Determination of greenhouse gas emission reductions from sewage sludge anaerobic digestion in China

H.-T. Liu, X.-J. Kong, G.-D. Zheng and C.-C. Chen

ABSTRACT

Sewage sludge is a considerable resource of greenhouse gas (GHG) emission in the field of organic solid waste treatment and disposal. In this case study, total GHG emissions from sludge anaerobic digestion, including direct and indirect emissions as well as replaceable emission reduction due to biogas being reused instead of natural gas, were quantified respectively. The results indicated that no GHG generation needed to be considered during the anaerobic digestion process. Indirect emissions were mainly from electricity and fossil fuel consumption in site and sludge transportation. Overall, the total GHG emission owing to relative subtraction from anaerobic digestion rather than landfill and replaceable GHG reduction caused by reuse of its product of biogas were quantified to be 0.7214 (northern China) or 0.7384 (southern China) $MgCO_2$ $MgWS^{-1}$ (wet sludge).

Key words | anaerobic digestion, emission, greenhouse gas, landfill, sewage sludge

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INTRODUCTION

In China, the amount of sludge generated by sewage plants has gradually increased since the year 2000 (Chen *et al.* 2012). However, owing to deficient policies, financing and technologies, a large amount of un-dewatered sludge has been discarded at random or buried non-standardly (Guo *et al.* 2012; Liu & Zhang 2013). In addition to increased environmental pollution risk to soil and water systems, current situation of improper sludge disposal has led to considerable and unordered emissions of GHG. For instance, methane generated from sludge landfill or anaerobic digestion is known as a kind of famous clean fuel (Abbasi *et al.* 2012). Because the sludge is rich in decomposable organic matter, it was regarded as a significant source for GHG emissions (Majumder *et al.* 2014). Most biogas from landfilled sludge is lost to the atmosphere instead of being captured and reused. However, biogas that is reclaimed is commonly used to generate heat and electricity by combined heat and power plant or fuel for vehicles (Tilche & Galatola 2008); therefore, biogas from anaerobic digestion leads to reduced carbon emissions and energy balance by supplying secondary biogas products (Weichgrebe *et al.* 2008; Komatsu *et al.* 2011; Niu *et al.* 2013; Remy *et al.* 2013).

In China, anaerobic digestion is generally only one process in the entire sludge treatment-disposal chain, which usually also includes thickening, dewatering or pyrolysis (Qiao *et al.* 2011). Nevertheless, anaerobic digestion remains an important method for achieving reduced carbon emissions, which could account for about 90% of the total GHG reductions resulted from all options of sludge treatment and disposal (Niu *et al.* 2013). Anaerobic digestion of sludge can be classified into mesophilic and thermophilic digestion. In China, most (about 80%) sludge anaerobic digestion reactors employ mesophilic technology. In such systems, biogas gathered from anaerobic digestion is dewatered and then subjected to desulfidation, after which it is used to generate electricity that is supplemented to maintain sludge plant working itself. If abundant, surplus electricity merged into the local electrical grid, reducing the need to burn coal or natural gas. Nevertheless, in spite of a small proportion of anaerobic digestion in sludge treatment structure, carbon debit and credit led by sludge anaerobic digestion and the amounts of these carbon reductions correlated with Certified Emission Reduction (CER) and financial support from international organization still deserves to be investigated (Liu *et al.* 2014b).

Previous reports showed that the lowest carbon emission was from sludge anaerobic digestion among all sludge treatment technologies (Barber 2009). Additionally, the present GHG accounting guidelines, which assume that all carbon emission from sludge is biogenic, may lead to underestimation (Law *et al.* 2013). However, a certain proportion of organic carbon in sludge originates from fossil fuels,

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such as carbon in daily expensed detergents. All the same, this portion of carbon in this study is tiny in direct emitted carbon from sludge anaerobic digestion. Therefore, all direct carbon emissions in this study was assumed as biogenic.

Currently, there is sufficient information available to quantify the GHG emissions triggered by sludge anaerobic digestion. But detailed GHG qualification to anaerobic digestion with comparison to baseline scenario and its corresponding GHG reduction potential based on IPCC guideline was rarely reported. Therefore, this study was conducted to investigate GHG emissions from all units of a treatment system during sludge anaerobic digestion, which is combined with mechanical dewatering generally employed in China, with a focus on identification of direct and indirect GHG emission and determination of the role of these emissions in the carbon budget and reduction potential.

METHODS

Definition of baseline scenario and quantification of its corresponding GHG emissions

In this study, Dalian and Xiamen were selected as representative northern China city and southern China city respectively, with divisiory demarcation line was set up as Huaihe River. In China, average 65%–70% of sludge is disposed of by landfill (Guo *et al.* 2012), with 90% and 85% of sludge generated in the cities of Dalian (northern China) and Xiamen (southern China) being disposed of by landfill respectively. However, there are no environmental laws or regulations regarding the disposal of sewage sludge, and landfill gas recovery and utilization is not common in China. Therefore, disposal of sludge without the capture of landfill gas was regarded as the baseline scenario for this study. The direct emission is referred to emission of greenhouse gas including carbon dioxide, methane and nitrous oxide, whose functional carbon and nitrogen originate from sludge itself. The definition of indirect emission is presumed as GHG emission resulted from fuel consumption and secondary electricity consumption, whose discharged carbon is from naturally and long-term formed petroleum or coal. As shown in Figure 1, the process flow and estimated GHG emissions from sludge anaerobic digestion and landfill were outlined and the boundaries of these two routes were labeled by dotted line. In this process flow exhibition, biogas emission including methane from landfill and anaerobic digestion, fuel consumption resulted from sludge and biogas residue transportation as well as electricity consumption on site were all included except for that from dewatering, which was assumed as start point associated with investigated boundary. Main units made of sludge anaerobic digestion and landfill and their GHG emission properties as well as the assumptions associated with GHG emission calculation were summarized and listed in Table 1.

The total GHG emissions ($PE_{TD,y}$) from sewage sludge landfill were quantified as follows:

$$PE_{TD,y} = PE_{elec,y} + PE_{fuel,y} + PE_{tran,y} + PE_{d,y} \quad (1)$$

where $PE_{elec,y}$ is indirect emission from electricity consumption on-site due to project activity ($MgCO_2$); $PE_{fuel,y}$ is indirect emission due to fuel consumption on-site ($MgCO_2$); $PE_{tran,y}$ is leakage emission from dewatered sludge transport ($MgCO_2$) and $PE_{d,y}$ is direct emission from the landfill ($MgCO_2$).

$$PE_{elec,y} = EG_{PJ,FF} \times CEF_{elec} \times (1 + TDL_y) \quad (2)$$

where $EG_{PJ,FF}$ is the amount of electricity consumed from the grid as a result of the project activity based on direct measurement (MWh) and CEF_{elec} is the carbon emission factor for electricity generation associated with the project activity ($MgCO_2\ MWh^{-1}$) calculated using the *Notification on Determining Baseline Emission Factors of China's Grid* (NDRC of China 2012). Additionally, CEF_{elec} was 0.806 $MgCO_2\ MWh^{-1}$, which is the average for the grid in China, and TDL_y is the loss of electrical transmission distance, which was 0.2 in this study (NDRC of China 2012).

$$PE_{fuel,y} = F_{cons,y} \times NCV_{fuel} \times EF_{fuel} \quad (3)$$

where $F_{cons,y}$ is on-site fuel consumption (l or kg), NCV_{fuel} is the net caloric value of the fuel ($MJ\ l^{-1}$ or $MJ\ kg^{-1}$), which was 42,652 $kJ\ kg^{-1}$ in this study based on the *Notification on Determining Baseline Emission Factors of China's Grid* (NDRC of China 2012), EF_{fuel} is the CO_2 emissions factor of the fuel ($MgCO\ MJ^{-1}$), which was 72,600 $kgCO_2\ TJ^{-1}$ based on the *Notification on Determining Baseline Emission Factors of China's Grid* (NDRC of China 2012).

$$PE_{tran,y} = \sum_{i}^{n} NO_{vehicles,i,y} \times DT_{i,y} \times VF_{cons,i} \times NCV_{fuel} \times D_{fuel} \times EF_{fuel} \quad (4)$$

where $NO_{vehicles,i,y}$ is the number of vehicles for transport with similar loading capacity, $DT_{i,y}$ is the average additional distance traveled by vehicle (km), $VF_{cons,I}$ is the vehicle fuel

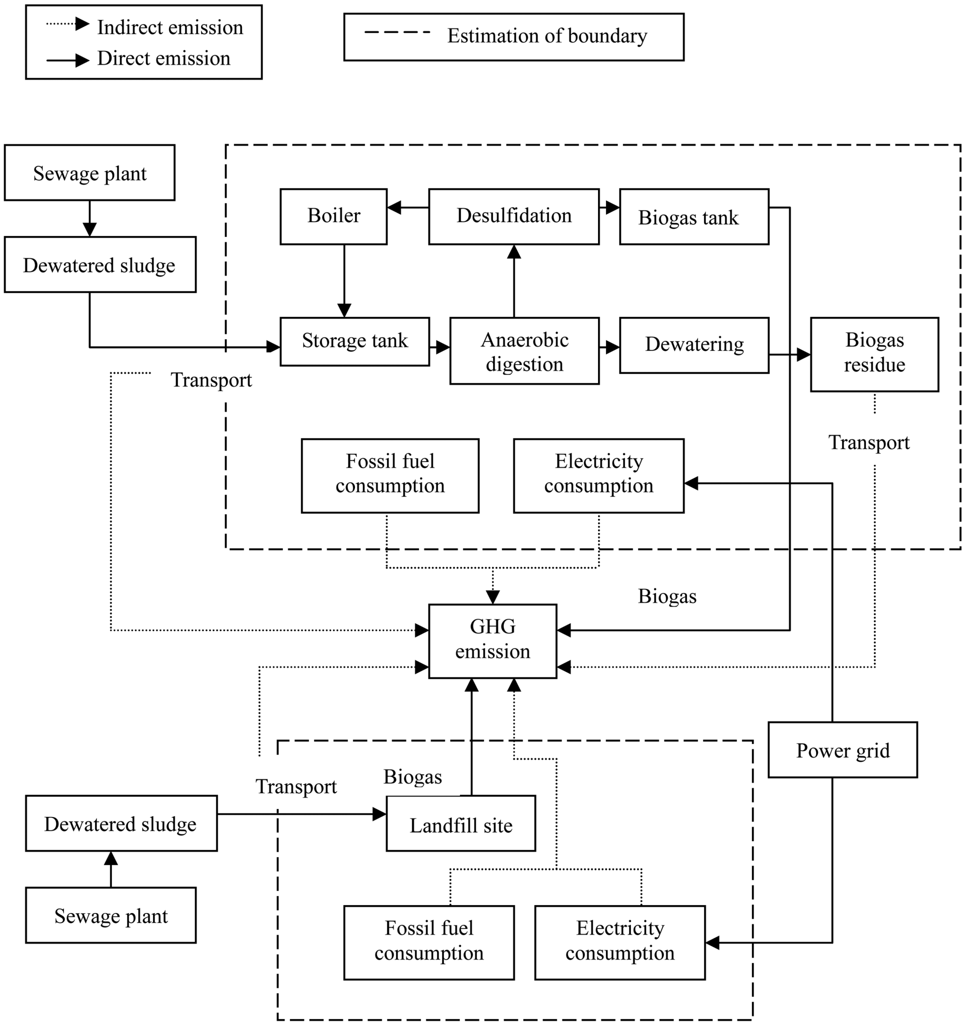

Figure 1 | Process flow chart and estimated GHG emissions from sludge anaerobic digestion and landfill.

Table 1 | Main units made of sludge anaerobic digestion and landfill and their GHG emission properties (direct or indirect, confirmed by '■') as well as the assumptions associated with GHG emission calculations

Sludge treatment or disposal	GHG emission unit	Assumption	Direct emission	Indirect emission	Replaceable reduction
Landfill ($PE_{TD,y}$)	Electricity consumption on-site ($PE_{elec,y}$)	Sludge dewatering from 80% to 60%		■	
	Fuel consumption on-site ($PE_{fuel,y}$)			■	
	Dewatered sludge transport ($PE_{tran,y}$)	Transport Distance is 20 km; unit loading capacity is 5 Mg		■	
	Methane from the landfill ($PE_{d,y}$)	■			
Anaerobic digestion ($PE_{TA,y}$)	Electricity consumption on-site ($PE_{elec,y}$)	Temperature in tank is elevated to 35 degrees		■	
	Fuel consumption on-site ($PE_{fuel,y}$)			■	
	Dewatered sludge and biogas residue transport ($PE_{tran,y}$)	Transport Distance is 20 km; unit loading capacity is 5 Mg		■	
	Biogas from anaerobic digestion ($PE_{a,y}$)	Biogas is all captured	■		
	Reduction from biogas instead of natural gas ($BE_{EN,y}$)	Biogas is all reused instead of natural gas			■

consumption in liters per kilometer ($l\,km^{-1}$), NCV_{fuel} is the calorific value of the fuel ($MJ\,kg^{-1}$), D_{fuel} is the fuel density ($kg\,l^{-1}$) and EF_{fuel} is the emission factor of the fuel ($MgCO_2\,MJ^{-1}$), which was 72,600 $kg\,kJ^{-1}$ based on the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*.

$$PE_{d,y} = MB_y - MD_{reg,y} \quad (5)$$

where MB_y is the emission of methane (CH_4) from the landfill ($MgCO_2$) and $MD_{reg,y}$ is the amount of biogas collection or flaring ($MgCO_2$).

$$MB_y = \varphi \times (1 - f) \times GWP_{CH4} \times (1 - OX) \times (16/12) \times F \times DOC_f \times MCF \times \sum_{x=1}^{y}\sum_{i} W_{j,x} \times DOCj \times e^{-k_j(y-x)} \times (1 - e^{-k_j}) \quad (6)$$

where φ is the correction factor to account for model uncertainties, which was 0.9 here, f is the fraction of methane captured at the solid waste disposal site (SWDS) and flared, combusted or used in another manner, which was 0 here, GWP_{CH4} is the global warming potential (GWP) of methane ($MgCO_2\,MgCH_4^{-1}$), which was 25 here, OX is the oxidation factor, which was 0 in this study, F is the fraction of methane in biogas, which was 0.5 in this study, DOC_f is the fraction of degradable organic carbon in sludge, which was 0.5 here, MCF is the methane correction factor, which was 1.0 in this study, W is the amount of sludge prevented from disposal (Mg), DOC_j is the fraction of degradable organic carbon, which was 0.5 here, K is the sludge decay rate, x is the year during the crediting period and y is the year during which the methane emissions are calculated (IPCC 2007).

Quantification of GHG emissions from sewage sludge anaerobic digestion

The total GHG emission ($PE_{TA,y}$) of anaerobic digestion was quantified using the following formula:

$$PE_{TA,y} = PE_{elec,y} + PE_{fuel,y} + PE_{tran,y} + PE_{a,y} - BE_{EN,y} \quad (7)$$

where $PE_{elec,y}$ is the emission from electricity consumption on-site due to project activity ($MgCO_2$), $PE_{fuel,y}$ is the emission on-site due to fuel consumption ($MgCO_2$), $PE_{tran,y}$ is the leakage emission from increased transport of sludge and biogas residue ($MgCO_2$), $PE_{a,y}$ is the direct emission from sludge anaerobic digestion ($MgCO_2$), $BE_{EN,y}$ is emission reduction from biogas (methane) produced by sludge anaerobic digestion substitution for natural gas ($MgCO_2$).

$PE_{elec,y}$, $PE_{fuel,y}$ and $PE_{tran,y}$ were calculated as described in the previous section.

$BE_{EN,y}$ can be expressed by the emission reduction as a result of substitutions of methane for natural gas in this study, which was calculated as follows:

$$BE_{EN,y} = Q_{ug,y} \times NCV_{ug,y} \times CEF_{NG} \quad (8)$$

where, $Q_{ug,\,y}$ is the volume of natural gas paralleled in the network ($m^3\,y^{-1}$), $NCV_{ug,y}$ is the gaseous fuel calorific value ($MJ\,m^{-3}$), and CEF_{NG} is the emission factor of natural gas ($kgCO_2\,TJ^{-1}$).

RESULTS

Direct GHG emissions from landfill and indirect GHG emissions as a result of electricity and fossil fuel use associated with landfill

Because the moisture content of sludge just leaving the sewage plant was 80%, dewatering was necessary to reduce the level to 60%. Therefore, indirect GHG emission caused by electricity consumption was mainly from sludge dewatering. Additionally, GHG emissions due to fossil fuel consumption were mainly from machines associated with landfill activities. According to formula (2) and (3), $PE_{elec,y}$ and $PE_{fuel,y}$ were 0.0068 $MgCO_2\,MgWS^{-1}$ and 0.0238 $MgCO_2\,MgWS^{-1}$, respectively. In addition to these two component units, another indirect GHG emission source was sludge transportation. In this case, the distance from the sewage plant to the landfill site was assumed to be 20 km (average distance from sewage plant to landfill site obtained from statistical data both in Dalian and Xiamen city), and the approved loading per sludge truck was limited to 5 Mg. Therefore, the $PE_{tran,y}$ was calculated as 0.0028 $MgCO_2\,MgWS^{-1}$ according to Equation (4). Overall, the indirect GHG emissions were 0.0334 $MgCO_2\,MgWS^{-1}$. With regard to direct GHG emissions, the $PE_{d,y}$ was quantified as 0.6776 $MgCO_2\,MgWS^{-1}$ based on the calculation according to formulas (5), Equation (6) and literature reported by Liu *et al.* (2014b).

Indirect GHG emissions from electricity and fossil fuel consumption associated with anaerobic digestion

During sludge anaerobic digestion, indirect GHG emissions were mainly associated with mechanical electricity, heat elevation and transportation to the digestion tank, as well as sludge transportation and loading on site. According to formula (3) and (4), the indirect GHG emissions caused by fossil fuel consumption ($PE_{fuel,y}$) and sludge transportation ($PE_{tran,y}$) were 0.0002 and 0.0033 (including biogas residue) $MgCO_2$ $MgWS^{-1}$, respectively. The GHG emissions from electricity use on site differed owing to differences in temperature between northern and southern China. When sludge was pumped to the storage tank, the temperature was elevated to 35 degrees, after which it was lifted to the anaerobic fermentor. The electricity use triggered by this process was 2.5 times higher in the Dalian sewage plant than the Xiamen sewage plant. In detail, the electricity consumption data of northern and southern cities in China (Dalian and Xiamen) were statistically counted to 27.5 kWh $MgWS^{-1}$ and 10.1 kWh $MgWS^{-1}$ respectively (main electricity consumption units associated with sludge anaerobic digestion and their percentages shown in Table 2). According to formula (2), the values of $PE_{elec,y}$ were accordingly quantified as 0.0244 $MgCO_2$ $MgWS^{-1}$ for the north (Dalian city) or 0.0074 $MgCO_2$ $MgWS^{-1}$ for the southern China (Xiamen city). Overall, indirect GHG emissions from sludge anaerobic digestion were 0.0279 (northern China) and 0.0109 (southern China) $MgCO_2$ $MgWS^{-1}$.

Direct GHG emissions from anaerobic digestion and emission reduction from replacement of biogas for natural gas

All biogas generated from sludge anaerobic digestion was captured and then purified for reuse in the form of heat converting electricity. One of the assumptions was that there was no leakage emission of methane throughout the anaerobic digestion period. Therefore, the direct GHG emissions from anaerobic digestion (value of $PE_{a,y}$) were considered to be 0 $MgCO_2$ $MgWS^{-1}$. According to formula (8) and biogas reclamation data in China, the value of $BE_{EN,y}$ was 0.0383 $MgCO_2$ $MgWS^{-1}$. After anaerobic digestion treatment, the sludge volume decreased by half, after which further dewatering was carried out by solid-liquid separation.

Table 2 | Electricity consumption units and its proportions in total on site associated with sludge anaerobic digestion process

Functional unit	Main machine or equipment	Proportion in total electricity consumption on site (%)	
Transferring unit	Belt conveyor; screw pump	Northern 8%	Southern 20%
Mixing unit	Blender	Northern 14%	Southern 35%
Heat preservation unit	Electric heater	Northern 70%	Southern 25%
Dewatering unit	Dehydrator	Northern 6%	Southern 15%
Other units	–	Northern 2%	Southern 5%

*The calculation of percentage of electricity consumption from each function unit in total electricity consumption is based on electricity consumption statistics at Dalian city (northern China) and Xiamen city (southern China).

Total GHG emission of sludge anaerobic digestion in comparison to landfill

The carbon debit consisted of indirect and direct GHG emission units, but the carbon credit only included replaceable emissions reduced by biogas from anaerobic digestion instead of natural gas. As shown in Table 3, total landfill emissions were calculated to be 0.711 $MgCO_2$ $MgWS^{-1}$, while those from anaerobic digestion were −0.0104 (northern China) or −0.0274 (southern China) $MgCO_2$ $MgWS^{-1}$. Consequently, a decrease in GHG emissions of 0.7214 (northern China) or 0.7384 (southern China) $MgCO_2$ $MgWS^{-1}$ can be achieved by simply not disposing of the sludge in landfills.

DISCUSSION

Anaerobic digestion is considered the optimum method for reduction of carbon emissions among currently available sludge treatment technologies (Wong *et al.* 2009; Fernandez *et al.* 2014). This is because biogas generated from sludge can be captured and reused as energy gas. The reduction in carbon emissions from reuse of this resource can offset the emissions associated with anaerobic digestion, including direct and indirect GHG emissions (Komatsu *et al.* 2011; Fine & Nadas 2012). In addition to biogas, the product of sludge anaerobic digestion also includes biogas slurry and biogas residue. Currently, biogas slurry is regarded as effluent that must be sent to the sewage plant for nitrogen and phosphorus removal, and cannot be reclaimed directly. Previously, biogas residue was directly sprayed into farm soil after being dewatered to moisture content of 80% without composting pretreatment prior to being amended to soil. However, there are problems associated with this approach, such as high salinity in the residue and relatively lower maturity after dewatering (Liu *et al.* 2014a). Therefore, stabilization and pretreatment are necessary for biogas residue

Table 3 | Carbon budget comparison of sludge anaerobic digestion and baseline scenario (landfill)

	Carbon debit ($MgCO_2\ MgWS^{-1}$)								
	Indirect emissions								
Sludge treatment or disposal	Electricity consumption		Fossil fuel consumption	Transportation	Direct emission	Carbon credit ($MgCO_2\ MgWS^{-1}$) replaceable emission reduction	Total Emissions ($MgCO_2\ MgWS^{-1}$)	
Baseline scenario	0.0068		0.0238	0.0028	0.6776	–	0.711	
Anaerobic digestion	Northern Southern	0.0244 0.0074	0.0002	0.0033	0	0.0383	Northern Southern	−0.0104 −0.0274
Total reduction in GHG emissions							Northern Southern	0.7214 0.7384

prior to application to soil. Additionally, there is still debate regarding whether biogas residue after sludge anaerobic digestion should be included in the investigative frame. In this case, aerobic composting of biogas residue was not taken to consideration. Correspondingly, reuse of biogas residue, such as application as organic fertilizer to farmland or grassland, was usually ignored because the interaction between soil and amended residue compost is complicated and the amount of GHG emitted from soil or residue compost cannot be accurately quantified (Lopez-Valdez *et al.* 2011; Liu *et al.* 2014b). Subsequently, GHG emissions from the treatments of the biogas slurry and biogas residue were all not taken to consideration of this study. Being ignoring this segment of treatment chain will result in reduction in carbon credit of replaceable emissions reduction, such as reuse of composted biogas residue to soil as organic fertilizer. Meanwhile, carbon debit from treatment of biogas slurry and biogas residue will also be omitted. Therefore, in some extent, this inconsideration poses a minor effect on total carbon emissions.

In China, the organic matter content in sludge is relatively low (Guo *et al.* 2009). Therefore, the potential production of biogas from sludge anaerobic digestion is not as high as in other countries. As a result, the proportion of anaerobic digestion in currently available sludge treatment plants in China is very low. In addition to the low organic matter content, the management level of operational department responsible for sludge treatment did not also match process requirements. In other words, the management level in China is not high enough to stable operation of sludge anaerobic digestion. As shown in Table 3, the increase in carbon credit was all from reduction of replaceable emissions of biogas reuse, while the carbon debit reduction was mainly due to decreased fossil fuel consumption on site and reduced direct GHG emissions. Especially, the distinct difference between anaerobic digestion and landfill is that the former allows effective collection of generated biogas and subsequent transformation into useable fuel (Batstone & Virdis 2014). However, the biogas, which is mainly made up of methane, generated slowly and unorderedly from landfill emitted into atmosphere. This emission is attributed importantly to carbon debit.

Overall, a total emission reduction of 0.7214 (northern China) or 0.7384 (southern China) $MgCO_2\ MgWS^{-1}$ was achieved. This is a considerable GHG reduction, in some extent, is important to obtaining certified emission reduction (CER), which enables access to financial support in the CDM frame (Rogger *et al.* 2011). For example, the current sludge yield of Xiamen is 500 Mg daily. If this amount of sludge can be treated by anaerobic digestion rather than landfill, there will be a CER of about 13,480 $MgCO_2$ annually.

Defined boundaries of investigative cases can influence reported potential changes in GHG emissions (Vergara *et al.* 2011). For instance, whether sludge just after effluent treatment can be regarded as investigative objective or it was dewatered to moisture content of 80%, then the volume reduced sludge was set up as boundary beginning point. There would be significant differences in GHG emissions differences between these two project boundaries. If dewatering was taken to the study's consideration, the corresponding electricity consumption will also increase, and this increase will lead to entire carbon debit raise up not as much as that portion of landfill. In China, the moisture content in sludge for landfill needs to be dewatered to 60% according to the limit value in criterion of sludge landfill. Therefore, the indirect GHG emission resulted from landfill will be more than anaerobic digestion. For sludge treatment, anaerobic digestion is the preferential method of reducing the carbon footprint, despite its not yet being widely applied in China. Additionally, anaerobic digestion is suitable for energy-saving and decreased carbon emissions. The positive effects of sludge anaerobic digestion also depend on reduced emissions owing to secondary product (biogas) replacement and low self-energy consumption during the treatment process.

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REFERENCES

Abbasi, T., Tauseef, S. M. & Abbasi, S. A. 2012 Anaerobic digestion for global warming control and energy generation-an overview. *Renew. Sust. Energy Rev.* **16** (5), 3228–3242.

Barber, W. P. F. 2009 Influence of anaerobic digestion on the carbon footprint of various sewage sludge treatment options. *Water Environ. J.* **23**, 170–179.

Batstone, D. J. & Virdis, B. 2014 The role of anaerobic digestion in the emerging energy economy. *Curr. Opin. Biotech.* **727**, 142–149.

Chen, H., Yan, S. H., Ye, Z. L., Meng, H. J. & Zhu, Y. G. 2012 Utilization of urban sewage sludge: Chinese perspectives. *Environ. Sci. Pollut. Res.* **19**, 1454–1463.

Fernandez, Y. B., Soares, A., Villa, R., Vale, P. & Cartmell, E. 2014 Carbon capture and biogas enhancement by carbon dioxide enrichment of anaerobic digesters treating sewage sludge or food waste. *Bioresour. Technol.* **159**, 1–7.

Fine, P. & Nadas, E. 2012 Options to reduce greenhouse gas emissions during wastewater treatment for agricultural use. *Sci. Total Environ.* **416**, 289–299.

Guo, G. H., Yang, J., Chen, T. B., Zheng, G. D., Gao, D., Song, B. & Du, W. 2009 Concentrations and variation of organic matter and nutrients in municipal sludge of China. *China Water Wastewater* **25**, 120–121 (in Chinese).

Guo, J., Ma, F., Qu, Y., Li, A. & Wang, L. 2012 Systematical strategies for waste water treatment and the generated wastes and greenhouse gases in China. *Front. Environ. Sci. Eng. China* **6** (2), 271–279.

IPCC (Intergovernmental Panel on Climate Change) 2006 2006 IPCC Guidelines for National Greenhouse Gas Inventories. http://www.ipcc.ch/publication_and_data/publications_and_data_reports.shtml (accessed 15 December 2012) Q1

IPCC (Intergovernmental Panel on Climate Change) 2007 *Climate Change 2007: Mitigation of Climate Change.* Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change, Geneva, Switzerland.

Komatsu, K., Yasui, H., Goel, R., Li, Y. Y. & Noike, T. 2011 Novel anaerobic digestion process with sludge ozonation for economically feasible power production from biogas. *Water Sci. Technol.* **63** (7), 1467–1475.

Law, Y., Jacobsen, G. E., Smith, A. M., Yuan, Z. G. & Lant, P. 2013 Fossil organic carbon in wastewater and its fate in treatment plants. *Water Res.* **47** (14), 5270–5281.

Liu, H. T. & Zhang, Y. 2013 Key issues on land application of sewage sludge in Chinese national conditions. *China Water Wastewater* **29**, 1–4 (in Chinese).

Liu, H. T., Gao, D., Chen, T. B., Cai, H. & Zheng, G. D. 2014a Improvement of salinity in sewage sludge compost prior to its utilization as nursery substrate. *J. Air Waste Manage.* **64** (5), 546–551.

Liu, H. T., Zheng, H. X., Chen, T. B., Zheng, G. D. & Gao, D. 2014b Reduction in greenhouse gas emissions from sewage sludge aerobic compost in China. *Water Sci. Tech.* **69** (6), 1129–1135.

Lopez-Valdez, F., Fernandez-Luqueno, F., Luna-Suarez, S. & Dendooven, L. 2011 Greenhouse gas emission and plant characteristics from soil cultivated with sunflower (*Helianthus annuus* L.) and amended with organic or inorganic fertilizers. *Sci. Total Environ.* **412–413**, 257–264.

Majumder, R., Livesley, S. J., Gregory, D. & Arndt, S. K. 2014 Biosolid stockpiles are a significant point source for greenhouse gas emissions. *J. Environ. Manage.* **143**, 34–43.

NDRC of China (National Development, Reform Commission of China) 2012 *Baseline Emission Factors for Regional Power Grids in China.* http://cdm.ccchina.gov.cn/Website/CDM/UpFile/File2975 (accessed 15 October 2012).

Niu, D. J., Huang, H., Dai, X. H. & Zhao, Y. C. 2013 Greenhouse gases emissions accounting for typical sewage sludge digestion with energy utilization and residue land application in China. *Waste Manage.* **33** (1), 123–128.

Qiao, W., Yan, X. Y., Ye, J. H., Sun, Y. F., Wang, W. & Zhang, Z. Z. 2011 Evaluation of biogas production from different biomass wastes with/without hydrothermal pretreatment. *Renew. Energy* **36** (12), 3313–3318.

Remy, C., Lesjean, B. & Waschnewski, J. 2013 Identifying energy and carbon footprint optimization potentials of a sludge treatment line with life cycle assessment. *Water Sci. Technol.* **67** (1), 63–73.

Rogger, C., Beaurain, F. & Schmidt, T. S. 2011 Composting projects under the Clean Development Mechanism: sustainable contribution to mitigate climate change. *Waste Manage.* **31** (1), 138–146.

Tilche, A. & Galatola, M. 2008 The potential of bio-methane as bio-fuel/bio-energy for reducing greenhouse gas emissions: a qualitative assessment for Europe in a life cycle perspective. *Water Sci. Tech*. **57** (11), 1683–1692.

Weichgrebe, D., Urban, I. & Friedrich, K. 2008 Energy- and CO_2-reduction potentials by anaerobic treatment of wastewater and organic kitchen wastes in consideration of different climatic conditions. *Water Sci. Tech*. **58** (2), 379–384.

Wong, B. T., Show, K. Y., Lee, D. J. & Lai, J. Y. 2009 Carbon balance of anaerobic granulation process: carbon credit. *Bioresour. Technol*. **100**, 1734–1739.

Vergara, S. E., Damgaard, A. & Horvath, A. 2011 Boundaries matter: greenhouse gas emission reductions from alternative waste treatment strategies for California's municipal solid waste. *Resour. Conserv. Recy*. **57**, 87–97.

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Q1 IPCC (Intergovernmental Panel on Climate Change) (2006) is not cited in the main text. Please confirm where it should be cited, or delete the reference.