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Continuous thermal hydrolysis and anaerobic digestion of sludge. Energy integration study

S. I. Pérez-Elvira and F. Fdz-Polanco

ABSTRACT

Experimental data obtained from the operation in a pilot plant are used to perform mass and energy balances to a global process combining units of thermal hydrolysis (TH) of secondary sludge, anaerobic digestion (AD) of hydrolysed secondary sludge together with fresh primary sludge, and cogeneration from biogas by using a gas engine in which the biogas produces electricity and heat from the exhaust gases. Three scenarios were compared, corresponding to the three digesters operated: C (conventional AD, 17 days residence time), B (combined TH + AD, same time), and A (TH + AD at half residence time). The biogas production of digesters B and A was 33 and 24% better, respectively when compared with C. In the case of the combined TH + AD process (scenarios A and B), the key factors in the energy balance were the recovery of heat from hot streams, and the concentration of sludge. The results of the balances showed that for 8% DS concentration of the secondary sludge tested in the pilot plant, the process can be energetically self-sufficient, but a fraction of the biogas must by-pass the gas engine to be directly burned. From an economic point of view, scenario B is more profitable in terms of green energy and higher waste removal, while scenario A reduces the digester volume required by a half. Considering a population of 100,000 inhabitants, the economic benefit is 87,600 €/yr for scenario A and 132,373 €/yr for B. This value can be increased to 223,867 €/yr by increasing the sludge concentration of the feeding to the TH unit to a minimum value that allows use of all the biogas to produce green energy. This concentration is 13% DS, which is still possible from a practical point of view. Additional benefits gained with the combined TH + AD process are the enhancement of the digesters rheology and the possibility of getting Class A biosolids. The integration study presented here set the basis for the scale-up to a demonstration plant.

Key words | anaerobic digestion, biogas, mass and energy balances, sludge, thermal hydrolysis

S. I. Pérez-Elvira (corresponding author)
F. Fdz-Polanco
Department of Chemical Engineering and Environmental Technology,
University of Valladolid,
Spain
E-mail: *sarape@iq.uva.es*

ABBREVIATIONS

AD	anaerobic digestion
CHP	combined heat and power
DS	dry solids
HRT	hydraulic residence time
HWAS	hydrolysed waste activated sludge
TH	thermal hydrolysis
TPS	thickened primary sludge
TWAS	thickened waste activated sludge
VS	volatile solids
WAS	waste activated sludge

INTRODUCTION

Owing to environmental, economic, social and legal factors, the treatment and disposal of excess sludge represents a bottleneck for wastewater treatment plants.

In large plants, primary and secondary sludge are stabilised applying anaerobic digestion (AD), resulting in the elimination of volatile solids and the production of biogas. However, hydrolysis is the rate limiting step for the biological degradation of sludge (Li & Noike 1992; Shimizu *et al.* 1993), and therefore the process is slow, big digesters are used due to long residence time needed, and large quantities of biosolids are produced, as only 25–40% of the organic matter is degraded.

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By improving the hydrolysis step, solid substrates are more accessible to anaerobic bacteria, accelerating the digestion, increasing the volume of biogas produced and decreasing the amount of solids to be disposed. Among the different existing alternatives, mechanical, thermal chemical or biological (Pérez-Elvira *et al.* 2006), thermal pre-treatment has proven to be of great interest.

The advantage of the combined TH + AD process is that the energy input needed for the hydrolysis process is thermal energy, and could be satisfied from the energy production of its own process, resulting in an energetically self-sufficient process. A combination of thermal hydrolysis (TH) and AD is widely investigated in literature from a laboratory-scale point of view, regarding disintegration and biodegradability (Fisher & Swanwick 1971; Haug *et al.* 1978; Li & Noike 1992; Kepp *et al.* 1999; Kepp & Solheim 2001; Bougrier *et al.* 2007; Fernández-Polanco *et al.* 2008). However, to date it has not been possible to optimise the energy balance of the process making it autothermic, as the existing full-scale plants, developed by the Norwegian company Cambi, operate in batch, and therefore do not allow exploitation of the full energy integration benefits. In contrast, the broad existing experience gained on the technology in full-scale plants, state several benefits, such as the possibility to increase the digesters load, the biogas production increase, the enhancement of sludge dewaterability, and low odour pasteurised product.

The aim of this research was to use experimental data (Pérez-Elvira *et al.* 2011) as the basis of an economic study, combining a continuous TH unit with AD and cogeneration from the biogas. All the factors affecting the energy integration were considered, such as feeding segregation, alternatives for energy recovery from biogas, recovery of heat from hot streams, and input concentration to the thermal unit. For some of them a start point was taken based on an exhaustive previous research (Pérez-Elvira *et al.* 2008).

MATERIALS AND METHODS

Experimental operation and data

The study is based on the experimental results obtained from the operation of a pilot plant for eight months at the Municipal Wastewater Treatment Plant of Valladolid (Spain). The description of the operation and the results is presented in Pérez-Elvira *et al.* (2011).

The plant is composed of two units: the TH unit and the AD unit.

The TH unit was fed with thickened waste activated sludge (TWAS). The pilot plant consisted of a feeding tank, a progressive cavity pump, a boiler, a hydrolysis reactor, a flash tank and automatic valves for steam inlet and decompression. Sludge (10 L) was pumped into the reactor, and the pressure–temperature control was activated allowing the entrance of steam from the boiler to keep at 170 °C. At the end of the 30 min reaction time, the decompression valve was automatically opened and the hydrolysed sludge flowed to the flash tank.

The AD unit is composed of three mesophilic anaerobic digesters (200 L each), corresponding to the three scenarios studied (A, B and C). Digesters A and B correspond to the combined TH + AD process, while digester C is the 'control' corresponding to conventional digestion. Digesters B and C were fed with a mixture of primary and hydrolysed secondary sludge, and operated at the same load and residence time, while in digester A the load was doubled by reducing the HRT to half.

The performance of the digesters is not the aim of this paper, but main data are given in Table 1, as the basis for the energy balances presented in this study. Therefore, Table 1 presents a summary of the experimental set-up and performance.

A comparative brief analysis of the digesters performance show the following.

First, comparing digesters B and C, operated in the same conditions of HRT (17 days) and organic load (2.2–2.4 kg VS_{fed}/m^3 d), it is clear that the performance of digester B was better, giving 33% more biogas and a corresponding 30% increase in VS removal. This better yield is explained by the combined benefits of cell lysis, solubilisation and rheology during the thermal pre-treatment.

Second, the operation of digester A at double load (4 kg VS_{fed}/m^3 d) and half residence time still presented a very good performance of 23–25% enhancement of biogas yield and VS removal, which is very interesting from the point of view of making better use of the digesters, as the volume of digester needed can be reduced to half for the same biogas production.

Mass and energy balances

The definition of an operation scheme is the first step to perform balances.

The scheme of the conventional process (scenario C) is clear: feeding of mixed sludge, and biogas use in a combined heat and power (CHP) system to produce electricity.

Table 1 | Operation and performance of digesters A, B and C (Pérez-Elvira *et al.* 2010)

	Digester C	Digester B	Digester A
Process	Conventional AD	Combined TH + AD	
Feeding	Mixed sludge	Primary + hydrolysed WAS	
Feeding concentration (% DS)	7.0	7.0	
HRT (days)	17	17	9
Volumetric load (kg VS_{fed}/m^3 d)	2.4	2.2	4.0
Biogas yield ($L_{biogas}/(L_{reactor}.d)$)	1.1	1.4	2.4
Biogas yield (L/kg VS_{fed}) [*Improvement*]	488	652 [*33%*]	607 [*24%*]
VS removal [*Improvement*]	42%	55% [*30%*]	50% [*25%*]

For the combined TH + AD process (scenarios A and B), a process configuration must be defined, as the steam needed for sludge heating in the TH process depends on the energy integration scheme. A first approach allows the conclusion that, in order to reduce the heating requirements, the following aspects must be considered:

(i) Primary sludge presents a high biodegradability, and the energy to treat the primary sludge in the thermal unit is too high compared with the subsequent little increase in biogas. Therefore, the best option is to segregate primary and secondary sludge in order to treat in the TH unit only the biological sludge. This scenario corresponds to the research performed.
(ii) The use of the biogas produced in the AD to get the energy needed for the TH unit. When a boiler is used, the biogas is burned to generate all the steam needed, whereas the use of a gas engine allows getting not only steam, but also electricity. Therefore, as long as it is possible to fulfill the sludge heating requirements with a CHP system, it is a better option than burning.
(iii) The electric and thermal yield of a CHP system is different for gas engines and turbines, as the electric yield is higher for a gas engine. For this study, the use of a gas engine was considered, as most of the full-scale installations for energy recovery are of this kind.
(iv) The economic sustainability of the process relies on the possibility of getting the energy needed for the TH from its own process, and therefore some kind of energy integration must be considered. The recirculation of the vapours produced in the flash and the recovery of heat from the exhaust gases from the CHP system in a boiler were considered. Still, the heat from hot hydrolysed sludge and hot water from the gas engine are spare heat available. The configuration of the TH pilot plant does not allow this in practice, and therefore the results presented correspond to calculations.
(v) The quantity of steam required depends not only on the process configuration, but mainly on the concentration of the sludge. There is an input concentration for the secondary sludge that optimises the process defined by considerations (i), (ii), (iii) and (iv), and this value is 17% DS, which allows use of all the biogas produced for electricity generation, and to get all the steam needed in the TH unit from the exhaust gases from the gas engine. This concentration was too high to manage from a practical point of view in the pilot plant, and therefore the concentration of WAS in the real operation was 8% DS, considered as a first reference for the balances.

Therefore, the most profitable scheme consists of a continuous TH unit to exploit the energy integration possibilities that are impossible to consider in a batch process fed with secondary sludge, without including primary sludge, followed by the AD of the hydrolysed sludge together with fresh primary sludge.

Figure 1 presents the operation schemes for conventional and combined TH + AD.

RESULTS AND DISCUSSION

Results of the mass and energy balances

From the experimental data obtained during the operation of the digesters, mass and energy balances were assessed

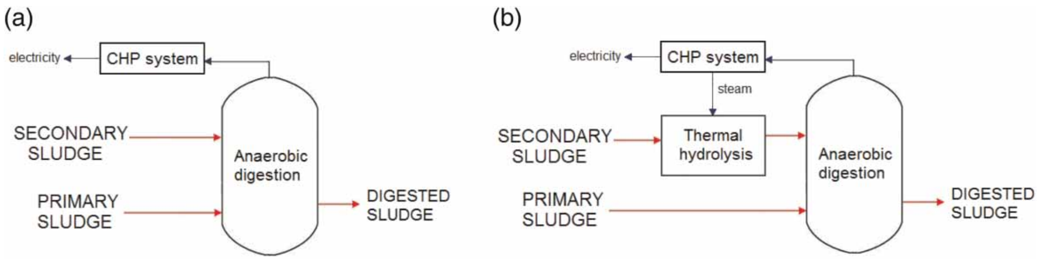

Figure 1 | Operation schemes selected for conventional AD (a) and combined TH + AD (b).

to evaluate the economics of the process and compare the enhanced digestion conventional digestion.

From the point of view of implementing the TH process in a new plant, the scenario of digester A can be preferred to B, as the digester volume required is half as a consequence of doubling the digester load. The drawback of this approach is that the biogas production in this case is smaller compared with process B. However, for an existing AD plant, option B can be preferred to A, as with the same digester volume, in order to exploit the biogas production increase and waste production decrease.

Therefore, the balances presented were performed considering the experimental operation and data for the three scenarios (A, B and C), in order to compare the different options from a global point of view, considering energy production, waste generation and foot print.

The mass and energy balances study is based on the real operation performed in the pilot plant (1 kg DS/d feeding) and on the results presented in Table 1.

Table 2 sums up the calculation basis for the three scenarios: conventional AD of mixed sludge with a cogeneration unit for biogas (C), and the combined TH + AD, composed by thermal pre-treatment prior to the AD, and the corresponding cogeneration from biogas (B and A).

Figure 2 presents the results of mass and energy balances for the conventional AD, and Figures 3 and 4 present the corresponding balances for the enhanced TH + AD process in scenarios A and B.

In this first approach, the real concentration of sludge tested during the plant operation (8% DS for WAS) was considered. For this concentration, the steam needed for sludge heating is approximately 2 kg of steam per kg of DS. The balances presented in Figures 3 and 4 allow the steam needed from the use of biogas produced during the AD in the CHP system to be obtained.

The results of the balances for the combined TH + AD process (Figures 3 and 4) show that the steam needed in the thermal process cannot be totally obtained from the

Table 2 | Calculation basis considered in mass and energy balances

Scenario	Digester C	Digester B	Digester A
Process	Conventional AD	Combined TH + AD	
Main figures	Mixed sludge fed: 1 kg DS/d; Secondary sludge: 0.4 kg VS/d; Primary sludge: 0.4 kg VS/d		
Thermal hydrolysis	No	Operation conditions: 175 °C for 30 min	
Anaerobic digestion	Continuous operation: 365 d/yr Feeding: TPS + TWAS Performance of digester C	Feeding: TPS + HWAS Performance of digester A	Feeding: TPS + HWAS Performance of digester B
Energy integration	Use of the biogas in a CHP system	Recovery of vapour in the flash; Recovery of heat from hot streams; Use of the biogas in a CHP system	
Gas engine	39% electric yield; 25% thermal yield (to exhaust gases)		
Exhaust gas boiler	64% efficiency of exhaust gases in boiler		

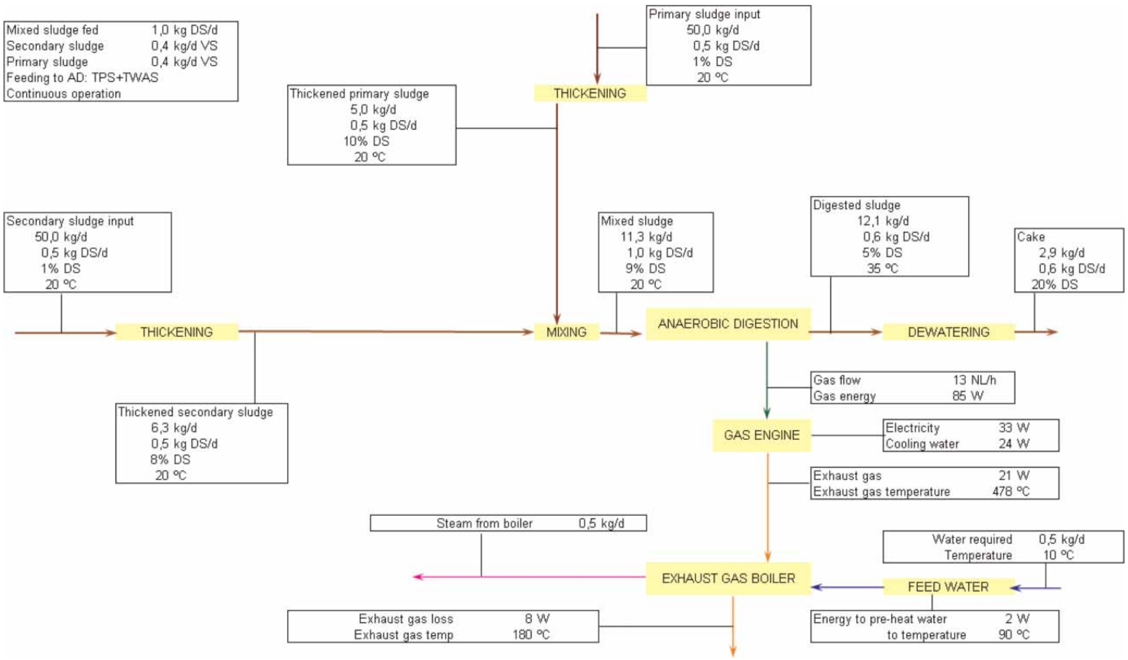

Figure 2 | Mass and energy balances for Scenario C (conventional AD, 17 d HRT), for 8% DS concentration in the WAS feeding and considering a CHP system for the biogas.

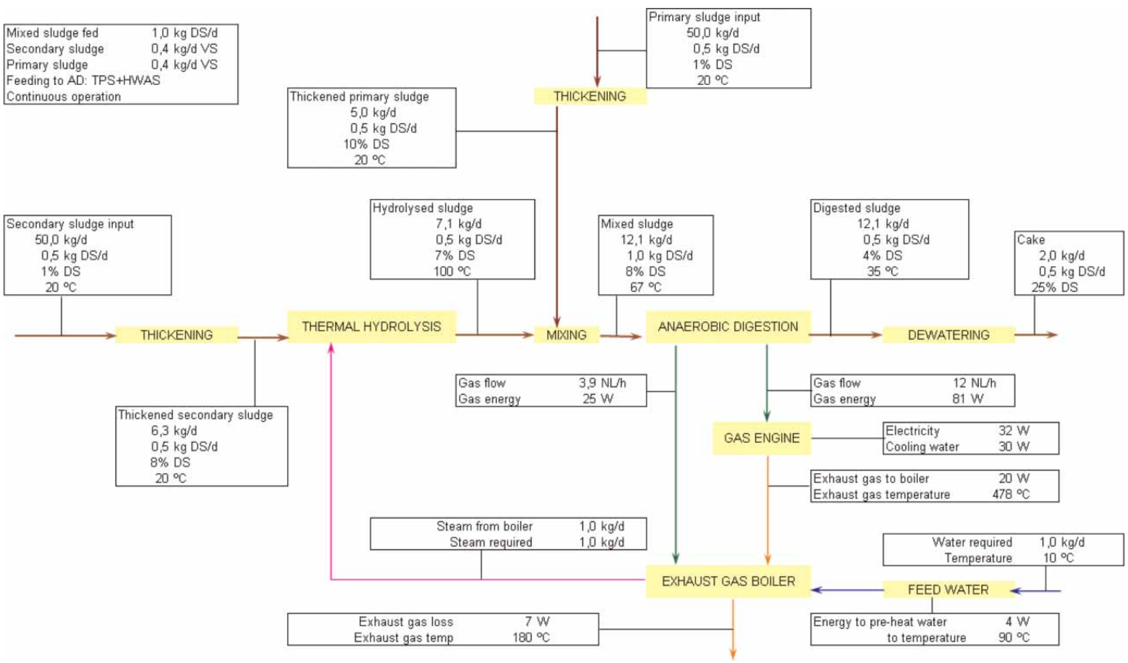

Figure 3 | Mass and energy balances for Scenario A (enhanced TH + AD process, 9 d HRT), for 8% DS concentration in the WAS feeding and considering a CHP system and boiler for the biogas use and steam generation.

exhaust gases of the gas engine, and therefore part of the biogas must be burned in the boiler to generate the steam needed for a self-sufficient process. In scenario A, the improvement in biogas production after the TH process (24%) matches with the fraction of biogas that must be burned in the boiler to fulfill the energy

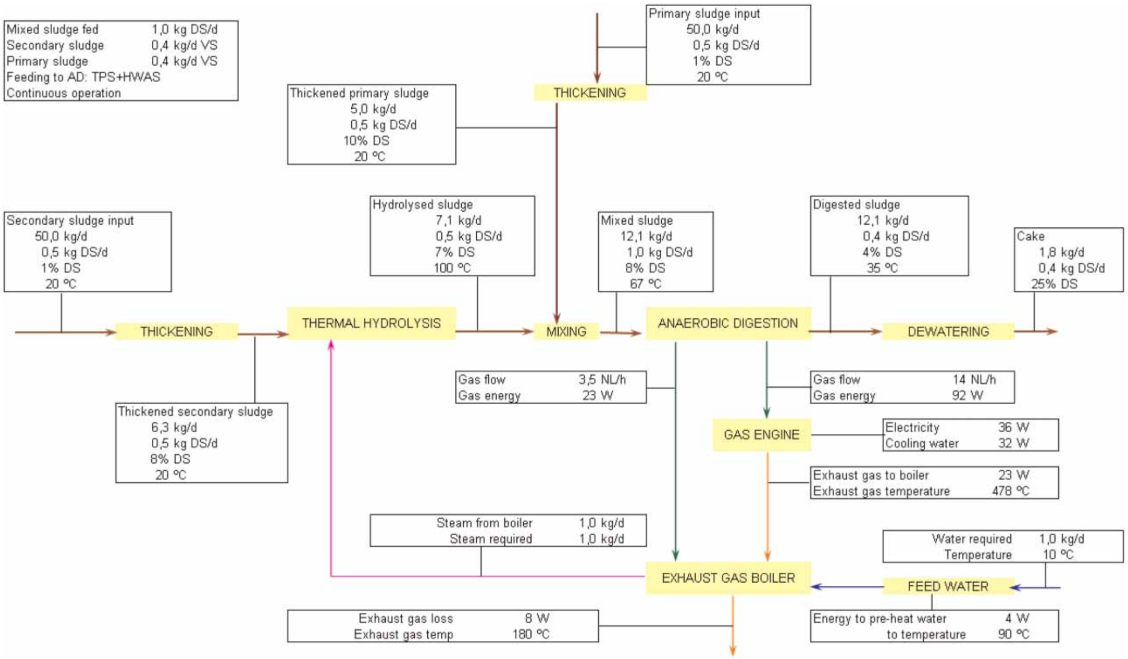

Figure 4 | Mass and energy balances for Scenario B (enhanced TH + AD process, 17 d HRT), for 8% DS concentration in the WAS feeding and considering a CHP system and boiler for the biogas use and steam generation.

requirements, while in scenario B, the fraction of biogas that must be burned (20%) is smaller than the biogas increase with the TH (34%).

With this configurations (A or B), it is possible to get the sludge heating requirements (1 kg steam/d) from the biogas produced in the most profitable way, resulting in a scheme energetically self-sufficient, that even produces surplus energy (32 W electricity in scenario A and 36 W in scenario B).

A comparison with the conventional process is needed to quantify the implications of the introduction of the TH unit. Table 3 presents the results of the balances in terms of electricity production, waste production and volumetric organic load.

Table 3 | Results of the energy integration study (expressed per kg DS treated and with respect to scenario C)

	Scenario C	Scenario A	Scenario B
Electricity (kWh/kg DS_{fed}) [*Improvement*]	0.78	0.78 [*0%*]	0.86 [*8%*]
Waste (kg/kg DS_{fed}) [*Improvement*]	2.9	2.0 [*31%*]	1.8 [*38%*]
Volumetric load (kg DS_{fed}/m^3 d) [*Improvement*]	3.1	5.7 [*82%*]	3.1 [*0%*]

The balances show different benefits, depending on the scenario: energy production and higher waste reduction in scenario B (as a consequence of the higher digester performance), but digester volume reduction for scenario A (due to the operation at double load).

The translation of these values into economic figures allows the difference between both scenarios to be clarified. Considering a population of 100,000 inhabitants and typical values for green energy income (0.16 €/kWh) and sludge disposal costs (40 €/ton), the economic benefit is 87,600 €/yr for scenario A and 132,373 €/yr for B. Therefore, for the implementation of the technology, it seems economically profitable considering option B.

There is still another option to make scenario B more interesting, which is the possibility of using all the biogas to produce green energy, instead of burning a fraction. This is only possible working with a higher concentration of the secondary sludge to the TH unit. The energy integration study performed for this option is presented in Figure 5 and shows that the concentration needed for the WAS is 13% DS, which is technically possible.

This last scenario allows the energy production from 0.865 to 1.1 kWh/kg DS_{fed} to be increased, for the same 1.8 kg waste/kg DS_{fed}. For a 100,000 inhabitant. population,

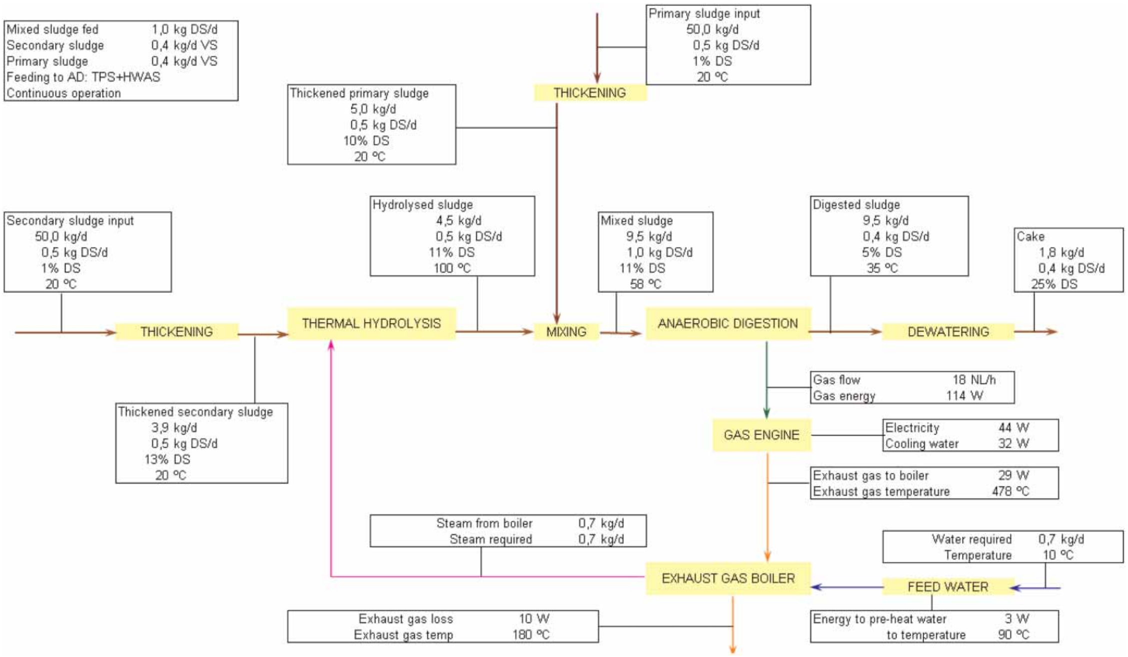

Figure 5 | Mass and energy balances for Scenario B (enhanced TH + AD process, 17 d HRT), for 13% DS concentration in the WAS feeding and considering a CHP system and boiler for the biogas use and steam generation.

these new values represent an income of 223,867 €/yr with respect to the conventional digestion.

CONCLUSIONS

A process scheme combining TH of secondary sludge and AD of the mixture with primary sludge was studied through the operation of pilot-scale digesters and mass and energy balance considerations. The energy integration was performed based on real values from the operation of the pilot plant, and considering the use of a gas engine and the recovery of heat from hot streams (flash vapours and exhaust gases). Three scenarios were compared: C (conventional AD), B (combined TH + AD), and A (TH + AD at half residence time).

Mass and energy balances to scenarios A and B show that, when feeding the TH unit at 8% DS concentration (possible with no polyelectrolyte), all the steam needed in the thermal process can be generated from the biogas, but part of the biogas must by-pass the gas engine and be burned in the boiler. Therefore, the TH + AD process is self-sufficient, and even economically profitable. Considering a population of 100,000 inhabitants, the economic benefit is 87,600 €/yr for scenario A and 132,373 €/yr for scenario B compared with the conventional process. The difference between both alternatives corresponds to the biogas benefit obtained in B, while in A no 'extra' biogas is obtained compared with C. For the implementation of the technology, option A would be preferred in the case of new plants limited by the size of the digester, as option A occupies half volume compared with conventional digestion.

The process can be more profitable when feeding the TH unit at a minimum of 13% DS concentration, which allows using all the biogas to produce energy instead of burning a fraction. The economic benefit in this case is 223,867 €/yr (for 100,000 inhabitants).

Other benefits are the viscosity reduction related to better digester homogeneity with lower mixing cost, and the improvement of the waste quality in terms of dewatering and hygienisation. Keeping the mixture of primary and hydrolysed secondary sludge at 75 °C for 30 min, the pathogen free waste (US EPA Class A) increases its added value, decreasing the disposal cost.

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REFERENCES

Bougrier, C., Delgenès, J. P. & Carrére, H. 2007 Effects of thermal treatments on five different waste activated sludge samples solubilisation, physical properties and anaerobic digestion. *Chemi. Eng. J.* **139** (2), 236–244.

Fernández-Polanco, F., Velázquez, R., Pérez-Elvira, S. I., Casas, C., Del Barrio, D., Cantero, F. J., Fernández-Polanco, M., Rodríguez, P., Panizo, L., Serrat, J. & Rouge, P. 2008 Continuous thermal hydrolysis and energy integration in sludge anaerobic digestion plants. *Water Sci. Technol.* **57** (8), 1221–1226.

Fisher & Swanwick 1971 High-temperature treatment of sewage sludges. *Wat. Pollut. Control* **70**, 355–373.

Haug, R. T., Stuckey, D. C., Gossett, J. M. & McCarty, P. L. 1978 Effect of thermal pretreatment on digestibility and dewaterability of organic sludges. *J. Wat. Pollut. Control Fed.* **50** (1), 73–85.

Kepp, U. & Solheim, O. E. 2001 Meeting increased demands on sludge quality – experience with full scale plant for thermal disintegration. In: *Proceedings 9th World Congress, Anaerobic Conversion for Sustainability*, Antwerp, Belgium, September 2001.

Kepp, U., Machenbach, I., Weisz, N. & Solheim, O. E. 1999 Enhanced stabilisation of sewage sludge through thermal hydrolysis – 3 years of experience with full scale plants. *Water Sci. Technol.* **42** (9), 89–96.

Li, Y. Y. & Noike, T. 1992 Upgrading of anaerobic digestion of waste activated sludge by thermal pre-treatment. *Wat. Sci. Technol.* **26** (3–4), 857–866.

Pérez-Elvira, S. I., Nieto-Diez, P. & Fdz-Polanco, F. 2006 Sludge minimization technologies. *Rev. Environ. Sci. BioTechnol.* **5**, 375–398.

Pérez-Elvira, S. I., Fdz-Polanco, F., Fdz-Polanco, M., Rodríguez, P. & Rouge, P. 2008 Hydrothermal multivariable approach. Full-scale feasibility study. *Electron. J. Biotechnol.* **11** (4) Article Number: 14, Published: OCT 15 2008.

Pérez-Elvira, S. I., Fdz-Polanco, F. & Fdz-Polanco, M. 2011 Continuous operation of a pilot plant combining thermal hydrolysis and anaerobic digestion of sludge. *X Latin American Workshop and Symposium on Anaerobic Digestion (DAAL)*, Ouro Preto, 23–27 October 2011.

Shimizu, T., Kudo, K. & Nasu, Y. 1993 Anaerobic waste activated sludge digestion-a bioconversion mechanism and kinetic model. *Biotechnol. Bioeng.* **41**, 1082–1091.

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