THERMAL HYDROLYSIS PRE-TREATMENT FOR ADVANCED ANAEROBIC DIGESTION FOR SLUDGE TREATMENT AND DISPOSAL IN LARGE SCALE PROJECTS

Zuliang LIAO
Cambi Group AS, Norway
School of Environmental Science and Engineering, Qingdao Technological University, P. R. China
Keith PANTER
Ebcor Ltd, UK
Chris PEOT
DC Water, USA
Richard LANCASTER
United Utilities, UK
Nick MILLS
Thame Water Utilities Ltd, UK
Marius KLEIVEN
Cambi Group AS, Norway

ABSTRACT

Sludge treatment becomes an international focus for urban municipal solid waste management due to stringent standard for sludge landfill and negative impact on groundwater, CO_2 and methane release, smells, space demanding, and economic drawback. Anaerobic digestion for sludge has been widely used worldwide, and becomes more attractive for its unique property in low carbon emission, especially combined with thermal hydrolysis pre-treatment (THP) since the beginning of this century. Thermal hydrolysis has several unique advantages compared to traditional pre-treatment and conventional digestion. Advanced anaerobic digestion enhanced by thermal hydrolysis results into far-reaching large scale projects like Davyhulme in United Utilities in UK, Blue Plains in DC Water in USA, and several plants including Crossness and Beckton in Thames Water in UK as well. Experiences from Cambi THP in the past two decades reveal that thermal hydrolysis helps to improve sludge strategies with high efficiency in organic stabilization, more biogas energy production, dramatically less digester volumes, much better cake dewaterability, superior Class A biosolids quality for non-limited land application, and better combination with optional incineration.

KEY WORDS

Sewage sludge, digestion, advanced digestion, thermal hydrolysis, Cambi THP, hygienization, land application, auto-thermal incineration, biosolids.

1. INTRODUCTION

Sewage sludge comes from wastewater treatment processes, including sludge from primary settling, wasted activated sludge or secondary sludge, and tertiary sludge from precipitation of chemically enhanced processes. Due to high concentration of organic matters which easily degrades under natural conditions, high potential of pathogen bacteria affecting with human and animal health, high water content in sludge for difficult transportation, and potential release of methane, a greenhouse gas, into atmosphere, it is critical to stabilise and convert organic matters through anaerobic or aerobic ways, to eliminate pathogens, to reduce total volume and weight for further disposal, and to recirculate valuable resources as bio-energy and nutrients for land application if possible.

Among various routes for sewage sludge treatment and utilization (AECOM Asia Co Ltd, 2011), anaerobic digestion as the core with various utilisation is the lowest carbon footprint technology, as shown in the Table 1 below:

Table 1: Carbon footprints of various technical routes for sludge treatment and utilization (AECOM Asia Co Ltd, 2011)).

Ref	Technical routes	Carbon footprint (tCO_2e per year)
1	Thermal hydrolysis, anaerobic digestion, biogas utilisation, heat drying (90%DS),coal substitution (e.g. in power plant or cement kiln)	-500
2	Anaerobic digestion, biogas utilisation, landfill with landfill gas utilisation	0
3	Thermal hydrolysis, anaerobic digestion, biogas utilisation, land application	200
4	Anaerobic digestion, biogas utilisation, compost, land application	450
5	Anaerobic digestion, biogas utilisation, land application	950
6	Heat drying (90%DS), coal substitution	1300
7	Composting, land application	2400
…		
10	Heat drying, incineration, energy recovery	5900
…		
12	Landfill without landfill gas management	30000

It is clearly indicated that effective energy extraction from sludge, energy utilisation, and methane gas management are among the critical elements for low carbon routes. It is of course important to realize the potential impact of landfill management on groundwater, which is out of this paper.

When considering potential alternatives for sludge treatment and disposal, the following aspects need to be carefully evaluated.

1. Organic stabilization until no obvious further degradation in natural environment for potential odour and impact on local air quality. This can be achieved by high degree anaerobic digestion and aerobic digestion (for example through composting), or ultimate conversion to inorganic matters through incineration.
2. Pathogen kills through proper processes, to eliminate potential health risk when application to human and animal related situation such as safe application to land.
3. Effective reduction of total volume and weight through both organic stabilization and removal of water content in sludge. It is important to recognise the high energy consumption for removal of water contents in sludge, such as heat drying and eventually incineration. Water content is also an important parameter for land application, i.e., too dry cake can’t be applied on land without further watering. Proper water moisture is necessary for both water conservation and transport cost.
4. Energy utilisation becomes more critical for sludge treatment and disposal due to steadily increased energy market price. Overall energy demand for sludge treatment becomes often a critical limiting factor for selection of viable treatment routes. Anaerobic digestion enhanced by thermal hydrolysis becomes more attractive partly due to effective extraction of biogas from organic matters, resulting balanced or even surplus energy production for sludge treatment.
5. The last but not the least factor for choosing proper technical routes is the potential of recycling valuable nutrients (including phosphorous and trace nutrients) and humic like soils back to land, in order to adjust further deteriorating conditions for soils after extensive application of chemical fertilizers.

In this paper, large scale projects such as Blue Plains AWTP sludge project (Peot, et al, 2013) in DC WATER in USA, Davyhulme sludge project (Barber et al 2012, Panter 2013, Belshaw 2013) in United Utilities in Manchester in UK, and several plants including Beckton, Crossness and Riverside sludge projects in Thames Water (Fountain et al 2013, Shana el al 2013) in London UK will be analysed in terms of the above aspects for illustrating the strategic decision making for sludge treatment, will illustrate the strategic shift for sludge treatment in the last decade worldwide and the potential impacts on future wastewater treatment in terms of energy balance.

2. CAMBI THERMAL HYDROLYSIS: DESCRIPTION AND CHARACTERISTICS

A typical thermal hydrolysis enhanced advanced anaerobic digestion can be illustrated in Fig. 1 below (Cambi internal publication). Primary sludge and secondary sludge are thickened and pre-dewatered to 15%-18% DS, then feed to Pulper tank in thermal hydrolysis pre-treatment (THP) system, then batch-wise pressure cooking under 150-170 degree Celsius and 6-8 bar pressure for 20-30 mins before flashed into Flashtank, with temp dropped to 102-107 degree Celsius. It follows by diluting and cooling to 38-42 degree Celsius to feed high DS digestion at 8-12% DS and 16-18 days HRT. Biogas is utilized for CHP or/and biogas boiler, with waste heat from CHP for boilers as well. The digestate is then post-dewatered to final cake (biosolids) with 30-40%DS depending types of dewatering processes.

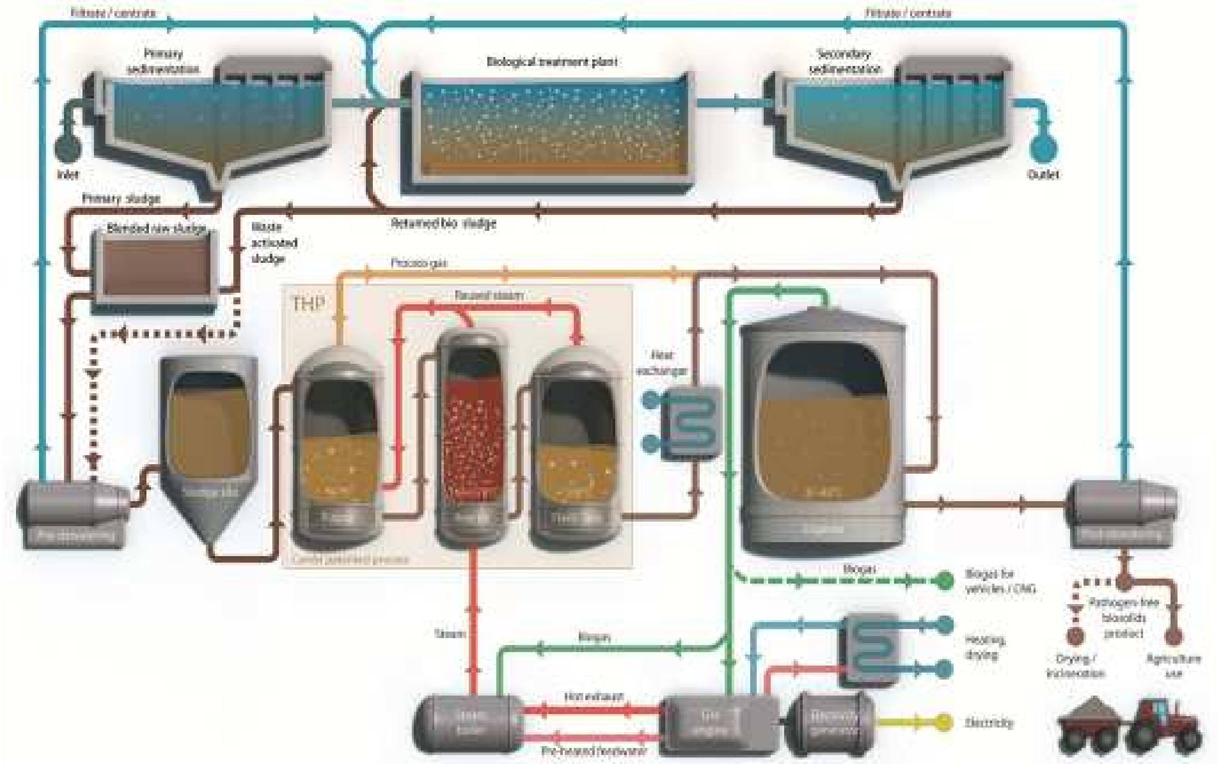


Fig.1. Typical flow sheet for Cambi thermal hydrolysis (THP) enhanced anaerobic digestion for sludge treatment

Comparison of THP advanced digestion and traditional digestion can be listed in the Table 2 below.

Cambi has delivered 42 plants in 19 countries and districts with 29 plants in operation and 13 plants under construction. The total capacity amounts to 935000 tDS/a, for a global market share of ca 90% for thermal hydrolysis type projects. Some typical operational results can be listed below in Table 3.

DC Water project is included for comparison only since it is still under commissioning. Operational data confirm the advantages of thermal hydrolysis bringing to new and upgrading projects with significant impacts on future biosolids strategy worldwide.

Table 2. A typical comparison of parameters for THP advanced digestion with traditional digestion

Parameters	Traditional digestion	THP digestion	Comparison
Feed DS%	3-6%	8-12%	Up to three times
HRT	20 days or above	15 days	Shorter time
Digestion volume	1	0.25-0.5	Save 50%-75%
VS reduction	30-45%	50-65%	Increase by 50% to 100%
VS loading rate	Low	High	As high as 6-7 kg/m^3
Digestion temp	35-37 degree Celsius	38-42 degree Celsius	
Digestion pH value	6.5-7.5	7.5-8	Higher buffer capacity with stable digestion
H_2S in biogas	3000-8000	Less than 200	No corrosion and no need for H_2S removal for CHP
Cake DS%	15-25%	30-40%	Depending on dewatering processes
Cake properties	Sticky, smelly	Porous, particulate, stackable, low odour	Wide land application
Hygienic quality (pathogen kills)	Class B	Class A	Complete elimination of pathogens for safe use
Upgrading and expansion	NA	Double to triple capacity within existing digesters	

Table 3. Operational results of several Cambi THP digestion projects for comparison

Project	**Capacity (tDS/y)**	**Sludge**	**Sludge VS%**	**HRT**	**Cambi VSR%**	**Original VSR%**	**Post-dewatering**	**Cambi DS%**	**Original DS%**	**Biogas utilization**
HIAS	3600	Primary / Secondary	78 %	14 days	58 %	N/A	Bucher press	38 %	23-25%	CHP 400KW
Chertsey	9600	Primary / Secondary	73.5 %	9 days	57 %	45%	Belt Press (Bucher test)	32% (40-45%)	N/A	CHP 1.2 MW
Naestved	1600	Extended aeration	62 %	40 days	52 %	30%	Belt press	29 %	18%	Boiler/CHP
Kapusciska	8000	Primary / Secondary	73 %	44 days	57 %	48%	Centrifuges	32%	22%	CHP 800 KW
Cardiff	30,000	Mostly SBR	77%	20 days	58 %	N/A	Belt Presses	27-29 %	21% centrifuge	CHP 2.8 -4.2 MW
Brisbane	12,900	Extended aeration	77%	17 days	52 %	25%	Centrifuges	29 – 30%	13%	Boiler/CHP
Lindum	6000	Mainly chemical primary	60%	18 days	52 %	N/A	Centrifuges	30 %	N/A	Boiler
Davyhulme	121,000	Primary / Secondary	75%	20-30 days	62%	45%	Centrifuges	33 %	27% (frame press)	CHP 8-12 MW
DC Water*	130,000	Primary/ Secondary Nitrification	75%	16 days	58%	N/A	Belt presses	32%	N/A	13 MW expected from Gas Turbines

3. EXAMPLES FOR LARGE SCALE SLUDGE PROJECTS USING THERMAL HYDROLYSIS ENHANCED ADVANCED ANAEROBIC DIGESTION

Large scale sludge projects include sludge treatment from single large scale centralized wastewater treatment project treating wastewater from several communities and centralized sludge treatment centre for several wastewater treatment plants. A brief introduction to the above mentioned large scale sludge projects will illustrate the different situations of each project in order to compare strategic decision making for such projects worldwide.

2.1. Blue Plains AWTP sludge project in DC WATER, USA

Blue Plains Advanced Wastewater Treatment Plant (AWTP) (Chris Peot 2013) services for around 2.2 million P.E. for Washington DC and portions of Maryland and Virginia in Eastern coast of USA. This plant is among one of the largest advanced wastewater treatment projects in the world, with sludge amount of 130000 tDS/y, or around 450 tDS/d at peak load.

Fig. 2. Blue Plains AWTP services for Washington DC and portions of Maryland and Virginia

The biosolids strategy for DC Water has been changed from composting before the end of 1990s, to lime stabilization until 2008, when traditional digestion was considered to produce energy via biogas, but the existing space and budget were not favourable, until adaption to thermal hydrolysis advanced digestion was finally approved through extensive investigation and pilot studies. With thermal hydrolysis to enhancing digestion, the DC Water's new biosolids programme helps to achieve the following benefits: 1) to reduce biosolids quantity by more than 50%, 2) to improve product biosolids quality to Class A, 3) to generate 13 MW (net 10 MW) of clean and renewable power from CHP, 4) to cut green-house gas emissions by 57000 t/y, and 5) to save million USD for operational cost compared with lime treatment. With DC Water's New Biosolids Program with Cambi THP as the core, a saving of around $US200 million investment compared with traditional digestion and reserved space for future expansion are achieved. Fig.3 illustrates the flow sheet and Fig. 4 shows the bird view and Fig. 5 depicts the layout of various upgrades in Blue Plains AWTP, Fig. 6 shows the 3D design for THP and digestion and real picture of facilities . As the largest THP project in the world, Blue Plains AWTP sludge project will be in operation from end of 2014, setting up a new standard for biosolids management in USA and worldwide.

Limitation of available space for existing sludge treatment and potential increase in future has constrained the original proposal using two stages of traditional digestion, and the original budget estimates for around $US 600 million was also above the potential investment capacity. Extensive experiences in THP for enhancing traditional digestion in Europe especially in UK has revealed opportunities for application in USA, through extensive investigation with cooperation between DC WATER, universities and research institutes, potential suppliers and consulting companies. The final decision was sole source from Cambi for THP system.

The flow sheet for New Biosolids Program is illustrated as in Fig. 3.

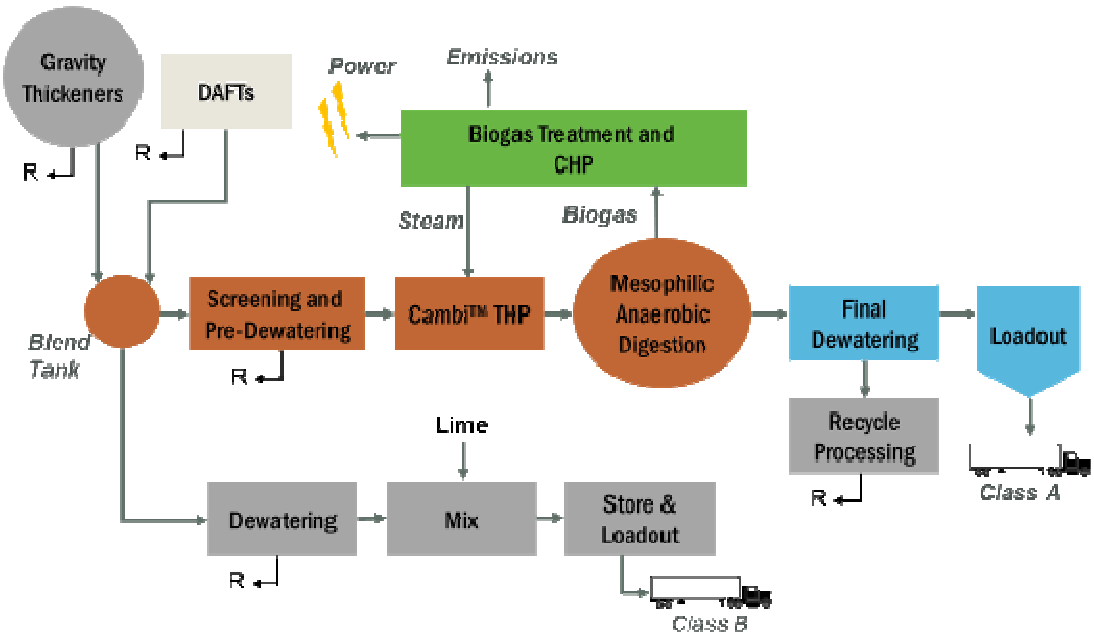


Fig. 3. Flow sheet for DC Water's New Biosolids Program

Fig. 4. A bird view of existing Blue Plains AWTP

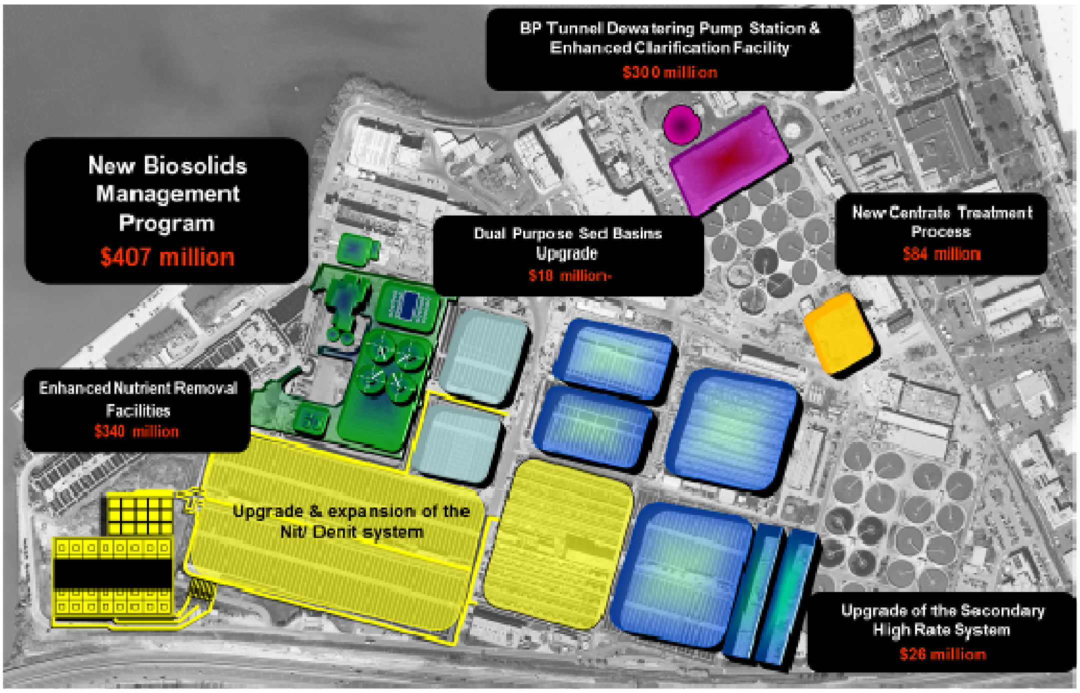


Fig. 5. Layout of various upgrades in Blue Plains AWTP including New Biosolids Management Program $US 407 million


(left) 3D view of Cambi THP and digestion design and (right) a view of Cambi THP and digesters from dewatering house on the corner

Fig. 6. SD model of Cambi THP and digestion (left) and real photo of THP and digesters (right)

2.2. Davyhulme SBP in United Utilities, Manchester UK

United Utilities in Manchester UK owns 13 WWTPs, in which Davyhulme WWTP is the largest one with existing 8 digesters with total effective volume of 60000 m^3, treating around 35000 tDS/y, and digested sludge pumped to Shell Green for dewatering and incineration in two fluidized bed incinerators (each 6.5 t/h) with external natural gas fuel 2 MWh to facilitate the operation. In AMP5 plan, all 13 WWTPs shouldl be upgraded in sludge treatment and disposal with 91000 tDS/y capacity. Original proposal was to build up another incineration plant to deal with sludge in other 7 WWTPs which are now lime treated for land application. Incineration of sludge largely depends on external fuels like natural gas, and any interruption in operation of incineration facilities will result into unsafe disposal of sludge and health risks. Fig. 7 illustrates the layout of 13 WWTPs and existing Davyhulme digestion and Green Shell incineration before upgrading.

Fig. 7. Layout of 13 WWTPs with Davyhulme digestion and Green Shell Incineration in blue dots and lime stabilization for land use in red dots.

After considerable evaluation of various alternatives, upgrading of existing digestion facilities in 8 digesters to treat all sludge in this area without building up more digester volume by integrating thermal hydrolysis system provided viable and stable option. After evaluation, the Sludge Balanced Asset Program (SBAP) required the selected alternative to meet the following three goals at the same time:

1. Better dewaterability of the final cake to facilitate less requirement of external fuel for existing incineration, and less cake quantity for land application if applicable.
2. More biogas production to facilitate better energy balance and potential external surplus energy export.
3. Superior final cake quality in Class A hygienic parameters to facilitate unlimited land application if possible, therefore further reduce the cake to incineration.

After evaluation of several advanced anaerobic digestion including thermal hydrolysis pre-treatment, Cambi THP was selected to provide the largest ever THP system then in the world, now in Europe. Nearly two years of operation of Cambi THP system in Davyhulme reveals the designated benefits in the following aspects:

1. All the 91000 tDS/d sludge is able to be treated in four lines of Cambi THP and existing 8 digesters, with better VS reduction than design value.
2. Less biogas is required to bypass for additional fuel for steam boilers fueled by the waste heat from CHP. 11 MW electricity is produced accordingly. VS reduction increased from 43% for conventional digestion before upgrading to 58% after Cambi THP digestion, and biogas production per tDS is achieved for design 422 Nm^3/tDS.
3. Superior cake hygienic quality enables the cake for land application, therefore less cake than design is sent to incineration.
4. Stable operation of the whole system and continuous upgrading of the existing digesters one stream after another.
5. A significant example for thermal hydrolysis enhanced advanced anaerobic digestion in Europe has attracted clients, experts, and consultants worldwide.

Fig. 8 shows the bird view of Davyhulme SBP, in the middle there are two groups of four lines of Cambi THP B12-5 type installed after three sludge silos, with two silos for imported sludge and one for Davyhulme itself. After cooling, the sludge is sent to 8 existing digesters through pipelines. Cambi THP is compact, with a small footprint. Fig. 9 illustrates the overall layout of Davyhulme SBP project, showing how the new part for Cambi THP is integrated into the existing digestion system. Except for pre-dewatering and silos for import sludge and Cambi THP, other equipment such as final dewatering, CHP, boilers, gas holders, and final cake silos are required for traditional digestion projects. Therefore Cambi THP is very compact for upgrading of existing projects.

It is important to describe more about the changes in E. Coli numbers during the commissioning of the four streams of digesters, from stream 1 (for Digester 1 and 2), to stream 2 (digester 3 and 4), to stream 3 (digester 5 and 6) and until stream 4 (digester 7 and 8). Fig. 10 depicts the difference in E. Coli in each stream and between streams.

Experiences in commissioning of existing digesters to Cambi THP digestion to meet the hygienic quality for pathogen kills in Davyhulme brings us valuable procedures for other projects in the world. The dewatered cake meets the Class A requirement on pathogen kills, less than 1000 cfu/gDS.

Through seamless project management, large scale sludge projects like Davyhulme could be well managed to complete within one and half years, and normally delivery of Cambi THP systems were not a limiting factor for implementation of the whole project due to its prefabrication of most of the components and well organized site installation and management.

Fig. 8. Bird view of Davyhulme SBP after Cambi THP installation

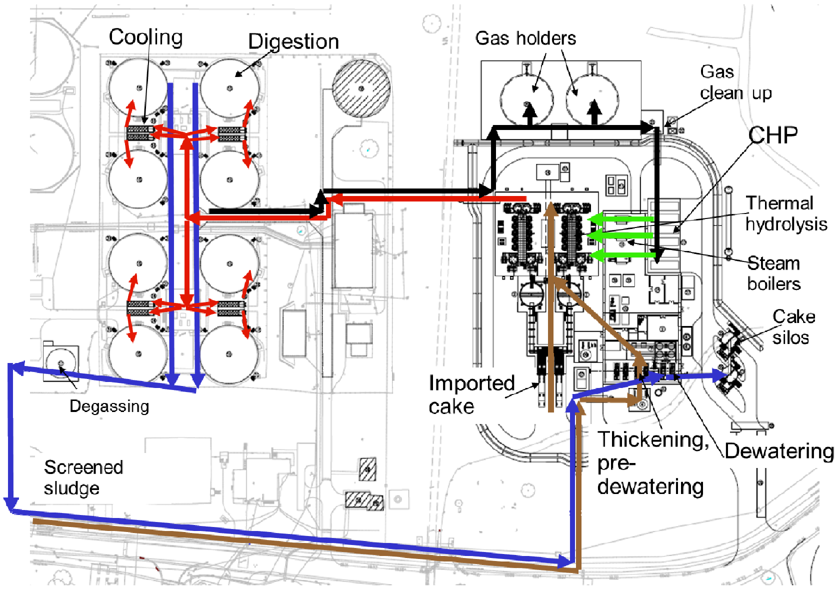
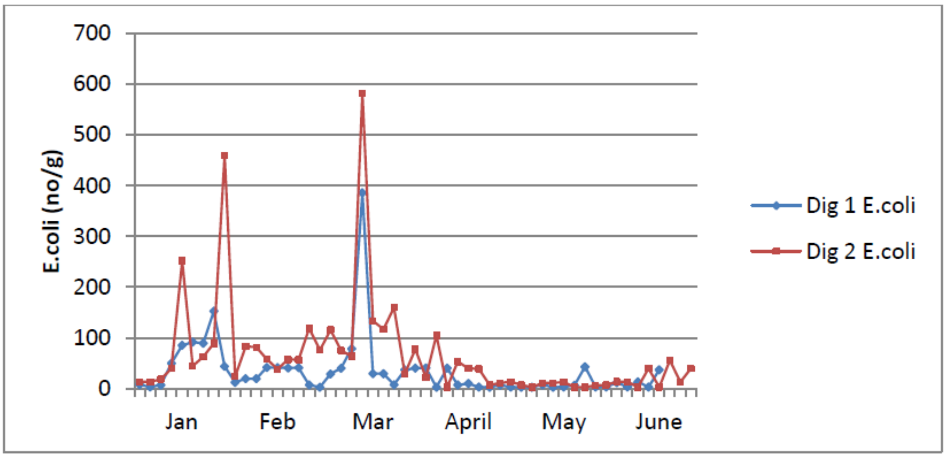
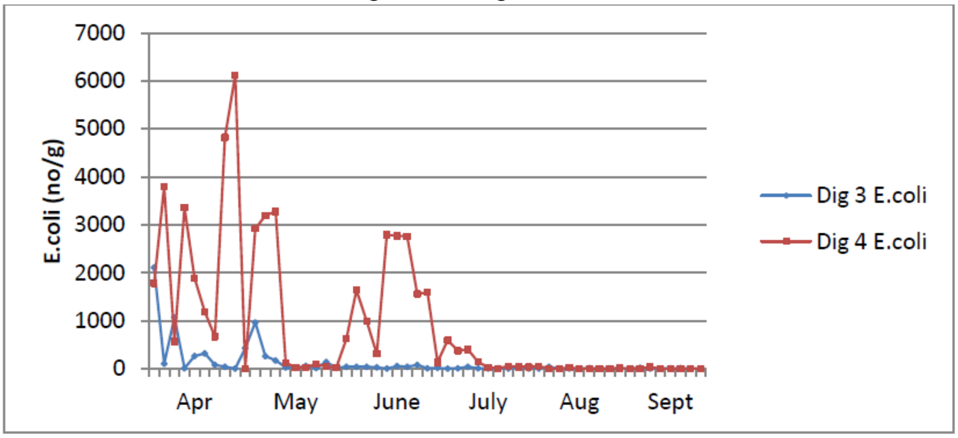


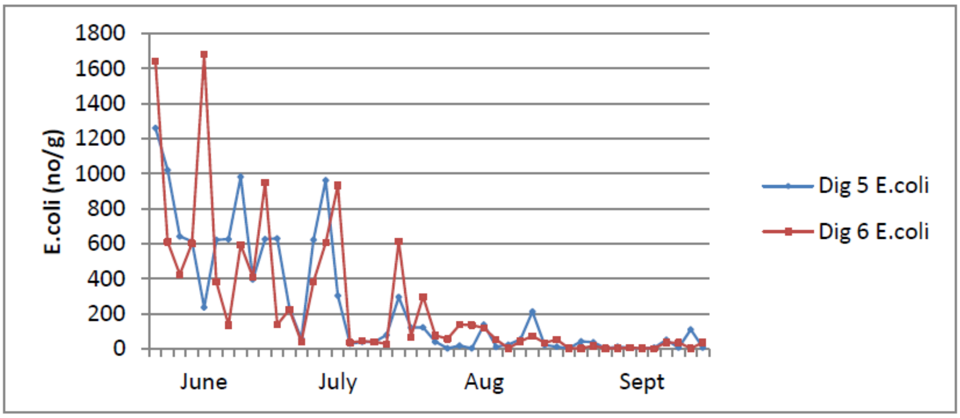
Fig. 9. Overall layout of Davyhulme SBP project after integration of Cambi THP system



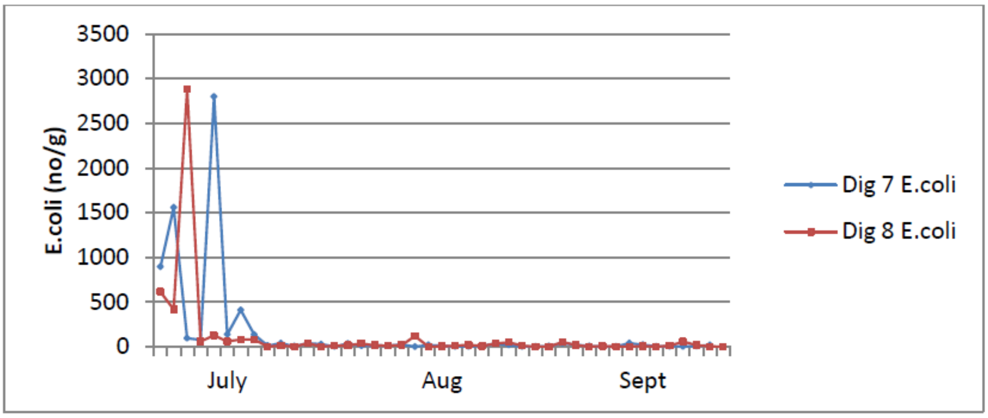
Stream 1, External THP sludge seeding to facilitate the stable reduction of E. Coli.



Stream 2, long time for washing out E. Coli by converting traditional to THP digesters.



Stream 3, shorter time than stream 2 for E. Coli washout



Stream 4, quick wash out of E. Coli during the last period of commissioning

Fig. 10. Changes in E. Coli for all streams during commissioning

2.3. Seven WwTWs in Greater London using THP in Thames Water until 2015

Thames Water manages around 15 million customers in 350 Wastewater Treatment Works, serving Greater London and surrounding areas. Total sludge amount in those plants amounts to around 1000 tDS/d, among them 70% of sludge is recycled to land. There are 20 generation sites, including 2 fluidized bed incinerators in Beckton and Crossness, 20 conventional digestion sites, and 7 thermal hydrolysis sites until 2015. First THP was built up in Chertsey in 1998 with continuous operation for 16 years. In its 5-year (2011-2015) plan, six THP plants are under construction, i.e., Riverside 110 TDS, operational, Crawley 31 tDS/d, under construction Oct 2014, Crossness 100 tDS/d, commissioning, Beckton 100 tDS/d, commissioning, Long Reach 81 tDS/d, under construction, Jan 2015, and Oxford (VEOLIA Bio-thelys) 67 tDS/d, seeding July 2014, end of August 2014 Operational. Total sludge through THP amounts to 40% of sludge amount in Thames Water. All this will generate potentially in 2015/16 of 318 GWh - more than 20 per cent of its annual power needs. Fig. 11 shows the locations of those seven THP sites (Basingstoke is location for Crawley).

In next 5-year plan, another around 400 tDS/d THP capacity will be built up, including expansion of Beckton and Crossness for 300 tDS/d, Basingstoke 100 tDS/d, and some small projects less than 30 tDS/d. Within next 5-10 years, a majority of sludge will be pre-treated with THP. Application of THP for sludge treatment has dramatically brought and will continue to bring up significant changes in biosolids strategy in Thames Water.

Fig.11 Locations of seven THP sites in Thames Water projects in Greater London

Based on successful application of THP in Chertsey and other projects in UK, Thames Water has made this significant strategy of applying THP to its main projects. In addition to those, Thames Water has paid much more attention to the impact of DS% of final cake on downstream treatment and disposal, by comparing various dewatering processes such belt press, centrifuges, and Bucher (twisting) press, a widely used dewatering in wine and juice production, now a new type of dewatering application for sludge treatment.

In UK there are 9 sludge incinerators as listed in Table 4. Among them Beckton and Crossness are two of them with total design capacity of 144000 tDS/y, 37% of total capacity in UK. In order to operate the two incinerators, called Sludge Powered Generators, supplementary natural gas is added to facilitate the combustion of raw sludge by plate press dewatering (Perrault et al 2013). Although dried sludge as alternative fuel can be added to reduce the amount of supplementary natural gas, but the incineration of raw sludge was still not auto-thermal.

Table 4. Sewage sludge incinerators in UK (2009)

Operator Name	Installation Name	Permit Capacity (TDS pa)	Through-put 2006	Through-put 2007	Through-put 2008	Through-put 2009
United Utilities	Widnes	100,000	24,654	26,006	1,737	7,177[2]
Thames	Beckton	90,500	59,441	59,291	67,342	71,540
Thames	Crossness	53,500	31,035	31,186	30,191	31,186
Severn Trent	Coleshill	40,000	17,574	15,550	0[3]	0
Severn Trent	Roundhill	15,000	6,737	888	0	0
Yorkshire	Knostrop	28,500	22,290	24,040	25,064	22,514
Yorkshire	Esholt	25,500	17,256	14,500	17,842	17,253
Yorkshire	Blackburn	18,000	10,052	11,913	13,160	12,936
Yorkshire	Calder Valley	16,500	7,395	10,451	12,377	12,505
Totals		387,500	196,434	190,825	167,713	175,111

In order to improve further the situation of two SPGs, a new type of dewatering of THP digested cake to replace raw sludge incineration was demonstrated under the following conditions:

1) Raw sludge was dewatered by plate press, achieving 30% DS, with 20 MJ/kgDS heat value
2) THP digested sludge was dewatered by Bucher press, achieving 45% DS, with 14 MJ/kgDS heat value.

Calculation of free board temp in incinerators for two conditions shows that no supplementary natural gas is required for THP sludge incineration within full range up to the maximum capacity of 6.3 t/h, but natural gas is required for raw sludge incineration above 5.6 t/h, see Fig. 12. Trials using THP digested cake at high DS% as alternative fuel confirmed that auto-thermal incineration can be steadily maintained to replace supplementary natural gas.

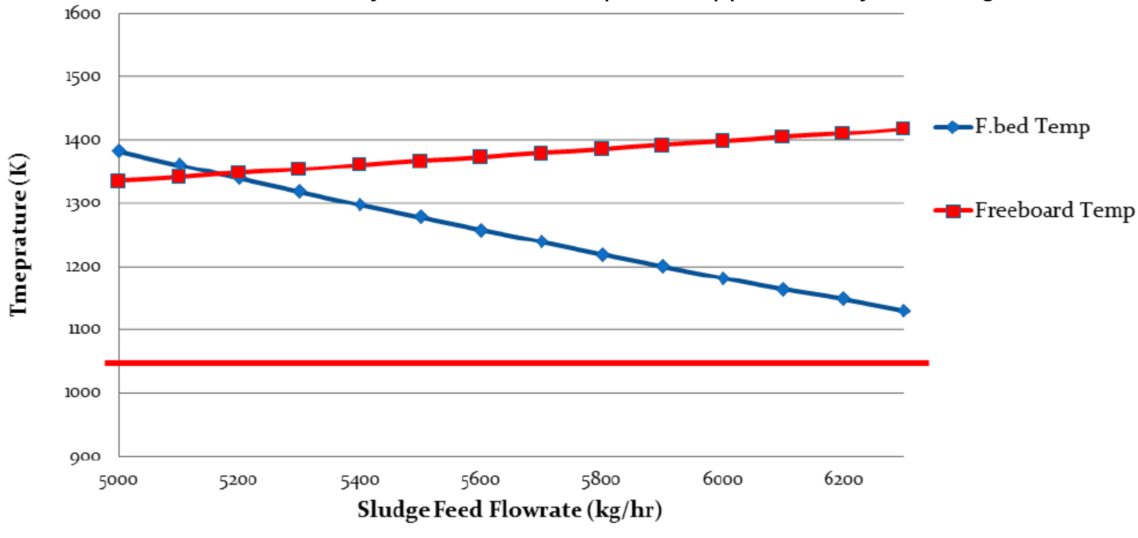


Fig. 12. Free board temp in incinerator, using THP digested cake at high DS% (45%)

Looking back to the trials of dewatering using Bucher compared with belt press, following Fig. 13 gave us clear and significant suggestion.

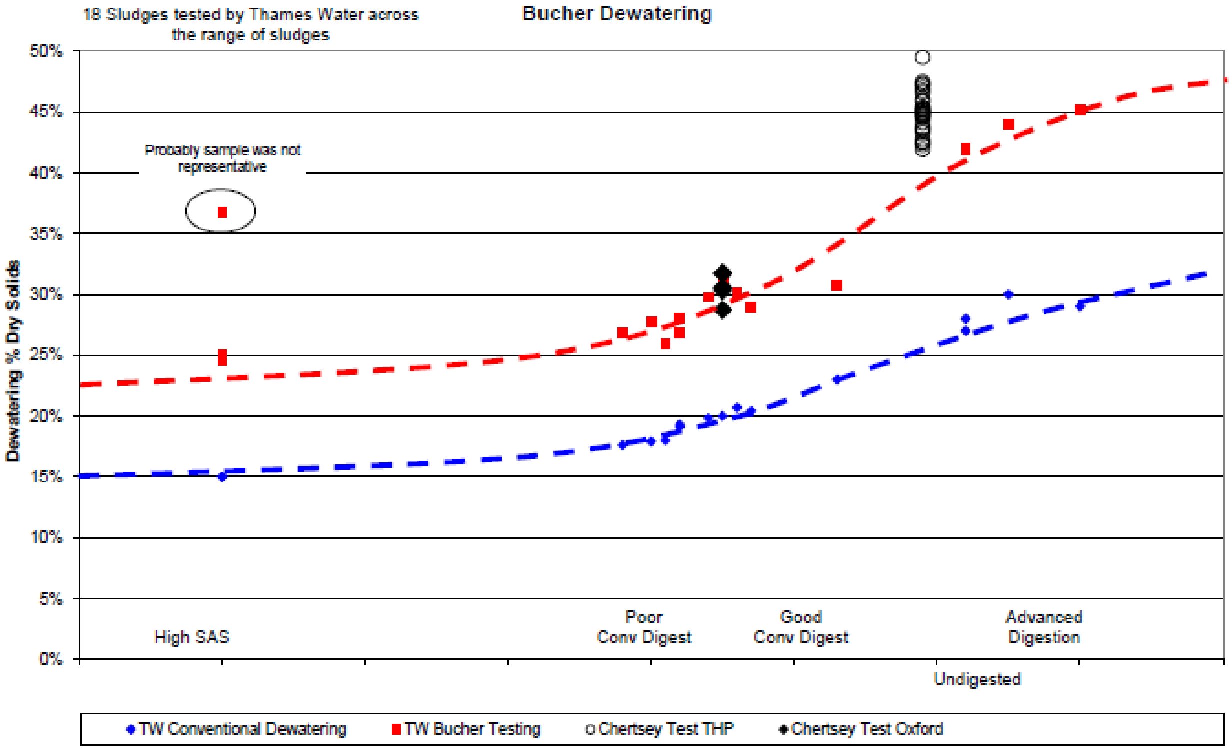


Fig. 13. Comparison of dewatering properties of Bucher and conventional dewatering for different types of sludge (high SAS, poor digested, good digested, advanced digested).

Superior dewatering of THP digested sludge by Bucher extends further significant benefits for less cake weight and volume, and higher energy value for alternative fuels to incinerators as well. Description of Bucher press can be found elsewhere. After extensive trials, 19 units of Bucher are planned to install in Thames Water projects, taking into account of Capex and Opex in 20 years of life time. There were significant benefits financially to utilising the Bucker Press, when considering the whole life cost. First Bucher Press has been installed and operational in Crossness.

The basic principle of Bucher press can be shown in Fig. 14 with a reference photo as well. The Bucher dewatered THP digested cake has a powder like stackable pile as shown in Fig. 15.

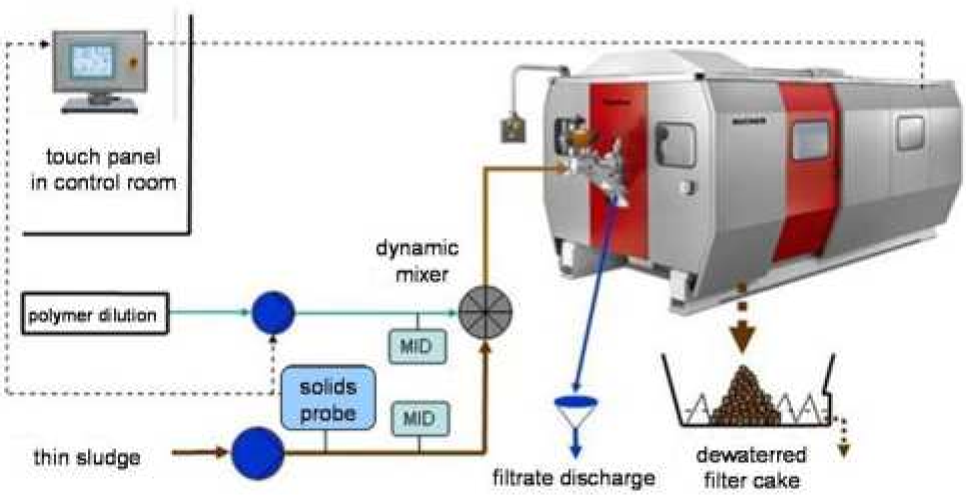


Fig. 14 Bucher press system with control and polymer addition (Huppert M 2013)

Fig. 15 Stackable final cake with 45% DS after Bucher press dewatering of THP digestion in Chertsey

3. DISCUSSION AND CONCLUSION

Thermal hydrolysis has been recognized as a viable option for expanding and upgrading existing sludge digestion projects and constructing green field sludge projects for large scale projects worldwide due to its superior properties in high degree of stabilization of organic matters and converting to biogas production, compact digestion facility with high DS feed, better and safer operation of biogas treatment due to low H_2S, considerably less final cake amount due to easy dewaterability, superior hygienic quality of biosolids for land application, overall energy positive system, and better operational environments for operators. Development of thermal hydrolysis and application in USA, UK, other European countries, and great potential in China and other Asian countries reveals a clue in both energy consumption and final cake quality as two main drivers in addition to total investment as well for strategic decision making for sludge treatment.

REFERENCES

Barber B, 2012, Influence of thermal hydrolysis on digestion and incineration of sludge in Davyhulme, presenting on 16th European Biosolids Conference, UK, 2011.

Belshaw, Dave, 2013, Comissioning Davyhulme WwTW Thermal Hydrolysis plant—turning black gold green, Proceedings for the 18th European Biosolids Conference, 19-21 Nov, 2013, Manchester, UK.

Fountain P et al, 2013, High dry solid dewatering—from pilot scale through to full scale implementation comparing performance, Proceedings for 18th European Biosolids Conference, 19-21 Nov, Manchester, UK.

Huppert M. et al, 2011, Top range dewatering of digested and THP sludge with Bucher HPS press in the UK, Proceedings for the 16th European Biosolids Conference, Leeds, UK, Nov, 2011.

Panter K et al, 2011, Comparison of centrifuge and belt press for compressible digested sludge after thermal hydrolysis, Proceedings for 14th European Biosolids Conference, 2009, UK.

Peot C, 2013, Reinventing Biosolids, presenting on WEX Global 2013, connecting the world of water and energy, Lisbon, Spain, 2013.