CO_2-neutral wastewater treatment plants or robust, climate-friendly wastewater management? A systems perspective.

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Abstract

CO_2-neutral wastewater treatment plants can be obtained by improving the recovery of internal wastewater energy resources (COD, nutrient energy) and reducing energy demand as well as direct emissions of the greenhouse gases N_2O and CH_4. Climate-friendly wastewater management also includes the management of the heat resource, which is most efficiently recovered at the household level, and robust wastewater management must be able to cope with a possible resulting temperature decrease. At the treatment plant there is a substantial energy optimization potential, both from improving electromechanical devices and sludge treatment as well as through the implementation of more energy-efficient processes like the mainstream anammox process or nutrient recovery from urine. Whether CO_2 neutrality can be achieved depends not only on the actual net electricity production, but also on the type of electricity replaced: the cleaner the marginal electricity the more difficult to compensate for the direct emissions, which can be substantial, depending on the stability of the biological processes. It is possible to combine heat recovery at the household scale and nutrient recovery from urine, which both have a large potential to improve the climate friendliness of wastewater management.

Key words: warm greywater, decentralized heat recovery, cold wastewater, urine separation, future

1 Introduction

In this special issue, CO_2-neutral wastewater management is the topic. In practice, this notion is often interpreted as CO_2-neutral wastewater treatment plants, which can be

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obtained by combining improvements of energy efficiency (Gao et al. 2014) and reduction of the emissions of N_2O and CH_4, the main greenhouse gasses emitted from wastewater treatment plants (Daelman et al. 2013). CO_2-neutral treatment plants are also a central topic in this paper, but the system boundaries are drawn slightly broader also embracing sewers and households, where equally important issues for the climate and for the robustness of different treatment configurations are determined.

Gao et al. (2014) list three main options for improving energy efficiency of wastewater treatment: 1) Nutrient recovery or direct reuse, 2) Low-energy NOD removal (NOD = nitrogenous oxygen demand), and 3) Energy recovery from NOD. The first option avoids energy costs for nitrification and reaps the ‘embedded’ energy in the nutrients. An example of the second option is the separation of nitrogen transformation and COD degradation, e.g. the mainstream anammox process (De Clippeleir et al. 2014). The third option, direct energy recovery from nitrous oxide or ammonia will not be discussed in this paper.

A large number of recent papers are dedicated to the issue of understanding and controlling N_2O emissions at wastewater treatment plants. Several modeling papers summarize these findings (Guo and Vanrolleghem 2014, Mampaey et al. 2013), but there is still no real consensus about the main pathways. As shown by Sweetapple et al. (2014), N_2O emission is an extremely important process for the resulting total greenhouse gas emission from wastewater treatment plants. Generally estimated at 0.5 % of the incoming nitrogen, real N_2O emissions at full scale treatment plants have been found to vary between 0 and 14 % of incoming N (Kampschreur et al. 2009).

Methane emissions stem primarily from the anaerobic digestion of sludge and can be an important part of greenhouse gasses from wastewater treatment plants. During nine measurement campaigns, Yoshida et al. (2014) found methane losses from 2.1 to 4.4 % of the methane produced under stable conditions, but up to 32.7 % when operational difficulties were observed. Daelman et al. (2014) discuss different technologies for removal of the dissolved methane in the effluent from sludge treatment, but gaseous emissions must be minimized by optimal operation conditions.

Apart from the more technical aspects of process engineering at the treatment plant, the choice of systems boundaries plays a major role for the identification of climate-friendly wastewater management. It is well known that the largest energy content of wastewater is found as heat (Gao et al. 2014), but it is seldom discussed that this energy can best be exploited from grey water at the household level (Meggers and Leibundgut 2011). Wastewater professionals understandably concentrate on the conventional system of sewers and treatment plants, but with the development of source separation and decentralized treatment options during the last two decades (Larsen et al. 2013), steps in the direction of household technologies have already been made. With the increasing emphasis on greenhouse gas emissions, it thus also makes sense to include the possibility of heat recovery at the household level as compared to heat recovery in the sewer system or after the wastewater treatment plant.

All the attempts of increasing energy efficiency at the treatment plant are effective. However, they also involve investments and result in different degrees of robustness and flexibility (defined by Spiller et al. (2015) as the ability of a plant to deal with foreseeable and unforeseeable changes in the environment, respectively). In order to discuss the potential on the one side and the robustness/flexibility on the other side of the different attempts to approach CO_2 neutrality of wastewater treatment plants, simple presentations of the potentials and a discussion of the consequences of external influences on the resulting treatment plants are useful. In the end, the plants shall not only be climate-friendly, but also protect the receiving water according to the local regulations during their entire lifetime.

In order to keep the presentations simple enough to allow for a consistent overview, only issues will be discussed, which are generic for all plants. Additionally, the risk of temperature changes of wastewater will be discussed, which may challenge the viability of nitrogen oxidation in treatment plants. The hypothesis is that careful choice of system boundaries and a global focus on efficiency improvements will prevent sub-optimization or increased environmental impacts from local efficiency improvements.

The following measures to improve CO_2 efficiency of wastewater management will be discussed:

1. Heat recovery from wastewater at the sewer scale *versus* the household scale.
2. Present standard *versus* energy-improved sludge treatment
3. Aeration with present standard *versus* more energy-efficient equipment.
4. Conventional wastewater treatment *versus* separation of nitrogen and organic matter.
5. Separation of nitrogen and organic matter *with and without* nutrient recovery.

The analysis is simplified in order to stay generic: A ‘pseudo’ net electricity production for a given treatment configuration is calculated based on the electricity production from sludge (via anaerobic digestion followed by electricity production from methane) and the electricity demand for aeration (often accounting for more than 50 % of the total electricity demand for wastewater treatment, Svardal and Kroiss (2011)). The other energy requirements at the treatment plant (e.g. pumping) depend on specific plant details and cannot be generalized in any meaningful way.

2 Methods

A simplified systems analysis is performed on the management of purely domestic wastewater from production in the household to release as treated wastewater to the receiving water. The analysis is based on European person equivalents as given in most textbooks (Table S1). The quantitative results on sludge production and oxygen demand at wastewater treatment plants are based on the German guideline A131 (DWA 2000), which is used for the practical design of wastewater treatment plants in large parts of Central Europe. The parts of the guideline used here are founded on conservation laws as discussed by Gujer and Larsen (1995) and empiric knowledge from European wastewater treatment plants. For the discussion of climate relevance, the three most important greenhouse gasses from wastewater treatment are included: CO_2 (indirect due to energy demand) and the direct emissions N_2O and CH_4. Since we can assume that the CO_2 emission from wastewater organic matter does not differ amongst the configurations discussed here, this emission is not taken into account.

3 Results

The following information is presented:

1. A semi-quantitative comparison of heat recovery at the household and the sewer level.

2. The possibilities for optimization of electricity demand/production at the wastewater treatment plant illustrated by three different configurations (conventional, mainstream anammox, and nutrient recovery based on urine separation). For all three configurations, the analysis is made taking only aeration (at different efficiencies) and electricity production from sludge via anaerobic digestion (at different efficiencies) into account.

3. The relative importance of N_2O/CH_4 and electricity at three different assumptions about the electricity used and replaced (present electricity mix in Denmark, present and future marginal European electricity production).

3.1 Heat recovery from wastewater at the sewer *versus* the household scale

As shown in Table 1, about 85 % of the energy contained in domestic wastewater is in the form of heat in warm water.

Table 1 ‘Content’ of energy in typical European purely domestic wastewater (kWh/person/year). Details in Table S1.

		Comments
Heat[*] contained in warm water	800	65 L/p/day, heated from 10 to 38 °C (Table S2)
Chemical energy contained in organic matter	150	120 g_{COD}/p/day; based on lower heating value of methane: 12.5 kJ/g_{COD}
Chemical energy ‘embedded’ in N and P	50	Maurer et al. (2003). Invested in the fertilizer industry, primarily for producing bioavailable N from N_2.

[*] Please note that heat has a lower quality than chemical energy

Presently, engineers primarily consider heat recovery from wastewater in the sewer system, either before or after the treatment plant (Abdel-Aal et al. 2014, Dürrenmatt and Wanner 2014). However, due to the higher temperature available, decentralized heat recovery from warm water sources at the household level holds a higher potential to extract useful energy, either with heat pumps (Meggers and Leibundgut 2011) or with simple heat exchangers. With improved energy efficiency of buildings, the significance of warm water also rises, from today’s typical 10-20 % of household energy demand to around 50 % (Meggers and Leibundgut 2011).

Although the same absolute amount of energy from wastewater enters the sewers as what is found inside the house, cold and warm water are mixed and the temperature of the wastewater typically decreases towards the treatment plant due to heat losses to the environment, especially in winter (Abdel-Aal et al. 2014). Furthermore, heat extraction is often regulated in order to retain sufficient nitrification capacity at the treatment plant. The Canton of Zürich in Switzerland, for instance, requires that the temperature of wastewater does not decrease below 10°C at the inlet to the treatment plant due to heat extraction from sewers (www.ara.zh.ch/abwaerme), a regulation which would not be conceivable for households. Heat extraction after the treatment plant is obviously not regulated, but often not interesting due to the low wastewater temperature and long transport distances for the heat extracted (Dürrenmatt and Wanner 2014).

A comparison of the efficiency of heat pumps at both extremes, at the household level and after the treatment plant, illustrates the advantage of the former. Meggers and Leibundgut (2011) analyzed how much energy is recovered relative to the electrical energy invested in the heat pump (COP - Coefficient Of Performance) of decentralized heat recovery from the warm water fraction in households. The purpose was hot water production at 55 °C, and the COP ranged from 5.5 to 7.3 depending on the release temperature of the wastewater (16-30 °C). Low release temperatures lead to lower COP, but to higher energy recovery. A simulation for a model household of four persons showed that for the production of the entire hot water demand, an average COP of 6.5 could be obtained with an average release temperature of the cooled wastewater in the range of 23 °C. As comparison, Nowak et al. (2015) considered centralized heat pumps for energy recovery in winter from treated wastewater, suggesting a temperature decrease from 10 to 8°C and production of 40° warm water for residential heating. With the suggested technology, a COP of 4 results. Heat recovery from wastewater in the sewer system before treatment will be situated between these two extremes, but with an abrupt decrease in efficiency at the point where warm and cold water are mixed in the household. Combining energy recovery at different scales are of course possible.

Heat exchange is a much simpler technology, which may be implemented at the household-level for preheating incoming cold water. A practical example is the Swiss shower named *Joulia* (www.joulia.com). *Joulia* recovers heat from used shower-water in real-time to heat the incoming cold water for this same shower to about 20 °C. According to the calculation tool on the website, one 5-minutes shower per day with a water-saving showerhead (6 L/minute) will bring a saving of about 100 kWh/year as compared to the same shower without heat recovery. It is easy to see how this simple technology can be extended to general preheating of cold water for hot water production.

As noted by Meggers and Leibundgut (2011), interest in energy recovery from warm water at the household level is only just emerging. Thus no literature was found on the possible use of heat pumps for residential heating purposes or use of water-air heat exchangers for preheating ventilation air. Neither was a comprehensive analysis of the entire potential of decentralized energy recovery from wastewater available. From the few examples here, it is however clear that the potential for recovery of useful energy from warm water at the household level will be much higher than the potential in the sewer system – not the least because of the immediate usefulness of the energy in the household during the entire year.

3.2 Optimizing energy management at the wastewater treatment plant

At treatment plants, energy is *produced* from sludge (primarily through anaerobic digestion) and *consumed* by aeration, pumping, drying of sludge, etc. In this paper, only aeration is considered and only one simple type of a conventional nutrient eliminating wastewater treatment plant consisting of primary sedimentation followed by nitrification / denitrification. This is sufficient to understand the main differences of the alternative treatment configurations discussed.

The following three configurations will be compared:

A. Conventional nitrification / denitrification (Figure 1A).

B. Energy-improved treatment though separation of N and organic matter (Figure 1B).

C. Energy-improved treatment through nutrient recovery from urine without nitrification / denitrification (Figure 1C).

In all three configurations, the same sludge treatment process is assumed: Anaerobic digestion followed by electricity production.

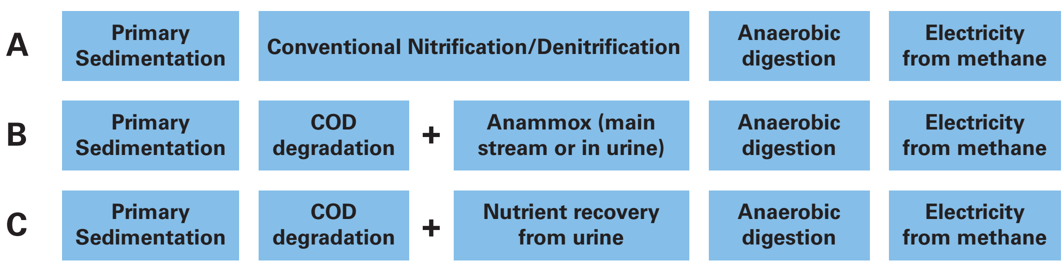

Figure 1 Treatment configurations to be compared. A: Simple conventional nutrient elimination wastewater treatment plant. B: Separation of nitrogen and COD either by mainstream anammox or urine separation. C: Nutrient recovery from urine (without nitrification / denitrification).

In Table 2 an overview of the three configurations is given. For conventional treatment (A), a typical SRT of 15 days, a primary sludge production of 35 % of the incoming COD, nitrification of 10 g_N/p/day and denitrification of 65 % of the nitrified ammonia are assumed.

For the separation alternative (B), an SRT of 4 days for COD degradation is assumed and a primary sludge production of 75 % of the incoming COD (as suggested by De Clippeleir et al. (2014)). Again a nitrification of 10 g_N/p/day is assumed, but a denitrification efficiency of 100 % (the maximum efficiency which can only be obtained if heterotrophic denitrification of the nitrate produced in the anammox process takes place).

In the nutrient recovery configuration (C), SRT and primary sludge production will be identical to alternative B, but phosphorus and nitrogen are recovered from urine without oxidation of nitrogen.

For all configurations, the same aeration efficiency is assumed in all processes and it is equally assumed that the specific methane production does not depend of the type of sludge. In order to avoid complications by adding different types of energy, only net electricity production from the two processes is compared and the issue of heat ignored. This means that in practice the optimizations must be done in a way which does not leave the plant short of heat for sludge treatment (if more electricity from methane is produced, obviously less heat is co-generated, see section 3.2.1).

Table 2 Overview of the WWTP part of the three alternatives to be compared

			SRT (days)	Primary sludge (% of COD_{in})	Nitrification (g/p/day)	Denitrification (%)
A	Conv. Treatment		15	35	10	65
B	Separation Nitrogen / COD	(Anammox in main stream or in urine)	4	75	10	100
C	Nutrient Recovery	(Urine separation)	4	75	0	0

3.2.1 Increasing electricity production from sludge at the treatment plant

Electricity production from sludge at the treatment plant can be increased in three steps:

1. Increasing sludge production
2. Increasing sludge transformation into primary energy (here methane)
3. Increasing electricity production from primary energy

Technically, sludge production can be increased in different ways (e.g. flocculation of primary sludge or microfiltration), but the amount of organic matter which can be removed from wastewater is highly dependent on the amount of organic matter required for denitrification. Although it may make sense to remove sludge and then add acidification products or methanol for denitrification, this intermediate solution will not be presented here.

As discussed by Gao et al. (2014), separating COD degradation and nitrogen transformation is a very effective way of decreasing energy consumption. One of the reasons is the higher sludge production possible (because no COD is necessary for denitrification). The mainstream anammox process (Lotti et al. 2014) and urine separation at the household level (Wilsenach and van Loosdrecht 2006) both result in equally high sludge production.

For sludge transformation, the combined process of anaerobic digestion and electricity production is the standard. For methane production, a low and a high efficiency in the anaerobic digestion are assumed: A standard efficiency of 40 % and a future efficiency of 75 %, which seems a realistic outlook (Jenicek et al. (2013) already report full scale methane efficiencies of 65 % from the Prague Central WWTP). For electricity production, also two different efficiencies are assumed: A standard efficiency of 35 % and a future efficiency of 50 %, e.g. based on fuel cell technology (Fraunhofer 2014). The results for these two marginal cases (see section 3.2.2) are illustrated later (in Figure 3).

3.2.2 Decreasing energy consumption for aeration

Increasing sludge production is obviously also a good way to decrease energy consumption because less oxygen is needed to degrade organic matter. Furthermore, the anammox process implemented in alternative B results in a smaller oxygen demand because in the overall process less nitrate and more N_2 is produced (for details of the calculation of oxygen demand, see Table S3). Nutrient recovery without oxidation of N (alternative C) saves aeration energy and reaps the energy contained in the nutrients.

Apart from these process engineering considerations, the energy demand of electromechanical and other equipment at the treatment plant can be lowered. In this paper, the effect of more energy-efficient aeration, alone and in combination with the process engineering measures is evaluated. Based on average numbers for surface aerators at the low end (Metcalf&Eddy 2004) and the most optimistic expectations for future membrane aeration at the high end, the span of aeration from 1-4 kg O_2 per kWh_e (under operational conditions) was chosen for illustrating the effect of improved aeration efficiency.

3.2.3 Total energy balance of a treatment plant

The alternatives A and B are used to compare the approximate size of the ’net electricity production’ resulting from electricity production from sludge and electricity demand for aeration. In figure 2, we see that there is good reason to praise the separation of ammonia transformation and COD degradation as a good measure for energy optimization.

We also observe that the ‘return on investment’ for improving the energy-efficiency of aeration devices is strongly diminishing with increasing aeration efficiency and – not surprisingly – is of much less importance in the more energy-efficient alternative B where oxygen consumption is lower (see also Figure 3). In addition we observe that for the two cases illustrated here, a shift from alternative A to B at the lowest aeration efficiency level produces approximately the same energy effect as increasing aeration efficiency from 1 to 4 kg_{O2}/kWh_e. Please note that 4 kg_{O2}/kWh_e is an extreme efficiency, which is not yet implemented in practice: Svardal and Kroiss (2011), for instance, use a maximum aeration efficiency of 2.2 kg_{O2}/kWh_e.

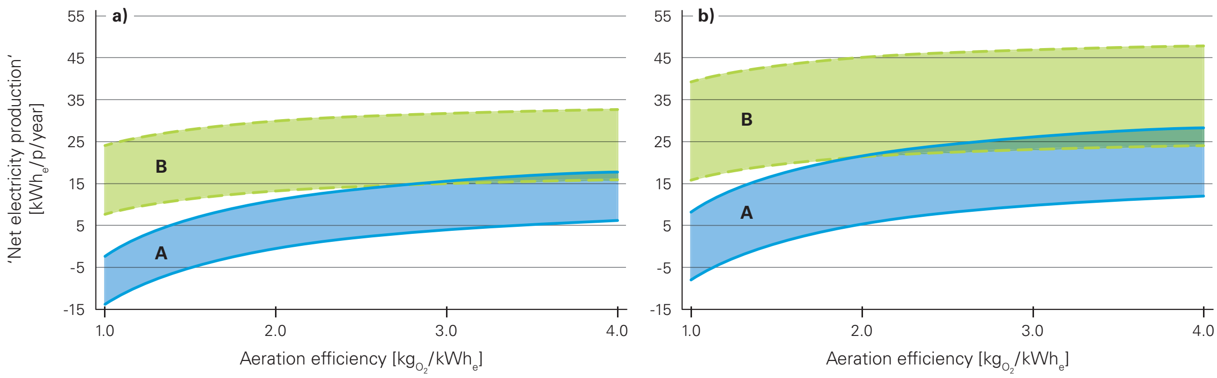

Figure 2 'Net electricity production' (only considering electricity consumption for aeration and electricity production from anaerobic digestion) from alternative A (conventional treatment) and alternative B (separation of nitrogen and COD). The graphs show the span of results between 40% (lower line) and 75% (higher line) transformation of sludge COD to methane.

Figure 2a) 35 % efficiency of electricity production. Figure 2b) 50 % efficiency of electricity production.

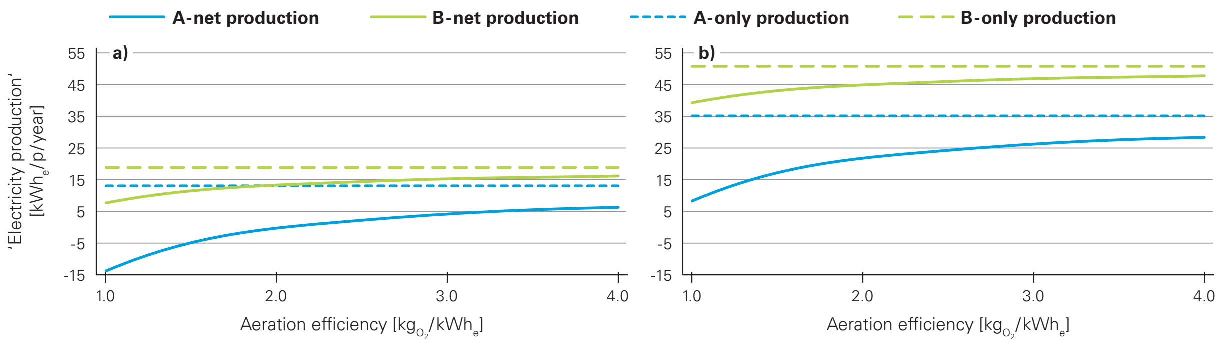

Figure 3 Electricity production from sludge and consumption by aeration.

A: conventional treatment. B: separation of nitrogen transformation and COD degradation.

Figure 3a) 40 % transformation of sludge COD to methane / 35 % efficiency of electricity production.

Figure 3b) 75% transformation of sludge COD to methane / 50 % efficiency of electricity production.

Figure 3 shows the details of production and consumption in the marginal cases discussed in this paper: low electricity production from sludge (Figure 3a) and high electricity production from sludge (Figure 3b). We observe that for conventional treatment, the percentage of internal consumption of the produced electricity decreases considerably with increasing aeration efficiency (see e.g. Figure 3b, where at the lowest aeration efficiency, about 80 % of the electricity produced is spent for aeration, whereas at the highest efficiency, little more than 20 % is spent). If we take into account similar improvements in other electromechanical equipment and other process engineering measures (e.g. decreasing the need for pumping by simplifying plant schemes), the notion of an energy producing wastewater treatment plant seems within reach. It is not discussed here whether there will be enough heat for sludge treatment if electricity production is drastically increased – this will depend on the energy efficiency of the sludge treatment technology.

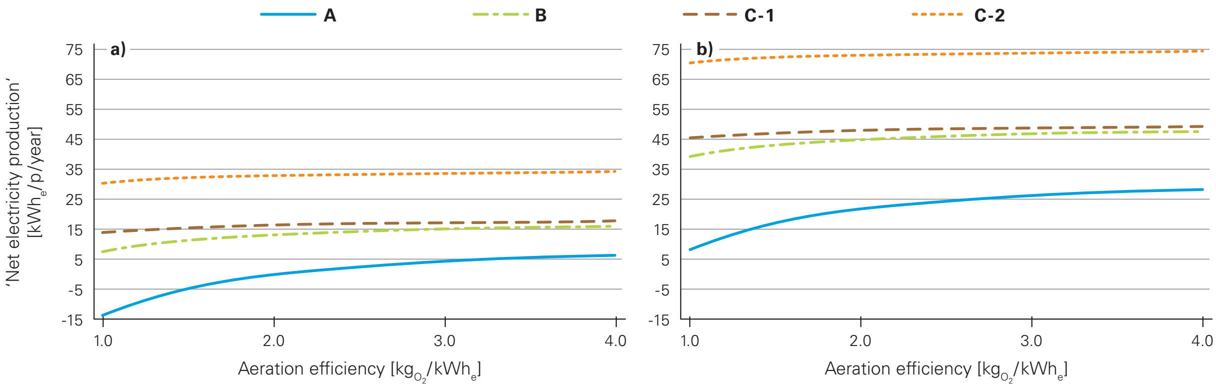

Figure 4 'Net electricity production' from the processes aeration and electricity production from sludge via methane. Comparison of alternative A (conventional), B (separation) and C (nutrient recovery). For alternative C, the results without (C-1) and with (C-2) embedded fertilizer energy in wastewater are shown (Table 1).

Figure 4a) 40 % transformation of sludge COD to methane / 35 % efficiency of electricity production.

Figure 4b) 75 % transformation of sludge COD to methane / 50 % efficiency of electricity production

Finally, the 'net electricity production' from all three alternatives is shown in the same two cases as illustrated above (Figure 4). For alternative C (nutrient recovery from separated urine without oxidation of nitrogen), two graphs are included: one with and one without counting the 'embedded' fertilizer energy in nitrogen and phosphorus. Since the primary energy used for fertilizer production primarily stems from natural gas (Maurer et al. 2003), the same transformation efficiency from primary energy to electricity is used as for the processes at the treatment plant (35 and 50 % respectively). We see that in alternative C the savings from not oxidizing ammonia to N_2 are marginal. In contrast, the embedded fertilizer energy has a large potential to improve the energy efficiency of the combined treatment processes. In order to reap this potential, however, energy-efficient technologies for urine treatment or short distances for bringing urine or treated wastewater to agricultural fields are required.

3.3 Comparison of N_2O and CH_4 emissions with different types of electricity production

Whereas electricity is easy to measure, N_2O and CH_4 emissions are not: gas measurements are complicated, especially at open treatment plants (Yoshida et al. 2014). For the quantification of the climate effect, it is the other way round: The effect of N_2O and CH_4 emissions is clearly defined by IPPC (as CO_2-equivalents), whereas the climate effect of electricity production depends on the way the electricity is produced: if produced by coal, the effect is large whereas production by wind power or photovoltaic has a very small climate effect. This means that it is difficult to discuss the trade-offs between energy saving and energy production at treatment plants on the one hand and the consequences for N_2O and CH_4 emissions on the other hand. And there are trade-offs: energy saving can come at the cost of N_2O emissions (Kampschreur et al. 2009) and energy production typically involve CH_4 production with an associated risk of CH_4 emissions.

Often, comparisons are made with the local electricity mix, but since electricity is freely traded within large regions, a comparison with the marginal electricity production in the relevant area (e.g. Europe) today and in future seems more suitable. This will often lead to a smaller relative weight of N_2O/CH_4 emissions than using the local mix (because the marginal electricity is always ‘worst case’), but the results will be more comparable. At the moment, marginal electricity in Europe (with respect to CO_2-emissions) stems from coal-fired power plants, but due to European climate policy, coal is assumed to be replaced by natural gas (Kemfert 2007). Table 3 presents some relevant numbers for comparing electricity production and demand with N_2O and CH_4 emissions from treatment plants.

Based on Table 3 it is easy to see that the way we account for electricity production is highly relevant for the possibility to achieve CO_2-neutral wastewater treatment plants. If we assume that the electricity produced at the plant replaces electricity from a coal-fired power plant, an emission of 1% incoming N emitted as N_2O will have to be offset by a net electricity production of 19 kWh_e/p/year. With a cleaner marginal electricity production based on natural gas, this number will be 34 kWh_e/p/year, and if the calculation is made based on an actual Danish electricity mix containing a high fraction of wind power, the net production has to be as high as 50 kWh_e/p/year.

The methane loss may also show a significant climate effect, but at a lower level than the loss of N_2O (Table 3; please note that a loss of one percent of *incoming COD* translates into several percent loss of *produced* CH_4). With increasingly cleaner marginal electricity, however, we have to keep in mind that electricity production from methane may get less attractive than it appears at the moment.

It is interesting to observe that the possibility of a CO_2-neutral wastewater treatment plant depends on developments in the electricity sector, which apparently have nothing to do with wastewater. This is due to the fact that the actual climate gas emissions from the plants have to be offset by smaller emissions somewhere else. On the negative side, we have the N_2O and CH_4 emissions with a fixed climate effect. On the positive side, we have a net electricity production, which will replace increasingly cleaner electricity from the power plants.

Table 3 Comparisons of N_2O and CH_4 emissions and electricity production/demand at a WWTPs

GHG (greenhouse gas) emission from electricity production			
From coal	$gCO_{2,eqv}/kWh_e$	888	WNA, 2011
From natural gas	$gCO_{2,eqv}/kWh_e$	499	WNA, 2011
Danish electricity mix 2012	$gCO_{2,eqv}/kWh_e$	340	(1)
(1) http://www.ens.dk/info/tal-kort/statistik-nogletal/nogletal/danske-nogletal			
GHG emission from pure combustion of natural gas	$gCO_{2,eqv}/kWh$	198	(2)
(2) based on lower combustion value of methane (50 kJ/gCH$_4$) and 2.75 g CO_2 / g CH_4 combusted			
Assumption 1 (A1): The marginal electricity in Europe stems from coal			
Assumption 2 (A2): The marginal electricity in Europe stems from natural gas			
Assumption 3 (A3): The actual electricity mix from Denmark 2012 is used			
GHG emission from electricity production (A1)	kg CO_2-eqv/kWh_e	0.89	
GHG emission from electricity production (A2)	kg CO_2-eqv/kWh_e	0.50	
GHG emission from electricity production (A3)	kg CO_2-eqv/kWh_e	0.34	
GWP_{100} of N_2O	gCO_2-eqv/gN_2O	298	(Myhre et al. 2013)
GHG effect of N_2O	gCO_2-eqv/gN	468	
GWP_{100} of CH_4	gCO_2-eqv/gCH_4	34	(Myhre et al. 2013)
GWP_{100} of CH_4	gCO_2-eqv/gCOD	8.5	
GHG emission per 0.1 g N/p/day as N_2O(3)	$kgCO_2$-eqv /year/p/%N_{lost}	17	
GHG emission per 1.2 g COD/p/day as CH_4(4)	$kgCO_2$-eqv/year/p/%COD_{lost}	2.7	
(3) roughly 1 % of domestic N-load to WWTP, (4) roughly 1 % of domestic COD-load to WWTP			
Electricity production with equal climate effect as emissions of N_2O and CH_4[5]		N_2O	CH_4
A1: Electricity from coal	kWh_e/year/p/% loss	19	4.2
A2: Electricity from natural gas	kWh_e/year/p/% loss	34	7.5
A3: Electricity mix Denmark 2012	kWh_e/year/p/% loss	50	11
[5] This part of the table reads as follows: 1 % loss of incoming N (COD) as N_2O (CH_4) from 1 person during 1 year has the same climate effect as the production of 19 (4.2) kWh of electricity from coal.			

The net recovery potential of (electrical) energy from domestic wastewater at the treatment plant is significant, but in order to translate into a CO_2-neutral or CO_2-positive plant, the positive effects of electricity production must at least outweigh the negative effects of the direct emissions of CH_4 and N_2O. In Table 4, different alternatives are compared, with low and high direct emissions, respectively, for the three different configurations and the highest (future) energy-efficiencies assumed in this paper.

Table 4 Emission of climate gases from energy-optimized wastewater treatment plants[1]. Negative emissions are savings due to electricity produced at the plant (avoiding emissions elsewhere). Since only electricity for aeration is accounted for, a 'break-even' additional electricity consumption is given, where the plant would still be CO_2-neutral[2].

Marginal electricity based on →			Coal		Natural gas		Break-even electricity demand with marginal electricity from	
	emissions		emissions		emissions			
	CH_4	N_2O	indirect	total	indirect	total	coal	natural gas
Low direct emissions[3]	[$kg_{CO2\text{-}eqv}$/p/y]		[$kg_{CO2\text{-}eqv}$/p/y]		[$kg_{CO2\text{-}eqv}$/p/y]		[kWh_e/p/y]	
A: Conventional treatment	3.4	9	-25	-13	-14	-2.2	15	4.3
B: Mainstream anammox	4.9	9	-42	-29	-24	-10	33	21
C: Nutrient recovery	4.9	-	-66	-61	-37	-32	69	64
High direct emissions[3]								
A: Conventional treatment	6.8	17	-25	-1.2	-14	9.8	1.4	-20
B: Mainstream anammox	9.9	17	-42	-15	-24	3.1	17	-6.3
C: Nutrient recovery	9.9	-	-66	-56	-37	-27	63	54

[1] 75 % sludge transformation to methane, 50 % methane transformation to electricity, aeration efficiency 4 kg_{O2}/kWh_e under operational conditions

[2] The break-even electricity consumption is the maximum amount of electricity (same type as electricity replaced), which can be spent for activities other than aeration and still result in at least a CO_2-neutral plant (without considering heat).

[3] Low emission: 2 % of produced CH_4 emitted, 0.5 % of nitrified N as N_2O emitted. High emission: 4 % of produced CH_4 emitted, 1 % of nitrified N as N_2O emitted.

From Table 4 we see that in the case of energy-optimized plants, the direct emissions and the type of marginal electricity assumed have a much higher influence on the total greenhouse gas emission than the shift from alternative A (conventional technology) to alternative B (mainstream anammox or urine separation with nitrogen removal via the anammox process). Only alternative C (nutrient recovery without oxidation of nitrogen) has a stable good performance because no N_2O emissions are possible and a large part of the positive effects is due to the energy contained in the nutrients.

4 Discussion

In this paper, two main approaches for improving the climate profile of wastewater management were discussed: energy recovery from warm water at the household level and improving the energy efficiency of the wastewater treatment plant. These two approaches can be in conflict because energy recovery at the household level may lead to cooler wastewater, thereby especially endangering the new energy-efficient mainstream anammox process. At present, viability of this process has been shown at 15°C and it is assumed that short-term lower temperatures in winter will not compromise the process (Lotti et al. 2014). If, however, this period of low temperatures is prolonged and the temperature gets lower due to heat recovery at the household level, stable operation may not be possible. This leads to the following question: Is mainstream anammox at the treatment plant or energy recovery from warm water at the household level the better strategy from a climate point of view?

From Table 4, we see that for energy-optimized plants, the change from conventional treatment to mainstream anammox has the potential to save 17 $kg_{CO2\text{-}eqv}$/p/y if marginal electricity is based on coal (today) and 10 $kg_{CO2\text{-}eqv}$/p/y if marginal electricity is based on natural gas (future). This is not taking into account that the methane emissions are expected to increase by 1.5 to 3 $kg_{CO2\text{-}eqv}$/p/y (at 'low' and 'high' CH_4 emissions, respectively) for the mainstream anammox configuration. Furthermore, it is assuming that all other emissions stay equal.

As a comparison, what would it bring to produce warm water by a heat pump extracting energy from warm wastewater in the household? This again depends on the alternative for warm water production (here clean combustion of natural gas is chosen) and the marginal electricity assumed (since the heat pump will run on electricity).

With the COP of 6.5 estimated by Meggers and Leibundgut (2011), the 800 kWh/person/year of heat energy for warm water production (Table 1) can be provided by an electrical input of roughly 125 kWh_e/p/y (without counting energy losses). With marginal electricity based on coal, this causes an emission of 111 $kg_{CO2\text{-}eqv}$/p/y; with marginal electricity based on natural gas, the emission is 63 $kg_{CO2\text{-}eqv}$/p/y (Table 3). If the 800 kWh/p/year are provided by clean combustion of natural gas, the emission would be 158 $kg_{CO2\text{-}eqv}$/p/y (just counting the CO_2 emitted from pure combustion of methane and again not considering any energy losses). The savings thus amount to 47 $kg_{CO2\text{-}eqv}$/p/y today and 95 $kg_{CO2\text{-}eqv}$/p/y if marginal electricity will in future be based on natural gas. This is obviously more substantial than the improvements obtained by a change from a conventional to a mainstream anammox configuration at an otherwise energy-optimized treatment plant. Furthermore, the gains will increase, not decrease with time and there are many more, still un-explored possibilities for extracting energy from warm water in the households.

The more radical change from conventional treatment to nutrient recovery from source-separated urine also has positive climate effects. If marginal electricity is based on coal, a maximal emission decrease of 48-55 $kg_{CO2\text{-}eqv}$/p/y is possible (depending on the direct emissions; Table 4). In a future scenario with marginal electricity based on natural gas, the possible decrease is 30-37 $kg_{CO2\text{-}eqv}$/p/y. Although there will be some additional energy costs to realize this scenario (i.e. for producing fertilizer from urine), the nice thing about nutrient recovery is that it functions well together with heat recovery at the household level: As opposed to conventional treatment and mainstream anammox, no nitrification is required at the treatment plant and the temperature of the wastewater is thus not critical. Alternative C is therefore very robust towards a possible temperature decrease of wastewater. It is also worth noticing that whereas the rationale for mainstream anammox is primarily energy savings (De Clippeleir et al. 2014), urine source separation aims at providing cheaper nutrient elimination (combined with recovery of phosphorus), especially where there is little chance of introducing treatment plants (Larsen et al. 2009, Larsen et al. 2007).

What do 10 or 100 $kg_{CO2-eqv}$/person/year mean for the climate? Today, typical European CO_2 emissions are in the order of 10 tons CO_2/person/year, but at least in Switzerland, a commonly accepted goal is 2 tons in 2050 and 1 ton in 2100 - with the idea that if these goals could be reached on a global scale, the average temperature increase could be kept at 2°C (http://www.2000watt.ch/). We are thus discussing 0.5-10 % of the 'allowed' CO_2 emissions in the future and it is easy to see that at least energy recovery from warm water at the household level has a large chance of being implemented – with the possible consequences for wastewater temperature.

A possible reduction in wastewater temperature also emphasizes the necessity of investigating the true influence of temperature on the total N_2O emissions from treatment plants. In some models, N_2O emissions are expected to decrease with temperature (Guo and Vanrolleghem 2014), but recent measurements of N_2O emissions during more than a year at a full-scale plant in the Netherlands revealed that it could also be the other way round (Daelman et al. 2013). Due to increased emissions in winter, a year-round average of 2.8 % of the incoming nitrogen was emitted as N_2O – a high value resulting in a significant climate-relevant emission of around 50 $kg_{CO2-eqv}$/p/year from the domestic part of wastewater (Table 3). If wastewater generally gets colder during winter, not only may nitrification capacity decrease, also N_2O emissions may increase – if the observations in the Netherlands are generalizable.

The simple calculations for the wastewater treatment plant have shown that the relative importance of N_2O and CH_4 emissions in the total CO_2 balance of treatment plants depend on the assumptions (and reality) of electricity production. As shown by a large number of authors, e.g. Kampschreur et al. (2009), energy savings based on changes in process engineering must be introduced very carefully in order not to compromise the climate goals of the plants due to an increase in N_2O emissions. Although technologies for N_2O removal from off-gas from N_2O producing processes are under development (Desloover et al. 2011), implementation will demand either totally covered wastewater treatment plants or urine separation, where nitrogen transformation is performed in small reactors as compared to conventional wastewater treatment plants.

It is clear that the radical innovation of urine separation with direct nutrient recovery (i.e. without transformation of nitrogen) holds a large potential for achieving CO_2-positive wastewater treatment and energy-optimized wastewater management: The temperature at the treatment plant would be of no importance (i.e. decentralized *and* centralized heat recovery from wastewater can be optimized), maximum net production of electricity is found (Figure 4) and practically no emissions of N_2O will occur. In Sweden, this type of urine separation has long been propagated for rural areas, with direct spreading of urine on local fields (Tidåker et al. 2007). For cities, only the production of more concentrated products for use in agriculture or as raw material in the fertilizer industry will be competitive. At the moment, this is possible based on partial nitrification and distillation (Udert and Wächter 2012), but other more energy-efficient technologies without oxidation of nitrogen are under development, e.g. based on chemical stabilization of urea followed by drying (own results, unpublished).

5 Conclusion

1. The highest potential for reduction of greenhouse gas emissions is found at the household level if warm water is produced from warm greywater with a heat pump. The reduction amounts to 47 $kg_{CO2\text{-}eqv}$/p/y (coal-based marginal electricity) respectively 95 $kg_{CO2\text{-}eqv}$/p/y (natural gas-based marginal electricity). With additional measures for heat recovery at the household level, wastewater temperature may however decrease in winter with negative consequences for nitrification at the treatment plant.
2. Improving aeration efficiency at treatment plants also has some potential for reducing emission of greenhouse gases. However, the trade-off between efficient aeration and N_2O emission must be carefully monitored, especially as marginal electricity becomes cleaner. With marginal electricity produced from coal, 1% of the inlet nitrogen lost as N_2O

can be compensated by an electricity production of 19 kWh_e/p/y, whereas with marginal electricity produced from natural gas, this number is 34 kWh_e/p/y.

3. Changing the process engineering configuration from a conventional energy-optimized nitrifying/denitrifying plant to an equally energy-optimized mainstream anammox plant offers a potential reduction of maximal 17 $kg_{CO2\text{-}eqv}$/p/y (coal-based marginal electricity) respectively 10 $kg_{CO2\text{-}eqv}$/p/y (natural gas-based marginal electricity). The mainstream anammox process may not be stable if wastewater temperature decreases in winter due to heat recovery at the household scale.
4. As compared to an energy-optimized conventional treatment plant, the introduction of nutrient recovery from urine without oxidation of nitrogen has a maximum greenhouse gas reduction potential of 48-55 $kg_{CO2\text{-}eqv}$/p/y (coal-based marginal electricity) respectively 30-37 $kg_{CO2\text{-}eqv}$/p/y (natural gas-based marginal electricity). This entire potential will not materialize, but the configuration hat the advantage that a possible wastewater temperature decrease is of no consequence.
5. N_2O and to a lesser degree CH_4 emissions are difficult to monitor and have the potential to dominate the greenhouse gas emissions from wastewater treatment plants, especially if the marginal electricity in a given area becomes natural gas-based instead of coal-based. Stable operation may therefore be more important than the choice of process, unless processes are chosen where direct emissions are not possible. This means that treatment processes without oxidation of nitrogen and energy recovery from sludge through pathways not involving methane production deserve more attention.

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