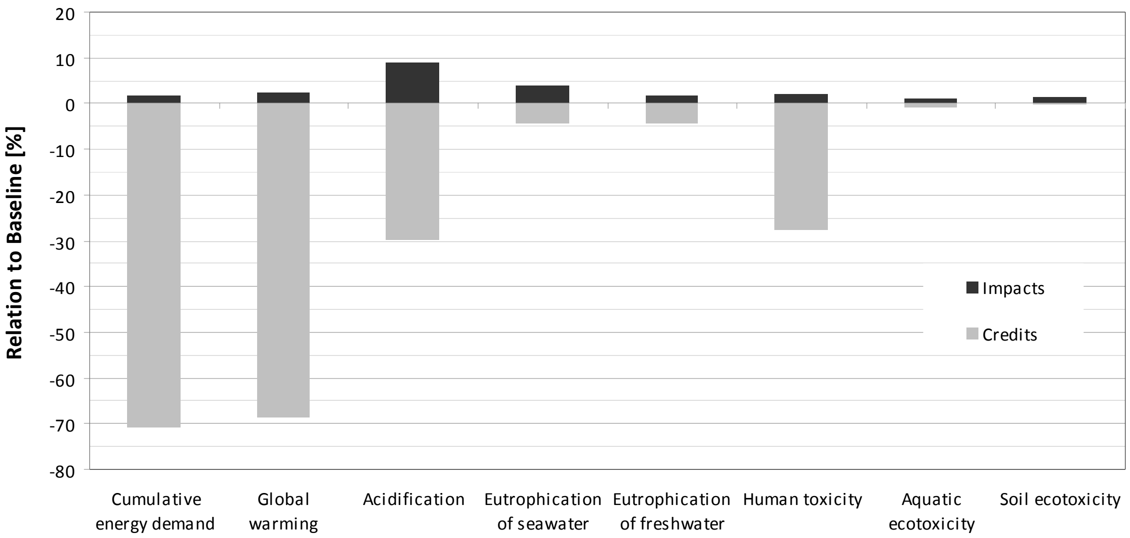


Figure 25: Environmental profile of scenario CoSub_Gras10 in relation to baseline

4.4.2 Thermal hydrolysis

Thermal hydrolysis of sludge leads to an increase in degradability of the organic matter through improved hydrolysis of organics. However, substantial amounts of energy (mainly steam) are required for this pre-treatment of sludge, which can be partially or completely delivered by off-gas heat from CHP plants. Consequently, the decisive issue within the energy balance of this process is the relation between energy benefits (in form of additional biogas) and necessary inputs of external energy (e.g. natural gas) for steam production. The latter amount heavily depends on the volume of sludge to be treated and the additional biogas production which increases off-gas heat from CHP plant. Both factors are different for each scenario of thermal hydrolysis and result in specific energy balances for each configuration of thermal hydrolysis.

The first configuration (Hyd_LD) assumes thermal hydrolysis of excess sludge in the existing system and results in a reduction of 21% for cumulative energy demand (Figure 26) and 19% for carbon footprint (Figure 27), based on the results of pilot-scale experiments in CoDiGreen. Additional energy demand for the hydrolysis unit is well compensated by additional electricity production, and no external fuels are required for producing steam. Combining the effects of thermal hydrolysis and addition of ensiled grass as co-substrate (Hyd_LDgrass), energy demand and carbon footprint are reduced by 80 and 77%, respectively. Again, results are based on pilot-scale experiments and assume that no external fuels are required for steam production.

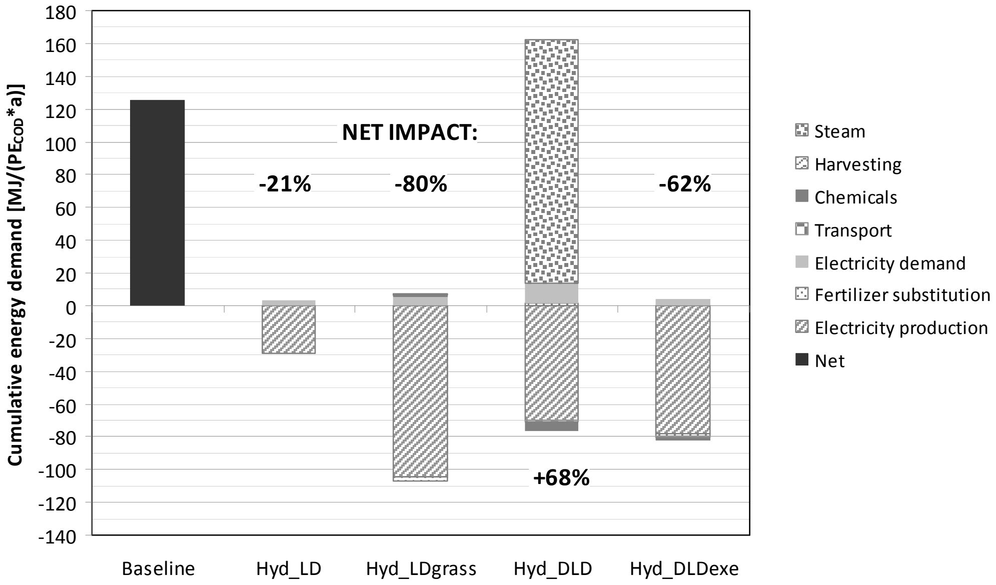


Figure 26: Change in cumulative energy demand due to thermal hydrolysis

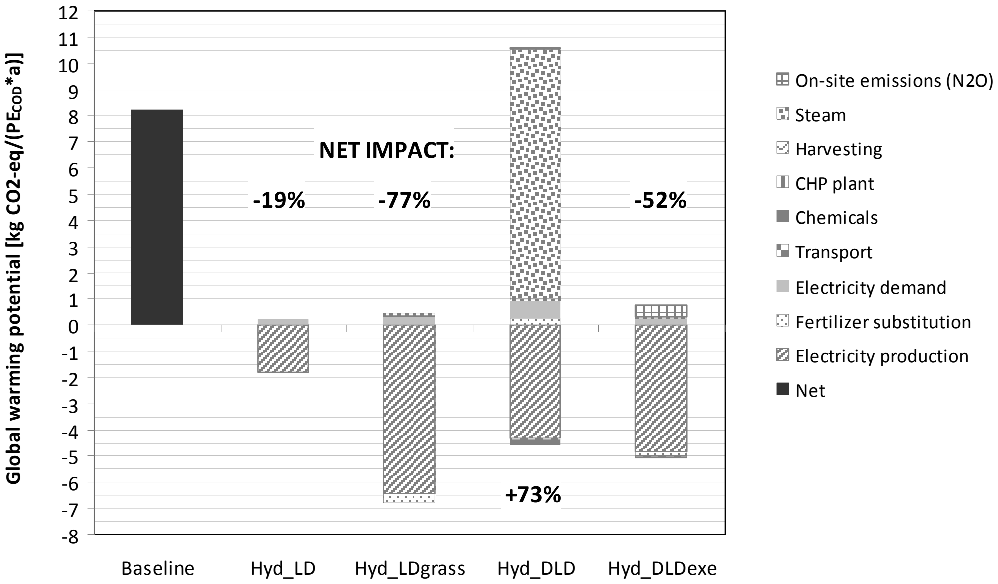


Figure 27: Change in carbon footprint due to thermal hydrolysis

For scenario Hyd_DLD, results show an increase of energy demand and carbon footprint by 68 and 73%, mainly due to the high demand of external fuels for steam production. In this configuration, both primary and excess sludge are treated in hydrolysis, so that the total volume of sludge is high (+240% compared to Hyd_LD). Consequently, 50% of the resulting steam demand has to be met by external fuels. However, this assumption is based on a rough estimation of the energetic balance of the process, and the proportion of required natural gas for steam production may vary considerably in a full-scale process. For the DLD scenario, the influence of this assumption on the overall results is investigated in sensitivity analysis.

The last scenario of thermal hydrolysis (Hyd_DLDexe) is based on supplier information on the performance of a specific configuration where all sludge is treated by hydrolysis, but with an upstream dewatering of the mixed sludge which reduces its water content and thus the steam demand of the process considerably. Based on information of the supplier, energy demand and carbon footprint of the Braunschweig system can be reduced by 62 and 52% with the DLD configuration using the EXELYS™ process. The intermediate dewatering step increases the nitrogen load in the return liquor, causing additional energy demand and N_2O emissions in the WWTP. However, these effects are well offset by the additional credits for electricity production, so that the overall effect of scenario Hyd_DLDexe is positive, provided that the increase in biogas yield predicted by the supplier can be realized in full-scale.

Regarding the comprehensive environmental profiles, thermal hydrolysis of excess sludge has benefits in each environmental impact category (Figure 28). Additional impacts by electricity demand for operation of the hydrolysis unit and emissions from combustion of biogas are well compensated by the benefits from the increase in substituted electricity. For the DLD scenario, the environmental profile shows an increase in all environmental impacts, mainly due to the required natural gas for steam production (Figure 29). The DLD configuration using the EXELYS™ process leads to an overall improvement of the environmental footprint (Figure 30), even though the increase in nitrogen return load has a distinct effect on direct emissions of the WWTP process, in particular N_2O for carbon footprint and NH_3 for acidification.

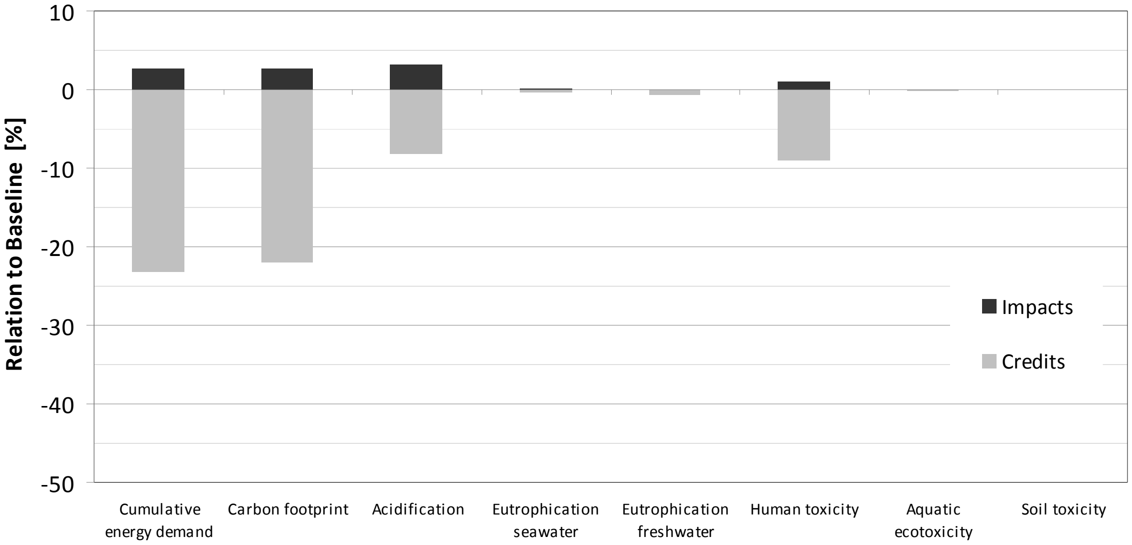


Figure 28: Environmental profile of scenario Hyd_LD in relation to baseline

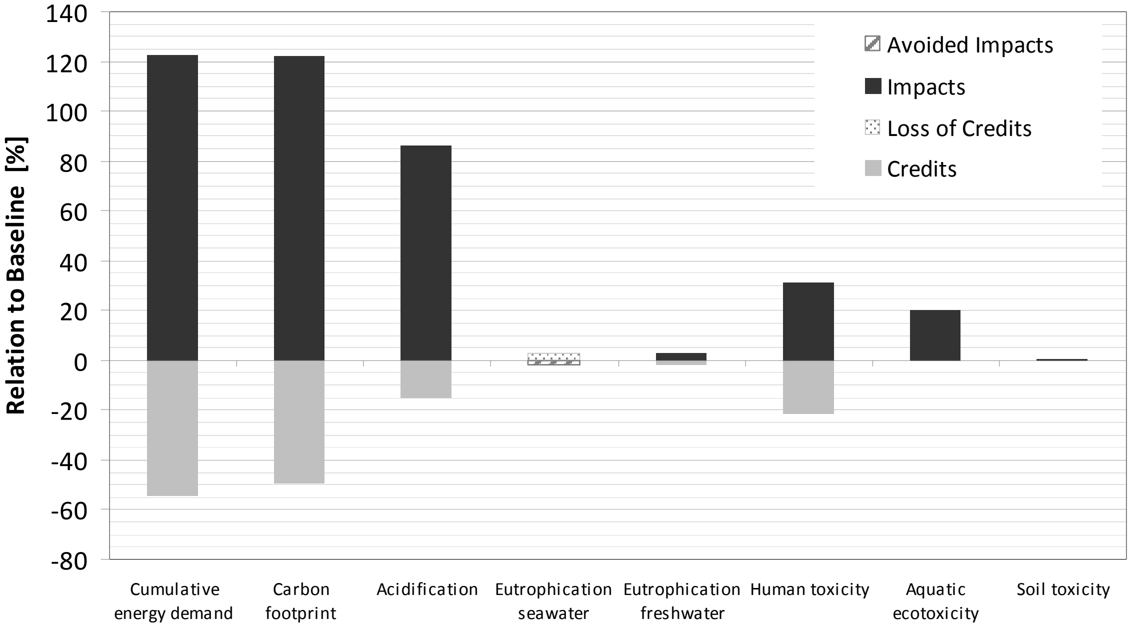


Figure 29: Environmental profile of scenario Hyd_DLD in relation to baseline

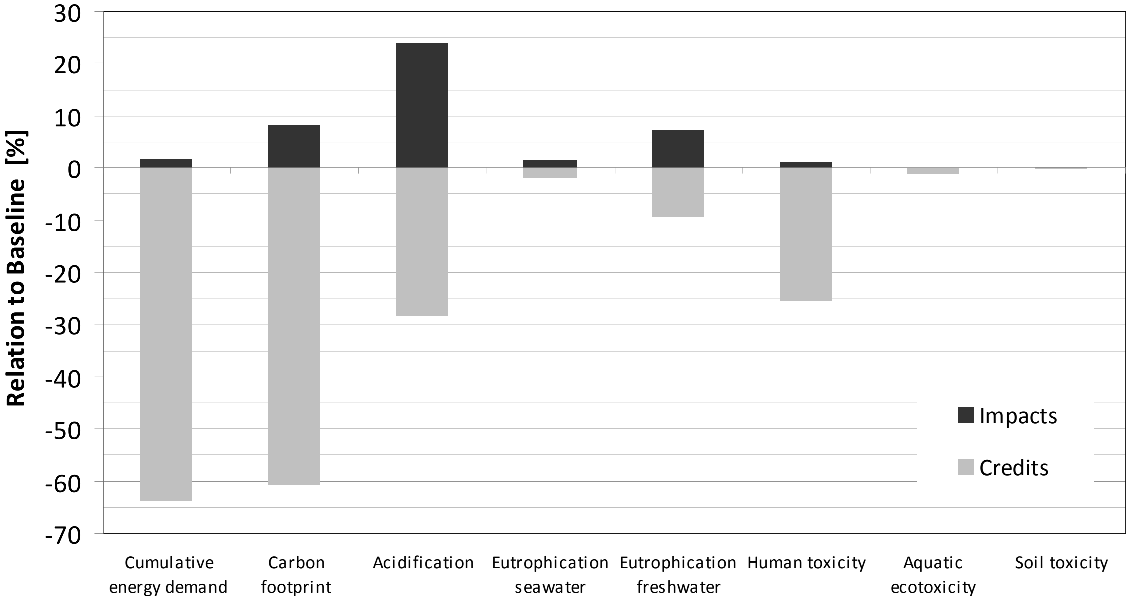


Figure 30: Environmental profile of scenario Hyd_DLDexe in relation to baseline

Overall, the implementation of thermal hydrolysis into the Braunschweig wastewater scheme leads to a decrease in its environmental footprint, mainly due to increased electricity production from biogas. If external fuels are required for steam production, the benefits can be offset depending on the effective biogas yield and the volume of sludge to be treated. The DLD configuration can only be beneficial if the demand for external fuels is minimized, e.g. by using the EXELYS™ process to reduce sludge volume in the hydrolysis unit. In general, a careful calculation of the final heat balance of the process is required to end up with an overall improvement of environmental impacts.

4.4.3 Nutrient recovery from sludge liquors

Additional steps for nutrient recovery from sludge liquors increase the amount of fertilizer that can be substituted in the Braunschweig wastewater scheme. While nitrogen can be stripped in the form of NH_3, phosphorus can be precipitated from sludge liquor in the form of MAP. It has to be noted here that sludge liquor is mainly loaded with nitrogen and to a lesser extent with phosphorus. Thus, nitrogen recovery from liquor can substantially increase the amount of substituted nitrogen fertilizer (+17% in total), whereas phosphorus recovery from liquor shows only marginal effects (+2% in total) on the amount of substituted P fertilizer. Additionally, the shift of MAP precipitation from the digested sludge (= status quo) to the liquor implies the decrease in dewatering performance, requiring additional polymer and increasing sludge volume in transport.

In total, the implementation of N and P recovery has only a marginal effect on the net cumulative energy demand (Figure 31). Nitrogen recovery increases the credits for substituted nitrogen fertilizer and avoids some electricity demand in the WWTP (= less aeration for nitrogen removal). However, chemical demand for operation of the NH_3 stripping unit (NaOH, H_2SO_4) offsets these benefits, so that the final energetic benefit amounts to only 3%. For phosphorus recovery, cumulative energy demand is even slightly higher than in the baseline scenario (+1%) due to a marginal effect on fertilizer credits and additional energy demand for chemical production ($MgCl_2$).

Similarly, nitrogen and phosphorus recovery lead to a change in net carbon footprint of -38% and +1%, respectively (Figure 32). For nitrogen recovery, avoided production of nitrogen fertilizer, avoided aeration and mitigated emissions of N_2O in the WWTP process are responsible for these substantial benefits. For the MAP process, benefits from avoided production of P fertilizer are completely offset by the impacts from the production of chemicals.

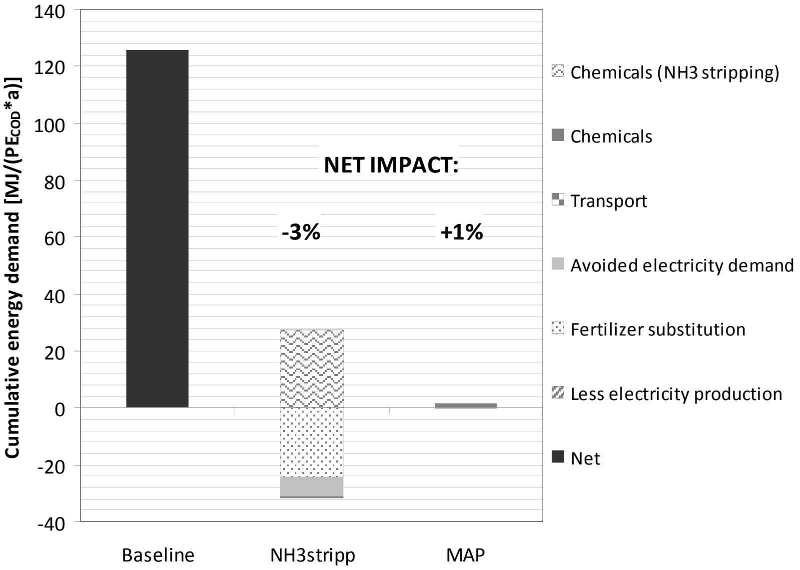


Figure 31: Change in cumulative energy demand due to nutrient recovery

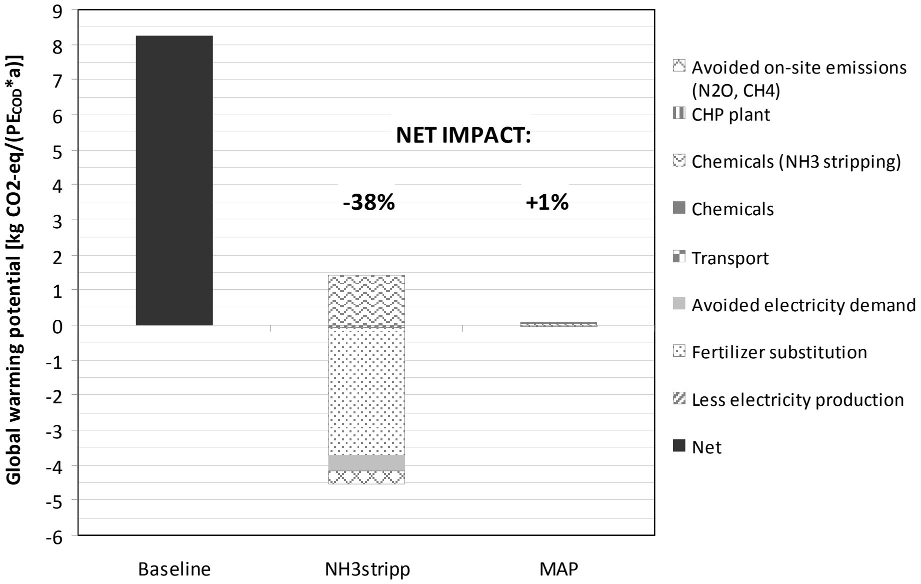


Figure 32: Change in carbon footprint due to nutrient recovery

For the acidification potential, stripping of NH_3 leads to a net increase (+6%) due to high impacts from the production of chemicals, mainly NaOH which is produced in electrolysis. The MAP scenario results in a marginal decrease (-1%) of the net acidification potential of the Braunschweig wastewater system. For human toxicity, these effects are even more pronounced: while the increase in substitution of nitrogen fertilizer has only marginal benefits in the scenario for N recovery, the production of chemicals (especially NaOH) has a high impact, resulting in an overall increase of 121% compared to the baseline (Figure 34). In this impact category, the MAP scenario has a counterbalanced effect (±0%).

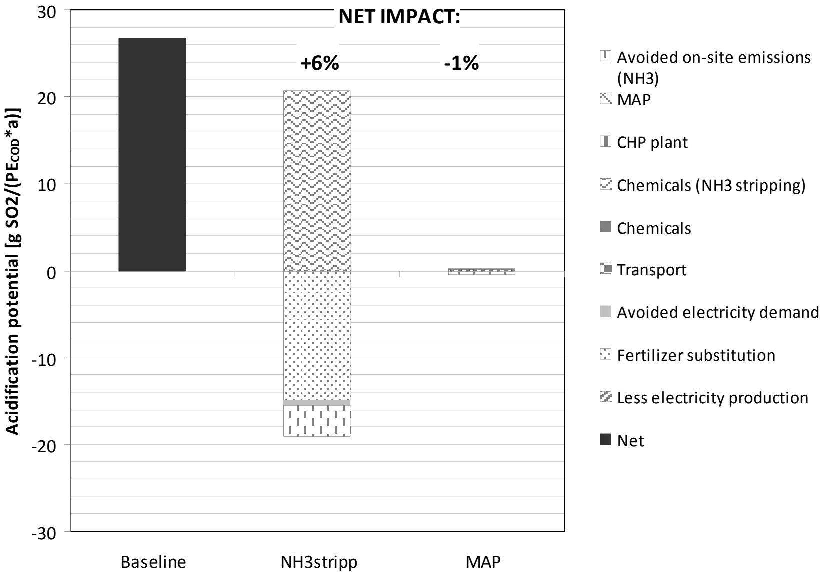


Figure 33: Change in acidification due to nutrient recovery

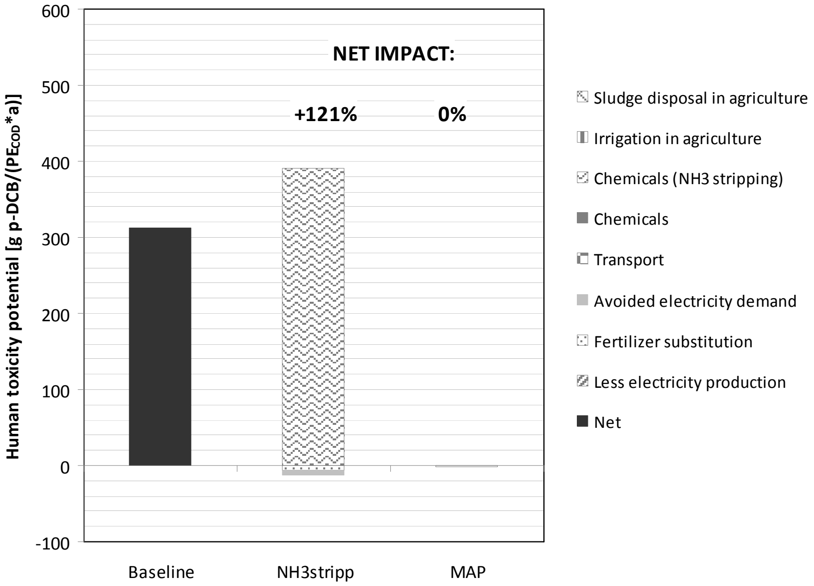


Figure 34: Change in human toxicity due to nutrient recovery

The environmental profile of nitrogen recovery via NH_3 stripping shows the trade-off between benefits of fertilizer substitution and additional impacts of chemical production: while some indicators decrease (energy demand, carbon footprint, eutrophication of seawaters), other indicators increase (acidification, human toxicity) (Figure 35). This effect reflects the shift of environmental impacts from the fertilizer industry to the chemical industry. Hence, the implementation of a NH_3 stripping process will reduce on-site emissions and energy demand of the WWTP, but leads to a higher burden from the production of required NaOH. Thus, a minimization of the dosage of NaOH is recommended to keep the impacts from chemicals production within an acceptable range. Otherwise, overall environmental benefits of nitrogen recovery are offset in the life cycle by additional emissions during the production of chemicals.

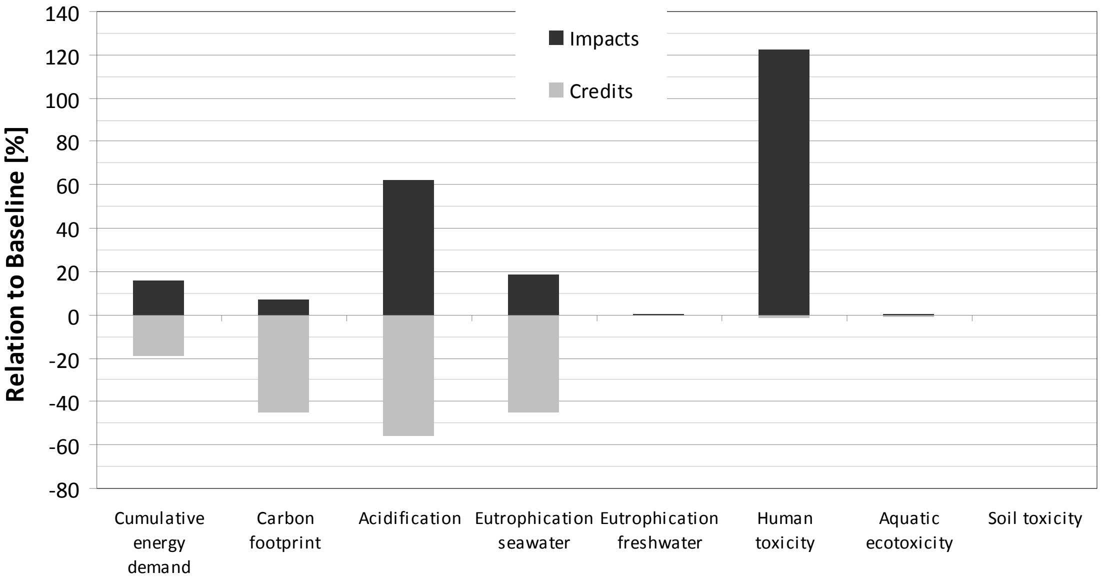


Figure 35: Environmental profile of scenario NH3stripp

For the MAP scenario, the environmental profile shows a negative effect or no improvement in many of the impact categories (Figure 36). This effect is due to the marginal increase in P recovery in this scenario, combined with the enhanced demand for precipitation chemicals ($MgCl_2$) and the decrease in dewatering efficiency. Due to the agricultural reuse of all sludge in the existing system, the potential for increase in P recovery with MAP precipitation from sludge liquor is only marginal. However, operational aspects may be in favour for shifting the MAP process from digested sludge to the liquor phase. This would decouple P recycling from the application of dewatered sewage sludge in agriculture, which is strictly regulated by authorities in terms of maximum applicable amount and heavy metal content.

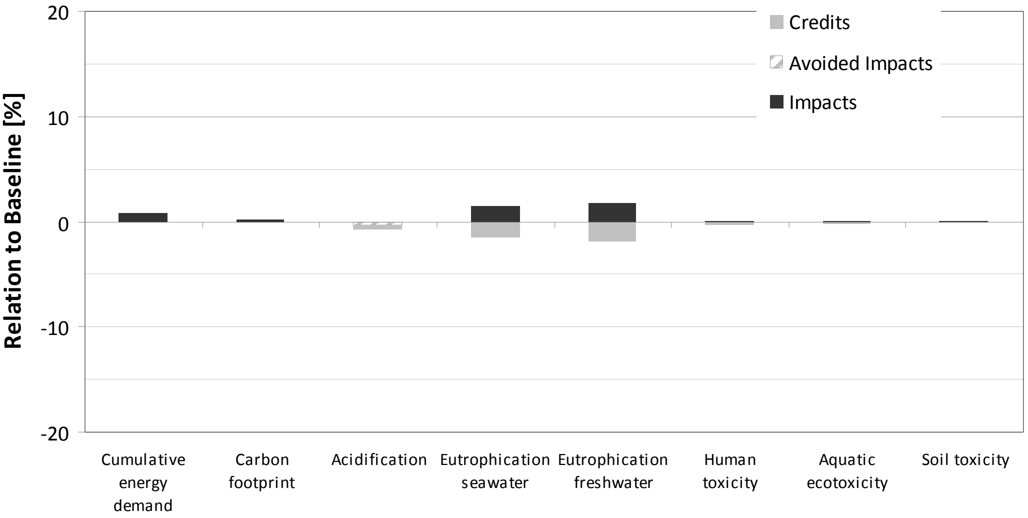


Figure 36: Environmental profile of scenario MAP

4.4.4 ORC process

The implementation of an ORC process for utilisation of excess heat from the CHP plants and its conversion to electricity is an environmentally preferable alternative, because the process does not generate additional emissions during operation and improves the energetic balance of the WWTP. As infrastructure is not included in this LCA (cf. 2.6), the additional expenditures for the infrastructure are not accounted here.

In this study, the ORC scenarios are combined with other measures (addition of grass as co-substrate, advanced thickening of primary sludge) to improve the amount of excess heat available for conversion, mainly due to economic considerations which were defined by the operators (SE/BS 2010). Thus, the results have to be seen as a combined effect of the ORC process and the additional measures for process optimisation.

The combination of an ORC process (100kW) and the addition of grass as co-substrates (scenario CoSub_ORC, based on results of full-scale trials with grass addition) shows a decrease in cumulative energy demand and carbon footprint of 25% and 27%, respectively (Figure 37 and Figure 38). Compared to the results of scenario CoSub_Gras12 (cf. 4.4.1), this is a relative effect of +13% for both energy demand and carbon footprint due to the ORC process.

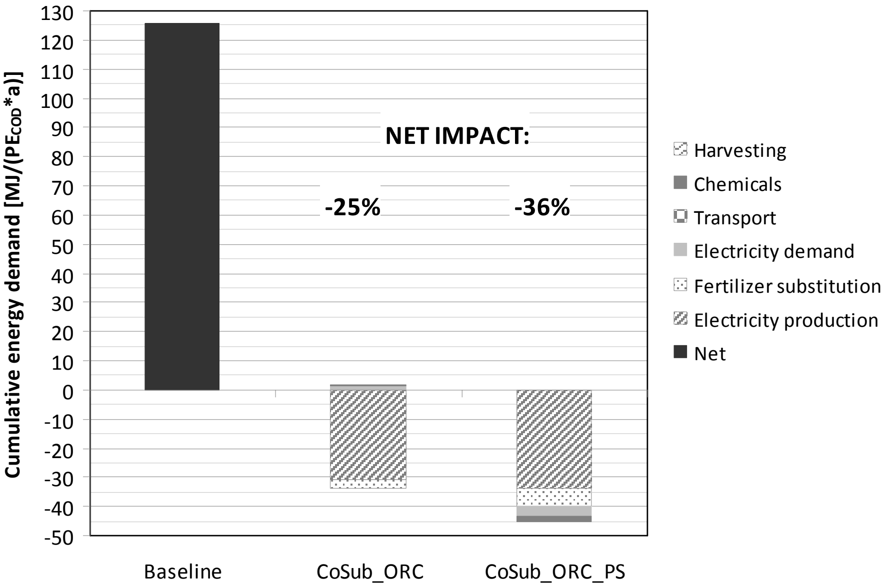


Figure 37: Change in cumulative energy demand due to ORC process

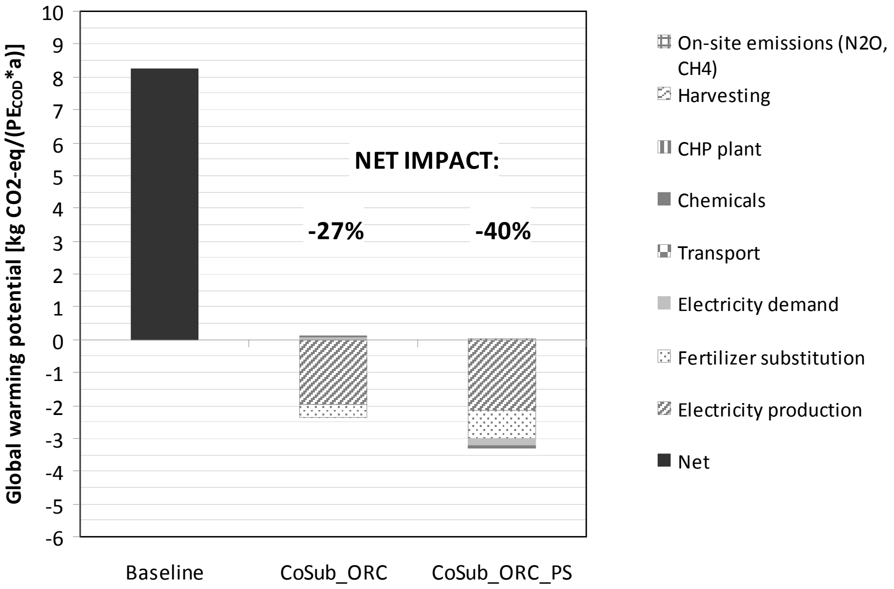


Figure 38: Change in carbon footprint due to ORC process

If primary sludge is thickened before digestion, heat demand for digestor heating is reduced and more excess heat is available for the ORC process. Consequently, energy demand and carbon footprint are reduced by 36% and 40% in scenario CoSub_ORC_PS, respectively. Subtracting the impacts due to the addition of co-substrates, the net effects of the ORC process and thickening of primary sludge amount to -24% in energy demand and -26% in carbon footprint. The overall environmental profile of scenario CoSub_ORC_PS shows benefits in many impact categories, with the exception of ecotoxicity indicators which are slightly increasing due to heavy metal content of grass entering the agricultural system (Figure 39).

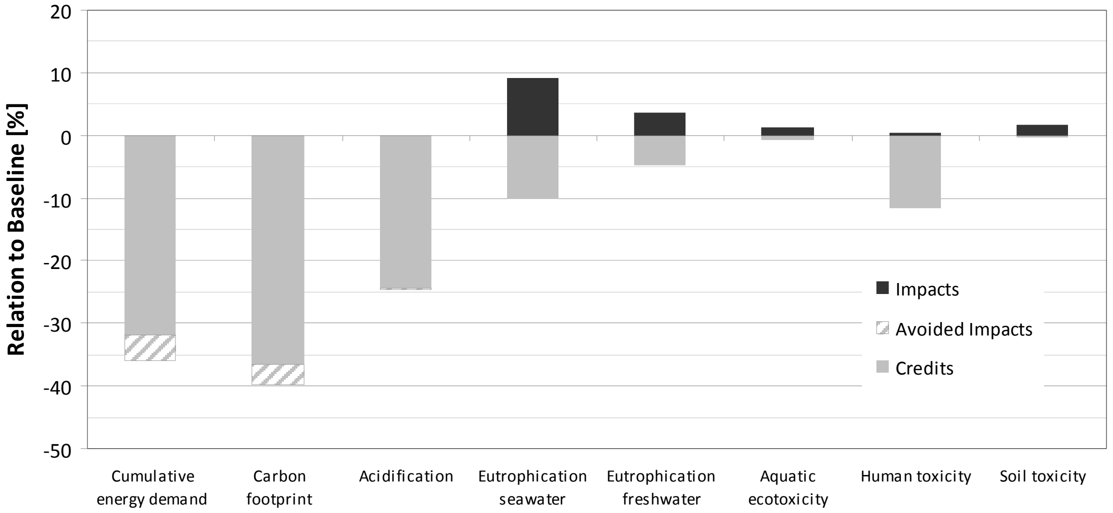


Figure 39: Environmental profile of scenario CoSub_ORC_PS

As it was expected, the implementation of an ORC process can substantially improve the environmental profile of the Braunschweig wastewater scheme by increasing energy recovery through enhanced production of electricity. If the process is combined with other measures which further increase the available heat for the ORC, the energetic benefits can be even higher. Finally, the implementation of an ORC process is fully recommended from an environmental point of view. For the sake of completeness, an assessment of additional needs of infrastructure could be considered to validate this conclusion with regards to impacts from system construction.

4.5 Summary of results for optimization measures

Summarizing the results for all optimisation scenarios, a distinct potential for a reduction in environmental footprint of the Braunschweig wastewater scheme can be identified. Depending on the specific measures, energy demand and carbon footprint of the system can be reduced by 80% and 77% at maximum, respectively (Figure 40). The most promising scenario in this study is the implementation of both addition of co-substrates and thermal hydrolysis of excess sludge (Hyd_LDgrass), followed by the addition of grass alone (CoSub_Gras10) or topinambur greens (CoSub_Topi10). However, it must be emphasized that the effects of these optimisation measures have been estimated based on the results of pilot experiments and have to be verified in full-scale before the potential improvements can be realized. Other optimisation measures such as nutrient recovery in the liquor or implementation of an ORC process have a less distinct effect in reducing energy demand and carbon footprint, but will as well result in a further improvement of the environmental profile. Only the DLD scenario with high demand of external fuels is energetically not beneficial, while the MAP scenario has a negligible higher energy demand than the existing system.

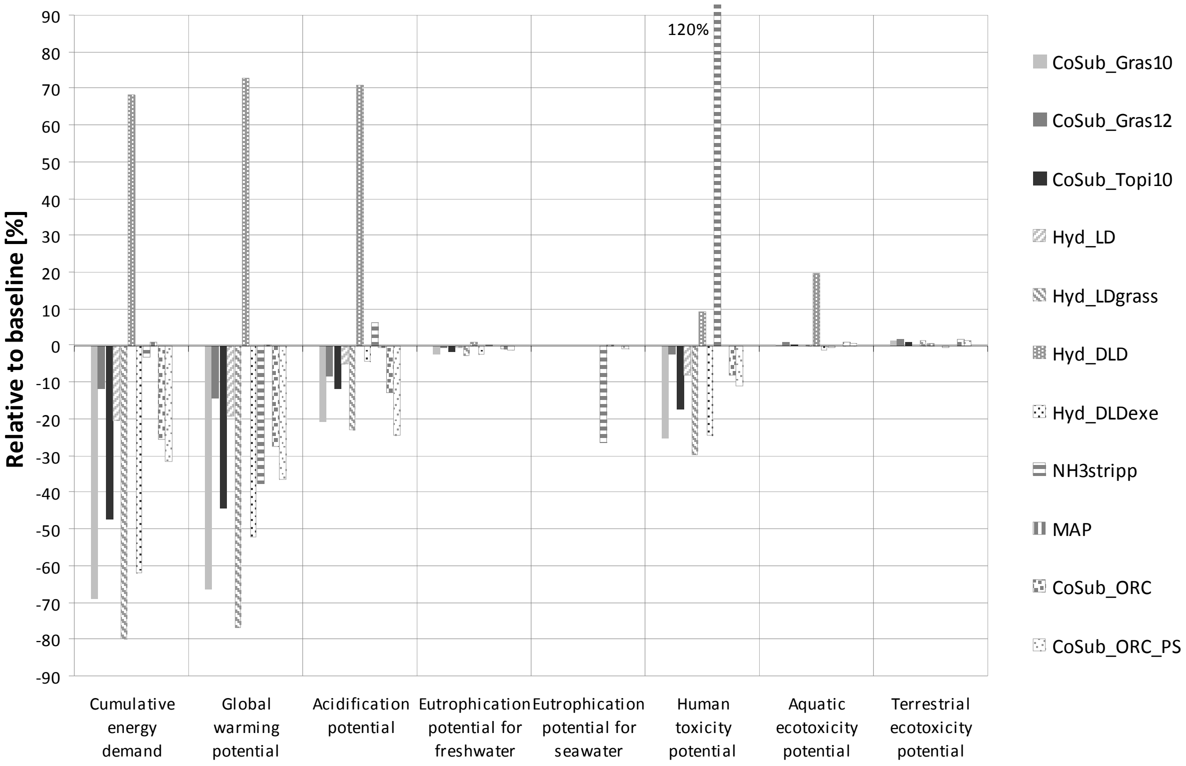


Figure 40: Summary of results for optimisation scenarios

In general, the optimisation of energy demand and carbon footprint can be reached without major compromises or trade-offs to other environmental impacts. Specific drawbacks have been identified for the implementation of nitrogen recovery from sludge liquor via NH_3 stripping: the resulting chemical demand substantially increases the impacts in human toxicity and acidification, mostly due to emissions associated with the production of NaOH (Figure 40). Furthermore, the addition of co-substrates leads to a small increase in heavy metal loads to agricultural soils, but this effect is negligible compared to the total heavy metal loads in the system.

The normalised comparison of the environmental profiles in baseline and optimisation scenarios underlines that the primary functions of the WWTP (i.e. the protection of surface waters by elimination of eutrophying or ecotoxic substances) is not compromised by the implementation of optimisation measures such as addition of co-substrates, thermal hydrolysis, or nutrient recovery options (Figure 41). Additionally, the agricultural part of the Braunschweig wastewater scheme is not affected negatively by an increase in terrestrial or human toxicity through enhanced transfer of heavy metals to agricultural soils. Overall, it can be concluded that the proposed measures for optimisation of energy demand and carbon footprint can be implemented without negatively affecting the environmental profile of the WWTP. However, the assumptions in this study and the effects of the optimisation measures on the overall treatment scheme should be carefully monitored and reassessed after full-scale implementation to detect any negative effects which were not taken into account in this LCA.

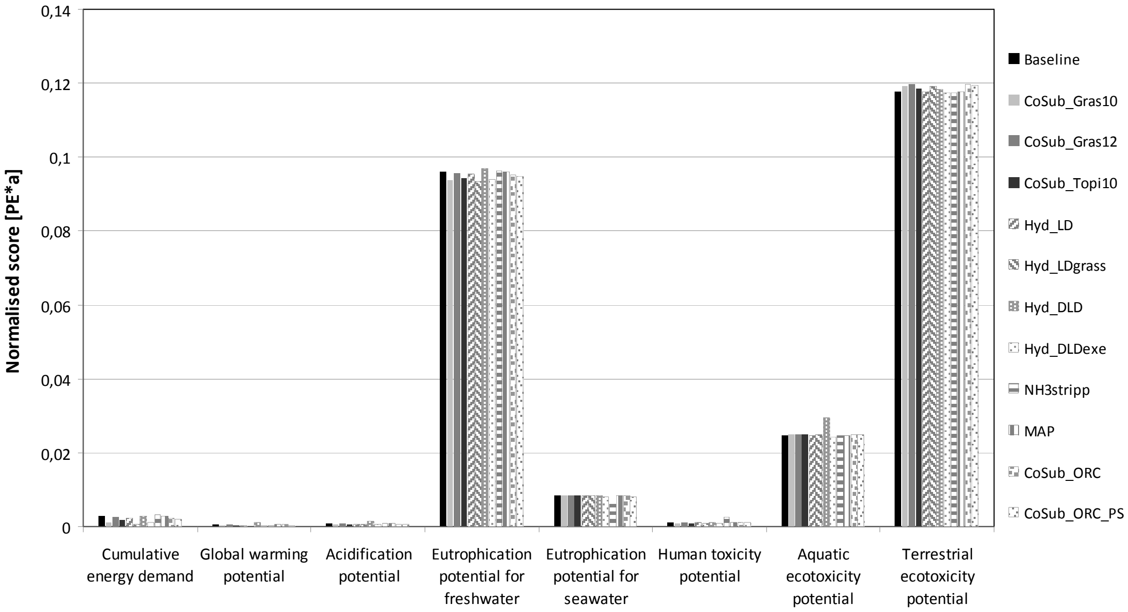


Figure 41: Normalised comparison of baseline and optimisation scenarios

4.6 Interpretation

4.6.1 Identification of significant issues

Significant issues of the inventory and impact assessment have been identified for the Braunschweig wastewater scheme by contribution analysis of the different categories of environmental impacts (cf. 4.1). Thus, the importance of specific sub-processes and parts of the system under study for the environmental footprint has been revealed with quantitative information. Via normalisation of the environmental footprint to total environmental impacts in Germany, the quantitative contribution of the wastewater scheme to the overall environmental footprint per inhabitant could be derived (cf. 4.2). Referencing to a hypothetical conventional system, the specific environmental aspects of the Braunschweig reuse system could be quantified in the framework of this LCA. Finally, a set of optimization measures was analysed in their effect on the environmental profile of the Braunschweig system, revealing promising measures and potential drawbacks for improvement of the system.

4.6.2 Sensitivity analysis

In sensitivity analysis, the influence of certain assumptions during the setup of this study and its inventory are quantified to test the stability of the results and the final conclusions. Based on the contribution analysis above, five dedicated fields for sensitivity analysis have been identified:

- Different power mix for grid electricity (year 2020)
- Secondary products: accounting of nitrogen and irrigation water
- Alternative datasets for mineral fertilizer production

- Emission factors for N_2O and NH_3 in the activated sludge process
- Proportion of external energy demand in scenarios for thermal hydrolysis

Different mix for grid electricity

The energy sector in Germany and especially the generation of electricity and the respective power mix will be subject to substantial changes in the coming years. Due to the decommissioning of nuclear power plants and the move towards the use of renewable sources of energy, the power mix is supposed to shift towards a more sustainable way of electricity production.

To reflect future changes in the power mix, a sensitivity analysis is done using a prospective power mix of Germany in 2020. Based on the assumptions of the federal association of renewable energy (BEE 2009), the following power mix for 2020 is assumed: lignite 17%, hard coal 19%, nuclear 1%, natural gas 11%, wind 25%, biomass 9%, hydropower 5%, PV 8%, others 5%. The inventory for the new power mix is calculated using datasets from ecoinvent (cf. Table 13).

Naturally, the renewable power mix will decrease the demand for non-renewable energy sources by 45% (Figure 42). Other indicators are only marginally affected: the carbon footprint will decrease by 8%, while acidification potential rises by 5%. This reflects the shift of nuclear energy with low carbon footprint towards renewable energy sources (wind, solar) which have a comparable carbon footprint. Finally, a shift in the power mix will decrease the relative demand of non-renewable energy sources (as for all other processes requiring electricity), but the results of this LCA should remain stable even with a move to renewable sources in the future. It has to be noted though that the new power mix is only calculated for direct generation of electricity demand of the foreground system, not for background processes such as the production of chemicals or mineral N fertilizer.

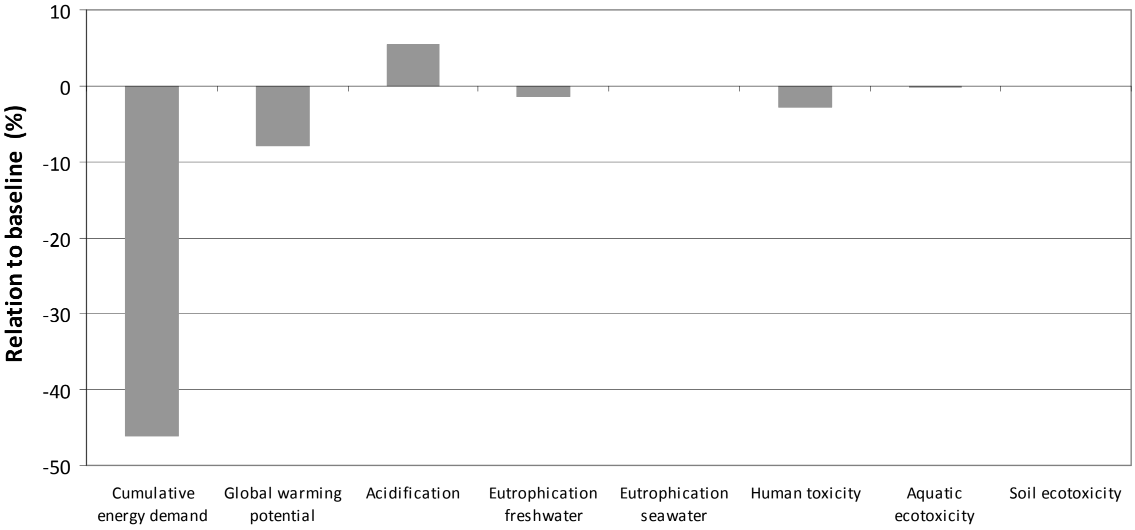


Figure 42: Influence of prospective power mix of 2020 on net environmental impact of baseline

Accounting of nitrogen and irrigation water

The accounting of nitrogen and irrigation water which is delivered in agricultural reuse of effluent and sludge is a decisive parameter for the benefits of the Braunschweig wastewater scheme. The substitution of mineral nitrogen fertilizer and groundwater pumping improves the energetic balance and associated environmental impacts (e.g carbon footprint) of the overall system considerably (cf. 4.1.1 and 4.1.2). However, based on the existing system and the seasonal demand of nitrogen and water, only a fraction of the annual nitrogen (40%) and irrigation water (100 mm/a) is accounted for effectively substituting other products in the Braunschweig system.

If more nitrogen could be delivered during periods of demand, the net cumulative energy demand and carbon footprint of the system can be substantially reduced (Figure 43). Accounting 100% of nitrogen in agricultural reuse, energy demand and carbon footprint decrease by 31% and 71%, respectively. This exemplifies the high potential for optimisation in the nutrient management system by decoupling the nutrient recycling from the irrigation water, basically by extracting and storing the nitrogen and delivering it during periods of high demand. However, the continuous need for disposal of effluent and sludge and the chemical speciation of nitrogen (highly water soluble) pose technical difficulties for an efficient extraction system and may limit the optimisation potential in nitrogen recovery.

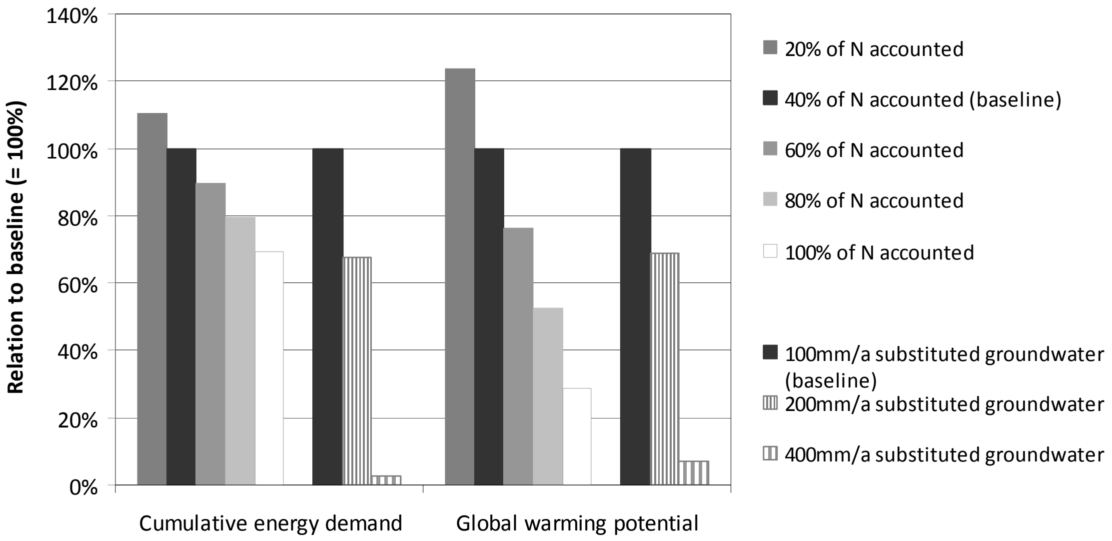


Figure 43: Influence of accounting for nitrogen and groundwater substitution on cumulative energy demand and carbon footprint

Another important factor for the energy balance of Braunschweig in this LCA is the accounting of irrigation water for the substitution of groundwater pumping. Due to over-irrigation beyond the actual demand (100 mm/a), the system requires a high amount of electricity for pumping the effluent to the agricultural fields. In this LCA, only a part of this electricity is offset by accounting for the substitution of groundwater pumping. If the applied effluent volume would be closer to the actual demand of the farmers (i.e. more groundwater would be substituted), the energy balance and carbon footprint would improve considerably (Figure 43). Accounting almost 100% of the irrigation water (= 400 mm/a) for groundwater substitution, the net cumulative energy demand and carbon footprint can be reduced by 97% and 93%, respectively.

Historically, the over-irrigation of the farmlands is due to the small size of the receiving river (Oker) which did not allow a discharge of high volumes of raw wastewater into surface waters. Thus, the raw wastewater and – after building the WWTP in the 1980s – the purified effluent was disposed in agriculture as a step of “soil treatment”. From an agricultural point of view, effluent disposal in times without water demand (e.g. in winter) could be reduced to safe pumping energy. From the side of the WWTP operators, it has to be checked whether an increased discharge of effluent into surface waters (via infiltration fields) is legally permitted and can be realized without impairing the final discharge quality into the river. Again, the primary function of the system (protection of surface waters) should not be deteriorated while optimizing the system energetically.

Alternative datasets for mineral fertilizer production

The LCI datasets for mineral fertilizer production are adopted from a previous study (Remy 2010). These datasets originate from relatively old primary data concerning fertilizer production (Patyk and Reinhardt 1997; Gaillard et al. 1997) and heavy metal content (Boysen 1992). Alternatively, datasets from ecoinvent database v2.1 can be used to model fertilizer production. However, it has to be noted that ecoinvent datasets are generated from comparably outdated inventories (Davis and Haglund 1999) mixing primary data from the 1990s (EFMA 1995; Patyk and Reinhardt 1997; Audsley et al. 1997; Gaillard et al. 1997; Kongshaug 1998).

In sensitivity analysis, ecoinvent datasets are used for nitrogen fertilizer (*ammonium nitrate, as N, at regional storehouse RER)* and phosphorus fertilizer (*triple superphosphate, as P2O5, at regional storehouse RER*) (Ecoinvent 2007). Heavy metal content of mineral fertilizer itself is not modelled in ecoinvent (only fertilizer production), so that heavy metal input with mineral fertilizer is estimated with latest available data from UBA (Kördel et al. 2007).

Using fertilizer data from ecoinvent, the net environmental impacts of the Braunschweig system are substantially decreased (Figure 44). In other words, the substitution of mineral fertilizers with nutrients recovered from wastewater results in even higher credits if it is calculated with the alternative datasets of ecoinvent. Whereas net cumulative energy demand and carbon footprint are only slightly decreased (minus 10-15%), a remarkable decrease is calculated for acidification, human toxicity, and eutrophication of freshwaters. The latter effects are mainly caused by high energy demand for N fertilizer production and P emissions to surface waters during the processing of raw phosphates. For terrestrial ecotoxicity, the alternative datasets calculate less credits for the Braunschweig system due to slightly lower heavy metal contents of mineral N and P fertilizer, resulting in a 3% increase of this indicator.

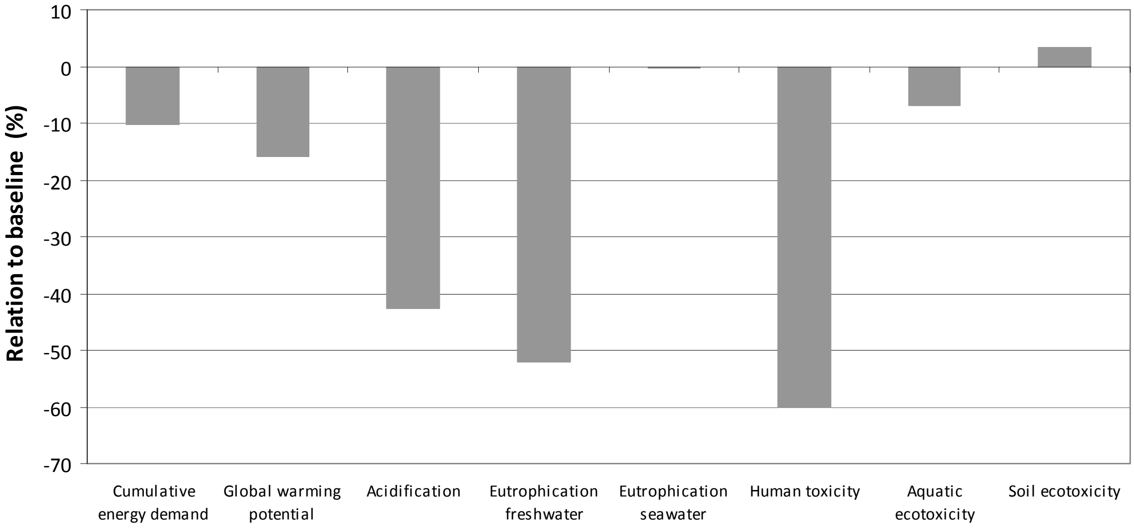


Figure 44: Influence of using alternative datasets for mineral fertilizer production on net environmental impact of baseline

In general, it can be concluded that the results of this study are even more pronounced if ecoinvent datasets are used for the calculation. However, a comprehensive update of datasets for mineral fertilizer production and heavy metal content with more recent data would be helpful to support the validity and representativeness of LCA studies comparing mineral and organic fertilizers.

On-site emissions of WWTP: N_2O + NH_3

On-site emissions of the activated sludge process are a major contributor to total environmental impacts for the impact categories of carbon footprint (by N_2O) and acidification (NH_3). Both emissions of nitrogen gases are related to the influent load of nitrogen and process conditions in the aeration tank, e.g. the level of dissolved oxygen, retention times, and the kinetics of nitrification and denitrification. Due to the lack of sampling data in this study, both N_2O and NH_3 emission factors are estimated from mean data published in the literature and do not relate to the specific conditions of the Braunschweig WWTP.

Increasing the generic emission factor for N_2O (0.6% in baseline) leads to a substantial increase in the net carbon footprint of the system: with N_2O emissions of 1.2% or 2.4% related to denitrified N, the net carbon footprint increases by 15% and 44%, respectively (Figure 45). In the literature, N_2O emission factors of 0.01 – 15% have been measured in full-scale plants depending on operating conditions and plant size (cf. 3.1.1). Hence, it can be concluded that carbon footprint calculations for a WWTP are highly sensitive to N_2O emission factors. For a solid verification of the presented carbon footprint calculations in this study, primary data should be generated via on-site sampling of N_2O emissions in the Braunschweig WWTP and the setup of a nitrogen mass balance.

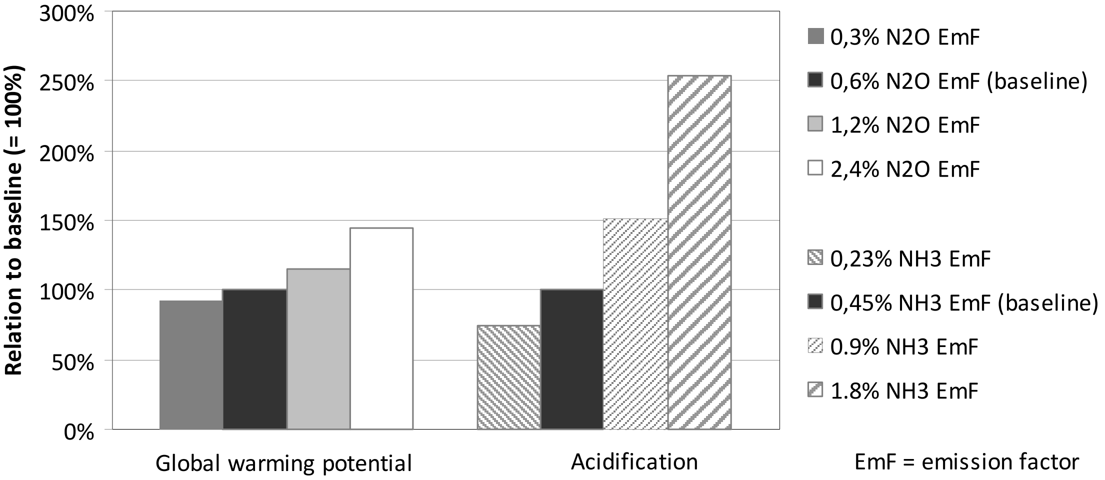


Figure 45: Influence of emission factors for N_2O and NH_3 on carbon footprint and acidification potential

Another emission factor of importance is the direct emission of NH_3, mainly by stripping of nitrogen in the form of NH_4-N from raw wastewater after primary sedimentation. If the generic NH_3 emission factor is increased from 0.45% of influent NH_4-N to 1.8%, the acidification potential increases by 154% (Figure 45). Again, on-site sampling of actual NH_3 emissions in the Braunschweig WWTP would strengthen the results of this LCA for acidification. However, both N_2O and NH_3 emissions of the process are not regulated by authorities, so that the operators are not obliged to measure or minimize these emissions by law. Whether emissions of nitrogen gases can be mitigated by specific measures in process operation of a WWTP is a current topic for intensive research in the wastewater community.

External energy demand of thermal hydrolysis in two-step digestion

The energy balance of implementing a process for thermal hydrolysis of sludge is heavily depending on the heat balance of the process. Sludge pre-heating to 90°C is usually done by recovering the heat from the sludge leaving the hydrolysis unit. Additional steam that is required for the hydrolysis process at 160°C (150-200 L/m³ sludge) has to be produced on-site, usually by using off-gas heat of the CHP plant. However, depending on the volume of the sludge to be hydrolyzed and the available off-gas heat, external fuels may be required to a certain proportion for augmenting the heat available for steam production. The need for external fuels is a decisive parameter for the energetic benefits of a process for thermal hydrolysis of sludge.

This effect is investigated by varying the external energy demand for thermal hydrolysis for scenarios Hyd_DLD (hydrolysis of mixed sludge 458 m³/d) and Hyd_DLDexe (hydrolysis of dewatered mixed sludge 73 m³/d), representing a hydrolysis of high and low sludge volume, respectively. From the net cumulative energy demand, it can be concluded that hydrolysis of low sludge volume always has an energetic benefit, irrespective of the amount of external fuels required for steam production (Figure 46). For high sludge volume, the point of trade-off is 20% of external fuel demand. In other words, the crucial point for improving the energy balance of a WWTP with a hydrolysis process is the minimization of the sludge volume to be treated. In the EXELYS™

process, mixed sludge is dewatered prior to hydrolysis to reduce its volume and reach an overall energetic benefit (Hyd_DLDexe). Without this intermediate step of dewatering, two-step digestion with intermediate hydrolysis (Hyd_DLD) can only be beneficial for the energy balance if other heat sources are available to supply > 80% of the energy required for steam production (e.g. from nearby industrial processes). Although the biogas yield is increased with the DLD configuration, the high energy demand for steam production in scenario Hyd_DLD quickly offsets the additional energy gains and will result in an overall increase in cumulative energy demand. Assuming a demand of 50% external energy, the energy balance is substantially impaired in the latter scenario (cf. Figure 29).

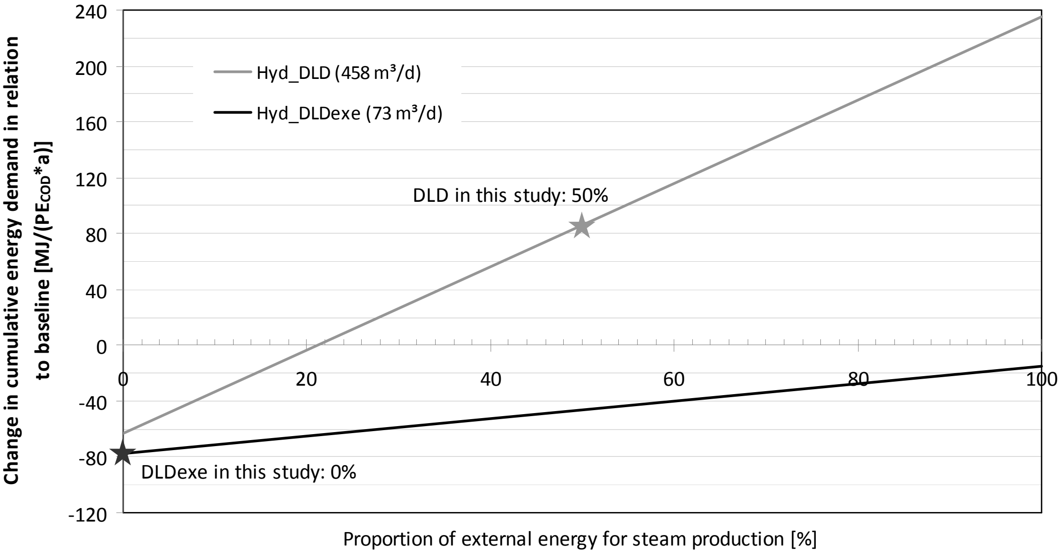


Figure 46: Influence of external energy demand of thermal hydrolysis on net effect on cumulative energy demand

4.6.3 Consistency and completeness

Consistency and completeness of the present LCA have been met according to the scope of the study. The completeness of the input-output model of the wastewater scheme was assessed together with the WWTP operators by comparing existing balances and key figures of the process with results from the inventory of this LCA. Apart from seasonal and annual variations inherent to a WWTP process, the inventory data for the plant is estimated to be complete in reasonable ranges (±10%). Especially the important emission pathways of effluent and sludge disposal are well characterized with regular sampling data.

The study uses a consistent approach for all parts of the system that are included into the assessment. Primary data from sampling (influent, effluent, sludge) is amended by generic emission factors for atmospheric emissions compiled from literature. For all background processes, most recent datasets are used if possible, complemented by specific datasets which have been calculated from literature data. Important assumptions for system expansion are set in consultation with experts from SE/BS and AVB and are further analysed in sensitivity analysis.

4.6.4 Conclusions, limitations and recommendations

Conclusions

This LCA study describes a defined set of environmental impacts caused by the operation of the Braunschweig wastewater scheme in 2010. Based on the available information, the main impacts of the Braunschweig system could be characterized with a reasonable consistency and completeness, allowing a first but robust illustration of the environmental footprint. Important contributors to the assessed categories of environmental concern could be identified and their contribution evaluated quantitatively. The normalised environmental profile showed where the wastewater scheme contributes substantially to the overall environmental impacts, and where its contribution is quantitatively low. Referencing to a hypothetical conventional system of wastewater discharge, the specific benefits and drawbacks of the Braunschweig reuse system could be identified and tracked back to the respective features of the system. Finally, different measures for optimisation have been analysed in their effect on the environmental profile to reveal promising options and intrinsic drawbacks of technical measures for lowering the environmental footprint.

Sensitivity analysis revealed a relative stability of the results towards the use of alternative datasets for electricity (power mix), but a high influence of the datasets for the production of mineral fertilizer on specific indicators. Assumptions for accountability of secondary products delivered to agriculture (nutrients and groundwater substitution) and of generic emission factors for gaseous emissions of the activated sludge process can also have a distinct influence on specific categories of environmental impact. However, credits for secondary products are always increasing in sensitivity analysis, revealing a rather conservative estimation of their benefits in the original data. Only for gaseous emissions of the WWTP process (N_2O, CH_4, NH_3), the environmental footprint of the system may either increase or decrease depending on the assumed generic emission factors.

Limitations

Limitations of the present study can be found both in the system definitions and in the inventory data. In particular, the following issues should be mentioned explicitly which may limit the conclusions:

- Infrastructure is excluded, but may contribute to the environmental impacts due to the large system of effluent distribution
- Organic pollutants are not accounted due to lack of data, buy may cause relevant impacts in human and ecotoxicity during reuse of effluent and sludge in agriculture
- Freshwater use and consumption is not evaluated in this LCA.
- Atmospheric emissions of effluent and sludge spreading in agriculture are excluded from this LCA, as they are estimated to be comparable to those of mineral fertilizer. This assumption has to be proved in future studies of reuse systems.

- Atmospheric emissions of the WWTP are estimated with generic emission factors, but may play a major role for certain impact categories (e.g. N_2O and CH_4 for carbon footprint, NH_3 for acidification).
- Datasets for mineral fertilizer production and heavy metal content are relatively old and should be updated with more recent datasets.
- Inventory data of scenarios for optimisation are mostly based on results of pilot experiments or literature. They should be validated in technical or full-scale trials prior to the implementation of these measures at the plant to ensure that potential benefits for the environmental footprint can be realized.

Recommendations

The results of this LCA can well be used to gain a quantitative assessment of the environmental footprint associated with the operation of the Braunschweig wastewater scheme. The methodological approach and the data quality of the study allow the identification of important sub-processes and system features for the environmental impacts included in this study. For future studies of the environmental footprint of the system, it is recommended to extend the study with the following aspects:

- Include organic pollutants in the inventory
- Include freshwater use as impact category
- Include atmospheric emissions during agricultural application of effluent, sludge, and mineral fertilizer
- Generate primary data for atmospheric emissions of the activated sludge process (N_2O, CH_4, NH_3)
- Update background datasets with most recent available information, especially for mineral fertilizer production
- Validate scenario data in technical or full-scale

Thus, both the completeness and the consistency of this LCA will be improved to increase the precision of the calculated indicators and strengthen the validity of the conclusions of this study.

Chapter 5

Conclusions

The present study 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. Products of the system (i.e. electricity from biogas combustion, nutrients, and irrigation water) are accounted with the respective substituted products, and the related environmental impacts are credited to the system as “avoided burden”.

Environmental footprint of the Braunschweig wastewater scheme in 2010

The energetic balance of the system is fairly good, as 79% of the cumulative energy demand can be offset by secondary products. Electricity from biogas generated in anaerobic sludge digestion is responsible for the major part of these benefits (58%). The substitution of mineral fertilizer (14%) and groundwater pumping (7%) via agricultural reuse of effluent and sludge contribute less to the energy benefits, because the continuous supply of water and nutrients is not matched to the seasonal demand of the agricultural system. In fact, 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. However, direct emissions of N_2O and CH_4 in the WWTP process can contribute substantially to the carbon footprint and should thus be monitored by on-site sampling if possible. The same effect can be observed for acidifying gases, where the energy-related emissions are substantially augmented by on-site emissions of NH_3.

Nutrient emissions in surface waters are relatively low due to the high elimination of nutrients in the WWTP and in polishing via infiltration fields. In total, 29 g phosphorus and 80 g nitrogen are emitted by the wastewater scheme per population equivalent and year. Negative effects of the WWTP effluent on human toxicity are small after normalisation; however, heavy metal input to agricultural soils has a detectable influence on the human toxicity potential, together with emissions from energy production. Concerning aquatic eco-systems, both effluent and sludge have a direct effect via WWTP effluent and an indirect effect via agricultural reuse, mainly due to high loads of Cu and Zn. Both metals are also responsible to a great extent for the potential impact in terrestrial ecotoxicity. For the entire toxicity assessment, it has to be noted though that only inorganic pollutants (= heavy metals) were accounted in this LCA as direct emissions of the system due to the lack of primary data for organic compounds. This states a clear limitation of the comprehensiveness of the presented results in terms of toxicity assessment and should be openly communicated to the target groups.

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. 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.

Reference to a (hypothetical) conventional system with direct discharge of effluent

The reference to a conventional system of wastewater treatment with direct discharge of effluent to surface waters reveals the specific environmental benefits of the reuse approach in Braunschweig. In fact, the Braunschweig system can further reduce nutrient emissions to surface waters, mainly due to polishing of effluent in infiltration fields and the transfer of nutrients to agriculture via effluent reuse. For the energy balance and carbon footprint, the present study shows that a conventional system will most likely have a better energy balance, which can be explained by the high electricity demand for pumping the water to the agricultural fields in Braunschweig. Finally, it can be concluded that agricultural reuse does not imply an intrinsic energetic benefit if the seasonal demand for water and nutrients is not adequately matched with the continuous supply of a WWTP. However, the transfer of effluent to agriculture relieves the receiving surface waters of the corresponding loads of nutrients and pollutants, thus serving as a post-treatment step for WWTP effluent ("soil treatment") which was in fact the primary objective of the implementation of agricultural reuse in Braunschweig in 1954.

Optimisation of the environmental footprint of the Braunschweig wastewater scheme

The analysis of a set of optimisation measures for improving the environmental footprint of the Braunschweig wastewater scheme gave valuable insight into the effects of the specific measures on the overall system. Both the addition of organic co-substrates into the digestion process 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 experiments 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. However, these results have to be verified in full-scale trials which could not be achieved within the CoDiGreen project. A two-step digestion process with intermediate dewatering and hydrolysis (DLD configuration with EXELYS™) seems promising in terms of energy benefits and carbon footprint.

Improving the nutrient management by recovering nitrogen or phosphorus from the sludge liquor of dewatering does not result in major benefits in the environmental profile. Chemical demand for nitrogen stripping is relatively high and is associated with major impacts in chemical production, whereas the recovery of phosphorus as MAP does not significantly improve the recovery ratio of P in the system, because all sludge and related P content is already applied in agriculture.

The implementation of an ORC process for energy recovery from excess heat can be fully recommended from an environmental point of view: the operation of an ORC unit with 100kW results in a decrease of >35% in energy demand and carbon footprint.

From the scenario analysis, it can be concluded that the energy balance and carbon footprint of the Braunschweig wastewater scheme can be substantially improved by additional measures to improve the biogas yield and energy recovery without major drawbacks in other environmental impact categories. Improving the nutrient and water management of the agricultural reuse is a more difficult task and should be the focus of future research, targeting the decoupling of water and nutrient management and the satisfaction of the seasonal demand of agriculture.

General experiences and outlook for further studies

Overall, LCA proved as a suitable tool for the holistic and comprehensive analysis of the environmental footprint of the Braunschweig wastewater scheme. The method provided insight into the contributions of the different processes to the overall picture and supported the discussion on potential optimisation measures. However, this LCA can still be improved both in methodology and inventory data. In particular, the following points should be tackled in future studies of the system:

- Include organic pollutants in the inventory
- Include water footprint in the impact assessment
- Include atmospheric emissions during agricultural application of effluent, sludge, and mineral fertilizer
- Update of representative datasets for mineral fertilizer production and heavy metal content
- Generate primary data for on-site gaseous emissions of the WWTP
- Verify scenario data for co-substrate addition and energy demand of thermal hydrolysis in full-scale

The implementation of the issues listed above will contribute both to the comprehensiveness and the reliability of the results of this LCA. Nevertheless, the general conclusions of the present study are expected to remain basically valid in future assessments of the environmental footprint of the Braunschweig wastewater scheme.

Appendix A

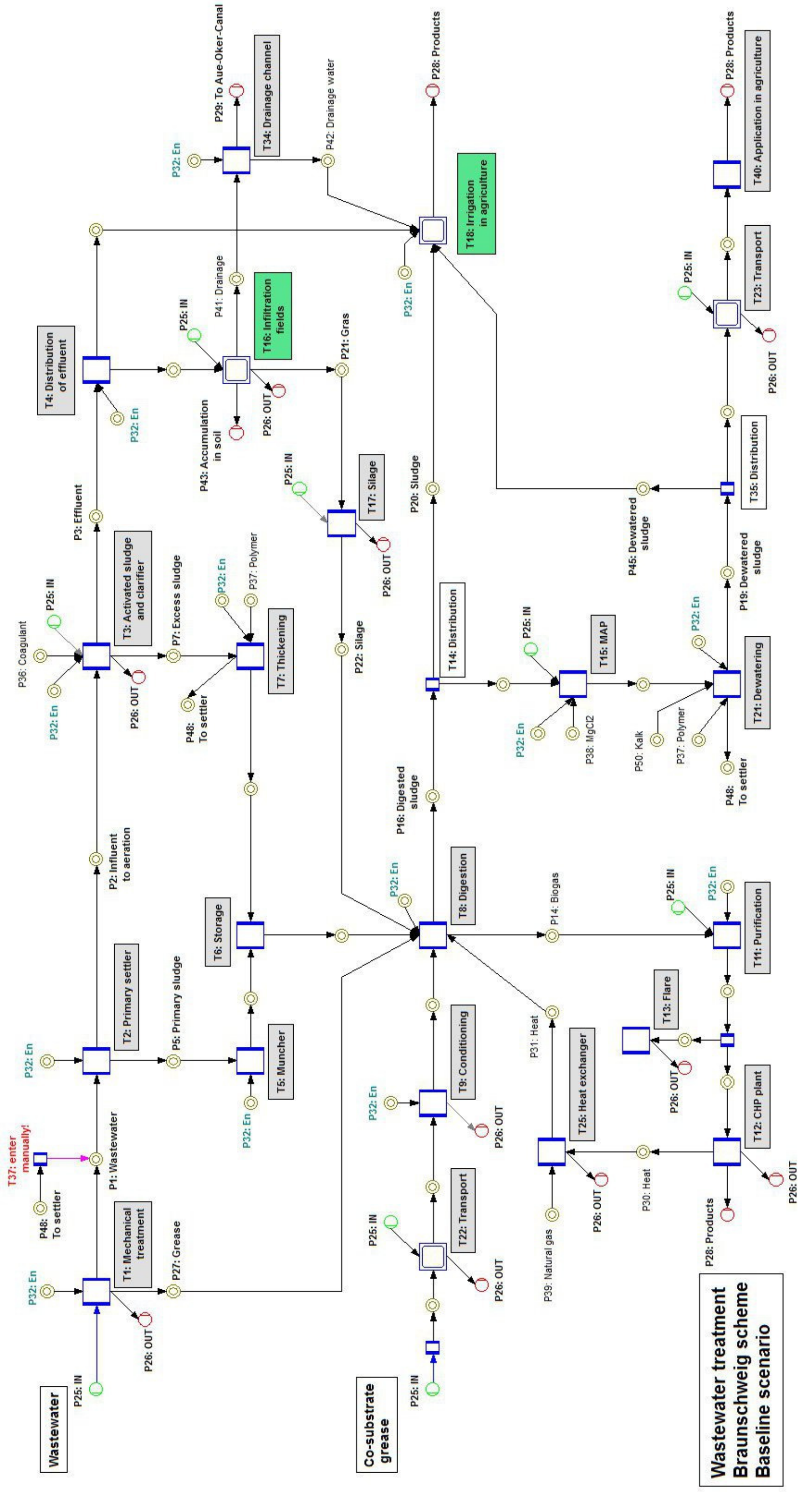


Figure 47: Screenshot of UMBERTO process model

Bibliography

AbfKlärV (1992): Klärschlammverordnung (Sewage sludge ordinance). Bundesgesetzblatt I S. 912, 2298,

AbwV (2004): Abwasserverordnung: Anhang 1 (Wastewater ordinance: Annex 1) Bundesgesetzblatt I S. 1108, 2605,

Ahn, J. H., Kim, S., Park, H., Rahm, B., Pagilla, K. and Chandran, K. (2010): N2O Emissions from Activated Sludge Processes, 2008–2009: Results of a National Monitoring Survey in the United States. *Environmental Science & Technology* **44** (12), 4505-4511.

ATV (2000): A131 Bemessung von einstufigen Belebungsanlagen (A131: Dimensioning of single stage activated sludge plants). Abwassertechnische Vereinigung e.V., Hennef, Germany.

ATV (1998): Arbeitsbericht: Entsorgung der Rückstände aus Abscheideranlagen für Fette (Working report: Disposal of residuals from grease separators) *Korrespondenz Abwasser, Abfall* **45** (5),

ATV (1996): Klärschlamm (Sewage sludge). Ernst & Sohn Verlag, Berlin, Germany.

Audsley, E., Alber, S., Clift, R., Cowell, S., Crettaz, P., Gaillard, A., Hausheer, J., Jolliet, O., Kleijn, R., Mortensen, B., Pearce, D., Roger, E., Teulon, H., Weidema, B. P. and van Zeijts, H. (1997): Harmonisation of environmental life cycle assessment for agriculture (final report ; concerted action AIR3-CT94-2028). European Commission DG VI Agriculture, Silsoe, United Kingdom.

AVB (2011): Data from Abwasserverband Braunschweig, personal communication. Braunschweig, Germany.

Bardtke, D., Müller, W. R. and Schäfer, C. (1994): Untersuchungen zur Optimierung der Denitrifikation hinsichtlich der Entwicklung von elementarem Stickstoff und Distickstoffoxid (Lachgas) (Investigations to optimize denitrification concerning the formation of elementary nitrogen and dinitrogenmonoxide). 53/94 Umweltbundesamt, Berlin, Germany.

BEE (2009): Stromversorgung 2020: Wege in eine moderne Energiewirtschaft (Electricity production 2020: ways to a modern energy management). Bundesverband erneuerbarer Energie e.V., Berlin, Germany.

Berger, M. and Finkbeiner, M. (2010): Water Footprinting: How to Address Water Use in Life Cycle Assessment? *Sustainability* **2** (4), 919-944.

BMWi (2009): Energiedaten (Energy data). Bundesministerium für Wirtschaft und Technologie, Berlin, Germany.

Boysen, P. (1992): Schwermetalle und andere Schadstoffe in Düngemitteln - Literaturauswertung und Analysen (Heavy metals and other pollutants in fertilizers - literature review and analysis). 55/1992 Umweltbundesamt, Berlin, Germany.

Coker, E. G. and Carlton-Smith, C. H. (1986): Phosphorus in sewage sludges as a fertilizer. *Waste Management & Research* **4** (3), 303-319.

Curran, M. A. (2007): Co-Product and Input Allocation Approaches for Creating Life Cycle Inventory Data: A Literature Review. *International Journal of Life Cycle Assessment* **12** (Special Issue 1), 65-78.

Davis, J. and Haglund, C. (1999): Life Cycle Inventory (LCI) of Fertiliser Production - fertiliser products used in Sweden and Western Europe. **SIK-report no. 654** Chalmers University of Technology, Gothenburg, Sweden.

Drescher-Hartung, S., Fruth, F. and Kranert, M. (2001): Umverteilung von Schwermetallen in der Umwelt durch Komposte im Vergleich zu anderen Einträgen auf Böden (Reallocation of heavy metals in the environment from compost application in comparison to other inputs on soils). 2 Entsorgergemeinschaft der Deutschen Entsorgungswirtschaft e.V., Braunschweig/Wolfenbüttel, Germany.

DWA (2009): Arbeitsbericht: Energiebilanz der Desintegration (Report: Energy balance of desintegration). *Korrespondenz Abwasser, Abfall* **56** (8), 797-801.

DWA (2005): Arbeitsbericht: Rückbelastung aus der Schlammbehandlung - Verfahren zur Schlammwasserbehandlung (Working report: return loads from sludge treatment - Processes for sludge liquor treatment). *Korrespondenz Abwasser, Abfall* **52** (6), 737.

Ecoinvent (2007): Ecoinvent data v2.0, ecoinvent reports No. 1-25, Swiss Center for Life Cycle Inventories, www.ecoinvent.org. Dübendorf, Switzerland.

EFMA (1995): Best Available Techniques (BAT) for Pollution Prevention and Control in the European Fertiliser Industry. BAT Sheets No. 1-8. European Fertiliser Manufacturers' Association, Brussels, Belgium.

Eggers, T. (2008): Verregnung von geklärtem Abwasser auf 3000 ha landwirtschaftlich genutzter Fläche (Spreading of purified wastewater on 3000 ha of agricultural fields). *gwf- Wasser-Abwasser* **149** (13), 25-31.

Foley, J., de Haas, D., Yuan, Z. and Lant, P. (2010): Nitrous oxide generation in full-scale biological nutrient removal wastewater treatment plants. *Water Research* **44** (3), 831-844.

Frischknecht, R., Althaus, H.-J., Bauer, C., Doka, G., Heck, T., Jungbluth, N., Kellenberger, D. and Nemecek, T. (2007): The Environmental Relevance of Capital Goods in Life Cycle Assessments of Products and Services. *International Journal of Life Cycle Assessment* **12** (Special Issue 1), 7-17.

Gaillard, G., Crettaz, P. and Hausheer, J. (1997): Umweltinventar der landwirtschaftlichen Inputs im Pflanzenbau (Life cycle inventories of agricultural inputs in crop production). Eidgen. Forschungsanstalt für Agrarwirtschaft und Landtechnik, Tänikon, Switzerland.

Goedkoop, M. J., Heijungs, R., Huijbregts, M. A. J., De Schryver, A., Struijs, J. and Van Zelm, R. (2009): ReCiPe 2008, A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level; First edition Report I: Characterization. http://www.lcia-recipe.net,

Hackenberg, S. and Wegener, H.-R. (1999): Schadstoffeinträge in Böden durch Wirtschafts- und Mineraldünger, Komposte und Klärschlamm sowie durch atmosphärische Deposition (Pollutant inputs into soils from manure and mineral fertilizers, compost and sewage sludge as well as atmonspheric deposition). M.I.C. BAEZA-Verlag, Witzenhausen, Germany.

IFU and IFEU (2005): Umberto - Software für das betriebliche Stoffstrommanagement, Version Umberto 5.0 (Umberto - software for operational substance flow management, version Umberto 5.0). Institut für Umweltinformatik GmbH und Institut für Energie- und Umweltforschung Heidelberg GmbH, Heidelberg/Hamburg, Germany.

IME (2005): Pflanzenverfügbarkeit von Stickstoff, Phosphor und Kalium bei Sekundärrohstoffdüngern (Plant availability of nitrogen, phosphorus and potassium in secondary fertilizers). Fraunhofer Institut für Molekularbiologie und Angewandte Ökologie (UBA FKZ 201 33 328), Schmallenberg, Germany.

IPCC (2007): Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change IPCC, Geneva, Switzerland.

ISO 14040 (2006): Environmental management - Life Cycle Assessment - Principles and framework. International Standardisation Organisation, Geneva, Switzerland.

ISO 14044 (2006): Environmental management - Life cycle assessment - Requirements and guidelines. International Standardisation Organisation, Geneva, Switzerland.

Kampschreur, M. J., Temmink, H., Kleerebezem, R., Jetten, M. S. M. and van Loosdrecht, M. C. M. (2009): Nitrous oxide emission during wastewater treatment. *Water Research* **43** (17), 4093-4103.

Kongshaug (1998): Energy consumption and greenhouse gas emissions in fertilizer production. Hydro Agri Europe, Norway. EFMA seminar on EU legislation and the legislation process in the EU relative to fertilizer, Prague, Czech Republic.

Kördel, W., Herrchen, M., Müller, J., Kratz, S., Fleckenstein, J., Schnug, E., Saring, U., Thomas, J., Haamann, H. and Reinhold, J. (2007): Begrenzung von Schadstoffeinträgen bei Bewirtschaftungsmassnahmen in der Landwirtschaft bei Düngung und Abfallverwertung (Limitation of pollutant inputs from fertilizing and waste utilization in agricultural cultivation). Heft 30/07 Umweltbundesamt, Berlin, Germany.

Krueger (2011): The combination of DLD and exelys(tm), personal communication with Nicholas Gurieff. Krueger A/S, Copenhagen, Denmark.

KWB (2010): Project CoDiGreen "Optimisation of energy and nutrient recovery in wastewater treatment schemes". Berlin Centre of Competence for Water, Berlin, Germany.

Larsen, H. F., Olsen, S. I., Hauschild, M. and Laurent, A. (2009): Methodology for including specific biological effects and pathogen aspects into LCA, NEPTUNE project, EU-FP6 Contract No. 036845, Deliverable 4.2. Technical University of Denmark (DTU) Lyngby, Denmark.

LAWA (2005): Leitlinien zur Durchführung dynamischer Kostenvergleichsrechnungen (KVR-Leitlinien) (Guidelines for dynamic calculation of cost comparison). Länderarbeitsgemeinschaft Wasser, Berlin, Germany.

Müller, J., Tiehm, A., Böcker, K., Eder, B., Kopp, J., Kopplow, O., Neis, U., Oles, J., Schmelz, K., Seiler, K., Wendler, D. and Winter, A. (2005): Wirtschaftlicher und betrieblicher Vergleich verschiedener Verfahren zur Klärschlammdesintegration (Economic and operational comparison of different processes for sewage sludge desintegration). *Korrespondenz Abwasser, Abfall* **52** (2), 189-196.

MUNLV (2001): Co-Fermentation von biogenen Abfällen in Faulbehältern von Kläranlagen (Co-fermentation of biogenic wastes in digestors of wastewater treatment plants). 22 Ministerium für Umwelt und Naturschutz, Landwirtschaft und Verbraucherschutz des Landes Nordrhein-Westfalen, Düsseldorf, Germany.

MUNLV (1999): Handbuch Energie in Kläranlagen (Handbook of energy in wastewater treatment plants). Ministerium für Umwelt, Raumordnung und Landwirtschaft des Landes Nordrhein-Westfalen, Düsseldorf.

Patyk, A. and Reinhardt, G. A. (1997): Düngemittel - Energie- und Stoffstrombilanzen (Fertilizers: energy and sustance flow balances). Vieweg, Braunschweig/Wiesbaden, Germany.

PFI (2010): Internal study on ORC process for SE/BS. Braunschweig, Germany.

Remy, C. (2010): Life Cycle Assessment of conventional and source-separation systems for urban wastewater management. Dissertation, Department of Water Quality Control (http://opus.kobv.de/tuberlin/volltexte/2010/2543/), Technical University, Berlin.

Ronchetti, C., Bienz, P. and Pridal, R. (2002): Ökobilanz Klärgasverstromung (Life cycle assessment of sewage gas electrification) Bundesamt für Energie, Bern, Switzerland.

SE/BS (2010): Operational data of Stadtentwässerung Braunschweig, personal communication with Christoph Siemers. Braunschweig, Germany.

Suntheim, L. (2001): Zur Phosphorverfügbarkeit von Klärschlamm (To the availability of phosphorus from sewage sludge). TK-Verlag, Neuruppin, Germany.

UBA (2010): Environmental data online, www.uba.de. German environmental agency, Berlin, Germany.

VDI (1997): VDI-Richtlinie 4600: 1997-06: Kumulierter Energieaufwand - Begriffe, Definitionen, Berechnungsmethoden (VDI guideline 4600: 1997-06: Cumulative energy demand - Terms, definitions, calculation methods). VDI Verlag, Düsseldorf, Germany.

Wicht, H. (1996): N2O-Emissionen durch den Betrieb biologischer Kläranlagen (N2O emissions during operation of biological wastewater treatment plants). Dissertation, Institut für Siedlungswasserwirtschaft, TU Braunschweig, Braunschweig, Germany.

Critical Review

OPTIMISATION OF ENERGY AND NUTRIENT RECOVERY IN WASTEWATER TREATMENT SCHEMES – LCA STUDY OF THE BRAUNSCHWEIG SYSTEM
PROJECT: CODIGREEN

Commissioned by:	Kompetenzzentrum Wasser Berlin gGmbH Berlin, Germany
Reviewer:	Prof. Dr. Matthias Finkbeiner Berlin, Germany
Reference	ISO 14040 (2006): Environmental Management - Life Cycle Assessment - Principles and Framework ISO 14044 (2006): Environmental Management - Life Cycle Assessment – Requirements and Guidelines

Scope of the Critical Review

The reviewer had the task to assess whether

- the methods used to carry out the LCA are consistent with the international standards ISO 14040 and ISO 14044
- the methods used to carry out the LCA are scientifically and technically valid,
- the data used are appropriate and reasonable in relation to the goal of the study,
- the interpretations reflect the limitations identified and the goal of the study, and
- the study report is transparent and consistent.

The review was performed according to paragraph 6.2 of ISO 14044, because the study is not intended to be used for comparative assertions intended to be disclosed to the public. This review statement is only valid for this specific report in its final version received on 08.12.2011.
The analysis and the verification of individual datasets are outside the scope of this review.

Review process

The review process was coordinated between Kompetenzzentrum Wasser Berlin (KWB) and the reviewer. As a first step of the review, a kick-off-meeting was held on 03.02.2011 to agree on the review process and to discuss some general aspects of the goal and scope definition for the project. The next step was the submission of the draft final report to the reviewer on 17.11.2011. After the evaluation of the draft final report the reviewer provided a set of 47 comments of general, technical and editorial nature to the commissioner by the 29.11.2011. The feedback provided and the agreements on the treatment of the review comments were adopted in the finalisation of the study. The final version of the report was provided on 08.12.2011. A review meeting was held on 13.12.2011 in which the commissioner explained the actions taken on the comments. All critical issues and a substantial amount of the recommendations of the reviewer were addressed in a comprehensive and constructive manner.

The reviewer checked the implementation of the comments and agreed to the final report. The reviewer acknowledges the unrestricted access to all requested information as well as the open and constructive dialogue during the critical review process.

General evaluation

The study is performed in a professional manner using state-of-the-art methods. The LCI modelling used for the study reflects the technical in-depth knowledge of the LCA practitioner with regard to the system under study. The product system and the broad range of scenarios are described comprehensively and transparently.

Several assumptions were checked by sensitivity analyses of critical data and methodological choices. As a result, the report is deemed to be representative for studied waste water treatment schemes. The defined and achieved scope for this LCA study was found to be appropriate to for the stated goals.

Conclusion

The study has been carried out in compliance with ISO 14040 and ISO 14044. The reviewer found the overall quality of the methodology and its execution to be of a high standard for the purposes of the study. The study is reported in a comprehensive manner including a transparent documentation of its scope and methodological choices.

Matthias Finkbeiner

Prof. Dr. Matthias Finkbeiner
15th December 2011