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Review

Energy feasibility study of sludge pretreatments: A review

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HIGHLIGHTS

- Pretreatments to sludge are efficient techniques to improve anaerobic digestion.
- Most of the pretreatments at lab-scale are not energy feasible in WWTP.
- Thermal pretreatments have higher energy feasibility than electric ones.
- Energy self-sufficiency is achieved in thermal hydrolysis plants with a CHP system.
- Sludge concentration is the key-parameter to reach energy self-sufficiency.

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ABSTRACT

Most of the pretreatments to sewage sludge in lab-scale studies show high potentials to be implemented in an anaerobic digester since they produce an increase in the biogas production. However, no energy assessments are usually considered in scientific reports. By making a simple evaluation of energy consumption by pretreatments, it can be stated that unfortunately not all the pretreatment technologies have an energy self-sufficiency to be implemented in a WWTP, requiring many times a continuous energy investment. Generally, pretreatments consuming electricity do not satisfy its energy demands from the biogas production in the same process, although high solubilization or biogas production increases are reached. Just ultrasounds applied in full-scale plants, with commercial technologies such as Sonix or Biosonator, provide an energetically self-sufficient pretreatment. In the case of thermal pretreatments, the potential to be implemented with full energy integration is much higher, since they can recover heat from the biogas engine as well as electrical energy in the same extent as for electric pretreatments. This way, full energy integration can be achieved in thermal hydrolysis plants; such is the case of commercial technologies such as Cambi, Exelys (Veolia) or CTH (Aqualogy). Several theoretical approaches and simulations also state that thermal hydrolysis presents a high potential to be fully integrated in WWTP with a complete energy recovery and self-sufficiency.

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1. Introduction

As a simplified model, wastewater is a diluted mixture of water and organic matter. From a thermodynamic point of view, the organic matter of wastewater can be considered as an energy source. All the organic compounds included in the wastewater contain energy stored within their chemical bonds. To perform energy balances, it is necessary to calculate the ‘energy content’ (EC) of the wastewater, what can be easily determined using calorific values of organic matter. According to Garrido et al. [1], in a conventional waste water treatment plant (WWTP) more than 60% of the initially diluted organic matter is concentrated as sludge (containing total and volatile solids: TS and VS respectively). Then, 60% of the initial energy content of the wastewater (3.2 MJ/kg TS) is now concentrated in the sludge (with a calorific value of 17.5 MJ/kg TS according to Werther and Ogada, 1999 [2]) and can be recovered as biogas produced in anaerobic digesters.

Anaerobic digestion is the key process to recover energy initially present in the wastewater. The improvement in digestion efficiency leads to increase energy production on the road to the energetically self-sufficient WWTP. Anaerobic digestion shows certain limitations in the first hydrolytic step, leading to slow degradation of the organic matter and too high retention times [3]. In order to improve the kinetics of anaerobic biodegradation of sludge, many pretreatment technologies have been tested with the aim of accelerating the hydrolysis limiting step and enhancing biogas productivity as well as the characteristics of the digested sludge. Pérez-Elvira et al. [4], Carrère et al. [5], Carlsson et al. [6] and Ariunbaatar et al. [7] have compiled most of these pretreatment techniques in very complete reviews. Some of these technologies tested at laboratory or pilot scale have been extrapolated to industrial scale and are operative in different WWTP. Thermal hydrolysis technology is the most spread technology to enhance sludge anaerobic digestion in WWTP. Since 1995, when the first Cambi thermal hydrolysis (THP) plant started up in Hamar, Norway [8], many other plants (up to 20) have adopted this technology. Other companies have recently commercialized their own thermal hydrolysis process for biosolids pretreatment, such as Biothelys (Veolia) in 2006 with ten full-scale operative plants, Exelys (Kruger-Veolia) in 2010 with one full-scale plant, Turbotec (Sustec) in 2011 with one pilot plant or CTH – continuous thermal hydrolysis – (Aqualogy) in 2012 with an industrial prototype. Other patented thermal hydrolysis technologies are under development to treat a wide variety of wastes: TPH (thermal-pressure-hydrolysis) by ATZ development center, TPP (thermo-pressure preparation) by NWT, Lysotherm (Stulz H + E) and Biorefinex (Biosphere Technology). Ultrasounds technology has also been worldwide applied in full-scale WWTP [9]. Sonix (Sonico, UK), Biosonator (Ultrawaves, Germany), smart DMS (Weber Ultrasonics) and Sonolyzer (Ovivo) are some of the patented technologies. Other pretreatments technologies to sewage sludge that have also been implemented in full-scale plants are high pressure homogenizers (MicroSludge – Pradigm Environmental Technology, Crown – Biogest, Cellruptor – Eosolids), OpenCEL focused-pulse technology [10], [11] and ozonization [12].

Table 1 shows the main technologies used at laboratory scale while Table 2 shows the main processes applied at industrial scale. It should be noted that commercial information is sometimes difficult to locate and standardize.

Given the high number of existing pretreatments, the aim of this work is to present the main guidelines to integrate pretreatment technologies in WWTP. Energy efficiency in WWTP is always an important issue when implementing new processes since WWTP are high electricity consumers. Literature on WWTP electricity consumption (kWh per cubic meter of wastewater treated) shows big differences among different facilities and countries. EPA [40] reports USA average values of 0.78 kW h/m^3, for Canada, Lidkea [41] found an average value of 0.35 kW h/m^3, Jonasson [42] obtains average value of 0.30 kW h/m^3 for Austria and 0.47 kW h/m^3 for Sweden, in Spain an average value of 0.51 kW h/m^3 is reported by Hernández-Sancho et al. [43], what entails an important economic and energy investment. Then, when pretreatments are implemented in anaerobic digesters from WWTP, a proper energy evaluation should be performed to check the real feasibility of these processes. Next, a useful and simple tool to assess process feasibility in terms of energy efficiency is described in order to evaluate the potential and sustainability of pretreatments.

Table 1
Pretreatment technologies tested at lab-scale.

	Pretreatments	References
Physical	High pressure homogenizer Impact grinding Electroporation/ Pulse electric fields Ultrasounds Microwaves	Nah et al. [13]; Engelhart et al. [14]; Bougrier et al. [15]; Climent et al. [16]; Donoso-Bravo et al. [17]; Pilli et al. [9]; Choi et al. [18]; Muller et al. [19]; Appels et al. [20]; Solyom et al. [21]; Perez-Elvira et al. [22]
Chemical	Acid Alkali Ozone	Kianmehr et al. [23]; Bougrier et al. [15]; Chu et al. [12]; Bohler and Siegrist [24]; Salsabil et al. [25]
Biological	Autoenzymatic External enzymes	Carvajal et al. [26]; Barjenbruch and Kopplow [27]; Davidsson et al. [28]; Hasegawa et al. [29]
Thermal	Heating freezing/thawing	Stuckey and McCarty [30]; Bougrier et al. [31]; Climent et al. [16]; Borges and Chernicharo [32]; Montusiewicz et al. [33]
Combined	Thermo-chemical Wet oxidation Thermal hydrolysis	Valo et al. [34]; Strong et al. [35]; Cacho Rivero and Suidan [36]; Donoso-Bravo et al. [37]; Perez-Elvira et al. [38]; Xu et al. [39]

Table 2
Pretreatment technologies applied at industrial scale.

Thermal hydrolysis	Ultrasounds	High pressure homogenizer	Pulse electric fields
Cambi (1995): 20 plants	Biosonator	MicroSludge	OpenCEL
Biothelys (2006): 10 plants	Sonix	Crown	PowerMod
Exelys (2010): 1 plant	Iwe.Tec	Cellruptor	
Turbotec (2011): 1 pilot	Smart DMS		
CTH (2012): 1 plant	Sonolyzer		
Lysotherm (2012): 1 plant	Hielscher		
Biorefinex (2013): 1 plant			

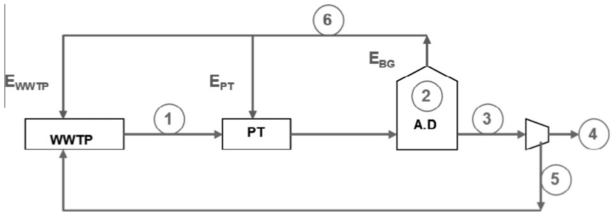

Fig. 1. Interaction between pretreatment (PT), anaerobic digestion (AD) and WWTP.

2. Energy interaction between pretreatment and WWTP

The main effects that pretreatments have on different substrates, as reported in literature [6], are: (i) particle size reduction, (ii) solubilization, (iii) biodegradability enhancement, (iv) formation of refractory compounds, (v) loss of organic material. As a matter of fact only the first three parameters are studied in most of the papers, while the last two parameters are referred only circumstantially. Pilli et al. [9] present a complete review of ultrasonic pretreatment of sludge evaluating sonication effect paying attention to particle size, dewaterability, settleabilty, solubilization, protein assessment and microbiological activity. Considering now the crucial aspect of energy consumption, the data presented in the section devoted to sludge biodegradability and methane production do not allow realistic energy balances to quantify energy consumption (kW h/m^3 sludge). In addition, these parameters refer only to the pretreatment itself and do not take into account the interaction between pretreatment and the WWTP plant.

According to Fdz-Polanco [44], Fig. 1 summarizes the physical links between the pretreatment and the rest of the elements of the WWTP. The circled numbers represent the WWTP streams or equipments which are affected by the presence of the pretreatment system. The main parameters affected in each location are shown in Table 3.

Comparing the parameters usually reported in scientific literature Carlsson et al. [6], Pilli et al. [9], Carrère et al. [5] and the parameters controlling technical and economic viability of the pretreatment process (Table 3), it is easy to verify that the objectives of scientific papers clearly differ from the technical requirements of the industrial scale. Among them, the key factors identified by Perez-Elvira et al. [45] in the energy balance are the recovery of heat from hot streams (6) and the concentration of sludge (1). First, it is immediately noticeable that the extra biogas produced in the digestion will directly influence the pretreatment feasibility, but the amount of recovered energy in terms of heat or electricity to the pretreatment is what would lead to an energy integrated process. On the other hand, the sludge concentration in the feed stream is one of the key parameters to assess the energy and economic feasibility of the pretreatment since it is directly related to the energy requirements per sludge volume (kW h/m^3 sludge). Most of the literature focuses on the biogas production increase with the pretreatment, without paying attention to the energy integration in the system and the influence of the sludge concentration. Hence, in this study, these two premises will be considered as starting points to perform an energy feasibility study of different pretreatment technologies: from theoretical energy considerations to the energy assessment of different lab-scale studies and industrial processes.

Table 3
Key parameters on pretreatment integration.

1. Sludge feed	Type of sludge (1°, 2°, mixed) concentration
2. Anaerobic digester	COD and VS removal Rheology (viscosity) Mixing energy Foam formation
3. Digestate	Dewaterability Filterability Centrifugability
4. Dewatered sludge	Sanitation PPCP's removal
5. Supernatant liquor	COD + nutrients Recycle to WWTP Recovery
6. Biogas	Energy to PT (electrical or thermal) and to WWTP (electrical)

3. Pretreatments energy feasibility

3.1. Energy balances

The energy production (E) in an anaerobic process can be expressed in a simplified model as a function of the process efficiency (η_{AD}) and the sludge concentration (c) fed into the system. Next, in a sequence of three equations, a simple mathematical correlation representing this statement is obtained; some typical values for sewage sludge have been substituted according to typical values from a municipal WWTP Metcalf and Eddy [46] and a calorific value of 11 kW h/N m^3 CH$_4$ for methane was set [47]

$$\begin{aligned}\text{Organic load} &= (\text{OL})\\ &= (\text{VS/TS})\ \text{kg VS/kg TS}\cdot(c)\ \text{kg TS/m}^3\\ &\quad\cdot(r_{\text{COD}})\ \text{kg COD/kg VS}\\ &= (0.7)\ (c)\ (1.4) = (0.98c)\ \text{kg COD/m}^3 \qquad (1)\end{aligned}$$

$$\begin{aligned}\text{Biogas produced} &= (B)\\ &= (\text{OL})\ \text{kg COD/m}^3\\ &\quad\cdot(\eta_{AD})\ \text{kg COD}_{\text{REM}}/\text{kg COD}\\ &\quad\cdot(r_{\text{CH4}})\ \text{Nm}^3\ \text{CH}_4/\text{kg COD}_{\text{REM}}\\ &= (0.98c)\ (\eta_{AD})\ (0.35)\\ &= (0.34\ c\ \eta_{AD})\ \text{Nm}^3\ \text{CH}_4/\text{m}^3_{\text{sludge}} \qquad (2)\end{aligned}$$

$$\begin{aligned}\text{Total energy} &= (E) = (B)\ \text{N m}^3\text{CH}_4/\text{m}^3\cdot(\Delta H_C)\ _{\text{CH4}}\text{kW h/N m}^3\ \text{CH}_4\\ &= (0.34\ c\ \eta_{AD})\ (11) = (3.77\ c\ \eta_{AD})\ \text{kW h/m}^3_{\text{sludge}}\end{aligned}$$

$$E = (3.77\ c\ \eta_{AD})\ \text{kW h/m}^3_{\text{sludge}} \qquad (3)$$

Anaerobic digestion efficiency (η_{AD}) can be considered as the biodegradability extent in the digestion and acquires typical values between 40% and 50% in full-scale digesters. In this study, an average value of 45% has been considered according to experimental

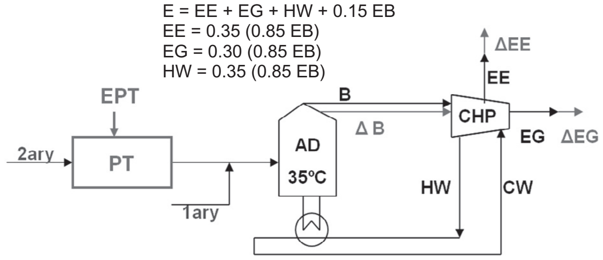

Fig. 2. Energy recovery from biogas with a CHP system.

values from sewage sludge [46]. However, when pretreatments are applied prior digestion, the biogas production and the biodegradation extent can surpass a 40% enhancement, leading to efficiencies over 60% [48]. This way, substituting these figures in Eq. (3) we obtain:

$$\text{Fresh sludge} \quad (\eta_{AD} = 0.45): \quad E_F = (1.70c)\ \text{kW h/m}^3_{\text{sludge}} \tag{4}$$

$$\text{Pretreated} \quad (\eta_{AD} = 0.63): \quad E_{PT} = (2.38\ c)\ \text{kW h/m}^3_{\text{sludge}} \tag{5}$$

Subtracting Eqs. (4) from (5), the amount of energy produced by the pretreatment can be expressed as $\Delta E = 0.68\ c$ kW h/m$^3_{\text{sludge}}$, which is less sensitive from the absolute values of η_{AD}, but from the relative increase between both of them (+40%). Therefore, these figures could be easily extrapolated to other WWTP data. In fact, it has to be remarked that the values here considered to obtain Eqs. (4) and (5) are average values taken as reference for implementing this methodology. However, if a study of energy feasibility for a specific scenario is pursued, the proper parameters values of the specific process should be considered to recalculate Eqs. (4) and (5).

The energy contained in the biogas has to be recovered and transformed in order to store it for selling or reuse it in the WWTP. A combined heat and power system (CHP) is an efficient way to produce electricity (EE) and recover heat in a gaseous stream at 400 °C (exhaust gases, EG) and in a liquid stream at low temperature (hot water, HW) (see Fig. 2). According to typical value of commercial biogas engines, 15% of the biogas energy (EB) is lost and, from the rest, 35% is converted into electric energy and 65% into thermal energy (30% in EG and 35% in HW). Unfortunately, most of the times, just the electric energy is useful and generates profit, which only represents a 30% of the total energy contained in the biogas.

Therefore, when a pretreatment is implemented in an anaerobic digester, its energy requirements (EPT) should be lower than the increase of electric energy that produces (ΔEE) in order to assure an energetically self-sufficient process. However, when talking about thermal pretreatments, the recovery of extra heat that is produced in the CHP (exhaust gases mainly, ΔEG) for the pretreatment step would lead to an efficient energy integration and the amount of energy which could be recovered for the pretreatment would be greater (ΔEG + ΔEE). This can be expressed as:

Pretreatments consuming:

$$- \text{Electricity} \quad EPT \leqslant \Delta EE \tag{6}$$

$$- \text{Heat} \quad EPT \leqslant \Delta EG + \Delta EE \tag{7}$$

From now on, the energy feasibility assessment will be considered separately for both pretreatment types. These inequalities could be arranged and expressed as a function of c, combining them with Eqs. (4) and (5) and considering: $\Delta E = E_{PT} - E_F$

Pretreatments consuming:

$$- \text{Electricity} \quad EPT \leqslant \Delta EE = 0.35(0.85\Delta E) = (0.20\ c)\ \text{kW h/m}^3_{\text{sludge}} \tag{8}$$

$$- \text{Heat} \quad EPT \leqslant \Delta EG + \Delta EE = 0.30(0.85\Delta E) + 0.35(0.85\Delta E) = (0.37\ c)\ \text{kW h/m}^3_{\text{sludge}} \tag{9}$$

3.2. Pretreatments consuming electricity

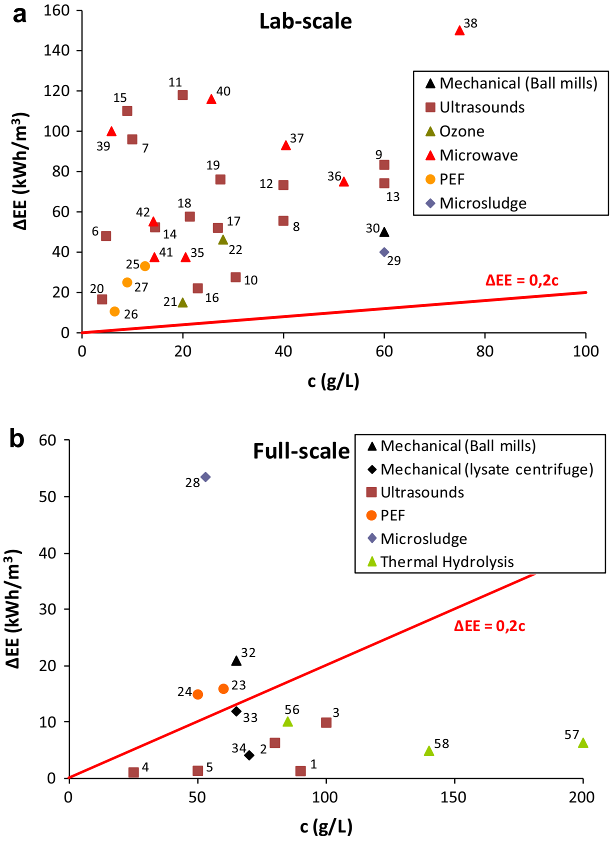

Fig. 3. Pretreatments consuming electricity: (a) lab-scale and (b) full-scale.

Most of the pretreatments (ultrasounds, microwaves, ozonization, pulse electric fields, high pressure homogenizers…) usually use electricity as energy source, which could be produced from the biogas in the same system. This would lead to a lower footprint, but in the other hand it would reduce the net profits of the digestion since the green electricity sold is lower. According to Eq. (8), the energy consumption during these pretreatments should be lower than:

$$EPT \leqslant (0.20\ c)\ \text{kW h/m}^3_{\text{sludge}} \tag{10}$$

The maximum energy consumed is a linear function of the sludge concentration, what means that the energy invested in the pretreatment increases proportionally as the solids content in the sludge rises (0.2 kW h for each kg TS). This simple Eq. (10) enables a quick evaluation of different pretreatment techniques, either applied at lab-scale or industrial scale, to check if the energy balances are satisfied and the process is energetically self-sufficient. Plotting the previous Eq. (10) in a graph representing the energy input versus the sludge concentration (Fig. 3, [2]red line), the different pretreatments can be placed according to energy consumptions obtained in literature and shown in Table 4: lab-scale studies on one hand, and full-scale results on the other (Fig. 3).

At a glance, the fact of representing separately lab-scale and full-scale results shows immediately the main conclusion: all lab-scale experiments lead to energetically inefficient pretreatments (points above the line) and full-scale ones reduce considerably their energy consumptions, leading in some cases to energetically self-sufficient pretreatments (points under the line) but not in all of them.

Ultrasounds pretreatment shows the most interesting behavior: lab-scale works have shown spread energy consumptions in a wild range (27–118 kW h/m$^3_{\text{sludge}}$) for different sludge concentrations (5–60 g/L) leading to quite heterogenic results but all of them far away from energy efficiency. In fact, Şahinkaya and Sevimli [62], after per-

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[2] For interpretation of color in Fig. 3, the reader is referred to the web version of this article.

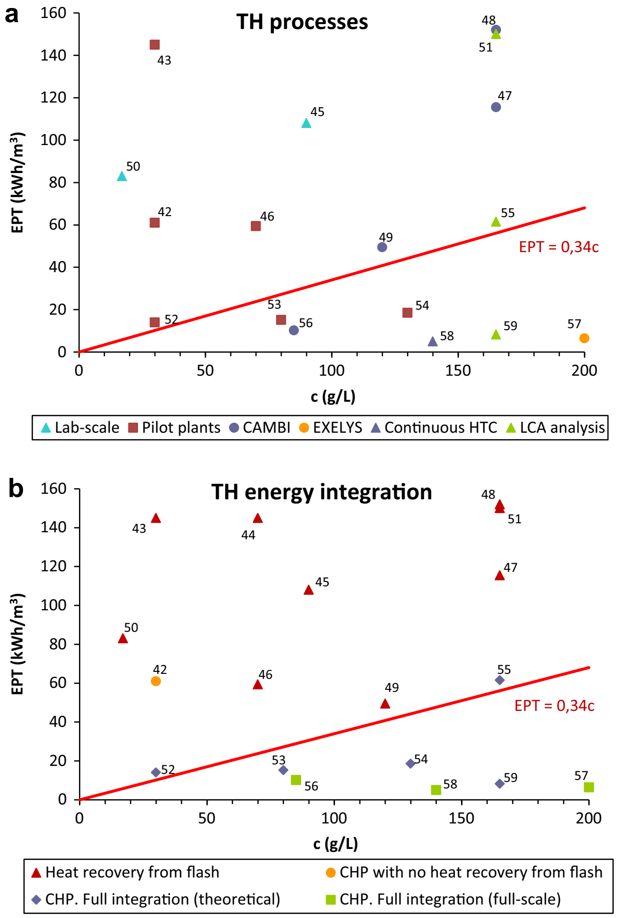

Fig. 4. Pretreatments consuming heat according to (a) technology and (b) energy integration.

forming some sono-thermal pretreatments to sewage sludge at lab-scale and an economical analysis, claimed that sonolysis is economically unfeasible due to its high energy requirements (producing losses of 1.42 $ per ton of sludge). On the other hand, talking about commercial sonicators (full-scale), ultrasounds enable treating concentrated sludge (till 10%TS) with low energy consumption (below 10 kW $\mathrm{h/m^3_{sludge}}$), what explains the wide extent of this pretreatment worldwide in WWTP. According to Ariunbaatar et al. [7], ultrasound pretreatment could be energetically feasible if a typical value of 6 kW $\mathrm{h/m^3}$ sludge for a full-scale application is considered (what in effect fits with the results here presented, corresponding with the maximum energy consumption for a sludge concentration over 30 g/L). If higher energy is required, another technology should be more appropriate.

Among the other technologies (concerning full-scale processes), mechanical grinding with ball mills and pulse electric fields (PEF) are placed in the limit of energy inefficiency, so they would not lead to any profit in the digestion process since all the extra energy obtained in the digester is back invested in the pretreatment. High pressure homogenizer (Microsludge) shows a strong negative energy balance and in no case could be considered as energetically efficient. Just mechanical disintegration with a lysate centrifuge could lead to an energy feasible pretreatment, although scarce information is available and a small profit could be obtained. Fig. 3b also shows some points from thermal hydrolysis pretreatment implemented in full-scale (although it is not an electricity consumer, but a thermal pretreatment, which will be later presented and discussed) just to compare their energy demand with pretreatments consuming electricity.

In the previous comparison, it is assumed that the same biogas production increase (40%) is taking place for all pretreatments, what is certainly untruth. However, this simplification enables a quick and easy comparison despite considerable uncertainties take place. Then, another alternative methodology has been developed: the relative biogas production increase (ΔB) that is needed to fulfil the energy requirements for each pretreatment (EPT) is calculated considering the same premise that just ΔEE could be used (Table 4). This way, the calculated biogas increase needed to make energy sufficient the pretreatment can give an idea of the feasibility of each pretreatment individually. From the values of Table 4, a very similar conclusion to the previous one can be deduced: lab-scale pretreatments require biogas increases over 100% (sometimes even over 1000%) what shows the energy unfeasibility of these pretreatments at these conditions, since these increases are not attainable in real processes. However, when talking about full-scale processes, energy feasibility is attainable (except for high pressure homogenizers): ultrasounds need biogas increases below 20% and a lysate centrifuge between 10% and 35%. Then, ball mills and PEF techniques require around 50–60% biogas increases, which could be hardly reached or in the limit of applicability concerning energy consumption.

3.3. Pretreatments consuming heat

In order to address this kind of pretreatments, different approaches can be considered. First, it has to be said that Eq. (9) leads to an inequality where a thermal energy term is added to an electrical energy term, what is a priori inconsistent. However, the resulted energy is the total amount of energy that could be recovered back to the pretreatment to satisfy its needs, either electrical or thermal, and is equivalent to Eq. (8) for electric pretreatments.

$$\mathrm{EPT} \leqslant (0.37\ c)\mathrm{kW\ h/m^3_{sludge}} \tag{11}$$

On the other hand, when a co-generation system (CHP) is considered to recover heat and electricity from biogas, just the hot gases thermal fraction (ΔEG) can be reused for the pretreatment requirements, since the electric fraction (ΔEE) will represent a net profit or will be dedicated to satisfy the electric requirements of the process. This way, the inequality would be expressed by the next system of Eqs. (12) and (13):

$$\mathrm{EPT_{thermal}} \leqslant \Delta\mathrm{EG} = (0.17c)\ \mathrm{kW\ h/m^3_{sludge}} \tag{12}$$

$$\mathrm{EPT_{electric}} \leqslant \Delta\mathrm{EE} = (0.20c)\ \mathrm{kW\ h/m^3_{sludge}} \tag{13}$$

However, taking into account that thermal pretreatments require thermal energy as energy source, it could be more appropriate to consider a biogas boiler which converts biogas energy into heat with an overall efficiency of 90%, which could be more efficiently reused in the pretreatment process. This way no electric energy is misused and maximum heat can be recovered. Then, inequality (12) is transformed into:

$$\mathrm{EPT} \leqslant (0.34c)\ \mathrm{kW\ h/m^3_{sludge}} \tag{14}$$

As it is reported by Carrère et al. [5], this thermal energy is generally in excess as compared to the WWTP needs and is one big advantage of thermal treatments.

Representing Eq. (14) in a graph (Fig. 4), it is obtained a very similar plot as for electrical pretreatments in Fig. 3, but with a line of different slope. It is noteworthy that the slope (0.34 kW h/kg TS) is 68% higher than the electric one (0.20 kW h/kg TS), what implies that the amount of thermal energy available for the pretreatment is higher than the electric one when considering a CHP system. This shows interesting perspectives concerning energy integration

Table 4
Electrical energy consumption (EC) by different pretreatments and theoretic expected biogas increase by pretreatments to fulfil their energy requirements (ΔB).

	No.	EC (kW h/m^3)	c (g/L)	ΔB (%)	Lab-scale	Full-scale	Reference
Ultrasounds	1	1.4	90	2.9		x	Sonix [22]
	2	6.4	80	14.8		x	Biosonator [22]
	3	10	100	18.6		x	IWE TEc [22]
	4	1.2	25	8.6		x	Xie et al. [49]
	5	1.4	50	5.3		x	Barber [50]
	6	47.9	4,8	1851.4	x		Wu et al. [51]
	7	96	10	1781.1	x		Wang et al. [52]
	8	55.5	40	257.4	x		Zhang et al. [53]
	9	83.3	60	257.6	x		Zhang et al. [53]
	10	27.6	30.5	167.9	x		Hart [54]
	11	117.9	20	1093.7	x		Visscher and Langehove [55]
	12	73.3	40	340.0	x		Visscher and Langehove [55]
	13	74.2	60	229.3	x		Visscher and Langehove [55]
	14	52.4	14.5	670.5	x		Feng et al. [56]
	15	110	9	2267.6	x		Chu et al. [57]
	16	22.1	23	178.3	x		Pham et al. [58]
	17	52	27	357.3	x		Bougrier et al. [59]
	18	57.6	21.4	499.4	x		Erden and Filibeli [60]
	19	76	27.5	512.7	x		Zhang et al. [61]
	20	16.6	4	769.9	x		Şahinkaya and Sevimli [62]
Ozone	21	15	20	139.1	x		Chu et al. [12]
	22	46.2	28	306.1	x		Bernal-Martinez et al. [63]
Pulse Electric Field (PEF)	23	16	60	49.5		x	OpenCEL [10]
	24	15	50	55.7		x	PowerMod [11]
	25	33	12.5	489.8	x		Lee and Rittmann [64]
	26	10.5	6.5	299.7	x		Salerno et al. [65]
	27	25	9	515.4	x		Zhen et al. [66]
High pressure homogenizer	28	53.6	53	187.6		x	Microsludge [67]
	29	40	60	123.7	x		Onyeche and Schafer [68]
Ball mills	30	50	60	154.6	x		Boehler and Siegrist [69]
	31	360	80	834.9	x		Perez-Elvira [70]
	32	21	65	59.9		x	Muller et al. [19]
Lysate centrifuge	33	12	65	34.3		x	Muller et al. [19]
	34	4.2	70	11.1		x	Jenicek et al. [71]
Microwaves	35	37.5	20.6	337.7	x		Qiao et al. [72]
	36	75	52	267.6	x		Kuglarz et al. [73]
	37	93	40.5	426.0	x		Appels et al. [20]
	38	150	20	371.1	x		Solyom et al. [21]
	39	100	5.9	3149.9	x		Wang et al. [74]
	40	116	25.7	837.4	x		Ahn et al. [75]
	41	37.5	14.4	483.1	x		Yu et al. [76]
	42	55.2	14.2	721.2	x		Ebenezer et al. [77]

Table 5
Energy consumption by thermal hydrolysis and theoretic expected biogas increase in pretreatment to fulfil its energy requirements.

Energy integration	No.	EC (kW h/m^3)	c (g/L)	ΔB (%)	Theoretical	Lab-scale	Full-scale	Reference
No heat recovery from flash (CHP)	42	61	30	146.7	x			Perez-Elvira et al. [45]
Heat recovery from flash	43	145	30	348.7	x			Perez-Elvira et al. [45]
	44	145	70	149.5	x			Theoretical calculation
	45	108	90	86.6		x		Carrère et al. [5]
	46	59.4	70	61.2	x			Perez-Elvira et al. [45]
	47	115.5	165	50.5			x	Cambi design value [78]
	48	152	165	66.5			x	Cambi Howdon WWTP [79]
	49	49.5	120	29.8			x	Cambi [80]
	50	83	17	352.3		x		Pérez-Elvira [81]
	51	150	165	65.6	x			LCA [82]
Full integration (CHP)	52	14	30	33.7	x			Perez-Elvira et al. [45]
	53	15.2	80	13.7	x			Pérez-Elvira and Fdz-Polanco [83]
	54	18.5	130	10.3	x			Pérez-Elvira et al. [84]
	55	61.5	165	26.9	x			LCA [82]
	56	10.2	85	8.7			x	Cambi Dublin WWTP [85]
	57	6.4	200	2.3			x	Exelys-Veolia (Hillerod WWTP)
	58	5	140	2.6			x	CTH (Valladolid WWTP) [84]
	59	8.25	165	3.6	x			LCA [82]

feasibility. Then, in Fig. 4, several thermal pretreatments obtained from different sources (lab-scale and pilot scale plants from scientific papers, commercial technologies or theoretical studies) have been plotted with points according to their energy consumption and sludge concentration (shown in Table 5), in the same way as previously. It has to be mentioned that this study has focused in thermal hydrolysis (TH) pretreatment, since it offers a big opportunity to be energetically integrated in a plant because it consumes steam, but also offers a high potential to hydrolyze microbial cellular material from sludge because the steam explosion at high pressure. Moreover, scientific and commercial thermal hydrolysis literature provides a large number of available references and data with which to work. On the contrary, pure thermal processes with sludge have just been applied at lab-scale and scarce research has been done in a higher extent.

Again, the relative biogas production increase (ΔB) that is needed to fulfil the energy requirements for the pretreatment (EPT) is calculated considering the same premise as for electric pretreatments, but in this case considering a boiler which burns biogas (Table 5). This way, the calculated biogas increase needed to make thermal hydrolysis pretreatment energy sufficient can give an idea of its feasibility. At a glance, it is clearly appreciated that full energy integration is required to drop ΔB below easily attainable values (below 35%). It is true that just recovering heat from flash could lead to certain feasible points, with biogas increases between 50 and 70%. In fact, there is literature which reports such biogas increases when applying thermal hydrolysis [5]. Compared with electric pretreatments, it is immediately appreciate that thermal pretreatments with thermal hydrolysis technology require lower biogas enhancement than electric ones.

First of all, the data in Fig. 4 show very diverse results in spite of talking about the same pretreatment: the range of sludge concentration that could be treated (rising up to 200 g/L) is very wide and the amount of energy needed (from 5 to 145 kW h/m^3) varies considerably. On one hand, different processes have been distinguished (Fig. 4a): lab-scale studies [5] present high energy consumptions above the red line, showing a lack of energy integration; pilot plants do not present a clear pattern, there are efficient plants which could treat till 13%TS sludge with a proper energy integration design [79] or very inefficient processes with huge energy consumptions [45]; finally, industrial plants with commercial technologies are also represented. Among them, there are spread technologies such as Cambi which energy inputs have lead to non-optimized processes (such is the case of Howdon WWTP [82], where a support fuel is needed) since a fully integrated system has not been considered. There are also processes with full energy integration, where all the steam required is produced from the biogas in a CHP and the electric energy demand is very low; such is the case of Cambi plant in Dublin WWTP [85] or continuous processes (Exelys in Hillerod WWTP or CTH prototype plant in Valladolid WWTP). A theoretical approach performed by Mills et al. [80] based on life cycle assessment (LCA) clearly shows for a certain sludge concentration (16.5%TS) how energy integration of thermal hydrolysis pretreatment affects on the energy consumption in different scenarios: biogas sent to grid (150 kW h/m^3), partial recovery of heat with a support natural gas (62 kW h/m^3), full energy integration with a CHP system (8 kW h/m^3).

In Fig. 4b, the same data have been plotted according to the energy integration setup. The simplest configuration is the thermal hydrolysis process with heat recovery from flash to the pre-heating stage, but no thermal energy is recovered from the biogas (no CHP); this is the basic design of Cambi [81] and all new pilot and industrial plants apply this configuration to reduce the steam requirements. Then, there is one pilot plant in which no heat recovery from the flash took place, but a CHP system was considered to recover heat for calculations [45]. Finally, fully integrated systems consider a CHP engine to burn biogas, produce electricity and recover heat; here we can find full-scale plants (Cambi in Dublin, Exelys in Hillerod or CTH in Valladolid) or theoretical estimations based on pilot plants results [45] or on LCA studies [80]. From these results, it is clearly appreciable how energy integration affects: while most of the non-integrated processes are placed above the red line, fully integrated processes (either real plants or theoretical approaches) show very low energy demands and are most of them placed below the red line. Among them, continuous processes (Exelys and CTH) show the best energy integration results and a wide margin respect to the maximum heat consumption limit (red line), spending just 9% and 10% of the thermal energy produced in the boiler respectively to treat highly concentrated sludge (20%TS and 14.5%TS respectively).

3.4. Other pretreatments

It has to be mentioned that no attention has been paid to other pretreatments that could be ascribed to different categories, such as the chemical or biological ones. In these cases, an external agent (acid, alkali, enzymes) is added, what entails an associate cost but not an energy requirement. Since this study focuses in energy aspects and feasibility, it is not possible to introduce these pretreatments unless an economical assessment is performed. However, this is not the aim of this study and therefore these pretreatments were excluded.

4. Pretreatments feasibility limits

To conclude, the limits of the pretreatments feasibility are studied theoretically: working with the same equations previously presented, the values for which the pretreatments begin to satisfy the energy requirements themselves are determined.

First, for pretreatments consuming electricity, a standard sludge concentration of 150 g/L has been set. Then, according to Eq. (10), the maximum energy consumption by the pretreatment is 30 kW h/m$^3_{\text{sludge}}$. This value is the limit below which the pretreatment will start to produce a net benefit for the process and is clearly represented by Eq. (10).

Concerning pretreatments consuming heat, the study is addressed from a different point of view: energy consumptions by thermal pretreatments are determined according to different energy integration configurations and then, the minimum sludge concentration is determined with the help of previous equations. This way, different approaches have been considered:

- No heat integration: no heat is recovered at all. The sludge is fed at 20 °C and has to be heated up to 170 °C. Energy requirements ascend to 205 kW h/m$^3_{\text{sludge}}$.
- Heat recovery from flash: steam vapors from flash are recycled to a preheating stage, where sludge is heated to 105 °C. The energy demand is reduced to 116 kW h/m$^3_{\text{sludge}}$.
- Thermal heating: the sludge is just heated to 170 °C, with a heat exchanger to recover heat from the output to the input. Thermal requirements are just 65 kW h/m$^3_{\text{sludge}}$. It is not anymore a thermal hydrolysis process, but a thermal heating pretreatment: no pressure and no steam explosion takes place.
- CHP full integration: complete energy integration is achieved with a CHP system. All heat requirements are satisfied by the exhaust gases from CHP and electrical requirements, estimated around 10–15 kW h/m$^3_{\text{sludge}}$, have to be satisfied by the CHP electricity co-generation.

For this last case, Eq. (13) has to be evaluated due to the electrical nature of the energy demand. For the other first three cases, a preferred scenario in which the whole thermal stream from a CHP - obtained from the overall biogas stream (EG + ΔEG), not just from the extra produced by the pretreatment (ΔEG) – and the electric extra generation (ΔEE) are considered for the calculation, in order to provide the most favorable scenario in which the overall

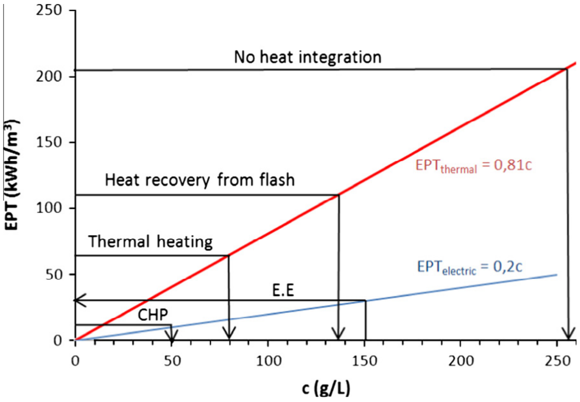

Fig. 5. Pretreatments feasibility limits.

Table 6
Pretreatments feasibility limits.

Pretreatments consuming	Energy integration	Energy demand (kW h/m^3_{sludge})	Sludge concentration (g TS/L)
Electricity	–	30	150
Heat	No heat integration	205	253
	Heat recovery from flash	116	143
	Thermal heating	65	80
	CHP full integration	10–15	50

thermal energy from the CHP is back invested in the pretreatment. In that case, the equation turns into:

$$EPT < 0.81c\ \text{kW h}/m^3_{sludge}. \tag{15}$$

As it is observed in Fig. 5 and Table 6, the minimum sludge concentrations to satisfy the previous energy demands drop down as the energy integration level rises. For the non-integrated system, a minimum sludge concentration over 250 g/L has to be achieved, what is certainly unfeasible from an operational point of view. When heat is recovered from the flash, the sludge must contain at least 143 g/L total solids, being much more attainable with a conventional centrifuge. A thermal heating process looks a priori more advantageous since just 80 g/L have to be reached to satisfy the energy demand. However, heating sludge does not offer the same advantages as thermal hydrolysis does (high disintegration power by steam explosion). Moreover, if a thermal hydrolysis plant includes a CHP system efficiently integrated, sludge has to be thickened just over 50 g/L, although a higher concentration would increase linearly the net profits of the plant by the extra electric energy output (with a rate of 0.2 kW h/kg $TS_{increase}$).

Finally, it can be affirmed that the sludge concentration is the key-parameter for energy integration of pretreatments and then, for energy integration of the whole WWTP. In fact, Jenicek et al. [71] state that thickening activated sludge is one of the key-measures to reach energy self-sufficiency in WWTP, at the same time of maximizing biogas (and electricity) production, also enhanced by pretreatment techniques.

5. Conclusions

Not all the pretreatment technologies have an energy self-sufficiency to be implemented in a WWTP. Generally, pretreatments consuming electricity do not satisfy its energy demands from the biogas production in the same process, except ultrasounds applied in full-scale plants (Sonix, Biosonator). In the case of thermal pretreatments, the potential to be implemented with full energy integration in WWTP is much higher, since they can recover heat from the biogas engine. This way, full energy integration can be achieved in thermal hydrolysis plants (Cambi, Exelys, CTH) and theoretical approaches set a minimum sludge concentration of 5%TS, as the main key factor to assure energy self-sufficiency.

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