Minimization of greenhouse gas emission by application of anaerobic digestion process with biogas utilization

Water Science & Technology Vol 52 No 1-2 pp 545–552

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Abstract To assess the impact on greenhouse gas emission, different process schemes for municipal sludge treatment were evaluated based on the data from pilot-scale experiments and review of annual operation reports. A modified anaerobic digestion process with partial ozonation of digested sludge to improve biological degradability and the conventional anaerobic digestion process were compared with respect to the energy demand in each process schemes. Options for beneficial use of biogas included (1) application of biogas for power production and (2) recovery as an alternative to natural gas utilization. The analysis indicated that the partial ozonation process with power production led to minimal greenhouse gas emission because the extra energy production from this scheme was expected to cover all of the energy demand for the plant operation. Moreover, the final amount of dewatered sludge cake was only 40% of that expected from the conventional process, this significantly minimizes the potential for greenhouse gas emission in the subsequent sludge incineration processes.

Keywords Anaerobic digestion; greenhouse gas emission; incineration; kyoto protocol; LCA; ozonation

Introduction

In accordance with the recommendations of COP3 (Third Conference of Parties to the U.N. Framework Convention on Climate Change), Japan has started a comprehensive project titled "Biomass Nippon Project" to meet the goals set by the international consensus for the minimization of greenhouse-gas emission. One of the major challenges of the project is to expand the use of renewable biomass energy from the current level of 0.054 million kL crude oil equivalent/year to 1.01 million kL by the year 2010. In this aspect, use of municipal sewage sludge as a source for biomass energy is attractive as it is not only the energy recovery but also the corresponding reduction in the quantity of sludge for disposal that could be highly effective in increasing the net worth of the process. At present, in Japan about 0.7 million ton-DS/year of sludge is anaerobically digested with about 50–60% biogas conversion efficiencies. Further improvements in biogas conversion efficiencies can be achieved through improved solid degradation efficiencies. Based on such understanding, there are many on-going studies to develop emerging technologies to convert more sludge solids to biogas. A modified flow scheme of anaerobic digestion process with partial ozonation on digested sludge is one of such technologies to achieve solid to biogas with conversion efficiencies of over 80% (Goel *et al.*, 2003, 2004, Yasui *et al.*, 2005).

In this paper, we will highlight Life Cycle Assessment (LCA) methodology for sludge treatment & disposal options and present a comparative analysis regarding greenhouse-gas

(GHG) emission for the conventional and the modified anaerobic digestion process with ozonation. For comprehensive analysis, the impact assessment will be performed considering the total sludge treatment system rather than only the individual unit process of anaerobic digestion. Moreover, as the impact of the process on sludge treatment system is highly site specific, it was decided to concentrate on a selected area for precise development and elucidation of the assessment procedure. Nagaoka city (Population: 130,000), Niigata prefecture, Japan was selected for this purpose. Comprehensively background data for different treatment processes were collected through field experiments in Nagaoka city. Additional data required for analysis was collected from the review of annual operation reports prepared by different treatment facilities. Current and future alternatives for sludge treatment and disposal were formulated considering the existing sludge treatment and disposal facilities at Nagaoka city. The existing treatment facilities of anaerobic digestion plant, two incineration plants and two landfilling leachate treatment plants were considered in alternative formulation. Current practices of recycling incinerated ash, as cement material and beneficial use of the biogas were also included in the analysis as sub-alternatives.

Methodology

Current status of municipal sludge treatment and beneficial use at Nagaoka City

The flow-scheme of municipal sludge treatment at Nagaoka city is illustrated in Figure 1. About 7.7 ton-TS/day of primary sludge and 3.7 ton-TS/day of excess sludge are produced by the conventional activated sludge process without nutrient removal. The mixed sludge is digested in a mesophilic anaerobic digestion process having a hydraulic retention time of 52 days. 4,500 Nm^3/day of biogas is produced in the process with 66% of VSS degradation. Most of the biogas is purified to reach 96% of methane gas concentration, using water scrubber to remove CO_2 gas. The methane gas is then forwarded to a local gas company and distributed as an alternative to natural gas for citizens. In this way, 3% of total natural gas consumption by Nagaoka citizens is saved consistently, which contributes in reducing about 1,000 ton of GHG emission every year. The daily production of dewatered sludge cake is about 21.6 ton having water content of 76% and VSS/SS ratio of 0.58. Approximately one-third of the dewatered sludge cake is incinerated along with municipal solid waste at a municipal incineration facility adjoining the wastewater treatment plant. Due to high calorific value of the solid waste, supplemental fuel is not used for the incineration. The incinerated ash is landfilled at a municipal disposal site located 15 km away from the plant. Inorganic compounds in the leachate are further removed at the site by coagulation and N/DN treatment. The rest of the dewatered sludge cake is hauled to a private incineration plant 16 km away from the city and incinerated together with municipal dewatered sludge cake collected from 27 other wastewater

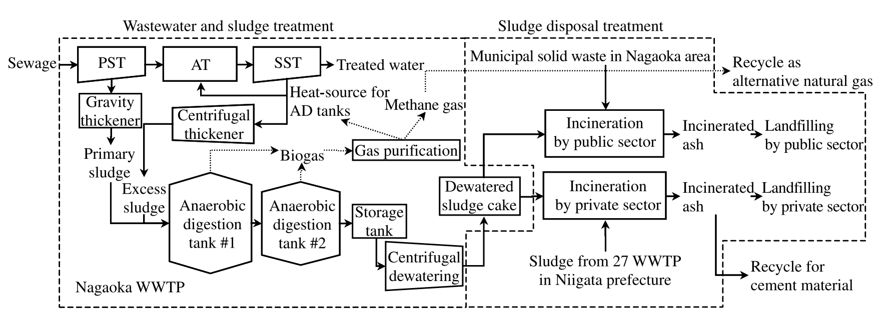

Figure 1 The current flow-scheme of sludge treatments at Nagaoka city

treatment plants in the prefecture (63 ton-cake/day in total). Heavy oil and rubber taken from waste tires as alternative fuel are used for the incineration. The operation of the incinerator is halted once in every two weeks for cleaning and maintenance purposes. Accordingly a significant amount of fuel is consumed for re-heating the incinerator after the maintenance. Every year 430 ton of incinerated ash is recycled to the cement industry as a raw material for cement and 1,900 ton is landfilled in the plant. The inorganic compounds in the leachate are removed in a similar manner to that mentioned the above.

System analysis

Model development for the anaerobic digestion processes. Basic performance data for the modified anaerobic digestion process with partial ozonation of digested sludge (Figure 2) and the conventional anaerobic digestion process were collected through pilot-scale experiments at Nagaoka central municipal wastewater treatment centre (Goel *et al.*, 2004). Based on the material balance in the experiments and plant survey, a process model was made to predict (1) the degree of sludge digestion with/without ozonation and (2) water content of dewatered sludge cake to estimate the quantity of sludge to be incinerated (Yasui *et al.*, 2005). In the process model, concept of first-order kinetics was applied to express the degradation of biodegradable solids. Also, the presence of biologically inert organics in the sludge was appropriately accounted for. For including the inorganic solids into modelling, experimental data were used from the pilot studies. Since the experiments showed that only 8% of inorganics in the municipal sludge were solubilized, the remaining part of the inorganics was considered to accumulate in the reactor.

Compilation of energy & material data for sludge treatment and disposal in Nagaoka. Additional data for LCA analysis, e.g. energy and materials consumed in the anaerobic digestion plant, the incineration plants and landfilling leachate treatment plants, were collected by conducting individual plant surveys and extracting information from annual operation reports and technical articles. The experimental data from pilot studies as described above were used to estimate the production of dewatered sludge cake from the two anaerobic digestion processes. The amount of dewatered sludge cake, energy and material data formed the basis for evaluating GHG emission in the subsequent treatment/disposal processes (Nagaoka city, 2002, JSA, 2001, MLIT, 2000). The energy and material of the processes is listed in Table 1.

Evaluation procedure to identify minimal GHG emission. The basic sludge treatment and disposal process flow scheme for Nagaoka city consists of conventional anaerobic digestion, dewatering, incineration and landfilling. In the alternative formulation, the modified anaerobic digestion process with ozonation was used in place of conventional

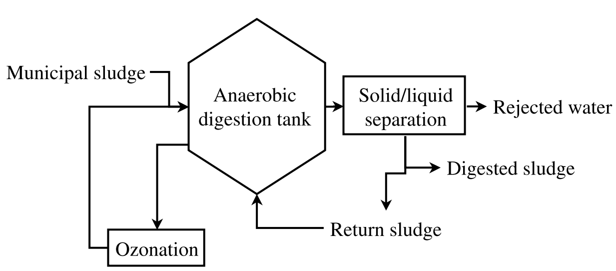

Figure 2 The high-concentrated anaerobic digestion process with partial ozonation on digested sludge

Table 1 List of LCA units

Facility	Fundamental unit of energy, material consumption
Collection of primary sludge	0.0060 kWh/kg-thickened sludge (dry weight basis)
Thickening, storage, pumping	
Collection of excess sludge	0.24 kWh/kg- thickened sludge (dry weight basis)
Thickening, storage, pumping	0.32 g-polymer/kg- thickened sludge (dry weight basis)
Anaerobic digestion tank	0.0022 kW/m^3-tank (mixing)
Mixing and heating	0.27 kWh/m^3-input sludge (heating) (dry weight basis)
Sludge dewatering facilities	0.23 kWh/kg-digested sludge (dry weight basis)
Withdrawing, dewatering by centrifuge, pumping	14 g-polymer/kg-digested sludge (dry weight basis)
Biogas purification facilities:	
Gas scrubbing	0.097 kWh/Nm^3-metahne
Compressing and pumping to the gas company	0.29 kWh/Nm^3-methane
Hauling of dewatered sludge cake	4 km/L-diesel oil (mileage)
Hauling by 4-ton lorry	
Sludge disposal by private sector	−469 mL-fuel/kg-VSS, 172 mL-fuel/kg-H_2O,
Incineration and treatment for landfilling leachate	35 mL-fuel/kg-Ash, 94.3 kWh/ton-cake 0.0374 kgN-N_2O/kgN-VSS (incineration at 850°C)
Sludge disposal by public sector	No supplement fuel used
Incineration and treatment for landfilling leachate	94.3 kWh/ton-cake, 0.0374 kgN-N_2O/kgN-VSS (incineration at 850°C)
Beneficial use of ash	
Recycle for cement material	75 gCaO/kg-ash
Power production facilities	Electricity generation efficiency: 34%*
Gas engine	Heat recovery efficiency: 42%*
Heat exchanger	
Facilities for the high-concentrated digestion process	0.056 kWh/kg-digested sludge (dry weight basis)
Solid/liquid separation by centrifuge	6.0 g-polymer/kg-digested sludge (dry weight basis)
Ozonation facilities	0.026-0.038 kWh/kg-digested sludge
Ozone production, ozone treatment	(dry weight basis, depending on facility scale)
Electricity by Tohoku electric company	0.425 kgCO_2/kWh (annual average), 0.441 kgCO_2/kWh (day time: 8:00-22:00), 0.395 kgCO_2/kWh (night time: 22:00-8:00), data for FY2002
Chemicals for thickening and dewatering	4.50 kgCO_2/kg-polymer
Diesel oil for lorry	2.64 kgCO_2/L-diesel oil
Heavy oil (class A) and rubber of waste tire	2.65 kgCO_2/L-heavy oil
Methane gas as alternative natural gas	−2.20 kgCO_2/Nm^3-methane
CaO for cement material	−0.786 kgCO_2/kgCaO

*On the basis of calorific value

anaerobic digestion. In each alternative, two scenarios were formulated based on the type of beneficial use of biogas, *i.e.* the scenarios of (1) Internal recycle: power production by gas engine to supply electricity for the plant facilities and (2) External recycle: distribution as alternative natural gas to local sectors. In all scenarios, it was assumed that ozonation equipments for the anaerobic digestion plant are operated in nighttime in order to utilize night electricity having lower GHG emission due to less consumption of fossil fuels at the power plants of the local electric power company. Total GHG emission in the sludge treatment system in Nagaoka city was given based on the models with input–output LCA procedure to analyze energy & material-flow matrix (Matsuhashi *et al.*, 1997, Yoshida *et al.*, 2002). The minimal LCCO_2 (minimal GHG emission) was identified by a Quasi-Newton method equipped in the Microsoft Excel® solver. The energy & material-flow matrix and its algorithm to seek solution for the optimum process scheme are shown in Figure 3 and Figure 4 respectively.

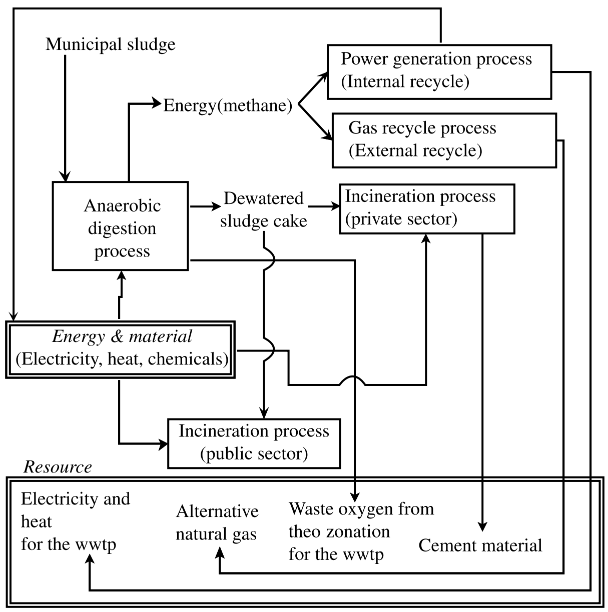

Figure 3 The energy & material flow matrix of Nagaoka city for municipal sludge treatments and disposal processes

Results and discussion

The results of pilot plant studies from the modified anaerobic digestion process with partial ozonation confirmed improvement of methane production and corresponding reduction in sludge amount for disposal. The biogas conversion efficiency reached about 80% of treated VSS, which was about 1.4 times higher than that in the conventional AD process. Due to the higher VSS degradation and corresponding lower VSS/SS ratio of the digested sludge, the production of dewatered sludge cake in the modified AD process was only 40% of that from the conventional AD process. Based on the experimental data and the results of the process model, the expected dewatered sludge cake production at Nagaoka wwtp is simulated as a function of daily ozone-input, as shown in Figure 5. It appears that the sludge production reduces significantly as the amount of ozone input is increased whereas the decrease in solid reduction is not a linear function. This is because addition of higher ozone input reduces the biological sludge retention time in the AD tank, since more sludge mass is withdrawn for the ozonation (Yasui *et al.*, 2005). The effect of this sludge recirculation through ozonation is that of reduced TVS digestion ratio for both the primary sludge and excess sludge. Consequently minimum achievable amount of dewatered sludge cake is expected to be about 3,100 ton/year under the given operating conditions at Nagaoka wwtp. The application of gas engine is expected to cover all of electricity and heat demand for the AD process if the daily ozone-input is below 360 kgO_3/day (data not shown).

GHG emission in the sludge treatment and disposal is summarized in Figure 6. Typical bathtub-curve was obtained for GHG emission depending on the amount of ozone-input. In the operation range of lower ozone-input (left hand), the amount of GHG emission became closer to that for the conventional AD process. The major contribution here is considered to be the production of N_2O derived from large quantity of dewatered sludge cake to be incinerated. Since more N_2O is generated from nitrogenous compounds in sludge organics at lower incineration temperature and it has 310 times higher GHG effect than CO_2, careful analysis is needed for a sludge incineration process to evaluate

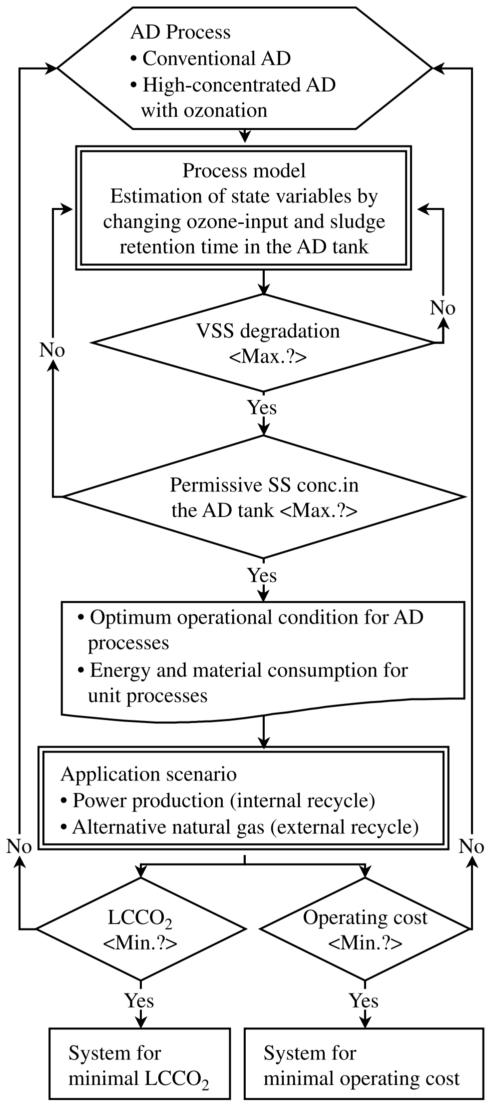

Figure 4 The algorithm to seek the optimum process scheme

GHG emission. On the other hand, in the case of higher ozone-input (right hand), also the GHG emission elevated due to more consumption of electricity for ozonation. The amount of GHG seemed to be minimum in the ozone-input range of 240–300 kg-O_3/day. In addition, the amount of waste oxygen as by-product from the ozonation is calculated to be 2,200–2,700 kg-O_2/day. This amount is expected to cover more than 60% of oxygenation demand in the aeration of the Nagaoka wwtp (data not shown). The reduction of GHG corresponds to the saving in crude oil consumption of 600 kL/year. Accordingly the application of the process can contribute to the reduction of 4.6 L-crude oil/p.e./year for Nagaoka city, which is 60% of government's goal on the basis of population equivalent.

Among the options for biogas utilization, the analysis suggests that internal recycle (for source of electricity by gas engine) would be a proper option for Nagaoka city and further 500 ton-CO_2 equivalent/year can be reduced from the current process scheme (external recycle for alternative natural gas). This result can be explained considering

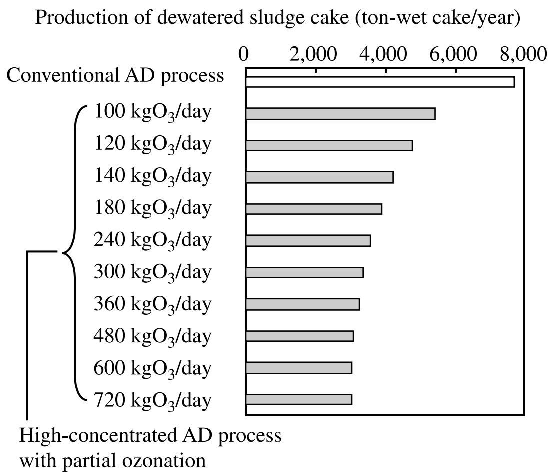

Figure 5 Expected dewatered sludge cake production

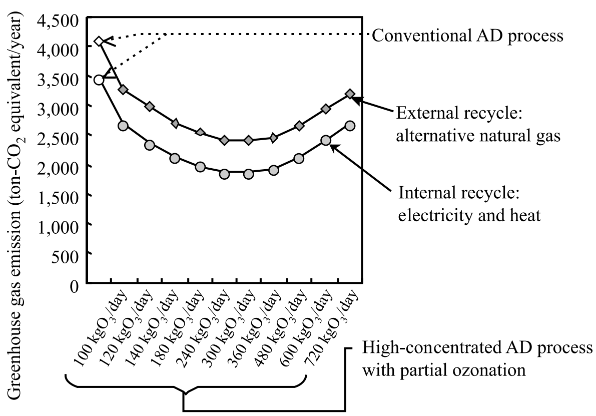

Figure 6 The estimation of greenhouse gas emission in sludge treatment and disposal in Nagaoka

the fact that the fundamental unit of CO_2 emission equivalent of the local electric power company serving Nagaoka area is higher than that of the gas company. Since fundamental unit of CO_2 equivalent (kg-CO_2/kWh) of an electric power company strongly depends on its composition of power source (e.g. nuclear, water, LNG, coal), the type of biogas utilization should be based on the local energy & material-flow matrix.

Conclusion

Different available sludge treatment and disposal options for Nagaoka city were formulated and the impact on total greenhouse-gas production was studied using the LCA approach. The results suggested that the scheme of the partial ozonation process combined with on-site power production gave minimum greenhouse-gas emission for Nagaoka city. The energy recovered from the biogas in the system is expected to cover all of the energy demand for the plant operation in the optimised process scheme. Moreover, the amount of dewatered sludge cake produced from the process was only 40% of that from the conventional process. This leads to substantial reduction in emission of CO_2 and N_2O at the subsequent incineration facilities. The LCA procedure formulated in this study is further applicable for a general planning of sludge treatment.

Acknowledgement

This study was conducted through the Technological Development Centre Projects (2001–2003) in TU Nagaoka.

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