Energy efficient thermal hydrolysis with steam explosion

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Abstract

Cambi A.S. of Norway has developed thermal hydrolysis (TH) with steam explosion since the early nineties into a proven technology for the treatment of sludge. This has resulted in a track record of 26 operational plants and in the largest advanced digestion project in the world (150,000 ton DS/y) today being built in Washington DC, USA. The first TH plants were built to increase digester loading, reduce sludge volumes and to create a Class A biosolid, a fully hygienised, low-odour cake easy and safe to return to land.

Today, however, energy consumption is a major topic for WWTP operators. Next to sludge handling, energy is usually the second largest operational expense in wastewater treatment with costs continue to rise. This has sparked a strong interest in TH as a means of improving the energy balance of a WWTP.

This paper discusses how the energy balance of the TH process can be optimized to achieve maximum energy efficiency.

Keywords

energy efficiency, thermal hydrolysis, sludge digestion

The Cambi thermal hydrolysis process with steam explosion

The Cambi Thermal Hydrolysis Process ("THP") hydrolyses and disintegrates pre-dewatered sludge and turns it into a sterilised liquid and an easily digested product with low viscosity, allowing more than double digester loading compared to conventional digestion. The core of the Cambi THP consists of batch hydrolysis reactors, however in combination with the pulper and the flash tank the overall process is fully continuous. In the hydrolysis reactor, pre-dewatered sludge is fed and then heated by direct injection of steam, to a temperature of about 165 °C and pressure of about 6 bar. At this temperature and pressure, organic matter is hydrolysed into soluble compounds. After some time, the sludge is pushed out of the reactor and into the flash tank using the available steam pressure. The rapid pressure drop causes steam explosion, or pressure-drop disintegration, of cells and fibres. The steam generated during flashing is recycled to the pulper to pre-heat the incoming cold sludge. The heating and cooling of sludge is done with direct heat transfer, using steam, with a resulting robust and stable system.

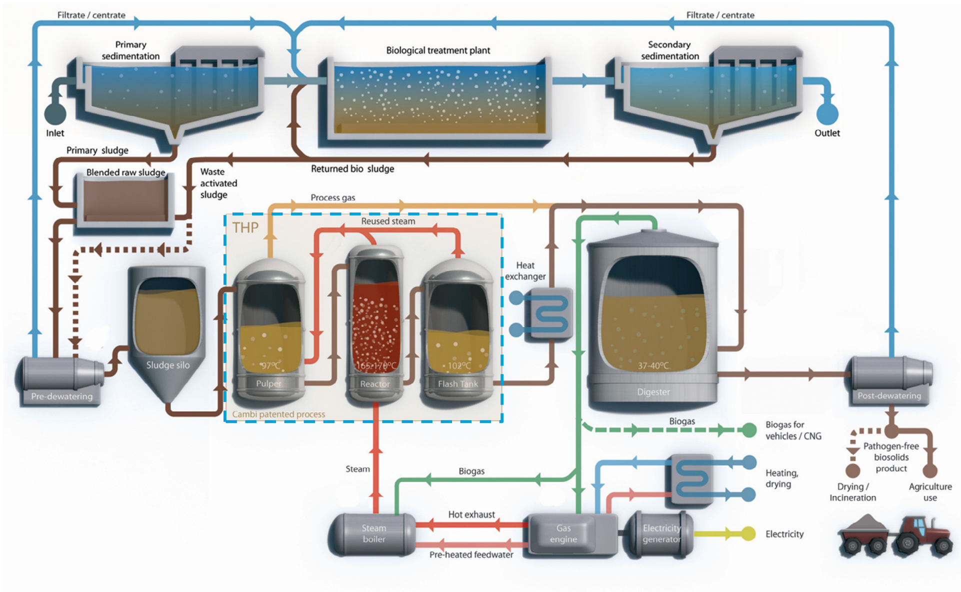


Figure 1: **The Cambi thermal hydrolysis process**

Overall energy balance of a thermal hydrolysis project

The overall energy balance of an advanced digestion project based on Cambi thermal hydrolysis will depend on the relationship between available energy and required steam. Steam is normally produced by recovering high temperature heat from the engines exhaust gas, supplemented with steam from a biogas (or fuel) fired boiler when required. Figure 2 illustrates all the elements involved in the overall energy balance.

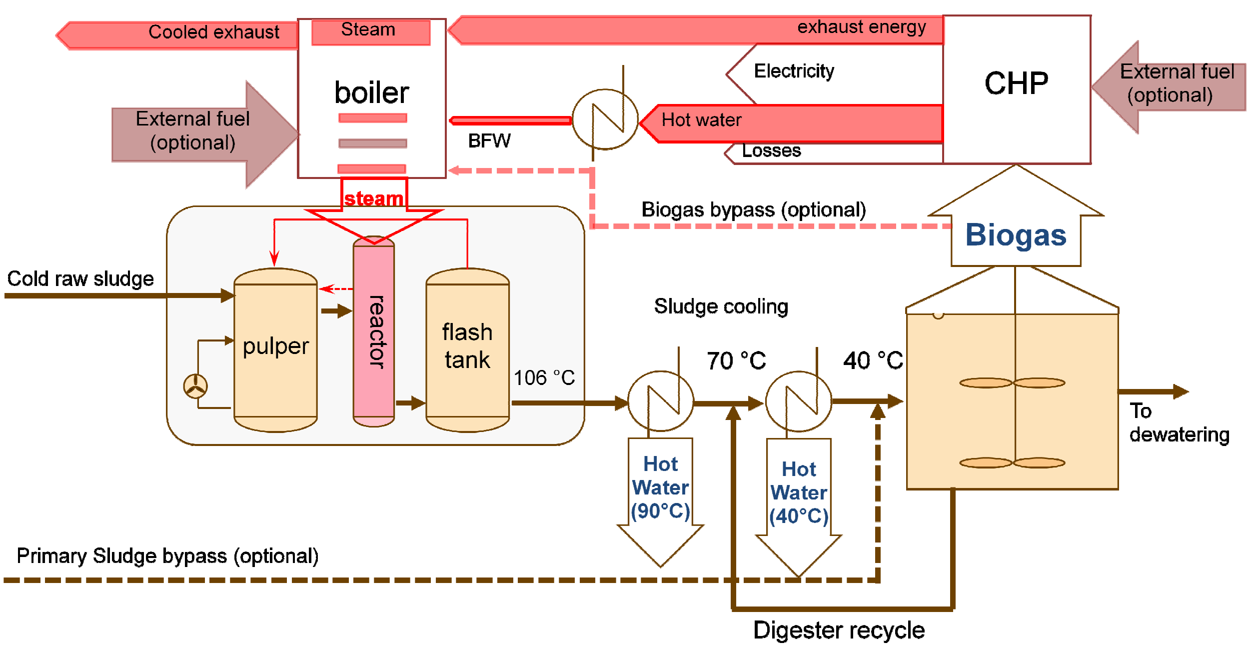


Figure 2: **Overall energy balance of the Cambi thermal hydrolysis process**

The optimum design has the lowest biogas bypass to a boiler and maximises the flow of biogas to CHP units or to gas upgrading. The biogas bypass can be calculated based on Equation 1:

$$\%Bypass = \frac{(P_{steam} - P_{Biogas} \cdot \eta_{S,CHP})}{(\eta_{S,B} - \eta_{S,CHP}) \cdot P_{Biogas}} \cdot 100 \qquad (eq. 1)$$

With:

%Bypass : % of total biogas production bypassed to a boiler for steam production

P_{steam}: total steam requirement (in kW) for the thermal hydrolysis process

P_{Biogas} : total available energy in biogas (in kW)

$\eta_{S,CHP}$: steam efficiency of the CHP unit (%)

$\eta_{S,B}$: steam efficiency of the boiler (%)

The required bypass will depend on the efficiency of making steam. A first step to improve the energy balance is therefore to assure an efficient steam production system, including items such as economisers, high quality boiler feed water (with low TDS) to reduce bleed, boiler feed water pre-heating, etc.

Second, the choice of sludge flows to be hydrolysed will strongly impact the steam demand and therefore the biogas bypass. In class A projects (aiming for high quality biosolids to be recycled to land) both primary and waste activated sludge are hydrolysed. If sludge quality is not a major issue, a “WAS only” (waste-activated or secondary sludge) solution is usually preferred, where only WAS is hydrolysed and mixed with raw sludge prior to digestion. In projects where biogas is sent to CHP units (Combined Heat & Power) there will normally be enough steam from exhaust gas recovery to thermally hydrolyze all the WAS. However, in some projects biogas is used for other applications (e.g. upgraded for injection into the gas grid or used as vehicle fuel) and biogas will need to be burned to produce steam (in conventional digestion biogas will also be burned to heat the digesters).

So finally, the steam consumption of the thermal hydrolysis process itself should be optimised to reduce the biogas bypass. This is discussed in the following chapters.

Steam consumption of a thermal hydrolysis plant

Using a black box approach (see Figure 3), the steam consumption of the thermal hydrolysis system based on direct heating by injection of steam can be calculated using equations 2 (steam demand per wet ton) & 3 (steam demand per dry ton):

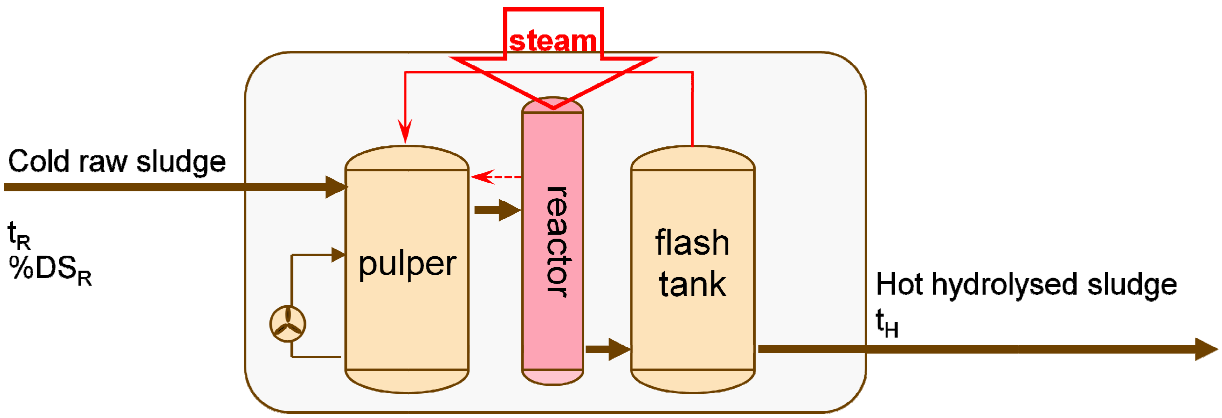


Figure 3: black box approach for the thermal hydrolysis process

$$X = (\boldsymbol{t_H} - \boldsymbol{t_R}).\frac{C_{P,W} - \%\boldsymbol{DS_R}.(C_{P,W} - C_{P,S})}{H_{steam} - \boldsymbol{t_H}.C_{P,W}} \quad (Eq.2)$$

$$\frac{X}{\%DS_R} = (\boldsymbol{t_H} - \boldsymbol{t_R}).\frac{C_{P,W} - \%\boldsymbol{DS_R}.(C_{P,W} - C_{P,S})}{\%\boldsymbol{DS_R}.(H_{steam} - \boldsymbol{t_H}.C_{P,W})} \quad (Eq.3)$$

With :

X = specific steam consumption (ton steam/ton wet sludge)

$X/\%DS_R$ = specific steam consumption (ton steam/ton dry solids)

t_H : temperature of hydrolysed sludge - t_R : temperature of raw sludge

$\%DS_R$: raw sludge dry solids as fed to the thermal hydrolysis system

$C_{P,W}$: specific heat of water - $C_{P,S}$: specific heat of solids

H_{steam} : enthalpy of steam fed to the THP system

These equations only have 3 variables (in bold in equations 2 and 3), the **raw sludge temperature**, the **hydrolysed sludge temperature** and the **sludge feed dry solids concentration**. Any change to these 3 parameters will influence the steam demand and therefore the overall energy balance of the project. Each parameter is discussed separately in the next chapters.

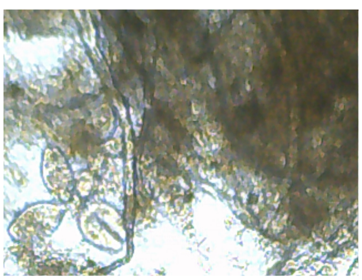
One ton of sludge dry solids will typically produce about 2 – 2.5 MWh_{lhv} of biogas energy, depending on sludge volatile solids and degradation. About 20% of the energy fed to the engine can be recovered as steam, so in order to reduce the biogas bypass to zero, the steam requirement should be lower than 0.4 to 0.5 MWh/tonDS (≈ 520 to 650 kg steam/tonDS) if all sludge is sent to the hydrolysis process. Hydrolysis of thickened sludge (5% DS, 15 °C) without any heat recovery would require almost 6 ton of steam per ton DS or 10 times the available energy. Special measures are therefore needed to guarantee an energy efficient hydrolysis project.

Impact of hydrolysis temperature on the steam demand

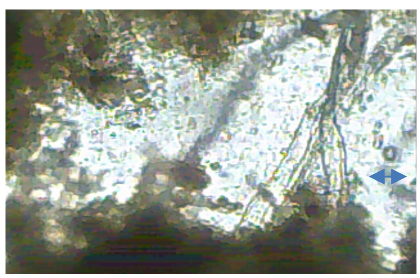
Equations 2 and 3 clearly show that the actual hydrolysis temperature (typically 165 °C) has no impact on the steam consumption of the process. The reason behind this is that the steam released during the flashing process is recycled to the pulper, thereby pre-heating the cold sludge. The steam demand is therefore directly proportional to the temperature difference between the hydrolysed sludge (after flashing) and the raw sludge. As long as the pulper is operated in an atmospheric mode, T_H is about 103 to 107 °C.

The internal recycle of steam reduces T_H from 165°C (hydrolysis temperature) to approx. 105 °C (flash tank temperature). Assuming a raw sludge temperature of 15 °C, the flashing and recycling of steam reduces the steam demand to: $\frac{(105\,°C-15\,°C)}{(165\,°C-15°C)} \cdot \frac{(2{,}785\frac{kJ}{kg}-165\ .\ 4.186\frac{kJ}{kg\,°C})}{(2{,}785\frac{kJ}{kg}-105\ .\ 4.186\frac{kJ}{kg\,°C})}$ = 54% of the steam demand of a system without steam recycle. The flashing & steam recycling is an important first step in achieving an energy efficient thermal hydrolysis process.

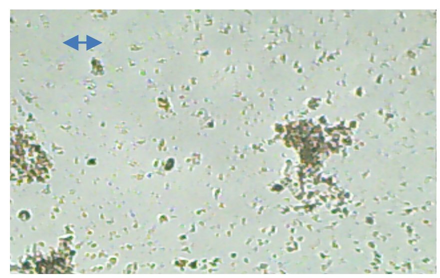
The steam flashing also creates a strong improvement in solids destruction. The following pictures show untreated sludge, hydrolysed sludge and steam exploded sludge. The steam explosion, which is a result of the flashing, strongly reduces particle size, reduces sludge viscosity and improves the digester kinetics.



Raw mixed sludge



Autoclaved (165 °C) sludge



Autoclaved + steam exploded sludge

Influence of the raw sludge temperature (t_R) on the steam demand

The sludge feed temperature clearly has a big impact on the overall energy demand of the thermal hydrolysis system. Figure 4 shows the relationship between the steam consumption (both per wet ton and per dry ton, for a fixed raw sludge dry solids concentration of 16.5%.

The steam consumption as a function of the raw sludge temperature shows a linear relationship. This relationship can be summarised as follows (assuming 16.5% feed DS):

X (**kg steam/wet ton) = 171.4 – 1.6 * t_R**

X/%DS_R (kg steam/dry ton) = 1,039 – 9.7 * t_R

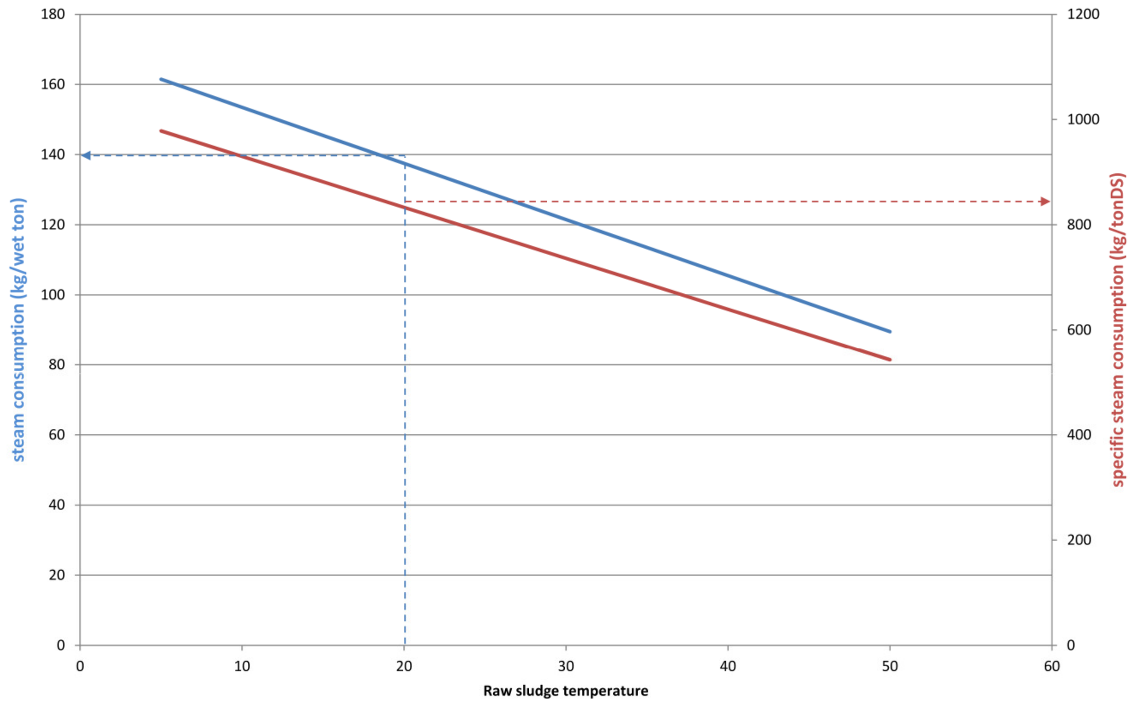


Figure 4: Steam consumption of the TH process as a function of the raw sludge temperature

The above equations show that for every degree of sludge temperature increase the steam consumption per dry ton will be reduced with 9.7 kg. The specific steam demand of a thermal hydrolysis system will therefore depend on the local climate (lower consumption in Middle East than in Scandinavia) and will also vary with the seasons. This also suggests that increasing the t_R is an effective way of reducing the specific steam demand. Increasing the raw sludge temperature can be done using low temperature heat (e.g. engine cooling water or hydrolysed sludge cooling energy). Two methods for increasing the raw sludge temperature are available:

- **Sludge pre-heating**

Sludge pre-heating involves heating of thickened sludge (4-6%DS) prior to the pre-dewatering step. Pre-heating diluted sludge will of course give increased heat consumption, so pre-heating should be designed based on available (waste) low temperature heat like waste engine heat and hydrolysed sludge cooling energy.

Increasing the sludge temperature from 15°C to 35 °C (before TH) reduces the steam consumption from 894 kg/tonDS to **700 kg/tonDS**, a saving of 22% in steam consumption.

- **Heat dilution**

Heat dilution relies on diluting high DS sludge with hot water. Reducing the DS seems counter-productive, however Cambi has found that an optimum DS concentration to the THP of 17% to guarantee full hydrolysis of the sludge. High dry solids sludge can be diluted with hot (90°C) water to reduce the DS to the optimum 16.5% DS and achieve an increase in sludge temperature. The required heat can be recovered from the engines cooling system and/or from the hydrolysed sludge cooling system.

Heat dilution requires higher water temperatures to produce the hot dilution water. Heat-dilution of sludge from 15 to 40 °C reduces the specific steam demand from 894 kg/tonDS to **651 kg/tonDS**, a saving of 27%! Heat dilution requires less heat (in kW) and will have less heat loss than pre-heating, but requires higher cooling water temperatures. Heat dilution should also be balanced against polymer costs for pre-dewatering purposes.

Influence of feed dry solids on the steam demand

Increasing the feed dry solids concentration to the THP process reduces (for a given dry solids load) the total flow to the thermal hydrolysis system. The relationship between the steam consumption and the feed dry solids concentration is, however, not as straightforward as the raw sludge temperature. Figure 5 shows the steam consumption as a function of increasing sludge DS concentration in the feed flow to the TH system.

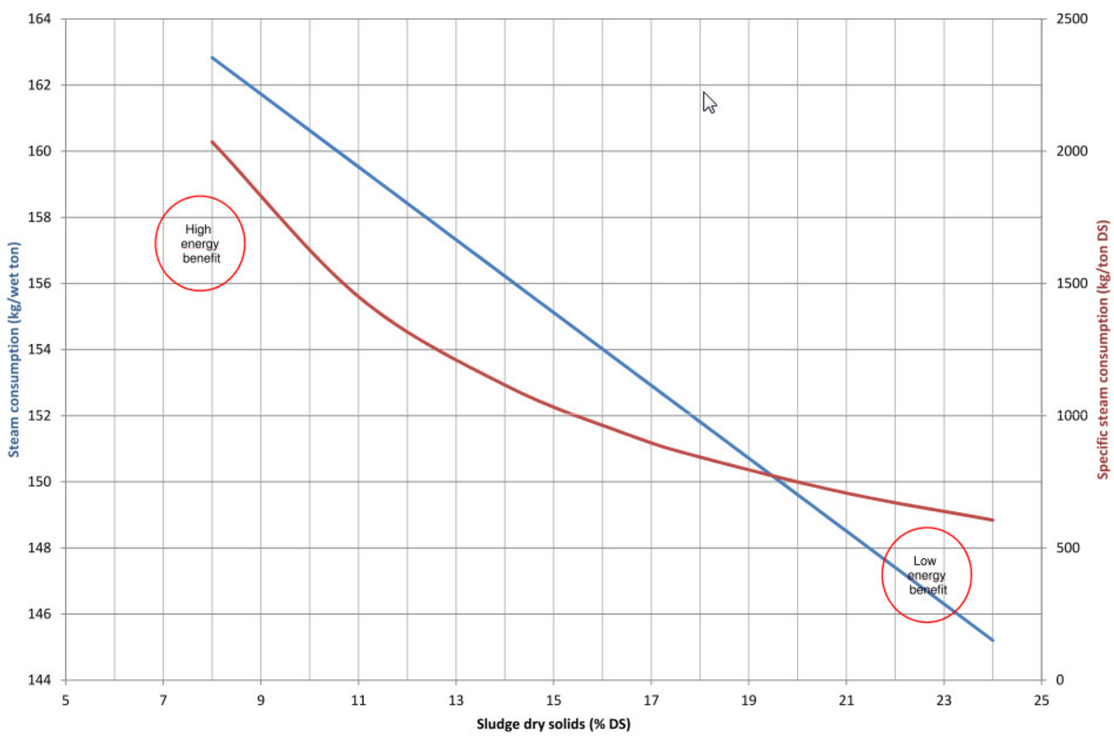


Figure 5: Steam consumption as a function of sludge dry solids

The left vertical axes shows the steam consumption per wet ton, which shows a linear relationship. However, the steam consumption per ton DS (right vertical axes) is not linear. At low dry solids concentrations, the energy benefit of additional thickening and/or pre-dewatering is much bigger than at higher dry solids concentrations. Increasing the dry solids from 8 to 10% DS reduces the steam demand from 1954 kg/ton DS to 1542 kg/ton DS, a reduction of 21.1%. However, increasing the dry solids from 18% to 20 % reduces the steam demand from 809.7 kg/tonDS to 718.2 kg/tonDS, a reduction of only 11.3%.

Increasing the dry solids concentration also comes at a cost since thickening and pre-dewatering require polymer and electricity. High dry solids feed therefore will have higher costs that need to be balanced against the energy benefit. Based on experience Cambi has established the optimum window for feed dry solids at 14 to 18% DS. Experience with higher dry solids has also suggested that incomplete hydrolysis takes place above 18% DS.

The Cambi THP system efficiently treats pre-dewatered sludge with a typical design dry solids concentration of 16.5%. The steam consumption at 16.5% DS (assuming 15 °C average raw sludge temperature amounts to **± 895 kg/tonDS,** equivalent to ± 700 kWh_{steam}/ton DS (assuming preheated boiler feed water to 85 °C).

Conclusions

The Cambi Thermal hydrolysis process is already an established technology for producing Class A biosolids, increasing biogas production, and for maximizing the load on existing digesters.

Cambi thermal hydrolysis is now also being considered as a key technology for the development of energy efficient and/or energy neutral wastewater treatment plants. This requires a very energy efficient thermal hydrolysis system.

As a result of the high dry solids feed and internal steam recycling the steam demand of the hydrolysis system is already highly optimised. Optimisation methods are available for a further improvement of energy efficiency, such as pre-heating and heat dilution.

Today therefore, Cambi thermal hydrolysis is considered a key technology for maximising the energy output of sludge digestion facilities in addition to the benefits of improved dewatering, high digester loading and Class A biosolids production.