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# Comparative analysis of the thermal hydrolysis integration within WWTPs as a pre-, inter- or post-treatment for anaerobic digestion of sludge

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ABSTRACT

Anaerobic digestion (AD) is the most widely applied technology for the treatment of sludge produced in WWTPs. At present, thermal hydrolysis (TH) is becoming the technology of choice to improve anaerobic digestion due to its techno-economic advantages. The drivers behind the decision to install this technology, however, differ widely as they depend on local legislation and prevailing pricing structure. Thermal hydrolysis can be applied with different objectives (increase biogas yield, reduce digestion volume, reduce digestate quantity, pathogens removal) that can result in different optimum configurations. In this context, the same TH process can be placed as pre-, inter- and post-treatment to AD, each with distinct advantages and drawbacks.

For all cases analysed there is a solid business case, with attractive payback, and the site-specific conditions will be key to determine the optimum location of the TH technology within the WWTP. Pre-treatment of mixed sludge is the configuration showing the lowest capex and is attractive for grassroots designs, but presents a poor energy balance. Inter-treatment incurs in higher capex, but in return this energy self-sufficient configuration yields the best operating numbers. Post-treatment is to be considered only attractive at relatively high biosolid prices and demands careful consideration of odour issues.



## 1. Introduction

In conventional wastewater treatment plants (WWTPs), 50–70% of the total incoming organic material contained in the wastewater ends up as sludge, and anaerobic digestion (AD) is the most commonly used process [1] to produce valuable biogas from it. Based on a Chemical Oxygen Demand (COD) energy content of 3.48 kWh/ton COD, AD becomes the cornerstone of sludge management strategies aiming to achieve energy self-sufficiency in WWTPs [2–4].

AD encompasses a series of biochemical reactions, carried out by specialized bacteria and archaea, converting solid organic material into biogas. Primary sludge (PS) is predominantly organic material of diverse origin and composition, while waste activated sludge (WAS) formed from dissolved organic material is largely made of exopolymers and bacteria [5]. The first stage, crucially the one that limits the global process kinetics, is the hydrolysis or solubilization of the organic material. Consequently, the best approach to improve the global kinetics is to accelerate this limiting stage by feeding the digesters with pre-hydrolysed material. By adding such pre-treatment, the digesters are fed with pre-hydrolysed material that can straightaway undergo the subsequent biological mechanisms. A myriad of physical, chemical and biological processes and technologies have been tested, as analysed by several reviews [6–9]. Among those technologies, Thermal Hydrolysis (TH) displays promising technical and economic features.

The first commercial TH technology, the Porteous process, dates back to the 1950s and aimed to improve the dewaterability of digested sludge via high pressure (10 bar) and temperature (200 °C) treatment [10]. The discontinuation of this process, predecessor of all TH processes and analogous to the post-treatment configuration with regards to its location, is linked to the $NH_3$ and organic products desorption, whose sulphur and nitrogen content result in obvious odour issues that are aggravated by the high temperatures.

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**Abbreviations**

| | |
|---|---|
| AD | Anaerobic Digestion |
| TH | Thermal Hydrolysis |
| WWTP | Waste Water Treatment Plant |
| DS | Dry Solids |
| VS | Volatile Solids |
| COD | Chemical Oxygen Demand |
| PS | Primary Sludge |
| WAS | Waste Activated Sludge |
| HRT | Hydraulic Residence Time |
| VSR | Volatile Solids Reduction |
| OLR | Organic Loading Rate |
| IRR | Internal Rate of Return |
| NPV | Net Present Value |
| CHP | Combined Heat and Power |

A review of the development and applicability of sewage sludge thermal hydrolysis [11] indicates that from a pioneer 1955 installation, there are currently 75 facilities in operation worldwide. In essence, all commercially available pure thermal processes (without chemicals addition) operate in the 140-170 °C temperature range and corresponding thermodynamic equilibrium pressure [12]. Although it is a topic that falls outside of the scope of this article, different papers have analysed the TH effect on different substrates such as pig manure, wheat straw, kitchen waste or the organic fraction of municipal solid waste, opening up avenues to apply TH processes to new substrates either directly or via co-digestion [13–16].

Proper integration of the TH process within the specific WWTP is of the utmost importance [17,18]. Applying a holistic WWTP vision, the TH process can be placed: i) upstream of AD, hydrolysing fresh sludge (pre-treatment), ii) downstream of a pre-AD, hydrolysing partially digested sludge and upstream of a post-AD of hydrolysed sludge (inter-treatment), iii) downstream of AD and thus hydrolysing digestate that is subsequently split into a solid and a liquid fraction, with the later typically recycled to AD (post-treatment). In essence, the same TH process can be placed as pre-, inter- and post-treatment to AD.

Due to abundant references and resulting experience, pre-treatment can be considered the conventional configuration, its main features and parameters being well documented [11,12].

In relation to inter-treatment, a comparison of conventional AD with double-stage mesophilic digestion [19] reports biogas yields improvements of 20% and 45% when the second digester is fed hydrolysed and non-hydrolysed pre-digested mixed sludge, respectively. Similar results are reported in Ref. [20], with second digestion methane yields increasing from 52 to 222 L $CH_4$/kg VS when inter-treatment is applied, while the hydrolysis kinetics constant increased by up to 127% with this configuration. The prevalence of the second digestion stage and the low significance of the first digestion HRT is underlined in Ref. [21]. A techno-economic assessment performed with pilot scale data [22], shows that inter-treatment offers an excellent solution for energy recovery having the best economic return, but the largest capex.

Regarding post-treatment, some papers study the solid and liquid phase separation after TH, concluding that 34% of the VS were released to the liquid fraction, generating nearly 50% of the total methane, with much faster kinetics than those of the solid fraction [23]. Relatedly, the hydrolysed sludge liquid fraction reached the biodegradability (262.6 L $CH_4$/kg $COD_{feed}$) on the 15th day during anaerobic treatment, while the hydrolysed sludge solid fraction only contributed 31.0% to the total methane production and required HRT of more than 30 days [24]. When the impact of recycling the final dewatering centrate back to AD is analysed, a 20% improvement in the biogas yield is found when comparing pre- and post-treatment [25]. Finally, the impact of post-treatment on pasteurization [26] and dewaterability [27] appears to be clearly beneficial: extrapolating thermogravimetry results, sanitized cakes with up to 43%DS are anticipated [28].

With this engineering background, the objective of this paper is to analyse different integration scenarios, and its significance lays in the fact that current research does not provide a thorough comparison of available options. In order to produce comprehensive results, all commercially installed configurations are analysed, placing TH as a pre-treatment, inter-treatment and post-treatment to AD.

## 2. Materials and methods

### 2.1. Configurations combining thermal hydrolysis and anaerobic digestion

Four scenarios were evaluated corresponding to different combinations of TH and AD stages:

a. Baseline configuration: Conventional AD of mixed sludge
b. Pre-treatment of thickened mixed sludge or pre-treatment of only biological sludge, prior to subsequent AD
c. Inter-treatment between two AD stages
d. Post-treatment of dewatered digested sludge

### 2.2. Calculation basis

The baseline is defined as a municipal WWTP treating the sewage produced by a 1 million population equivalent city, operating with the standard design conditions prevalent in Spain [29]. The key parameters are listed in Table 1 and references indicated as footnote. For the biogas methane content, an average value (65%) was considered, neglecting its small and little significant variation ( ±3%). The polymer dosing in TH feed dewatering and final dewatering is poorly standardised and documented, and the values applied were extracted from Ref. [30].

### 2.3. Economic parameters

Apart from those parameters related to sludge properties and process yield, economic parameters were included to translate operation figures into economic performance. Although some of the economic parameters driving the decision-making process vary widely with location and background conditions, Table 2 attempts to select the most representative economic parameters.

### 2.4. Simulation methodology

Fundamental tools for this study are rigorous energy and material balances around a common system for the different configurations, as well as the quantification of design and operating variables commonly utilized in the WWTP sector [32]. Technical and economic parameters were included in the simulation, together with rigorous physical properties, thermodynamic equations and main processes modelling (Fig. 1). A proprietary simulator was used to perform all the balances and calculations. This tool was developed in-house using Microsoft's Visual Basic for Applications (VBA) programming language.

The anaerobic digestion parameters and associated calculations

**Table 1**
Technical parameters.

| | Parameter | Units | Value |
|---|---|---|---|
| [a] Primary sludge | Flowrate | kg DS/d | 30,000 |
| | Concentration | % DS | 6% |
| | Volatiles ratio | kg VS/kg DS | 0.70 |
| | COD ratio | kg COD/kg VS | 1.70 |
| | COD content | % of influent's COD | 35% |
| [a] Surplus WAS | Flowrate | kg DS/d | 24,500 |
| | Concentration | % DS | 6% |
| | Volatiles ratio | kg VS/kg DS | 0.75 |
| | COD ratio | kg COD/kg VS | 1.40 |
| | COD content | % of influent's COD | 25% |
| [a] Mixed sludge | Flowrate | kg DS/d | 54,500 |
| | Concentration | % DS | 6% |
| | Volatiles ratio | kg VS/kg DS | 0.72 |
| | COD ratio | kg COD/kg VS | 1.56 |
| | COD content | % of influent's COD | 60% |
| [a] Anaerobic digestion | Temperature | °C | 35 (mesophilic) |
| | Feed concentration | % DS | 8% |
| | Methane specific yield | $Nm^3CH_4/kg\ COD_{remov.}$ | 0.35 |
| | Biogas methane content | % $CH_4$ | 65% |
| [b] Polymer dosing | Baseline dewatering | kg/t DS | 12 |
| | TH feed dewatering | kg/t DS | 6 |
| | Final dewatering | kg/t DS | 8 |
| [c] Engine | Electric efficiency | % | 38% |
| | Thermal efficiency: | % | 48% |
| | · Engine cooling | % | 29% |
| | · Exhaust gases | % | 19% |

[a] [29].
[b] [30].
[c] [18].

**Table 2**
Economic parameters.

| Parameter | Units | Value |
|---|---|---|
| Power price | €/kWh | 0.12 |
| Sludge management price | €/t | 15 |
| Polymer price | €/kg | 3 |
| Operating time | h/year | 8400 |
| Discount rate | % | 7.0% |
| Plant life | years | 10 |

Reference [31] as average values and realistic current prices.

were performed according to Ref. [33], and energy balances for the steady state defined in accordance to Ref. [34].

## 3. Results and discussion

### 3.1. Comparison perspective: TH issues, effects and impacts on global performance

Key insights on the commercially available TH technologies are gained by understanding how they tackle three key issues: applied hydrolysis mechanisms, operating regime used and heat transfer method employed. Fig. 2 summarises the alternatives within each category.

A thorough comparison of existing technologies falls outside the scope of this study. To keep the focus on the stated objective of analysing different TH configurations, and based on publicly available references, it is assumed that all TH technologies achieve similar efficiencies [35–38]. Furthermore, it is important to note that both the TH process and the TH technology are identical regardless of the TH location within the overall WWTP configuration.

While the objective of the original Porteous process [10] was to improve dewatering, subsequent technologies rather focused on the biogas yield increase. Yet recently, the TH drivers are evolving, tend to be site-specific and are closely related to local legislation and to the relative energy and sludge management prices. Table 3 illustrates the three key TH effects and their impact on the surrounding AD and dewatering processes.

The TH installation must be examined from those different

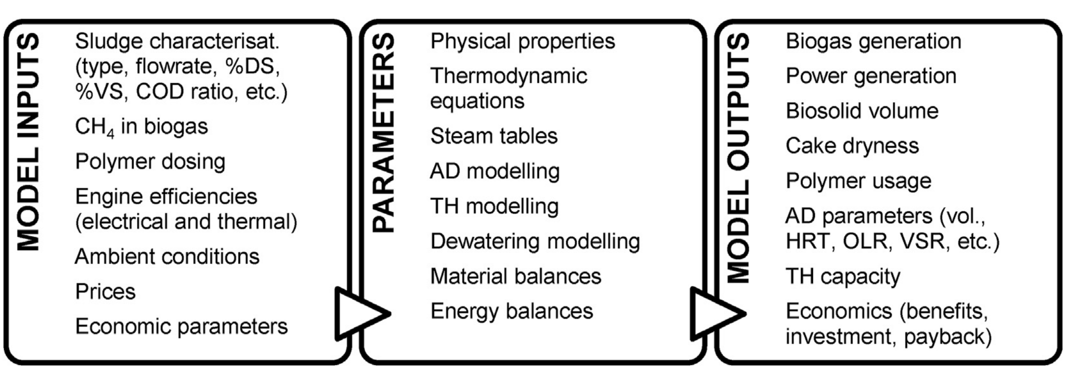


**Fig. 1.** Simulation structure.

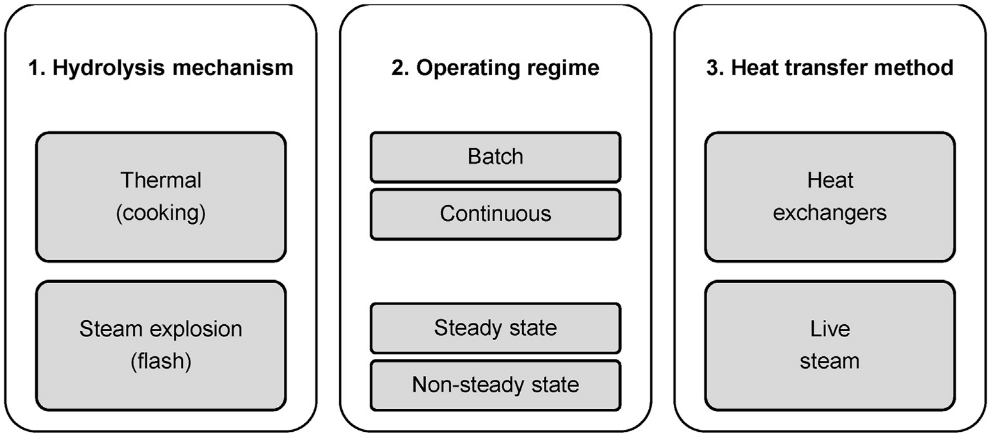


**Fig. 2.** Key parameters characterising TH technologies.

angles and the relative weight of each factor will depend on the prevalent background conditions. Hence, each situation requires a tailor-made solution and standardization is not an option when exploring technical alternatives since one-size-fits-all answers fail to consider the specific conditions and configuration that makes each site unique.

### *3.2. Comparison and analysis of different configurations of TH and AD*

The following analysis compares the different TH configurations to a conventional AD installation used as baseline for comparison. For each alternative, a simplified process diagram is presented, as well as key design and operating values and results.

#### *3.2.1. Baseline configuration*

Based on the parameters presented in Table 1 and on the scheme presented in Fig. 3, a baseline for comparison is quantitatively defined. For a 20 days design HRT, the resulting total digestion volume is 18,200 $m^3$ and the OLR is 2.2 kg VS/$m^3 \cdot$d. The VSR is assumed to be 44%.

#### *3.2.2. Pre-treatment*

Maintaining the baseline parameters to ensure a fair comparison and for the configuration illustrated by Fig. 4, a 14 days design HRT results in a total digestion volume of 9538 $m^3$, approximately half of the baseline capacity. The increased OLR to 4.1 kg VS/$m^3 \cdot$d is reasonable for hydrolysed sludge digestion and the VSR improvement to 55% is partially offset by the biogas burnt in the boiler to generate the steam driving the TH, as this configuration is not energy self-sufficient (i.e. the waste heat in the engine exhaust gases are insufficient to meet the TH steam demand).

A particular pre-treatment case is the configuration (Fig. 5) hydrolysing only surplus WAS and not primary sludge (PS). The energy balance greatly improves, making the TH self-sufficient (i.e. driven solely by the exhaust gases waste heat) and increasing the net biogas production and thus the generated power. The main disadvantage is that fails to sterilise the sludge.

#### *3.2.3. Inter-treatment*

In this configuration (Fig. 6), the mixed sludge is first digested (pre-digestion), then hydrolysed in the TH plant and finally digested again (post-digestion). The pre-digestion VSR improves the energy balance and results in TH energy self-sufficiency (i.e. engine waste heat provides the TH steam demand). Designing for 16 and 12 days of HRT for pre- and post-digestion respectively, the total digestion volume becomes 20,106 $m^3$.

#### *3.2.4. Post-treatment*

The mixed sludge is first digested, then hydrolysed in the TH plant and finally dewatered (Fig. 7). The key benefit is a dewatering improvement which enables higher cake concentrations. Since the final dewatering centrate is recycled back to AD, standard HRT of 20 days result in the largest digestion volume of all analysed configurations (22,811 $m^3$). While the recycled centrate allows a significant part of the hydrolysed sludge COD to be converted to biogas, another part is lost in the solid, negatively impacting the overall biogas yield. Finally, high temperature dewatering poses its own operating challenges.

### *3.3. Comparison of technical outpus*

All the previous calculations result in the quantification of those model outputs previously stablished in Fig. 1. The key technical parameters for the above configurations are summarised in Table 4, facilitating a quick comparison of the relative merits of the different

**Table 3**
Main TH effects and their impact AD process and biosolids quality.

| TH effect | Impact on AD and biosolids |
|---|---|
| Improved sludge biodegradability | F0A7 Increased biogas yield |
| | F0A7 Reduced digestate volume |
| | F0A7 Higher N, P in digester & centrate (nutrient recovery) |
| Pathogen destruction and sterilisation | F0A7 EPA Class A biosolid |
| | F0A7 New sludge applications (agriculture) |
| Rheology changes | F0A7 Lower mixing energy in digesters |
| | F0A7 Improved dewaterability, higher concentrations |
| | F0A7 Lower final biosolid volumes |

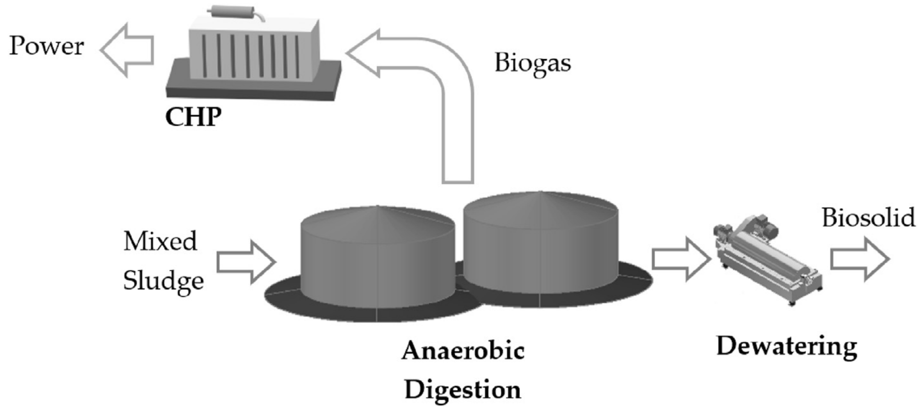


**Fig. 3.** Baseline configuration.

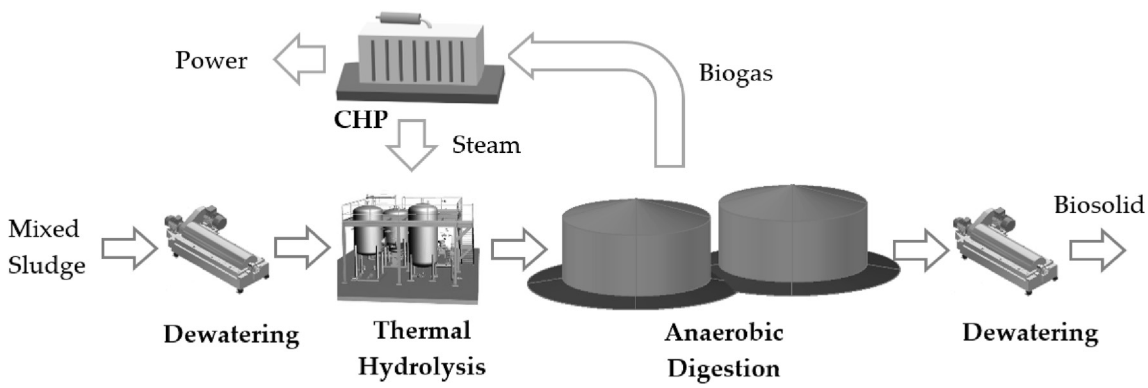


**Fig. 4.** Pre-treatment configuration (all sludge hydrolysed).

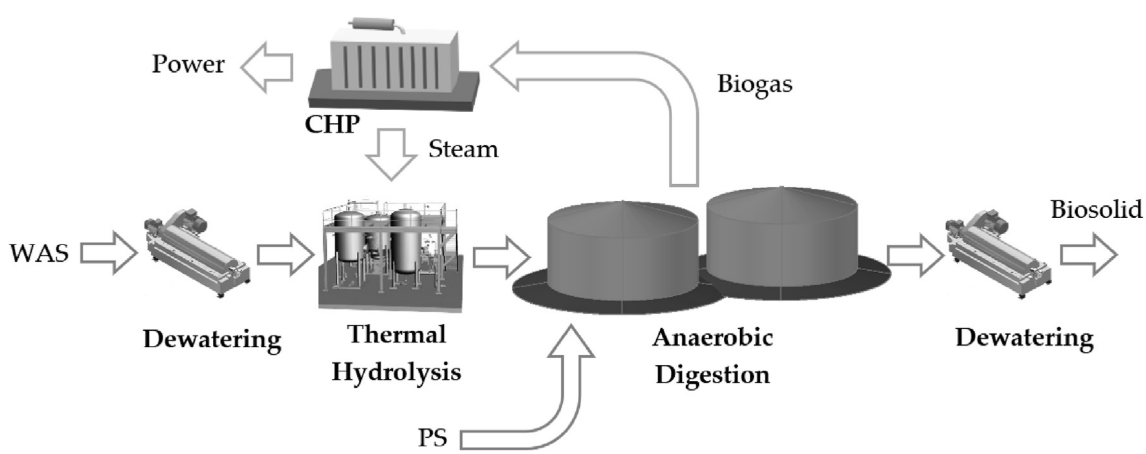


**Fig. 5.** Pre-treatment configuration (only WAS hydrolysed).

alternatives. In addition, Table 5 presents their percent change when compared to the baseline values.

The parameter showing the largest uncertainty is the polymer dosing. In the absence of specific data for each configuration, the same values have been applied to all cases, as per Table 1.

From the above tables, the pre-treatment configuration of all sludge is not energy self-sufficient and needs to burn a fraction of the biogas, penalising the power output in the CHP, while the inter-treatment option is the one that extracts more biogas and power from the sludge. Regarding biosolids, the post-treatment configuration achieves the greatest dryness and volume reduction, but at the expense of an increase in polymer usage. Finally, the pre-treatment alternative significantly reduces the required AD volume, with the corresponding avoided capex for grassroot designs; this effect, however, is partially off-set by a larger TH plant and peripherals.

### 3.4. Comparison of economic parameters

Based on the economic data defined (Table 2) and comparing

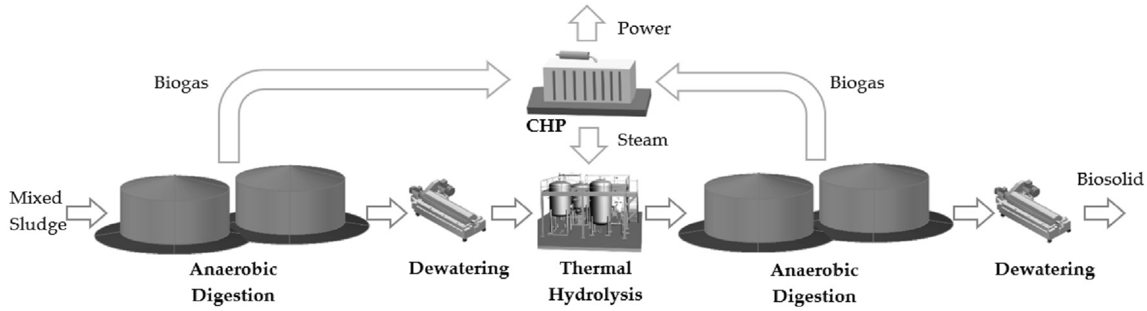


**Fig. 6.** Inter-treatment configuration.

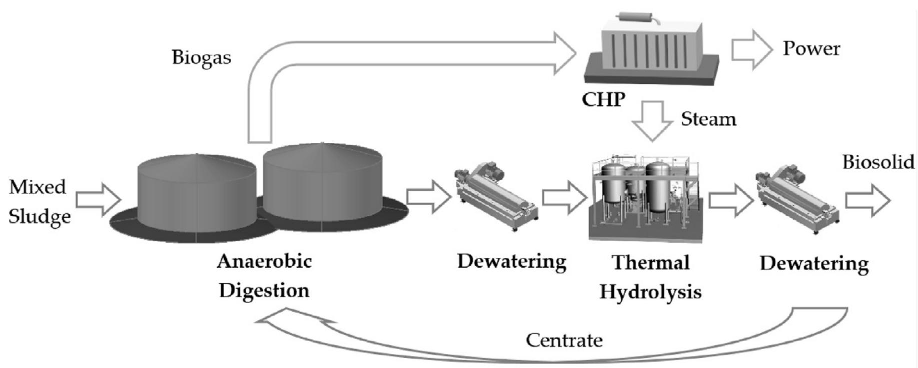


**Fig. 7.** Post-treatment configuration.

**Table 4**
Technical comparison: main parameters.

| | | | Baseline | Pre-(all sludge) | Pre-(WAS) | Inter- | Post- |
|---|---|---|---|---|---|---|---|
| Biogas | Gross | $Nm^3/d$ | 14,844 | 18,253 | 17,753 | 19,380 | 17,883 |
| | To boiler | $Nm^3/d$ | – | 2575 | – | – | – |
| | Net | $Nm^3/d$ | 14,844 | 15,678 | 17,753 | 19,380 | 17,883 |
| Power | Power | kW | 1523 | 1609 | 1822 | 1988 | 1835 |
| Biosolid | Dryness | %DS | 22% | 30% | 28% | 32% | 40% |
| | Volume | ton/d | 169 | 109 | 119 | 98 | 84 |
| | Sterilisation | – | – | Class A | – | Class A | Class A |
| Polymer | Total use | kg/d | 446 | 589 | 413 | 475 | 592 |
| AD | Volume | $m^3$ | 18,200 | 9538 | 13,714 | 20,106 | 22,811 |
| | HRT | days | 20 | 14 | 20 | 16/12 | 20 |
| | OLR | kg VS/$m^3$·d | 2.2 | 4.1 | 2.9 | 2.7/4.0 | 2.0 |
| | VSR | % | 44.1% | 55.3% | 53.9% | 58.5% | 53.3% |
| TH | Capacity | t DS/year | – | 19,893 | 8943 | 13,559 | 15,434 |

**Table 5**
Technical comparison: percent changes vs. baseline.

| | Pre-(all sludge) | Pre-(WAS) | Inter- | Post- |
|---|---|---|---|---|
| Biogas (net) | +6% | +20% | +31% | +20% |
| Power | +6% | +20% | +31% | +20% |
| Biosolid volume | −36% | −30% | −42% | −50% |
| Polymer usage | +32% | −7% | +7% | +33% |
| AD volume | −48% | −25% | +10% | +25% |

each scenario to the baseline, Table 6 summarises the economics of the different configurations. Maintenance costs and parasitic loads are comparable for all configurations and thus excluded from the analysis.

The main savings versus the baseline come from additional power generated, diminished biosolids volume and reduced polymer dosing (or increased polymer usage resulting in negative savings). Adding those three figures, the expected total savings are calculated for each configuration.

On the capex side, the required additional investment versus the baseline takes into account its two main contributors: AD capacity change and TH plant investment. Total installed costs of 800 k€ for a 4500 $m^3$ digester and of 2500 k€ for a 20,000 tDS/year TH plant, including all necessary peripherals, have been considered. The sources of this data are commercial manufacturers of comparable, installed digesters and TH plants.

By comparing the estimated savings to the required investment, the economic attractiveness of each alternative is assessed applying different metrics: simple payback, internal rate of return (IRR) and net present value (NPV).

Table 6 shows that the pre-treatment configurations, due to the avoided capex for grassroots designs, result in the lower paybacks for the selected price set. The inter-treatment option, however, presents the best operating results at the expense of higher capex.

**Table 6**
Economic analysis vs. baseline.

| | | | Pre-(all sludge) | Pre-(WAS) | Inter- | Post- |
|---|---|---|---|---|---|---|
| Savings (vs. baseline) | Power | k€/year | 353 | 301 | 469 | 314 |
| | Biosolid | k€/year | 313 | 262 | 370 | 447 |
| | Polymer | k€/year | −150 | 34 | −30 | −154 |
| | Total | k€/year | 516 | 597 | 809 | 607 |
| Additional capex (vs. baseline) | Total | k€ | 960 | 1.150 | 2.420 | 2.800 |
| Payback | Payback | years | 1.9 | 1.9 | 3.0 | 4.6 |
| | IRR | % | 53.0% | 51.1% | 31.2% | 17.3% |
| | NPV | k€ | 2662 | 3045 | 3264 | 1465 |

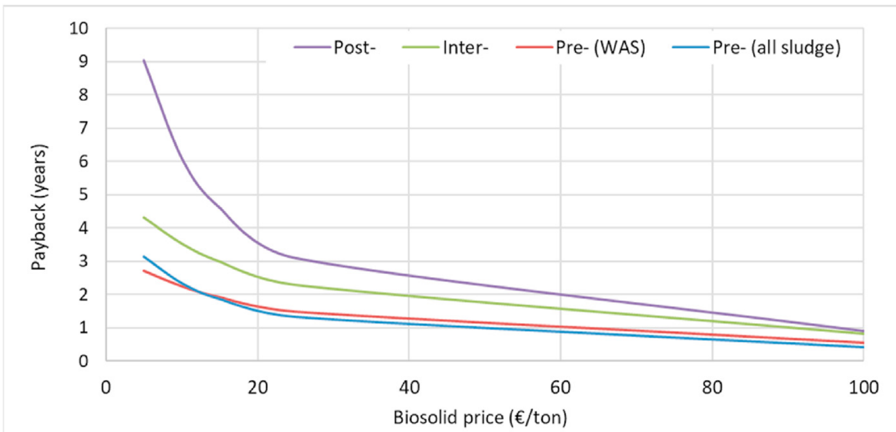


**Fig. 8.** Payback sensitivity to biosolid prices.

### 3.5. Sensitivity analysis

While the values of the economic parameters used as basis for this study attempt to represent prevailing conditions, some of them can differ significantly from site to site. Importantly, and unlike commoditised items like power and polymer prices, the sludge management price varies widely with location.

To capture this, a sensitivity analysis has been performed (Fig. 8) that evaluates the effect of changes in the biosolid management price on the resulting payback. The main salient point of this exercise is that the post-treatment configuration is only attractive at relatively high biosolid prices, while at high enough biosolid prices all paybacks tend to converge.

## 4. Conclusions

There is a solid business case, with attractive payback, to consider the installation of a Thermal Hydrolysis process and enhance Anaerobic Digestion of sludge, by boosting biogas yields and reducing biosolid volumes. Besides, the project drivers, site-specific conditions and pricing structure will be critical to determine the optimum location of the TH plant within the WWTP.

The comparative analysis performed to pre-, inter- and post-treatment configurations combining TH and AD exhibits the following features:

- Pre-treatment of all the sludge is the configuration showing the lowest capex (i.e. lowest AD volume) and will be of special interest in WWTP grassroots designs or sludge line expansions. The main drawback is the biogas burning in the boiler, that negatively impacts the energy balance and the operating results.
- Pre-treatment of WAS may well be the optimum configuration if biosolid sterilisation is not one of the project objectives.
- Inter-treatment incurs in a higher capex since it requires additional AD volumes, but in return this energy self-sufficient configuration yields the best operating numbers. It will be particularly attractive in existing WWTP with oversized AD systems.
- Post-treatment is only appealing at relatively high biosolid prices. And careful consideration must be given to odour issues, high temperature dewatering and the lack of operating experience with this configuration.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2021.120041.

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## Credit author statement

Diego Fernández-Polanco: Conceptualization, Writing – original draft, Writing – Review, Simulation Calculations, TH technology development and contrasted data, Erik Aagesen: Methodology, Simulation Calculations, TH design, Supervision, María Fdz-Polanco: Formal analysis, Visualization, Validation, References review, Sara Isabel Pérez-Elvira: Writing – original draft, Writing – review & editing, Investigation, Discussion, Visualization, Supervision.

## Intellectual property

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

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