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Optimum energy integration of thermal hydrolysis through pinch analysis

D. Fernández-Polanco [a, *], H. Tatsumi [b]

[a] teCH$_4^+$, San Agustín 16 2° Izq., Valladolid, 47003, Spain
[b] Simulation Technology, Ltd. 1-1-1 Fukuura, Kanazawa-ku, Yokohama, 236-0004 Japan

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ABSTRACT

Anaerobic digestion, a well-established technology to generate biogas from sewage sludge, is constrained by the hydrolysis (or solubilization) stage. Several pretreatments attempt to overcome this limitation, with thermal hydrolysis emerging as the technology of choice due to its techno-economic advantages. The objective of this work is to optimize the integration of this energy intensive pretreatment within the wastewater treatment plant, ensuring that the digestion performance improves in an energy-efficient way. By applying pinch analysis, a methodology to optimize energy systems, a strategy is suggested that selects a second-generation thermal hydrolysis technology designed to recover all process vapors, defines the optimum combined heat and power scheme to ensure an efficient integration and determines the minimum sludge feed concentration to guarantee energy self-sufficiency, the recovery of all waste heat and the minimization of expensive polyelectrolyte use.

1. Introduction

Anaerobic digestion is a well-established technology to generate biogas from organic matter, importantly from sewage sludge. This biogas can be directly used to produce electrical and thermal energy or, after upgrading, it can be transformed into biomethane and be injected in the natural gas grid or used by the automotive sector [1–3].

Anaerobic digestion is limited by the hydrolysis (or solubilization) stage. To overcome this limitation, different types of pretreatments have been suggested: biological (enzymatic), chemical (ozonization, acid or alkaline hydrolysis), physical (ultrasonic, pulses, high-pressure homogenization, centrifuge) and thermal (thermal hydrolysis). An abundance of literature [4–6] discusses the relative merits of each technology. Among those, thermal hydrolysis (TH) has emerged as the pretreatment of choice due to its techno-economic benefits [7]: increased biogas yields, reduced biosolid volume, biosolid pasteurization to EPA Class A standards and at least a twofold increase in organic loading rates to the anaerobic digesters.

Alongside these advantages, the main drawback of thermal hydrolysis is a significant energy consumption [8]. The objective of this work is to optimize the energy integration of the thermal hydrolysis within wastewater treatment plant (WWTP), ensuring that this technology improves the anaerobic digestion performance in an energy-favorable way. To achieve this aim, a two-pronged approach is used: (i) minimize thermal hydrolysis energy consumption by selecting a process design that includes all the energy efficiency measures (ii) optimize the integration of the TH plant within the WWTP energy system, exploiting the synergies with the different combined heat and power (CHP) technologies.

A powerful tool to assist in this endeavor is pinch analysis, an energy systems optimization methodology. Although the application of pinch technology is a standard in process industries, it has been traditionally neglected by the water industry, probably due to the simplicity of its energy systems. Now, the layer of complexity introduced by the integration of thermal hydrolysis pretreatments acts as the prerequisite to fill this gap.

2. Material

The baseline for this work is a WWTP treating the sewage produced by a 1,250,000 population equivalent and operating at the standard design conditions prevalent in Spain. In particular, such WWTP is characterized by the parameters listed in Table 1.

Abbreviations: TH, thermal hydrolysis; WWTP, waste water treatment plant; CHP, combined heat and power; DS, dry solids; VSS, volatile suspended solids.

* Corresponding author.
E-mail address: dfpolanco@tech4plus.com (D. Fernández-Polanco).

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Table 1
Main parameters characterizing the base wastewater treatment plant (WWTP) operation.

Sludge	Total flowrate (m^3/d)	1,604
	Primary sludge flowrate (kg DS/d)	35,000
	Primary sludge concentration (% DS)	3
	Secondary sludge flowrate (kg DS/d)	35,000
	Secondary sludge concentration (% DS)	8
Anaerobic digesters	Number of digesters	6
	Volume per digester (m^3)	5,000
	Diameter (m)	27
	Height above ground (m)	7.7
	Height below ground (m)	3.0
	Total digesters volume (m^3)	30,000
	Digestion temperature (°C)	35
Other parameters	Organic loading rate (kg VSS/m^3·d)	1.6
	Hydraulic residence time (days)	19
	Yield (% VSS)	45
	Productivity (m^3 biogas/m^3 digesters)	0.6
	Specific power consumption (kWh/m^3 wastewater)	0.35

To analyze the impact of different combined heat and power (CHP) technologies, a gas engine and a gas turbine are considered (section 3.2. *Combined heat and power (CHP) technologies*). To properly represent these equipment, and as summarized in Table 2, data has been obtained from two representative manufacturers [9,10] for similarly sized equipment designed to burn biogas.

3. Theory

3.1. Thermal hydrolysis

This pretreatment to the anaerobic digestion improves the sludge biodegradability by means of two distinct mechanisms [11]. The first one is a thermal mechanism, with the sludge maintained at high pressure and temperature during a pre-determined length of time to improve its solubilization. The second one is steam explosion, where a sudden decompression (flash) of the pressurized sludge fractures the cellular structures and makes it easier to digest.

Fig. 1 illustrates the thermal hydrolysis plant fit within the WWTP. Depending on the final objective of the pretreatment, there are two main options [12]: (i) hydrolyze only the secondary sludge when the aim is to increase biogas yields and reduce biosolids volume, as this allows most of the benefit to be captured without the energy consumption associated with treating the primary sludge and (ii) hydrolyze both the primary and the secondary sludge when the additional objective exists to pasteurize the biosolid, yielding an EPA Class A biosolid in return for an increase in steam demand.

The biogas is routinely sent to either a gas engine or a gas turbine to generate power. The associated waste heat can be used to keep the anaerobic digestion temperature and, importantly, to generate steam for the thermal hydrolysis process. The optimum interaction of all these elements is the key to successfully integrate the thermal hydrolysis plant within the WWTP.

3.2. Combined heat and power (CHP) technologies

Wastewater treatment is an energy-intensive endeavor that demands mostly electrical power. An obvious way to reduce the power consumption is to generate it internally from the digesters biogas. This not only reduces the operating costs, but also utilizes a renewable energy source and displaces fossil fuels. While other options such as fuel cells and steam turbines exist, three are the commonly considered CHP technologies to convert anaerobic digester gas to electrical power and process heat. Those are discussed below, and their relative advantages and disadvantages compared (Table 3).

Gas Engines. These reciprocating internal combustion engines are the most widely used and time-tested CHP technology fueled by digester biogas. The vast majority of the applications are of the spark-ignition type, and virtually none of them is of the compression-ignition type (commonly called diesel engines). While in the early days the gas engines where of the rich-burn type (i.e. high fuel-to-air ratio), in the last 30 years manufacturers have developed lean-burn engines, with lower fuel-to-air ratios that result in lower emissions and higher fuel efficiency. Most of the heat, the primary byproduct of the mechanical power generation, is recoverable in two different forms: continuous engine cooling with jacket water and hot exhaust gases.

Gas Turbines. Another well-proven industrial prime mover, its application in WWTPs is far more frequent in the USA than in other regions. Gas turbines consist of three primary sections: a compressor that compresses large quantities of atmospheric air, a combustion chamber where the air ignites the fuel and the expander where mechanical energy is extracted from the combustion gases, driving the compressor and generating power. In contrast to gas engines, which have multiple sources, heat recovery from gas turbines is only available from the exhaust gases. Due to their high temperature, more heat can be recovered in the form of high-pressure steam.

Table 2
Gas engine and gas turbine characteristics.

	Gas engine (Jenbacher J612)	Gas turbine (Solar Centaur 40)
Fuel input (kW)	6,902	12,547
Power output (kW)	3,044	3,500
Thermal output (kW)	2,782	5,625
Power efficiency (%)	44.1%	27.9%
Thermal efficiency (%)	40.3%	44.8%
Cogeneration efficiency (%)	84.4%	72.7%
Exhaust temperature (°C)	425	450

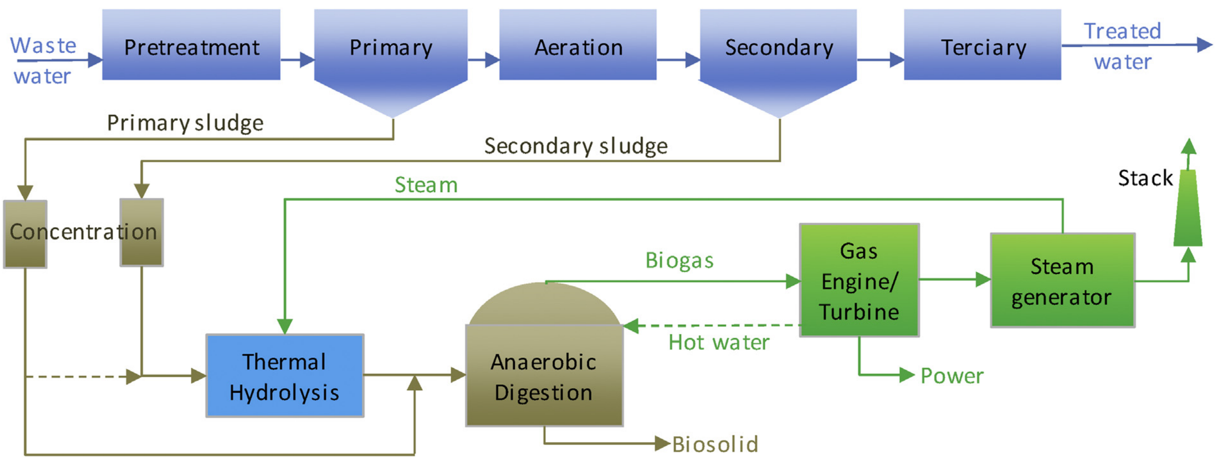

Fig. 1. Thermal hydrolysis process fit within the WWTP.

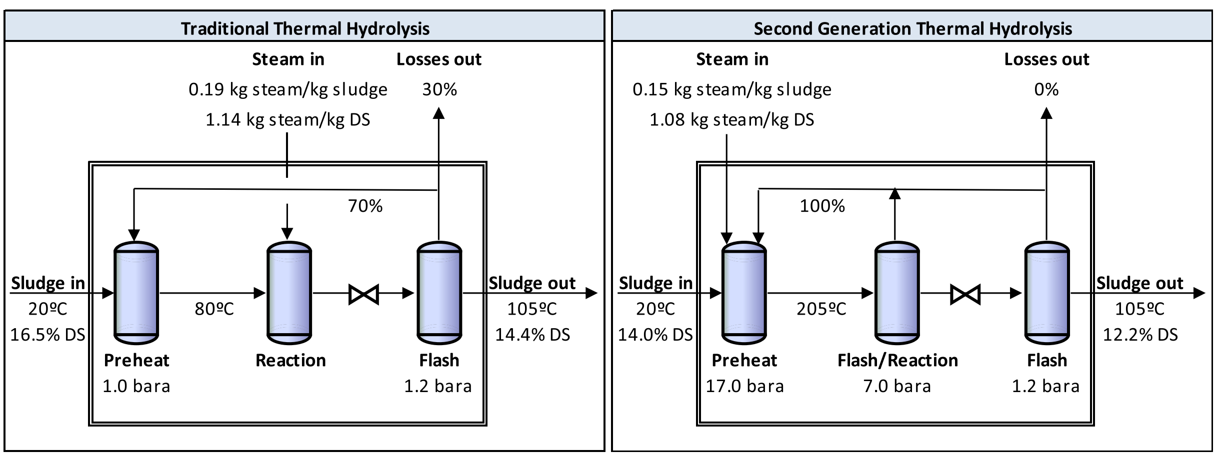

Fig. 2. Simplified balances for traditional (left) and second-generation (right) thermal hydrolysis.

Table 3
Advantages and disadvantages of combined heat and power (CHP) technologies [13].

CHP technology	Advantages	Disadvantages
Gas Engines	• Wide range of sizes (110–4000 kW) • Higher electrical and cogeneration (electrical + thermal) efficiencies • Reliable, well-proven technology from several manufacturers • Non-specialized maintenance • Requires low fuel pressure	• Requires continuous cooling • May need fuel pretreatment to avoid potential engine damage or efficiency loss
Gas turbines	• Higher thermal efficiency • Reliable, well-proven technology from several manufacturers • Fewer moving parts, generally require less frequent maintenance • Clean exhaust emissions • Suitable for unattended operation	• Available in a limited number of larger sizes (>1,500 kW) • Lower electrical efficiency • Warm weather and elevation reduce electrical efficiency • Require high pressure fuel • Specialized maintenance
Micro-turbines	• Smaller sizes (30–250 kW) • Low levels of NOx and CO exhaust emissions • Quiet and suitable for outdoor installation without adding a separate building	• Lower electrical and thermal efficiencies • Lower exhaust temperatures • Limited number of vendors • Require fuel gas cleanup • Poorer track record

Microturbines. As the name suggests, they are much smaller versions of the gas turbines. First introduced about 20 years ago, microturbines are a relatively new CHP technology that has become more popular lately due to their low emissions and small, fully packaged, modular designs. Similar to the larger gas turbines, heat recovery is only available from the exhaust gases. Most microturbines, however, are equipped with a recuperator that preheats the combustion air with the exhaust gases. This improves the electrical efficiency, but it also limits the heat recovery potential: recovered heat is available for digester heating or other low temperature heating needs in the form of hot water, but the lower exhaust gases temperature restrict the generation of high-pressure steam. Due to this limitation, microturbines are not considered in the work presented in this paper.

3.3. Pinch analysis

Also referred to as pinch technology, process integration and heat integration, pinch analysis is a methodology, originally developed by Linhhoff [14,15] and later refined by others [16,17], to minimize the energy consumption of industrial processes. In broad terms, this approach follows two basic steps. The first one is energy targeting, where the process energy flows are represented in the so-called composite curves, of which Fig. 3 act as an example. These are graphical representations of two key thermodynamic variables: temperature (i.e. the quality of the energy) and enthalpy (i.e. the quantity of energy). The hot composite curve (red line) is the combination of all the streams that need to release heat, while the cold composite curve (blue line) groups all the process streams that require to pick up heat. With both the heat sources and the heat sinks in the same plot, it is simple to assess the maximum extent of energy that can be transferred from one to the other. The remaining heat has to be provided or removed via utilities such as steam or cooling water. In other words, for the given driving forces, or temperature differences, thermodynamically feasible energy targets (i.e. minimum utility requirements) are determined. The second step is the design of the energy system and starts with the notion that the point of closest temperature approach between the hot and the cold composite curves, so-called pinch point, represents the area where the driving forces are smallest in the process and thus the design is most constrained. By starting the design of the energy recovery system there, and following certain design rules [18], the pinch methodology ensures that the identified energy targets can be achieved in practice.

4. Results and discussion

To achieve an optimum energy integration of the thermal hydrolysis within the WWTP, the two logical steps that structure this section must be followed. To begin with, the pretreatment energy consumption has to be minimized by implementing energy efficient design features. Once the thermal hydrolysis process is optimized, the resulting energy demands must be provided in the most efficient way via integration with the combined heat and power (CHP) system. As a corollary, an optimization strategy is suggested.

4.1. Minimize thermal hydrolysis energy demand

As illustrated by the global balances in Fig. 2, the TH steam demand is determined by the energy required to heat up the sludge from the inlet temperature to the outlet conditions, and by the need to make up any losses. Thus, four parameters that can be adjusted in order to minimize steam consumption: (i) sludge inlet concentration, with steam demand lower at higher concentrations, since less water needs to be heated up (ii) sludge inlet temperature, as lower steam consumptions will be realized at higher inlet temperatures with constant losses (iii) sludge outlet temperature, since the pressure in the flash vessel can be reduced to even slight vacuum to reduce the outlet temperature and the steam usage at the cost of increased hydrolyzed sludge pumping needs (iv) losses, as the inability to recover all process vapors increases the steam usage of the thermal hydrolysis plant.

From an energy standpoint, the main limitation of traditional thermal hydrolysis processes, of which Cambi's THP™ process [19] is the main exponent, is the extent to which the sludge can be preheated: under atmospheric conditions, it is limited to relatively low temperatures (80 °C in Fig. 2). This results in the inability to recover about 30% of the flashed vapors, which have to be rejected to the atmosphere, and in the corresponding steam consumption increase (Fig. 3). In addition, a sludge inlet temperature rise would only mean greater losses, as even less process vapors could be absorbed by the hotter sludge.

Second-generation thermal hydrolysis technologies, such as the tH_4^+ process by $teCH_4^+$, overcome this obstacle by preheating and flashing at higher pressures. This, and the novel use of a thermocompressor, expand the heat sink and increase the temperature of the flashed vapors, allowing to recover 100% of the process vapors and reducing steam usage (Fig. 4). Furthermore, it enables a sludge inlet temperature increase as a handle to further reduce the steam consumption.

Since most of the energy used by thermal hydrolysis processes is in the form of steam, the energy merits of different designs are typically compared in terms of their specific steam consumption. In particular, two indicators are used. The first one is the wet specific steam consumption (kg steam/kg wet sludge) that, out of the four parameters discussed, mostly depends on the last three. In other words, it is just a function of the inlet and outlet enthalpies and of the losses, and it is essentially independent of the sludge inlet concentration. The second indicator is the dry specific steam

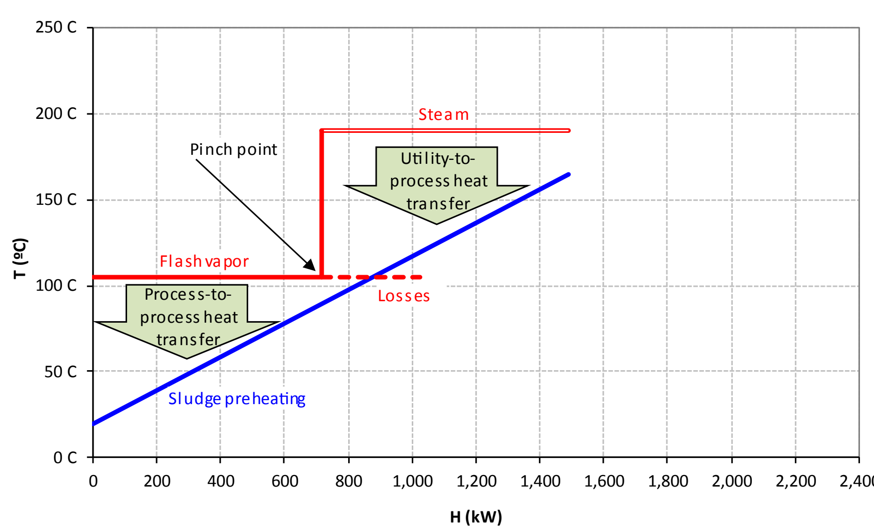

Fig. 3. Composite curves for the traditional thermal hydrolysis processes.

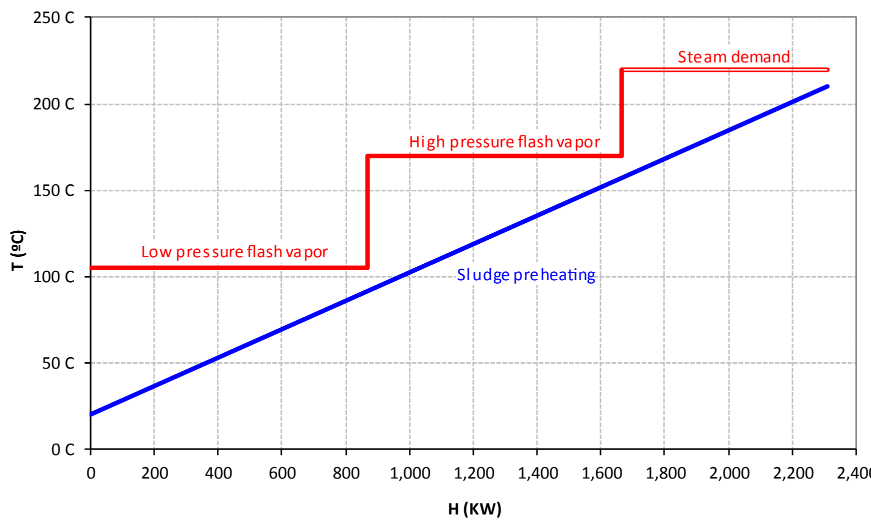

Fig. 4. Composite curves for second-generation thermal hydrolysis processes.

consumption (kg steam/kg DS), dependent on the sludge inlet concentration since the higher the concentration, the lower the steam usage (Fig. 5). For this reason, it is a more meaningful index and will be the one used to formulate an energy optimization strategy (see section 4.3. *Energy integration strategy*). It is important to realize that there is a downside to achieving higher concentrations: the greater use of expensive polyelectrolytes.

4.2. Optimize the integration of the TH plant within the WWTP energy system

As discussed in section 3.2. *Combined heat and power (CHP) technologies*, the two prevalent technologies (gas engine and gas turbine) are considered, with the features listed in Table 2. Starting with no thermal hydrolysis is in operation, different scenarios are analyzed in this section. To simplify, out of the two options discussed in section 3.1. *Thermal hydrolysis*, the analysis is based on the hydrolysis of only secondary sludge. For completeness, however, the numbers for the hydrolysis of both the primary and the secondary sludge are presented at the end of this section.

4.2.1. Scenario 0. No thermal hydrolysis

The baseline is established by the WWTP operation before thermal hydrolysis is installed. As illustrated by the Sankey-type diagram in Fig. 6, and assuming that a gas engine is operating, 44% of the energy contained in the biogas is transformed into power. The remaining power to meet the total WWTP demand is imported from the grid. Thermal energy, both from engine cooling and from exhaust gases, is used to keep the digesters temperature. A better environment to understand the thermal part of the thermal energy flows is the composite curves in Fig. 7. As the heat provided by the engine cooling is not enough to keep the digesters temperature, part of the exhaust gases are used to supplement it. The exhaust heat that is not used for this purpose is rejected to atmosphere, as there is no other heat sink available. The digesters heat demand is estimated for the geometries and conditions listed in Table 1, ambient temperature of 10 °C, sludge feed temperature of 15 °C and standard heat transfer coefficients from the literature [20]. A total of 305 kW are needed per digester: 256 kW for feed heating and 49 kW to compensate heat losses.

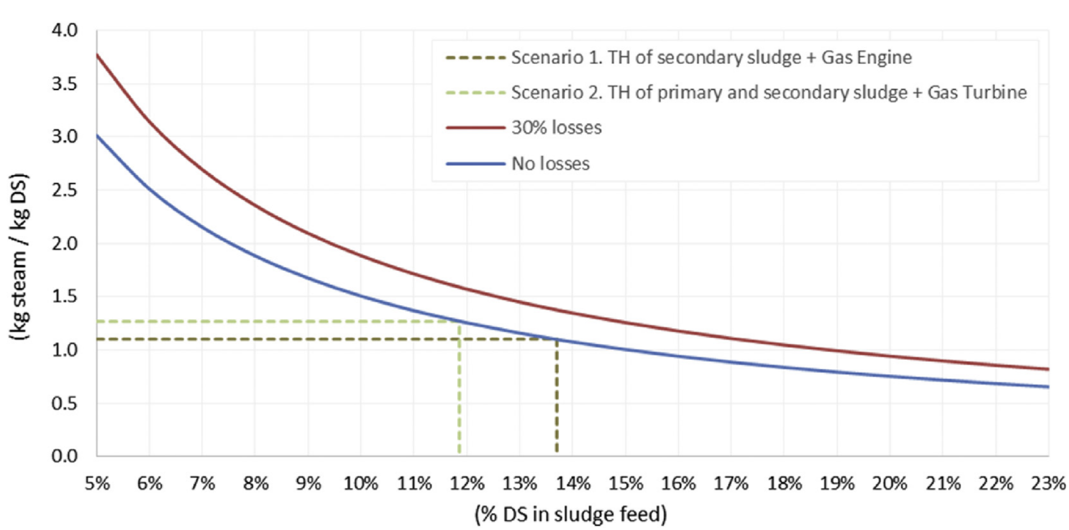

Fig. 5. Thermal hydrolysis dry specific steam consumption as a function of sludge feed concentration.

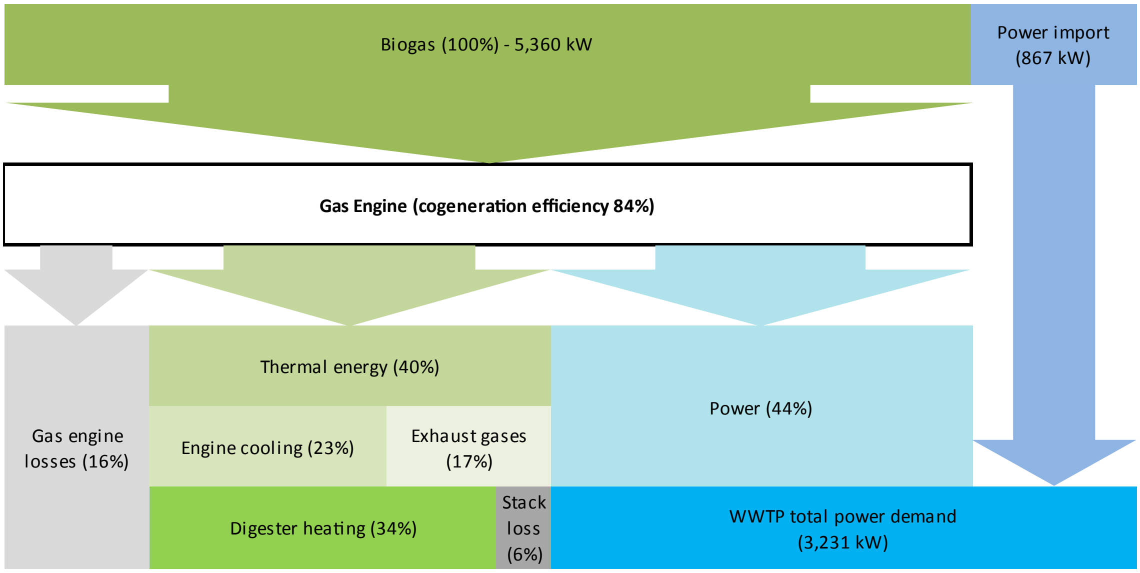

Fig. 6. Energy flows for Scenario 0. No thermal hydrolysis and gas engine.

4.2.2. Scenario 1. Thermal hydrolysis and gas engine

If thermal hydrolysis is installed, the biogas yield increases by about 25%. This boosts the power generation and reduces the amount of imported power (Fig. 8). Regarding thermal energy, the thermal hydrolysis plant feeds hot sludge to the digesters, which in turn decrease very significantly their heat requirement. This opens up the opportunity to generate high-pressure steam from the hot exhaust gases (Fig. 9). If a second-generation thermal hydrolysis process, hydrolyzing only secondary sludge and featuring low specific steam consumption, is installed (see section 4.1. *Minimize thermal hydrolysis process energy demand*), the generated steam is enough to meet the demand. This is not the case for traditional thermal hydrolysis processes, which demand more steam that can be produced in a gas engine. In any case, if both primary and secondary sludge are hydrolyzed, the steam demand exceeds the steam generation potential of the gas engine.

4.2.3. Scenario 2. Thermal hydrolysis and gas turbine

If the objective is to increase the steam generation, the option exists to install a gas turbine instead of a gas engine. In this case, with all the waste heat in the form of high-temperature exhaust gases, more than enough steam can be generated to meet the demands of a second-generation TH plant hydrolyzing both primary and secondary sludge (Figs. 10 and 11). The disadvantage of this approach is the lower electric efficiency of the gas turbine, which results in a greater power import from the grid. To compensate for this, the steam in excess to the demand could be expanded in a condensing steam turbine, generating additional power. This extra power, estimated to be less than 200 kW, does not seem to justify the complexity of a combined cycle operation.

4.2.4. Scenario 1a. Thermal hydrolysis and gas engine + standalone boiler

As an alternative to the gas turbine, an option to meet the steam demand of a thermal hydrolysis plant treating both primary and

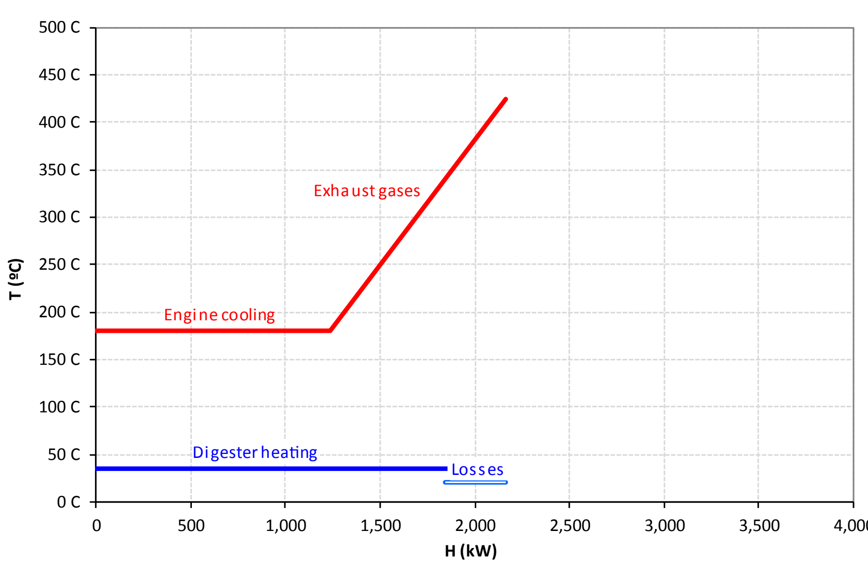

Fig. 7. Composite Curves for Scenario 0. No thermal hydrolysis and gas engine.

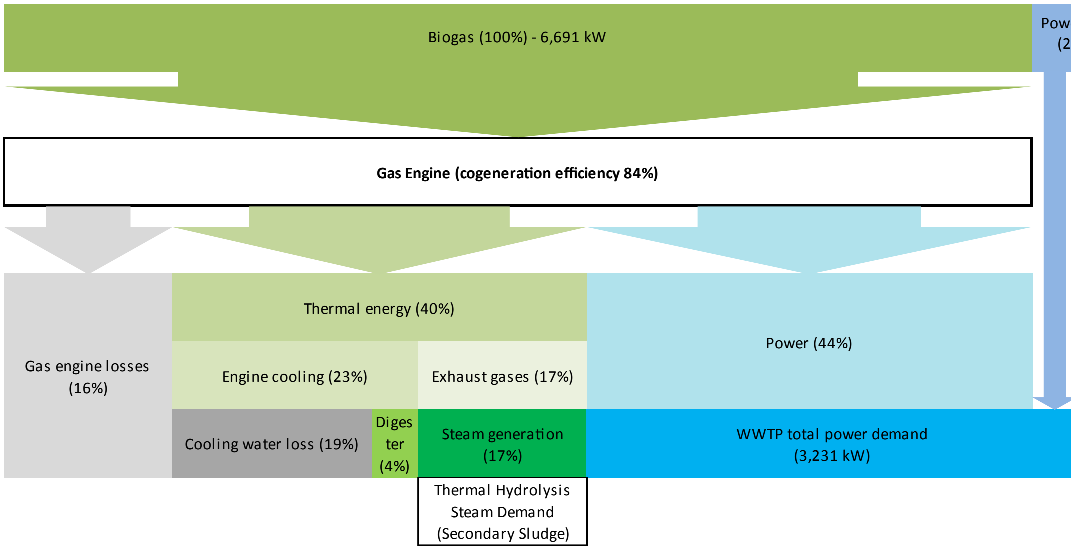

Fig. 8. Energy flows for Scenario 1. Thermal hydrolysis and gas engine.

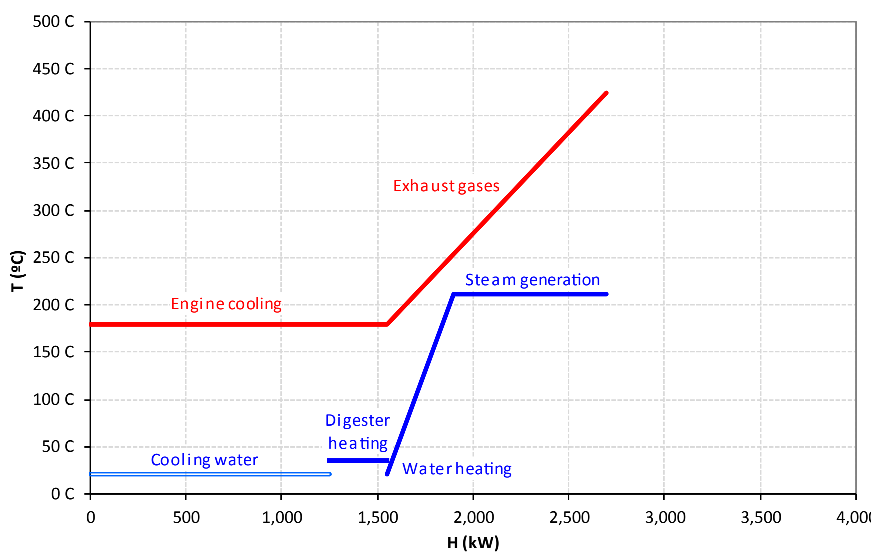

Fig. 9. Composite Curves for Scenario 1. Thermal hydrolysis and gas engine.

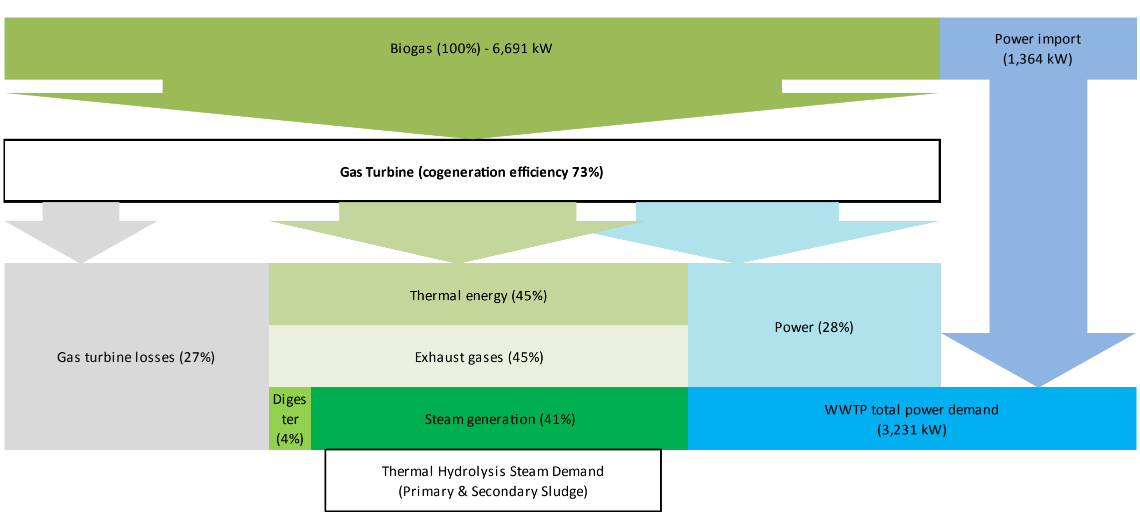

Fig. 10. Energy flows for Scenario 2. Thermal hydrolysis and gas turbine.

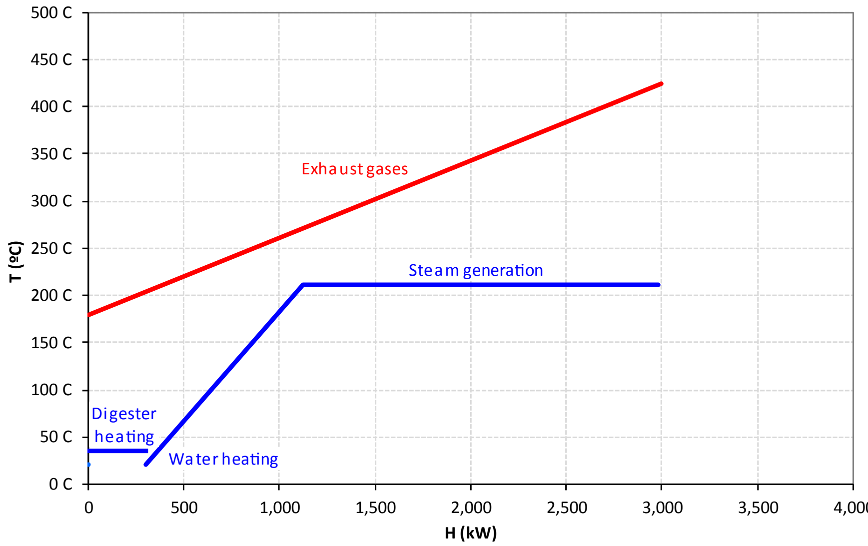

Fig. 11. Composite Curves for Scenario 2. Thermal hydrolysis and gas turbine.

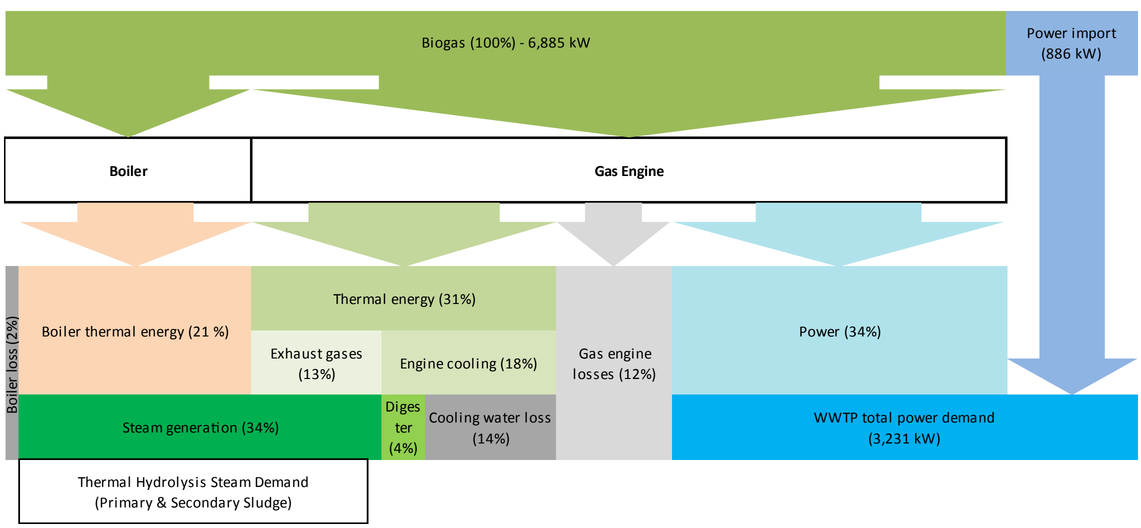

Fig. 12. Energy flows for Scenario 1a. Thermal hydrolysis and gas engine + standalone boiler.

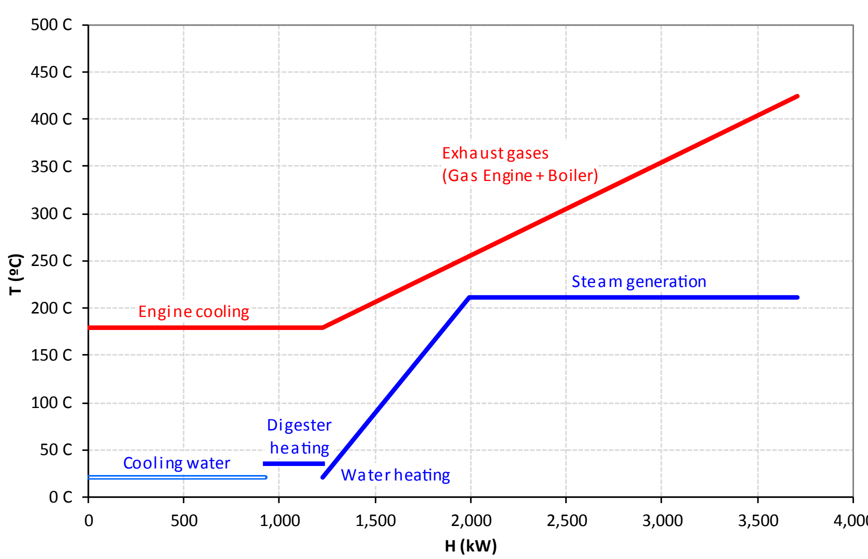

Fig. 13. Composite Curves for Scenario 1a. Thermal hydrolysis and gas engine + standalone boiler.

secondary sludge is to install a standalone steam boiler to supplement the gas engine. While this boiler could burn an external fuel (e.g. natural gas), for fair comparison purposes it is assumed to burn biogas. In this case, and to match the steam demand, 21% of the biogas has to be burnt in the boiler. This reduces the amount of biogas that can be used in the gas engine to generate power (Figs. 12 and 13). The result is an increase of the power imported from the grid when compared to Scenario 1, but a reduction when compared to Scenario 2.

As a summary, the figures behind the energy balances and composite curves graphically presented in Figs. 6–13 are presented in Table 4.

Table 4
Energy balances for all scenarios (all figures in kW).

		0. No TH	Only secondary sludge hydrolyzed		Primary and secondary sludge hydrolyzed	
			1. Gas Engine	2. Gas Turbine	1a. Gas engine + boiler	2. Gas Turbine
Energy in	Power import	867	280	1,364	886	1,310
	Biogas	5,360	6,691	6,691	6,885	6,885
	Power	*2,364*	*2,951*	*1,866*	*2,345*	*1,921*
	Thermal (exhaust gases)	*920*	*1,149*	*3,000*	*913*	*3,087*
	Thermal (engine cooling)	*1,240*	*1,548*	*0*	*1,230*	*0*
	Gas engine/turbine losses	*836*	*1,044*	*1,824*	*829*	*1,877*
	Boiler	–	–	–	*1,567*	–
	Total in	**6,227**	**6,971**	**8,055**	**7,770**	**8,195**
Energy out	Power demand	3,231	3,231	3,231	3231	3,231
	Digester	1844	300	300	300	300
	Gas engine/turbine steam	0	1,149	2,700	913	2,787
	Gas engine/turbine losses	836	1,044	1,824	829	1,877
	Cooling water losses	0	1,248	0	930	0
	Stack losses	316	0	0	0	0
	Boiler steam generation	–	–	–	1,442	–
	Boiler losses	–	–	–	125	–
	Total out	**6,227**	**6,971**	**8,055**	**7,770**	**8,195**

4.3. Energy integration strategy

A strategy is suggested to achieve the optimum energy integration of thermal hydrolysis pretreatments within a wastewater treatment plant, that starts by selecting a second-generation technology designed to recover 100% of the process vapors and minimize the specific steam consumption. The selection of sludge to be hydrolyzed is unrelated to energy considerations and will only depend on the pretreatment objective (section 3.1. *Thermal hydrolysis*). The next step is to define the optimum combined heat and power scheme to ensure an efficient integration of the pretreatment within the WWTP. Finally, the dry specific steam generation potential of the selected CHP system is estimated (Table 5) and the optimum sludge feed concentration to match the steam generation potential is determined by using Fig. 5. This ensures the best use of the available waste heat and, importantly, minimizes the usage of expensive polyelectrolyte. In other words, the thermal hydrolysis plant operates with the minimum sludge concentration that guarantees energy self-sufficiency.

5. Conclusions

Through optimum integration, the benefits of thermal hydrolysis can be realized in an energy-favorable way. Visualizing the WWTP as a black box, the power import in Table 4 is the best indicator to prove that. If only secondary sludge is hydrolyzed, power purchases can be reduced by virtue of the additional biogas from the baseline of 867 kW to 280 kW. In this case, a gas engine is the best CHP choice as it exhibits the highest electric and cogeneration efficiencies and also generates enough steam to meet the thermal hydrolysis demands. If both primary and secondary sludge is hydrolyzed, a gas engine supplemented by a standalone boiler is the most energy-efficient configuration. Although 21% of the biogas is burnt in the boiler to raise steam for the pretreatment, this scheme allows to capture additional benefits such as the sludge pasteurization while being essentially self-sufficient: the power import of 886 kW represents just a 2% increase over the baseline power purchase.

Out of the other CHP options considered for the combined sludge case, gas turbines generate enough steam to satisfy the thermal hydrolysis needs, but their lower electrical efficiency results in a significant power import of 1310 kW. A combined cycle operation, where the excess steam is expanded in a condensing steam turbine, could improve the situation, but the additional power generated is small to justify the extra complexity. Finally, microturbines are not a good fit, since they are equipped with a recuperator that improves the electrical efficiency but restricts the steam generation potential.

Table 5
Steam consumptions and generation potential for different scenarios.

	Only secondary sludge hydrolyzed		Primary and secondary sludge hydrolyzed	
	1. Gas Engine	2. Gas Turbine	1a. Gas engine + boiler	2. Gas Turbine
TH plant steam consumption (kg/h)	1,563	1,563	3,125	3,125
Steam generation potential (kg/h)	1,602	3,583	3,125	3,698
Wet specific steam consumption[a] (kg steam/kg wet sludge)	0.15			
Dry specific steam consumption[a] (kg steam/kg DS)	1.07			
Dry specific steam generation potential (kg steam/kg DS)	1.10	–	–	1.27
Optimum sludge feed concentration[b] (%DS)	13.7	–	–	11.9

[a] Assuming 14% DS and second-generation TH technology.
[b] See Fig. 5.

It is important to note that this paper discusses the merits of the different combined heat and power technologies only from an energy efficiency point of view. Other considerations such as capital investment and operating costs must be factored in to have a holistic understanding of the challenge.

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