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 in order to evaluate the mass and energy balances on anaerobic digestion followed by gasification of digested sludge in order to improve energy recovery. Calculations are 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 show a very important potential of energy recovery. More than 95% of the energy content from sludge was extracted. This extraction resulted in a 5% reduction of biogas but final product was a totally dry biochar. Final product was then a fraction of the initial mass. This analysis suggests that anaerobic digestion followed by dewatering, 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 elimination by 2020. Low cost of landfill has historically been a major barrier but it is being 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 previously discussed 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 AD-gasification sludge management system. Results will lead to a better understanding of the heat and mass transfers prior to full 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 the energy consumption of an anaerobic digestion process and gasification system. In order to do so, the theoretical energy and mass balance are established in conjunction with measures 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 theses 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 (VS, TS, COD, phosphorus, etc.) were taken following *Standard Methods for examination of water and wastewater* [1].

ANALYSIS

The analysis is based on previous works found in scientific literature and measurements taken on sludge samples that were anaerobically digested and gasified after. The analysis is based on parameters 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 over affect the observations. However, more advanced analyses had to be conducted for a limited of times for logistical reasons. 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 shown in Figure 1.

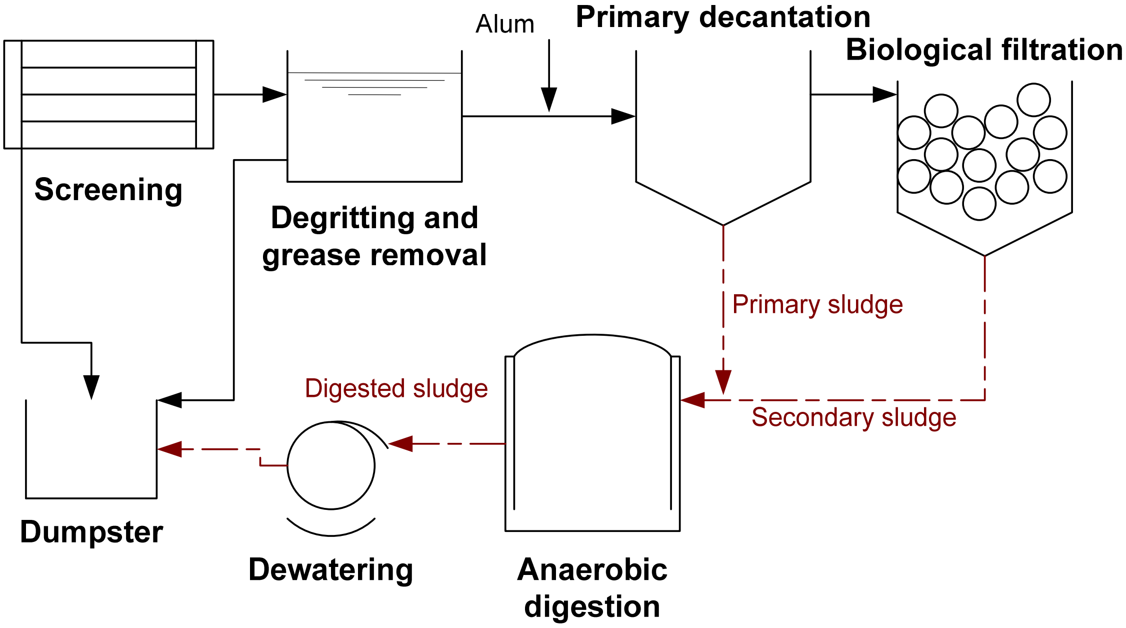

Figure 1. WWTP simplified process diagram

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 directed in the anaerobic digester as well.

Samples from both mixed raw sludge (MRS) and anaerobically digested sludge are collected and regularly analyzed. In the normal process, digested sludge mixed with polymer is dewatered through a filter-press before being sent to landfill. Energy consumption from the dewatering step is not included 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. showed an excess energy of 8.86 GJ per dry ton of sludge anaerobically treated and then gasified excluding energy requirement of equipments (dewatering, pumping, etc.) but including heating requirements (sludge heating, etc.) [2]. Cao et al. 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 [3]. Assuming a dry digested sludge LHV of 17 MJ • kg^{-1}, this would lead to a 12.14 GJ per dry ton.

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 [4]. 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 [5]:

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

Methane production over incoming volatile solids (VS) flow indicates methane yield in $Nm^3 \bullet kg_{VS}^{-1}$. 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 [6] but volume are relatively low and thus are neglected for this analysis. General performances 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 • kg^{-1} VS [2, 5, 7-9]. 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 and biogas stocking. 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 1.56 kg VS m^{-3} digester • 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 ($m^3 \bullet d^{-1}$)	Dryness	Specific gravity	VS	Dry flow ($t \bullet d^{-1}$)
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 assumed CH_4 content (60%), VS reduction (48%) and biogas average flow, a CH_4 yield of 0.45 Nm^3 CH_4 • 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 is conjunction with on-site data [2, 4, 10-13]. Energy consumption data is presented in Table 2 and reflect expected values from the WWTP based on annual average.

Table 2. Annual energy data for anaerobic digestion

Parameter	Electrical input (GJ)	Thermal input (GJ)	Losses (GJ)	Thermal output (GJ)
Pumping and stirring	615	-	185	430
Affluent heat (35.5°C)	-	2932	-	2932
Digester heating	-	974	974	0
Total	615	3906	1159	3362

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% TS is 75 m^3 per day. Then, biogas production is 1453 m^3 per day with a LHV taken at 21.5 [2, 9]. The end result is a digestion overall energy investment of 4521 GJ • a^{-1} for a potential recovery of 3362 GJ • a^{-1} in low temperature thermal energy and 11402 GJ • a^{-1} of biogas energy.

Gasification

The gasification process has been widely studied for several decades. Many researches focused on municipal sludge because of its particular management requirements and its very challenging high moisture content. 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. Kinetics of pyrolysis, oxidative pyrolysis and gasification has been extensively described and modeled in literature, which is used for design parameters evaluation [3, 14-19]. Many researches use three parallel reactions to predict results of the models with decomposition temperature around 250°C, 350°C and 550°C [20, 21].

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 [2]. This implies that lower dryness level would require auxiliary fuel. Also, in order to minimize loss of highly volatile inorganic elements, 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, it is known to show very little volatilization below 600°C [22]. Phosphorus (P_2O_5) typical concentration in digested sludge is considered to be around 2.5 to 3.6 % TS [11, 19]. 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 to 100 kg • h^{-1}) designed for waste energy recovery using air as the gasifying agent. The gasifier simplified process is shown at Figure 2.

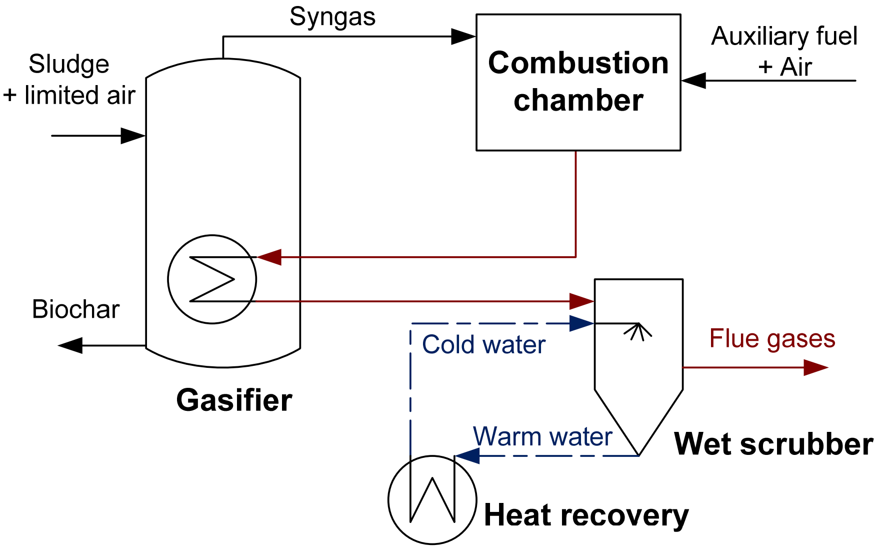

Figure 2. Simplified gasifier process diagram

Syngas is produced in the gasifier at around 450°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. Collected residue is carbonaceous ash or biochar. Multiples physical analyses were performed on digested sludge and gasified sludge (biochar). Properties of analyzed products are presented in Table 3.

Table 3. Properties of digested and gasified sludge

Type	Dryness	VS	HHV (MJ/kg_{dry})
Digested sludge	22%	55%	12.1
Gasified sludge	100%	15%	2.0 to 3.5

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 88% on a wet basis. Measure HHV of biochar is about 20% of digested sludge but measurements were not very accurate due to very low energy content.

On the energy side, inputs to the system are provided by electrical equipments and auxiliary fuel. However, electrical consumption 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	Thermal input (GJ)	Losses (GJ)	Thermal output (GJ)
Auxiliary fuel	3321	332	2989
Sludge energy	6996	1014	5981
Total	10 317	1346	8970

Preliminary evaluations show a 10 317 GJ investments for 8970 GJ of potential recovery. Losses include remaining energy from the biochar and energy that is not recovered from the process. About 95% of the total energy content was released during gasification. Thermal efficiency of the gasification configuration excluding electricity to run the process is presumed to be 90%. Overall thermal efficiency is then 87%.

Anaerobic digestion and gasification coupling

By merging the energy and mass balances, many transfers can be achievable. Values as inserted in Figure 3. These values are calculated on an annual basis from the average data. First chain is sludge (full line) is sludge (brown) and biogas (green). Water direction (blue) is represented by small dashes lines. Finally, heat (red) is shown by large dashes lines. Mass and energy values are shown in boxes. Thick border boxes include final recoverable products and energy with the temperature of recovery.

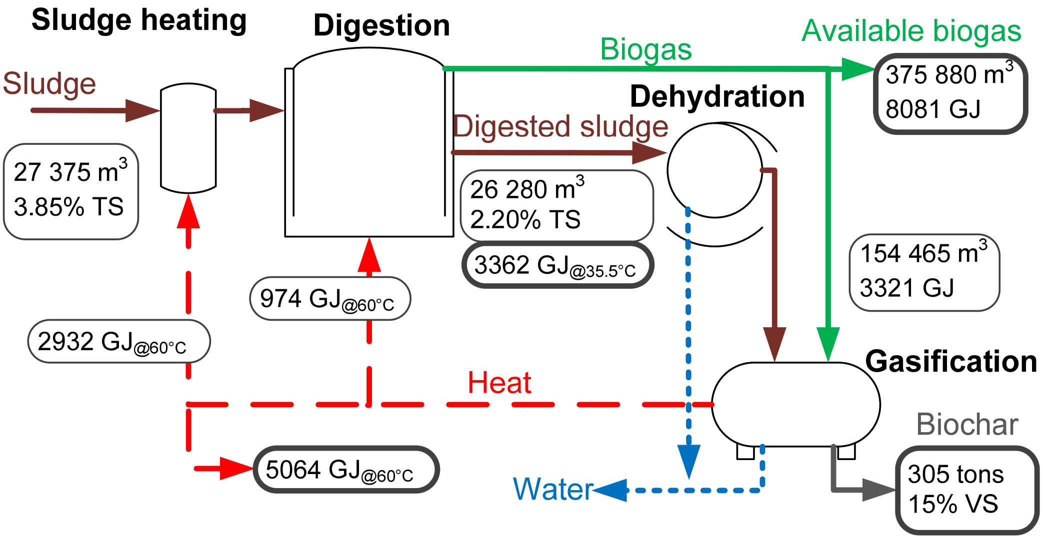

Figure 3. Anaerobic digestion and gasification process diagram

The coupled process proposes transfer of biogas to the gasifier. On the other hand, energy recovered from the gasifier (around 60°C) is used to heat the incoming sludge and the digester. The recoverable energy is 8081 GJ in the form of biogas, 5064 GJ of water at 60°C and 3362 GJ of sludge at 35.5°C. Losses are considered but not shown on the figure in order to ease understanding. Excess energy, excluding electricity consumption and heat available at 35.5°C, go up to 12.9 GJ • dry ton^{-1}.

DISCUSSION

For the anaerobic digestion, it is obvious that the main energy requirement is heating of incoming sludge. This is especially important because higher insulation of digesters can have a limited impact on energy consumption. Energy recovery from outgoing flow is technically challenging due to the nature of sludge and its low temperature differential. However the presence of a gasifier brings a new higher density source of energy to fulfill the AD needs. Therefore, it should deserve consideration in digestion system design. The excess energy result of 12.9 GJ per dry ton of sludge is coherent with other works but is probably overestimated. Excess biogas is a valuable resource and coupling of AD with gasification could potentially result in a 5% reduction of biogas use but produces a totally dry residue. Consequently, it would be wise to replace biogas for drying applications when applicable because it is a higher energy density and more versatile gas than syngas. Waste excess heat could be used to pre-dry the sludge which would reduce the biogas consumption even more. This leaves more potential for other uses such as biomethane upgrade for grid injection. Most of the heat generated by gasification in this experiment is in the form of hot water around 50 to 60°C. This abundant energy source includes recovered latent energy from condensation of flue gases. There is 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. Nevertheless, more complete calculations are required before attempting a full scale installation because of the many assumptions used for this work.

CONCLUSION

This project 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 energy efficiency improvement was possible by combining the two processes. A reduction of 35% of energy from biogas was obtained for the studied WWTP. Confidence in results would benefit from a more integrated large 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 downside the equipment such as in [15]. 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 agriculture or phosphorus extraction techniques should preferred.

ACKNOWLEDGEMENT

Authors are grateful for the research funders and partners: Ecosystem, Terragon, ÉTS, t3e industrial research chair, STEPPE, CRSNG, FQRNT, Recyc-Québec and Fondation unversitaire Arbour.

NOMENCLATURE

AD	Anaerobic digestion
DS	Digested sludge
HHV	Higher heating value
Nm^3	Normal cubic meters at 0°C and 1 bar
TS	Total solids
VS	Volatile solids
WWTP	Wastewater treatment plant

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