Evaluating new processes and concepts for energy and resource recovery from municipal wastewater with life cycle assessment

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ABSTRACT

Energy and resource recovery from municipal wastewater is a pre-requisite for an efficient and sustainable water management in cities of the future. However, a sound evaluation of available processes and pathways is required to identify opportunities and short-comings of the different options and reveal synergies and potentials for optimization. For evaluating environmental impacts in a holistic view, the tool of life cycle assessment (LCA, ISO 14040/44) is suitable to characterize and quantify the direct and indirect effects of new processes and concepts. This paper gives an overview of four new processes and concepts for upgrading existing wastewater treatment plants towards energy positive and resource efficient wastewater treatment, based upon an evaluation of their environmental impacts with LCA using data from pilot and full-scale assessments of the considered processes.

Key words | energy recovery, life cycle assessment, phosphorus recovery, wastewater treatment

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INTRODUCTION

Raw municipal wastewater contains significant amounts of resources both in energy and material terms, originating mainly from human excreta. The theoretical chemical energy potential of organic matter measured as chemical oxygen demand (COD) has been estimated as 4 kWh/kg COD (Heidrich *et al.* 2010). In addition, valuable plant nutrients such as phosphorus (P) and nitrogen (N) are found in high amounts in municipal wastewater, amounting to 1.8 g P and 11 g N per person equivalent (pe) per day on average (ATV 2000). In total, the annual energy and nutrients potential in municipal wastewater can thus be calculated as 175 kWh of chemical energy potential (assuming 120 g COD/(pe*d)(ATV 2000)) and 0.66 kg P and 4 kg N per year. Other materials that could potentially be recovered from raw wastewater include cellulosic material such as toilet paper (Ruiken *et al.* 2013), but also biochemically produced basic chemicals (Matassa *et al.* 2015).

On the other hand, major demands of energy and chemicals are required to remove organic matter and nutrients from wastewater in wastewater treatment plants (WWTPs). In Germany, large WWTPs require 33–35 kWh/(pe*a) on average for wastewater treatment in conventional activated sludge processes including nutrient removal (DWA 2012), with many smaller WWTPs <10,000 pe having an even higher demand >40 kWh/(pe*a). The major fraction of this electricity demand originates from aeration for microbial degradation of COD and nitrification, but also recirculation pumps to promote denitrification. Thus, a major part of the chemical energy potential in COD is lost by microbial oxidation to CO_2, whereas a smaller part is transferred to the sludge via primary sedimentation (particulate COD in primary sludge) or microbial biomass (waste activated sludge). Many WWTPs recover a part of this energy potential in the mixed sludge via anaerobic digestion, converting typically around 50% of the organic dry matter into biogas. Using this biogas in combined heat and power (CHP) plants for electricity and heat production, operators can cover up to 50–70% of their plant-wide electricity demand (i.e. 10–16 kWh/(pe*a)) and provide sufficient heat to meet on-site demand (e.g. for heating of digestors). However, the recovered electricity amounts to only 6–10% of the chemical energy potential in raw wastewater as described above, indicating the potential for designing an energy-positive wastewater treatment process if energy recovery from raw wastewater could be improved. Some of the remaining

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energy potential in digested sludge can additionally be recovered in sludge incineration (i.e. mono-incineration in dedicated facilities for sludge, or co-incineration in power plants, waste incineration plants, or cement kilns), but the relatively high water content in dewatered sludge (20–35% dry matter content) yields only a low heating value or requires energy-intensive drying processes.

Nutrients in raw wastewater are typically eliminated via biological processes (nitrification and denitrification for N, and enhanced biological P removal (EBPR)) or dosing of chemicals (precipitation of P with Fe/Al salts). Whereas a major fraction of N (up to 80%) is denitrified into N_2 and lost for recovery, the remaining N is contained in the mixed sludge. After digestion, part of this N is redissolved into the sludge liquor as NH_4-N and recycled back to the WWTP influent after dewatering, thus contributing again to a significant energy demand in the main stream process with up to 20% of total N load. In contrast, the entire P load eliminated from raw wastewater ends up in the mixed sludge, enabling a highly efficient recovery of this limited and non-substitutable plant nutrient. However, traditional nutrient recycling strategies such as agricultural land application of digested and dewatered sludge pose the risk of organic and inorganic pollutants in the sludge and suffer from non-optimal nutrient usage due to seasonal variability of nutrient demand and sludge application or limited plant availability of chemically precipitated P (Kratz *et al.* 2010). In addition, agricultural application prevents energy recovery from digested sludge, whereas energy recovery in incineration does not include nutrient recovery, revealing the existing trade-off between energy and nutrient recovery from sewage sludge. To overcome this trade-off and to enable the recovery of P as limited resource for plant nutrition, strategies have been developed to recover P from sewage sludge, liquor, or ash from mono-incineration (Petzet & Cornel 2011; Schoumans *et al.* 2015).

Overall, the exploitation of the significant energy and nutrient potentials in raw wastewater will be a major goal for future concepts of wastewater treatment to minimize the demand of resources and energy for WWTP operation and maximize the recycling of nutrients, finally targeting an energy-positive process with high recovery of resources such as non-renewable mineral P or energy-intensive N fertilizers. During this optimization process, the original and primary target of wastewater treatment (i.e. cleaning of wastewater to protect receiving waters from negative influence of COD, nutrients, and pollutant loads) should never be compromised. Hence, the intelligent integration of new technologies and concepts for improved energy and nutrients recovery into a consistent WWTP scheme with lowest environmental impact will rely on a careful assessment of options and processes, making use of existing synergies and overcoming potential trade-offs.

A useful tool for a comprehensive assessment of environmental impacts of WWTP schemes is the methodology of life cycle assessment (LCA), standarized in ISO (ISO 14040 2006; ISO 14044 2006). It has been extensively used for characterizing the environmental impacts of WWTP schemes and sludge treatment (Corominas *et al.* 2013). Assessing both direct and indirect (i.e. upstream and downstream) effects in different categories of environmental concern, LCA provides a holistic picture for plant-wide evaluation of new processes or entire concepts for wastewater and sludge treatment.

The present paper discusses four different options for improving energy and nutrient recovery from wastewater and their evaluation with LCA, focussing on the energetic aspect of processes and related environmental effects such as the emission of greenhouse gases, defined as global warming potential (IPCC 2007) or carbon footprint. Focus is given on the use of the LCA method and the related main findings in the assessment of the new technologies, while methodological details and data can be found in the referenced papers and reports.

EXAMPLES FOR ENHANCING ENERGY AND RESOURCE RECOVERY FROM WASTEWATER

Upgrading sludge treatment with thermal hydrolysis

Energy recovery in anaerobic sludge treatment via biogas valorization is limited by the degradation ratio of the organic matter in digestion, typically around 50%. To increase this degradation ratio and increase biogas production, a thermal pre-treatment at high temperature (up to 160 °C in thermal hydrolysis (TH)) can be implemented for mixed or waste activated sludge prior to digestion. This TH process can be partially or totally driven by excess heat from the CHP plant depending on the total heat demand of the WWTP and suitable heat exchangers. TH can also be combined with upstream dewatering to reduce the water content in hydrolyzed sludge and to minimize the overall heat demand for TH. A combination of primary sludge digestion, intermediate dewatering, TH, and secondary digestion step (digestion–lysis–digestion (DLD)) can further increase the biogas production considerably and decrease the relative heat demand of the TH unit.

In an LCA study of the full-scale WWTP of Braunschweig (Germany) with a capacity of 350,000 pe, both options (TH of excess sludge and DLD of mixed sludge) have been assessed based on process data of pilot trials for biogas yield and supplier data for the hydrolysis process (KWB 2012). Using the indicator of cumulative energy demand, it could be shown that TH will reduce the net energy demand of the entire WWTP system by 21%, whereas DLD even saves 62% of current net energy demand (Figure 1). Based on a simple heat balance, both TH and DLD systems could be fed 100% from the CHP excess heat in this study, eliminating the need for additional fuel for TH operation. The DLD process includes an intermediate dewatering step (20% DM) after the first digestor and heat recovery from the TH output for sludge pre-heating prior to TH. Based on these promising results, a DLD system is currently in planning for implementation at WWTP Braunschweig.

Improving energetic valorization of digested sludge in incineration with hydrothermal carbonization

Another route for energy recovery from organic matter in sewage sludge is available with incineration of dewatered sludge, either in mono-incineration or in co-incineration in power plants or cement kilns. However, the remaining water content in the dewatered sludge has a significant impact on the effective heating value of the dewatered sludge and finally the amount of energy that can be recovered via this route. Recently, the process of hydrothermal carbonization (HTC) has been proposed as a potential alternative for improved dewatering of sewage sludge. Through heating of the digested and dewatered sludge to $>180\,^{\circ}C$ for a longer time (150 min), superior dewatering up to 65% total solids can be reached in final dewatering in a filter press. However, the produced process water is highly loaded with COD and nutrients, thus increasing the return load to the WWTP main stream. On the other hand, adding the process water back into the digestor can yield additional biogas from the dissolved COD. High nutrient loads (NH_4-N > 5,000 mg/L, PO_4-P > 500 mg/L) and refractory COD will still pose an additional load to the main stream and require energy for treatment.

In a theoretical desktop study with a sludge disposal scheme (digestion, dewatering, incineration) of a model WWTP for 500,000 pe, it could be shown that HTC has the potential to improve the net energy balance of sludge disposal considerably in comparison with traditional dewatering in centrifuges or filter press (Remy *et al.* 2014b) (Figure 2). Again, the theoretical heat balance of the sludge line indicated that HTC could be driven completely from the excess heat available at the CHP plant, provided that no other heat consumers except digestor heating are present. Additional biogas yield from process water and improved energy recovery in incineration were responsible for the energy benefits of HTC implementation. However, this theoretical potential of HTC has to be confirmed in real case studies with realistic data of excess heat, also taking into account potential effects of refractory COD on effluent quality of the WWTP in the environmental assessment.

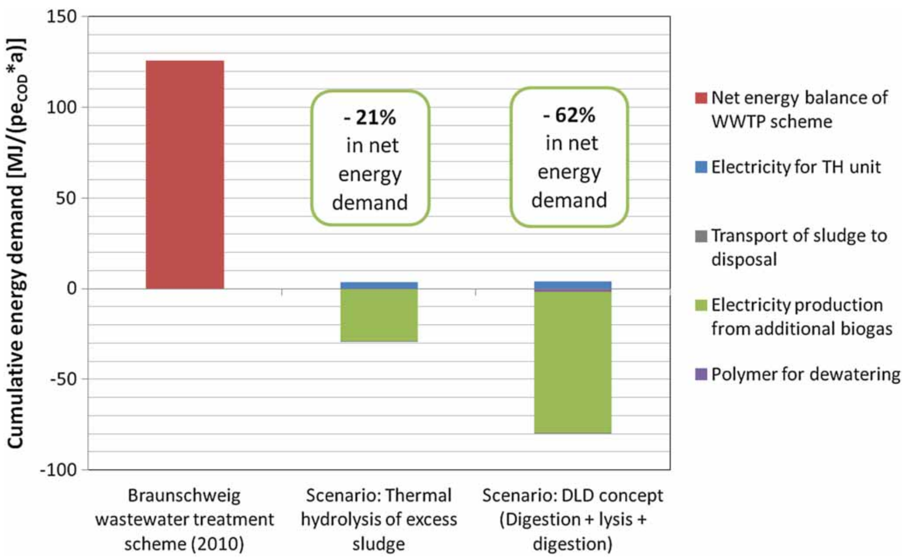

Figure 1 | Impact of implementation TH of excess sludge or a DLD treatment on total net cumulative energy demand of WWTP Braunschweig, Germany.

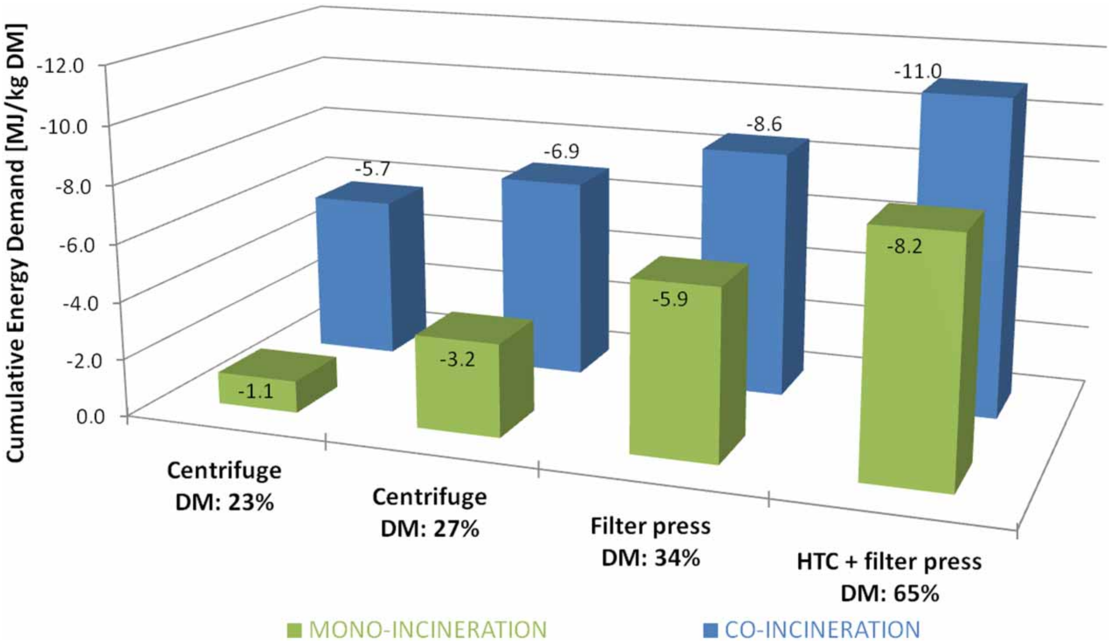

Figure 2 | Net energy balance (inverted axis) of sludge treatment and energetic disposal in mono-incineration or co-incineration for different dewatering aggregates and respective dry matter (DM) content in dewatered sludge (Remy *et al.* 2014b).

These results also show that sludge disposal in mono-incineration has a distinctively lower energy recovery than in co-incineration (power plants), especially for sludge with high water content which requires high amounts of additional fuel oil in fluidized bed mono-incinerators or pre-drying with available waste heat. However, mono-incineration of sludge has other benefits over co-incineration in terms of phosphorus recovery from residual ashes with high P content and superior pollutant control in off-gas cleaning. Hence, energetic optimization of mono-incineration facilities should be a major target in the future to enable simultaneous recovery of energy and phosphorus.

Phosphorus recovery from sewage sludge

Phosphorus as a non-renewable and essential nutrient can be recovered from sewage sludge through different routes, i.e. from sludge or sludge liquor, from the ash of mono-incineration, or via land application of sludge. The latter form is still practiced widely throughout Europe and can be an effective way of nutrient recycling, if sludge quality (e.g. content of heavy metals, organic pollutants) is sufficiently good and nutrient availability is high. Against the background of unknown effects of emerging pollutants and long-term application on soil quality, new routes for P recovery have been developed.

Different pathways are available to recover P from sludge, with a multitude of process concepts available on the market. Some of them have been assessed within the EU project P-REX (www.p-rex.eu): precipitation of struvite in sludge or sludge liquor, sludge leaching with acids and subsequent precipitation of P products, or treatment of mono-incineration ashes with acid leaching or thermo-chemical removal of heavy metals. A potential process for combined recovery of energy and P from sludge is metallurgic gasification of dried sludge in a cupola oven (>1,500 °C), but this process has only been shown to work in pilot scale. All these processes have been assessed with LCA in their environmental impacts (Remy & Jossa 2015), focussing here on the energy demand for P recovery in relation to a reference WWTP sludge line (digestion, dewatering, mono-incineration). The substitution of mineral P fertilizer has been credited to account for the total P content in the extracted product.

The results for the cumulative energy demand of P recovery in comparison to the traditional sludge line show that P recovery pathways differ heavily in their effect on the overall energy balance, but also in the amount of P that can be recovered from sludge (Figure 3). Whereas P recovery from sludge via direct struvite precipitation in sludge yields high additional side benefits of improved dewatering and energy recovery in final incineration, this pathway is limited by dissolved P content in sludge (16% of total P) and difficult

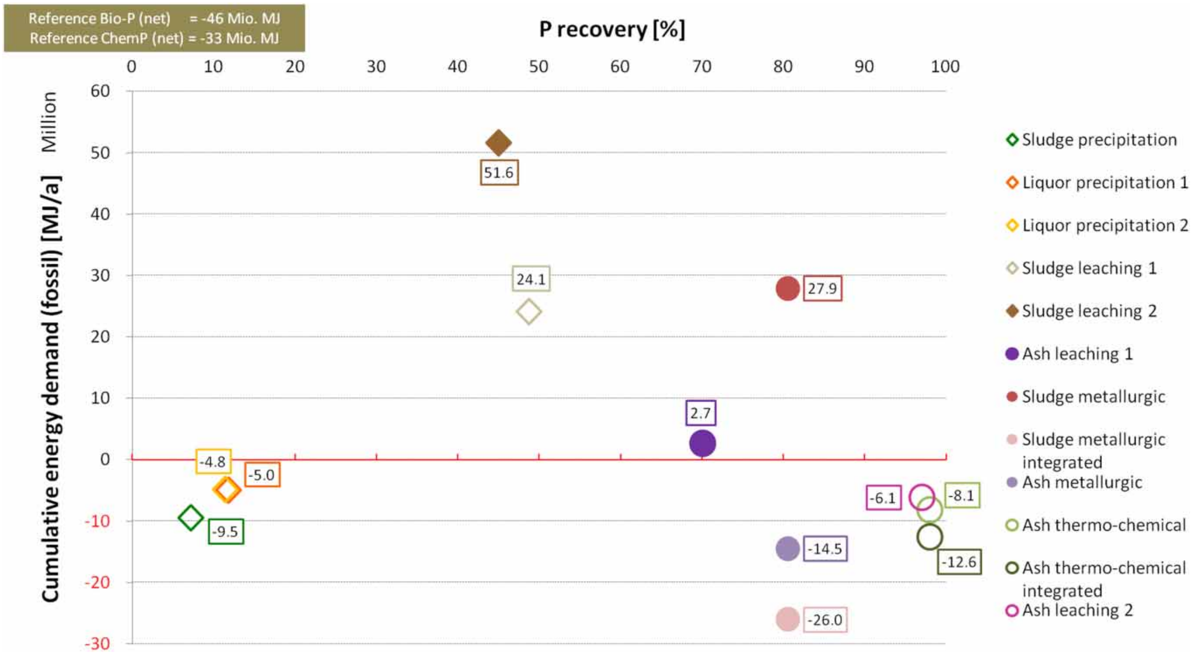

Figure 3 | Cumulative energy demand (fossil) for P recovery from 1 Mio pe WWTP sludge line, related to relative amount of recovered P for different recovery pathways (Remy & Jossa 2015).

harvesting of formed struvite crystals from the sludge matrix. Struvite precipitation in sludge liquor can yield an excellent product quality with relatively low effort and high harvesting efficiency, but is also limited to the dissolved P load in liquor. Sludge leaching can mobilize up to 50% of total P in sludge into the dissolved form with high acid demand, but the following separation of heavy metals and P prior to precipitation requires additional measures such as addition of citric acid for metal complexation or sulphidic precipitation by adding Na_2S. Overall, sludge leaching requires a fairly high amount of chemicals and is not favourable from an energetic point of view. Ash leaching also requires high amounts of acid reaching 70% of P recovery, while thermo-chemical treatment of ashes for metal removal needs natural gas and recovers 98% of P. Metallurgic sludge treatment can recover more than 80% of the P content, but depends on efficient recovery of energy content in the exhaust gas (containing the heating value of gasified organic material), which is best realized via an integration of metallurgic sludge treatment into an existing incineration facility for municipal waste.

Overall, the LCA of P recovery pathways shows that P recovery can be realized with overall energy benefits when taking into account the substituted production of mineral P fertilizer from fossil P rock. However, a careful investigation of the entire life cycle of P recovery schemes is required to identify the optimum strategy for simultaneous P and energy recovery from sewage sludge. Again, the optimization of energy recovery in mono-incineration should be targeted to provide both energy and resource efficiency for future routes of sewage sludge disposal.

New concepts for wastewater treatment

Most measures for increasing energy recovery in wastewater treatment still yield only marginal improvements in energy balance, tapping the energy potential in raw wastewater only to a limited extent. The activated sludge process developed in the middle of the last century is based on the energy-intensive mineralization of the organic matter to CO_2 via biological metabolism in the activated sludge. Hence, entirely new concepts for wastewater treatment are developed to overcome the inherent energetic drawbacks of the conventional activated sludge process. These concepts try to improve the overall energy balance of WWTPs by reducing the energy demand for treatment and increasing the energy recovery at the same time, finally targeting energy-neutral or even energy-positive WWTP without compromising the treatment performance in terms of effluent quality.

A promising new concept builds up upon advanced primary treatment, extracting as much organic matter as possible with physico-chemical processes to maximize primary sludge production and minimize energy demand for downstream biological treatment. This concept consists of coagulation and flocculation of raw wastewater, followed by low-energy microsieve filtration (mesh size: 100 μm) to separate the primary sludge. However, post-treatment will still be required to remove nitrogen and residual organic matter and guarantee high effluent quality in terms of COD, N, and P concentration. Pilot trials of microsieve filtration with real wastewater in industrial-scale modules proved that it is feasible to extract 70–80% of COD from raw wastewater with this concept (Remy *et al.* 2014a). Holistic energy balances of an entire WWTP scheme including post-treatment in biofilter for nitrification and denitrification with external carbon source show that this new concept is superior to a reference activated sludge process in net energy balance, reaching a comparable effluent quality for mid-sized WWTP (100 mg/L COD, 18 mg/L N, 2 mg/L P) (Figure 4). Although energy demand for chemicals production has been taken into account in this LCA-based analysis via primary energy factors, microsieve filtration and subsequent biofilter have a positive net energy balance, making this scheme finally an 'energy-positive' and carbon-neutral WWTP (Remy *et al.* 2014a). Following this proof of concept, the new scheme will be demonstrated in terms of performance and energy balance in a full-scale WWTP of smaller size (2,000 pe) as a next step.

CONCLUSION

The processes and concepts described in the paper show that there are multiple options to enhance energy and nutrient recovery from municipal wastewater without compromising the primary function of wastewater treatment, i.e. the removal of contaminants from raw wastewater to reach legal effluent standards. With a major fraction of energy bound in sewage sludge, processes for increasing biogas production in anaerobic digestion such as TH or DLD have a significant potential to improve the overall energy balance of WWTPs, provided that they are intelligently integrated into the entire sludge treatment process and make optimum use of available excess heat. Energy recovery in sludge incineration can be enhanced by more efficient dewatering, which can be realized by HTC treatment of the digested and dewatered sludge. Potentials for an improved energy balance with HTC have been identified, but the HTC technology has still to be evaluated in full-scale with careful consideration of potential side effects on effluent quality of the WWTP, especially in terms of refractory COD contained in the process water.

For recovery of P from sewage sludge, different pathways and processes are available which can also improve the overall energy balance if substitution of mineral P fertilizer production is taken into account. However, pathways for P recovery differ heavily in their amount of recovered P and also their in energy balance, indicating the need for detailed assessment of strategies for combined recovery of energy and nutrients from municipal wastewater.

In addition to conventional concepts of wastewater treatment based on the activated sludge process, new concepts prove to be able to provide adequate treatment of wastewater with maximized extraction of carbon into sludge, thus improving their electricity balance towards

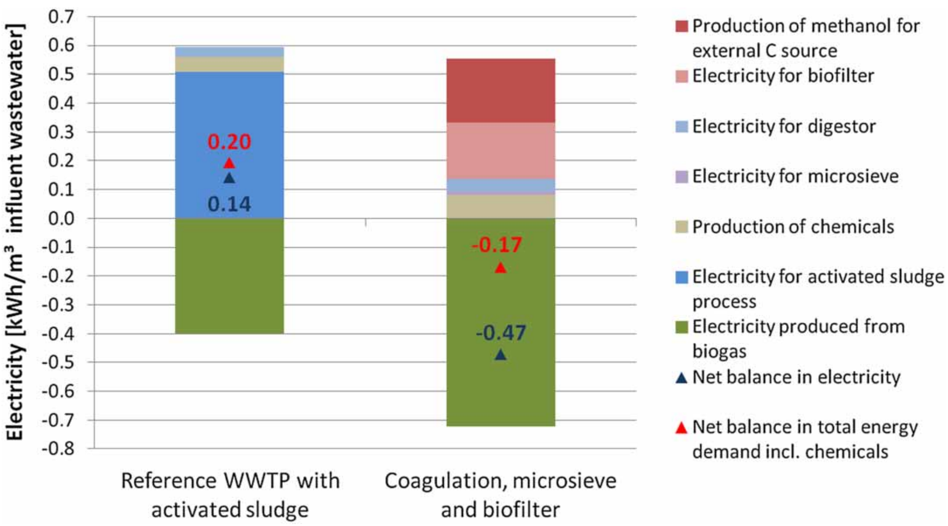

Figure 4 | Energy balance for reference WWTP and new treatment scheme with comparable effluent quality (Remy *et al.* 2014a).

'energy-positive' wastewater treatment schemes. However, the presented concept still requires a high amount of energy for downstream nitrogen removal after carbon extraction, revealing another inherent trade-off of energy recovery. In the future, the intelligent combination of maximum carbon extraction via physico-chemical or biological processes with an energy-efficient nitrogen removal process (e.g. main-stream deammonification (Wett *et al.* 2013)) could be a viable option for energy-positive wastewater treatment with high effluent quality, thus exploiting the existing energy potential in municipal wastewater to a higher degree.

For both optimization of the existing schemes and the development of new concepts, life-cycle based tools such as LCA should be used to assess all direct and indirect environmental effects via LCA to prevent the shift of environmental impacts between areas of concern (e.g. effluent water quality vs. energy demand or carbon footprint) and identify synergies or potentials for optimization in a holistic approach. LCA proves to be a suitable tool for a comprehensive assessment of the complex process of wastewater treatment, facilitating the transition to energy and resource-efficient wastewater management concepts without overlooking side-effects on other environmental areas of protection. Although this paper focuses on assessing the energy aspects, other LCA indicators are available to characterize the effects of WWTP effluent discharge on receiving waters, e.g. via eutrophication by nutrients P and N or aquatic ecotoxicity from inorganic or organic pollutants.

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