Anaerobic digestion and gasification coupling for wastewater sludge treatment and recovery

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ABSTRACT

Sewage sludge management is an energy intensive process. Anaerobic digestion contributes to energy efficiency improvement but is limited by the biological process. A review has been conducted prior to experimentation in order to evaluate the mass and energy balances on anaerobic digestion followed by gasification of digested sludge. The purpose was to improve energy recovery and reuse. Calculations were based on design parameters and tests that are conducted with the anaerobic digester of a local wastewater treatment plant and a small commercial gasification system. Results showed a very significant potential of energy recovery. More than 90% of the energy content from sludge was extracted. Also, about the same amount of energy would be transferred to the gasifier (biogas) as thermal energy to the digester. This extraction resulted in the same use of biogas as the reference scenario but final product was a totally dry biochar which represented a fraction of the initial mass. Phosphorus was concentrated and significantly preserved. This analysis suggests that anaerobic digestion followed by dehydration, drying and gasification could be a promising and viable option for energy and nutrient recovery from municipal sludge in replacement of conventional paths.

KEYWORDS

Municipal sludge, gasification, anaerobic digestion, biosolids, nutrient recovery

CONTEXT OF RESEARCH

Quebec, a Canadian province, is currently investing important funds and resources in order to divert organic waste from landfills and incineration facilities. The main target is to avoid

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all organic waste burial or incineration by 2020. Low tipping fees for landfill have historically been a major barrier but it became widely contested because of the high environmental impacts of this disposal pathway. Focus was brought to municipal sludge earlier because of their high moisture content, which is directly related to disposal cost, whether it is hauled to landfill or thermally degraded on site. Anaerobic digestion (AD) is strongly encouraged by environmental authorities for all types of organic wastes. However, this approach solves the problem only partially. Sludge volume and mass are greatly reduced by AD but the water content of the digested sludge, often called digestate, is still high.

In order to find solutions to this problem, different scenarios have been discussed by the research team but one drew more attention: the treatment of digestate by low temperature gasification. Further investigation was conducted in order to evaluate the potential of anaerobic digestion and gasification coupling for the treatment of municipal wastewater sludge. The current work is presented as the first step of a new research effort at *École de technologie supérieure* (ÉTS) of Montreal. The main objective of this research is to establish a global energy and mass balance of a coupled anaerobic digestion - gasification sludge treatment system. Results will lead to a better understanding of the heat and mass transfers prior to a larger scale application of a combined installation.

METHODOLOGY

The core of this work is divided in three parts. The first and second parts aim to evaluate, respectively, the energy consumption of anaerobic digestion and gasification processes. In order to do so, the theoretical energy and mass balance are established in conjunction with measurements taken at a local wastewater treatment plant (WWTP). Sludge from this site is treated successively through AD and dewatering. Digested sludge is then treated off-site by gasification. The last part merges these analyses in order to optimize the energy transfers between the two processes. The calculation procedure is customizable to fit a specific case. Results are then compared to other studies involving a similar approach. Measurements of parameters (volatiles solids: VS, total solids: TS, chemical oxygen demand: COD, phosphorus, etc.) were taken following *Standard Methods for examination of water and wastewater* (Eaton & Franson, 2005).

ANALYSIS

The analysis is based on data from scientific literature and measurements taken on sludge samples that were anaerobically digested and gasified after. AD parameters are taken from a full scale local WWTP located in the municipality of Châteauguay (Québec). General data is mainly based on annual averages so that temporary conditions do not affect the observations. However, more advanced spot analyses have been conducted in order to evaluate specific parameters. Missing data is based on assumptions derived from literature. The plant uses a primary decantation process followed by a trickling filter and it was originally commissioned in 1991. The solid chain is schematically depicted in Figure 1.

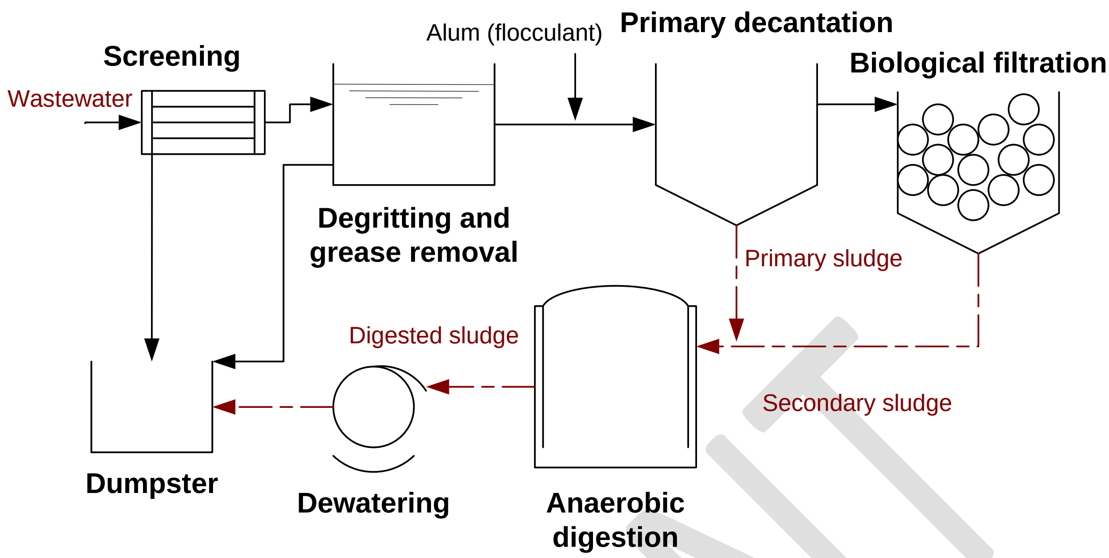

Figure 1. WWTP simplified process diagram

Figure 1 indicates that after screening, degritting and grease removal, the sludge is decanted to obtain a primary sludge that is directly introduced in an anaerobic digester while the remaining wastewater is subject to biological filtration. This secondary sludge is then mixed with primary and directed in the anaerobic digester as well.

Samples from both mixed raw sludge (MRS) and anaerobically digested sludge are collected and regularly analyzed by the plant operators. In the normal process (reference scenario), digested sludge mixed with polymer is dewatered through a filter-press before being sent to landfill. No specific pre-treatment has been applied prior to digestion. Energy use for dewatering is not included in the energy balance because it is related to polymer selection, technology used and operation parameters. Therefore, the value for dewatering can vary significantly. In addition, water extraction process would be exactly the same with or without gasification in the context of this research. The gasification step is considered as a replacement for the dumpster or drying solutions which comes after dewatering.

For comparison with this analysis, work conducted by Boran et al. (2008) showed an excess energy of 8.86 GJ per dry tonne of sludge anaerobically treated and then incinerated excluding energy use of equipments (dewatering, pumping, etc.) but including heating energy (sludge heating, etc.). Cao et al. (2012) presented an energy efficiency of 71.4% for waste activated sludge treated by AD and then by pyrolysis excluding energy requirements for ensuring the processes. Assuming a dry digested sludge LHV of 17 MJ • kg^{-1}, this would lead to a 12.14 GJ per dry tonne.

Anaerobic digestion

Characteristics and kinetics of AD are well described in the literature. It is composed of four major steps: hydrolysis, acidogenesis, acetogenesis and methanogenesis. Rate determining step is generally known to be hydrolysis (Appels et al., 2008). For calculation of mass balance, digester input is mixed raw sludge (MRS) which is composed of primary and secondary sludge. Outputs are digested sludge and biogas. Methane yield (R_{CH4}) can be expressed as follow (Bernet & Buffière, 2011):

$$R_{CH4} = \frac{Q_{CH4}}{Q_e \times [VS]_e} \quad (1)$$

Methane production over incoming volatile solids (VS) flow indicates methane yield in $Nm^3 \cdot kg_{VS}^{-1}$ (Nm^3: normal cubic meter at 0°C and 101.3 kPa). This is very important to compare equivalent scenarios. Inorganic content is considered unchanged before and after digestion. It is noted that siloxanes, hydrogen sulfide, ammonia, nitrogen and other volatile compounds are released into biogas during AD process (Ryckebosch et al., 2011) but volume are relatively low and thus are neglected for this analysis. Average performance data indicate a 50% conversion of VS to biogas for a 70% VS sludge. In these conditions, the methane yield can vary greatly and is expected to be between 0.40 and 0.65 Nm^3 $CH_4 \cdot kg^{-1}$ VS loaded (Arnaud, 2011; Bernet & Buffière, 2011; Boran et al., 2008; Camacho & Prévot, 2011; Nallathambi Gunaseelan, 1997). Biogas has a presumed composition of 60% CH_4 and is saturated in water vapor at process temperature. The mass balance of the AD process is performed using annual average data collected by the plant operators of the WWTP. The plant uses a mesophilic digester of 1500 m^3 followed by another similar tank that is used for settling also with gas recovery. Temperature is kept around 35.5°C during normal operation of the digester. Average hydraulic residence time (HRT) is about 25 days. Organic load is approximately 1.56 kg VS m^{-3} of digester $\cdot$ d^{-1}. The main flows and characteristics of MRS, DS and biogas are presented in Table 1.

Table 1. Average daily flows

Type of flow	Direction	Flow ($m^3 \cdot d^{-1}$)	Dryness	Specific gravity	VS	Dry flow ($t \cdot d^{-1}$)
Mixed raw sludge	In	75	3.85 %	1.04	73 %	2.89
Digested sludge	Out	72	2.20 %	1.02	53 %	1.58
Biogas	Out	1453	Sat.	-	-	-

Biogas exact composition on a yearly basis is not precisely known. However, based on an assumed CH_4 content (60%) (Camacho & Prévot, 2011; Tchobanoglous et al., 2003), VS reduction (48%) and biogas average flow rate, a CH_4 yield of 0.45 Nm^3 $CH_4 \cdot kg^{-1}$ VS is evaluated using Equation 1. Remaining compounds are considered to be CO_2 and saturated water vapor.

Energy consumption factors are taken or adapted from published energy analyses and wastewater treatment references in conjunction with on-site data (Appels et al., 2008;

Bohn et al., 2007; Boran et al., 2008; Lübken et al., 2007; Moletta, 2011; Tchobanoglous et al., 2003). Energy consumption data is presented in Table 2 and reflect expected values from the WWTP based on annual average and literature (Tchobanoglous et al., 2003).

Table 2. Annual energy data for anaerobic digestion

Parameter	Electrical input (GJ)	Thermal input (GJ)	Losses (GJ)	Thermal output (GJ)
Pumping and stirring	613	-	184	429
Affluent heat (35.5°C)	-	2823	-	2823
Digester heating	-	974	974	0
Total	613	3797	1158	3252

Digester heating is calculated using degree-days from Montreal, Canada and all heat contained in the biogas outflow is neglected. Combined electrical and mechanical efficiency of pumping and stirring is assumed to be 70%. For one insulated concrete digesters and one insulated concrete settling tank, the total volume is 3000 m^3 for a total surface area of about 1300 m^2. Average daily sludge flow at 3.85% total solids (TS) is 75 m^3 per day. Then, biogas production is 1453 m^3 per day with a LHV taken at 21.5 (Boran et al., 2008; Camacho & Prévot, 2011). The end result is a digestion overall energy investment of 4410 GJ • a^{-1} for a potential recovery of 3252 GJ • a^{-1} in low temperature thermal energy and 11 402 GJ • a^{-1} of biogas energy.

Gasification

The gasification process has been widely studied for several decades. Many studies focused on municipal sludge because of its particular management requirements and its high moisture content that represents a challenge. Various gasification approaches exist. The intent here is not to expose them but to evaluate the expected potential. The major steps incurred in gasification are drying, pyrolysis and partial oxidation. Kinetic behavior of pyrolysis, oxidative pyrolysis and gasification has been extensively described and modeled in literature, which is used for design parameters evaluation (Cao & Pawłowski, 2012; J. A. Conesa & Domene, 2011; Font et al., 2005; Groß et al., 2008; Manyà et al., 2006; Scott et al., 2006; Werther & Ogada, 1999). Several studies use three parallel reactions to predict results of the models with decomposition temperature around 250°C, 350°C and 550°C (J. Conesa et al., 1998; Manyà et al., 2003).

For this research, generated syngas is used to tend, as much as possible, toward self-sustainability of gasification. However, experiments have led to a minimum dryness of 45-55 % for autothermic combustion of digested sludge (Boran et al., 2008). This implies that lower dryness level would require auxiliary fuel. Also, in order to minimize loss of moderately volatile elements, such as phosphorus, a low temperature process (400 to 500°C) is used in this study. This is especially important as phosphorus is one of the most valuable fertilizing elements contained in sludge. Also, this element is known to show very little volatilization below 600°C (Bourgel et al., 2011). Phosphorus (expressed as P_2O_5) typical concentration in digested sludge is considered to be around 2.5 to 3.6 % TS

(Tchobanoglous et al., 2003; Werther & Ogada, 1999). The mass balance of gasification is based on literature data in addition to VS, mass and heating value reduction. All mass losses are assumed to end up as condensed water and flue gases. For experimentation, digested sludge was transported to an offsite gasifier right after being dewatered. The gasifier is a small capacity commercial unit (50 kg • h^{-1}) designed for energy production from waste using air as the gasifying agent. The gasifier simplified process is shown at Figure 2.

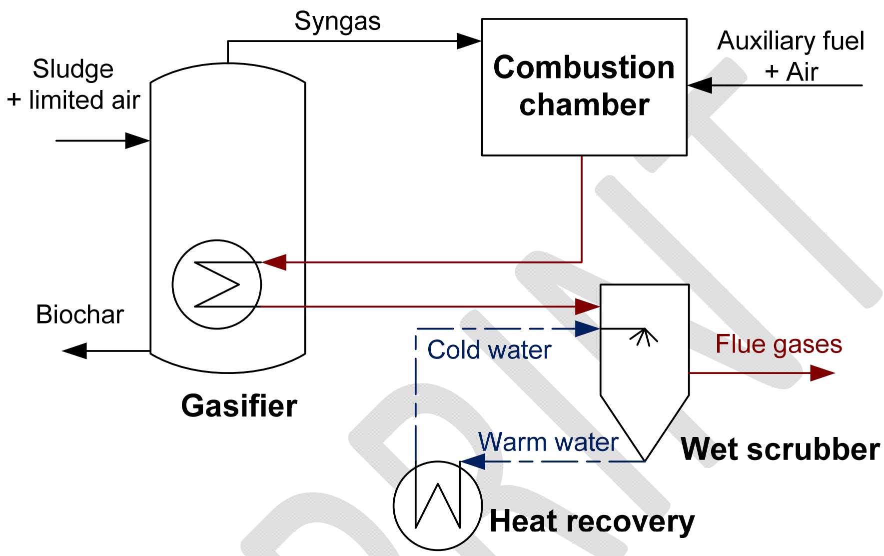

Figure 2. Simplified gasifier process diagram

Syngas is produced in the gasifier at around 450-550°C. It is automatically sent to a combustion chamber maintained at constant temperature (1100°C) with an auxiliary fuel. Flue gases are then directed to a heat exchanger in the gasifier before being quenched in a wet scrubber. Heat is recovered from warm water which is sent back to the scrubber. The collected residue is carbonaceous ash or biochar. Multiples physical analyses were performed on digested sludge and gasified sludge (biochar). The properties of the analyzed products are presented in Table 3.

Table 3. Properties of digested and gasified sludge

Type	Dryness	VS	HHV ($MJ\ kg^{-1}{}_{dry}$)
Digested sludge	22%	55%	12.1
Gasified sludge	100%	15%	1.2

In the gasification process, VS went down from 55% to 15% and water content became negligible. This is equivalent to a mass reduction of 47% on a dry basis and 90% on a wet basis. Measured higher heating value (HHV) of biochar is about 10% of digested sludge but measurements were not very accurate due to the very low residual energy. A biochar sample is shown on Figure 3.

Figure 3. Gasified sludge sample (biochar)

On the energy side, inputs to the system are provided by electrical equipments and auxiliary fuel. However, electrical consumption calculation is excluded because it cannot be considered directly proportional to scaling up and because it is highly dependent upon the technology used. Energy output is the thermal energy recovered from warm water flow. Table 4 contains energy values used for the analysis.

Table 4. Annual energy data for gasification

Parameter	Energy (GJ)
Auxiliary fuel	3891
Sludge energy	6572
Heat losses	-2267
Biochar energy	-242
Balance	7948

Preliminary evaluations show that for an input of 10 463 GJ of energy (auxiliary fuel and sludge), there would be 7948 GJ available for recovery. Losses include remaining energy from the biochar and energy that is not recovered from the process due to uncontrolled heat transfer directly to the surrounding environment. About 90% of the total energy content was released during gasification.

Anaerobic digestion and gasification coupling

By merging the energy and mass balances, many transfers can be achievable. Values of potential energy flows are provided in Figure 4. These values are calculated on an annual basis from the average data. The first mass flows (full lines) are sludge (brown) and biogas (green). Water flow (blue) is represented by small dashes lines. Finally, heat (red) is shown by large dashed lines. TPA stands for *tonne per annum* and is expressed on a dry basis.

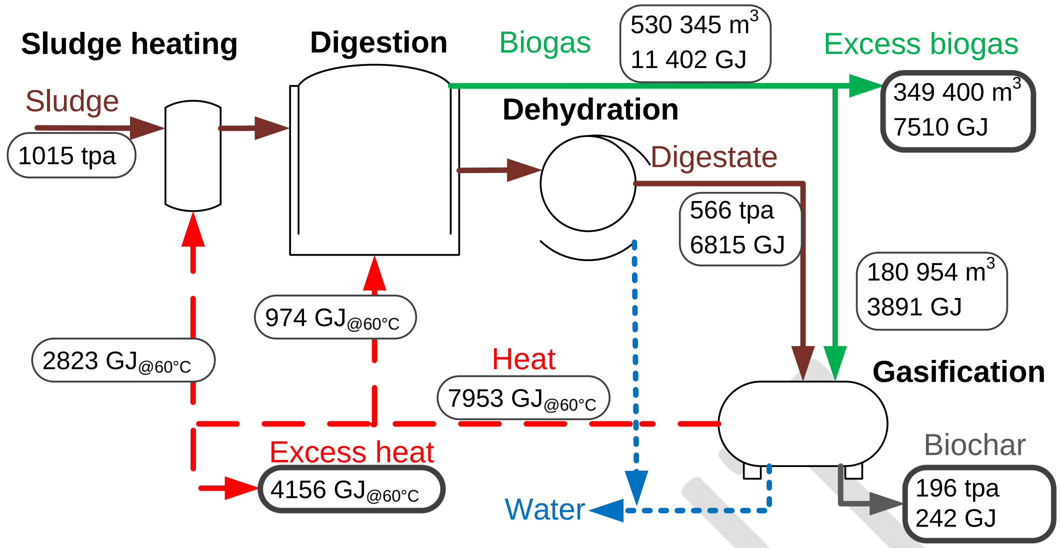

Figure 4. Anaerobic digestion and gasification process diagram and annual flow rates

The coupled process includes transfer of biogas to the gasifier. On the other hand, energy recovered from the gasifier (around 60°C in this case) is used to heat the incoming sludge and the digester. The recoverable energy is 7510 GJ in the form of biogas and 4156 GJ as water at 60°C. Losses are considered but not shown on the figure in order to ease understanding. Excess energy is then evaluated to be 11.5 GJ • tonne^{-1} on a dry basis (7.4 GJ has biogas and 4.1 GJ as heat).

Finally, phosphorus content has been evaluated. Concentrations in digested sludge and biochar were 19 600 mg • kg^{-1} (1.9%) and 39 400 mg • kg^{-1} (3.9%) respectively. By deducting the VS reduction, these results show a preservation of 95% of the initial phosphorus content.

DISCUSSION

For the anaerobic digestion, it is obvious that the main energy requirement is heating of incoming sludge. This is especially important because improvement of digesters insulation can have a limited impact on energy consumption. Energy recovery from outgoing flow of the digester is technically challenging due to the nature of sludge and its low temperature differential. However the presence of a gasifier brings a new higher temperature source of energy to fulfill the AD needs. Therefore, it should deserve consideration in digestion systems design. The excess energy result of 11.5 GJ per dry tonne of sludge is coherent with other works (Boran et al., 2008; Cao & Pawłowski, 2012) but is probably slightly overestimated. It is interesting to acknowledge that the energy transferred from the digester to the gasifier (3891 GJ of biogas) is almost the same as the thermal energy taken from gasification to fulfill the heat requirements of the digester and the incoming sludge flow (3797 GJ). Consequently, using the gasification waste heat in an attempt to maximize biogas excess can be seen as an improvement because biogas has a higher energy density and is a much more versatile gas than syngas.

Waste excess heat (4156 GJ), if recovered at a higher temperature, could be partly used to pre-dry digestate which would reduce the biogas use even more. This leaves more potential for other outcomes such as biomethane upgrade for grid injection. From another angle, sludge thermal pre-treatments have shown impressive improvement in biogas yields by many studies (Bougrier et al., 2008; Climent et al., 2007). The initial composition of sludge has also been described as highly important and directly related to its degradability (Gavala et al, 2003). The increase in sludge conversion to biogas would result in a lower VS content in digestate, thus leaving less energy for the gasification process. However, dehydrated digested sludge volume would be reduced even more, assuming a similar dewatering potential. Hence, more energy per volume of digestate would be required for gasification but the total energy requirement would decrease because of the reduced volume to be treated.

Most of the heat generated by gasification in this experiment is in the form of hot water around 60°C but it could be optimized by a proper heat exchanger selection. This abundant energy source includes recovered latent energy from condensation of flue gases. There is a major potential for fulfilling most, if not all, of the heating requirements of the AD system depending on the simultaneity of the demand and the production. A comfortable excess of energy is available and should be used for on-site application such as water and air heating. Heat pumps could help increase recovery potential if needed. Nevertheless, more complete calculations are required before attempting a larger scale installation because of the many assumptions made in this work.

CONCLUSION

This project was intended first to evaluate whether or not the anaerobic digestion and gasification coupling could be beneficial from an energy efficiency point of view. Theoretical calculations combined with experimental analyses showed that an important improvement of energy recovery and reuse was possible by combining the two processes. Biogas use remained almost unchanged but the initial scenario did not include any drying while the coupling produces totally dry biochar. Confidence in results would benefit from a more integrated pilot scale coupled process using biogas as the auxiliary fuel. Additional research should be conducted in order to optimize energy transfers and maximize valuable energy outputs such as biogas. Furthermore, an air drying step using waste heat could improve energy efficiency of the process and has been studied (Groß et al., 2008). A very important potential exists for the anaerobic digestion and gasification coupling so emphasis should be put on economical analyses based on local contexts, legislations and incentives. Finally, biochar analyses would help determine whether this product is suitable for agricultural use but it is safe to admit that phosphorus is preserved and concentrated by low temperature gasification.

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