THE INFLUENCE OF HEAT BALANCE ON THE ECONOMICS OF ADVANCED ANAEROBIC DIGESTION PROCESSES

Mills, N.[1] Pearce, P.[1], Farrow J.[1], Thorpe, R.[2], Kirkby, N.[2]
[1] Thames Water, [2] University of Surrey
Nick Mills Tel. 077476 42919 Email nick.mills@thameswater.co.uk

Abstract

The UK Water Industry currently generates approximately 800 GWh pa of electrical energy from sewage sludge, a renewable by-product from wastewater treatment. Advanced anaerobic digestion processes are beginning to improve energy yields from this resource which the industry has in abundance. These processes are being implemented across the UK and within Thames Water. However, these processes are still being driven by the operational and regulatory requirements for sludge disposal and significant opportunities for increased energy extraction are not being exploited.

A model has been created which compares current advanced sludge to energy processes, based around anaerobic digestion. Particular attention is made to the use of heat within these advanced processes such as the Thermal Hydrolysis Process. Factors that affect the heat balance and the subsequent economics are explored. CHP engine selection and the combined heat and power configuration are critical to optimising the operational economics.

Keywords

Sewage sludge, Thermal Hydrolysis Process, Heat Balance, Combined Heat & Power, OpEx

Background

This paper presents some preliminary results from the first of a four year collaborative research project between Thames Water and the Centre for Environmental Strategy at the University of Surrey; employing an engineering doctorate student, the primary author of this paper.

Anaerobic Digestion

Anaerobic Digestion (AD) is a very effective stabilisation technique for sewage sludge that has been used by the water industry for over 100years (McCabe 1957). Traditionally this complex biological process has been implemented primarily to provide a pathogen kill and odour reduction to allow sludge to be disposed to agricultural land. AD has the added benefit of producing sustainable energy in the form of a methane rich bio-gas which can be used in gas engines to generate electricity and heat to maintain the process, commonly referred to as combined heat and power (CHP). Currently 90% of the UK's biogas is produced from the AD of sewage sludge (Andrews 2008).

Advanced AD processes began to appear in the UK 15 years ago (Riches 2010) these include Enzymatic Hydrolysis and Thermal Hydrolysis. These processes and some variants are now well established across Europe and offer similar benefits over basic AD, mainly:

- Improved volatile solids destruction
- Improved dewaterability of digested sludge
- Reduced disposal costs
- Higher loading rates in existing assets
- Increased energy yields

Thermal Hydrolysis Process

The research for this paper has concentrated on Thermal Hydrolysis Process (THP), one of the most effective advanced processes currently available to the industry that enables high volatile solids destruction and a grade-A sludge favoured by farmers. It is also very effective at treating surplus activated sludge[i] (SAS): the root cause of many sludge treatment issues.

The additional biogas yield using THP is 35% (Merete) and the process offers the potential for the water industry to become a large renewable energy generator.

THP forms a large part of Thames Water's sludge strategy and it is very important that its implementation and operation is optimised to maximise the performance to reduce costs and increase revenue. This research focuses on the energy and heat balance of THP and the parameters that influence performance. It is a relatively unexplored and unpublished area and the potential to make a contribution to knowledge is high. Although progress has been made there is much work still to be completed, it is planned that this paper will be followed by several more over the course of the four year research project.

THP description

THP uses steam to heat and pressurise sludge, this action hydrolyses the sludge. Hydrolysis is the rate limiting step for AD and by pre-hydrolysing sludge AD can achieve the benefits described by its advocates. The most common THP process is that developed by Cambi™ which uses three batch vessels: the pulper, reactor and flash tank (Cambi 2010). The pulper receives the fresh sludge at ambient temperature which is preheated using recycled steam from the flash tank. The preheated sludge enters the reactor vessel where it is heated with fresh steam and maintained at 165degC and 7barg for 30mins. The reactor is emptied into the flash tank where the pressure is released and the steam produced is sent to the pulper as described previously. Information is readily available on the Cambi™ process and has been used for this initial modelling exercise. Alternative processes such as the Veolia's Biothelysis™ will be explored in the future.

Process Model

A model was constructed that compares the relative performance of anaerobic digestion with and without THP on a 'greenfield' site under various configurations. The model uses global and process specific assumptions as inputs to each unique process variant module. The outputs from these can be compared and are used to calculate operational expenditure (OpEx). A flow diagram for the model can be seen in Figure 1, along with technical and economic assumptions in Tables 1, 2 & 3.

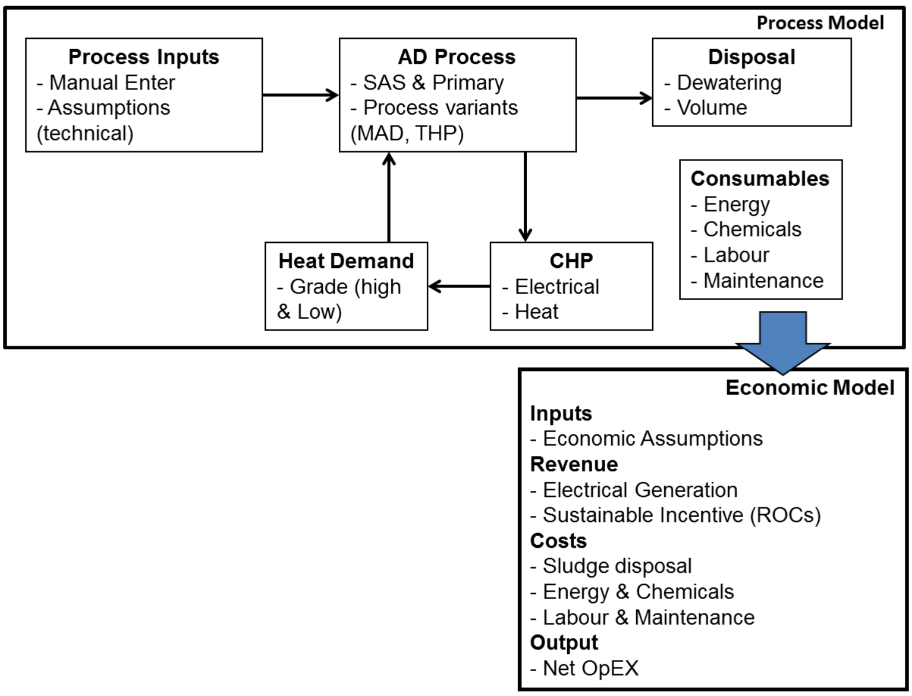

Figure 1 – Model Flow Diagram

Table 1 - Global Assumptions

Parameter	Units	Qty
Primary proportion	%	60
Primary VS content	%	80
SAS VS content	%	75
Bio-gas yield	M^3/kgVS	1.0
Bio-gas CV	MJ/m^3	23
CHP electrical efficiency	%	38
CHP electrical parasitic load	%	10
CHP low grade heat efficiency, hot water for MAD	%	17
CHP high grade heat efficiency, steam for THP	%	18

Table 2 – Process Specific Assumptions

Parameter	Units	Qty
MAD – combined feed DS	%	6.0
MAD – Primary VSD	%	60
MAD – SAS VSD	%	15
MAD – Process Electrical load	kW/TDS/d	6.0
MAD – Cake DS	%	21
THP – combined feed DS	%	16
THP – Primary VSD	%	63
THP – SAS VSD	%	55
THP – Process Electrical load	kW/TDS/d	12
THP – Cake DS	%	32
THP – Steam requirements	kg/TDS	900

Table 3 – Economic Assumptions

Parameter	Units	Qty
Electricity	£/MWh	75.0
Natural gas	£/MWh	25.0
Polymer	£/kg	2.0
Sludge cake disposal	£/wT	15.0
ROC value	£/ROC	45.0
ROC quantity	ROC/MWh	0.5

The global assumptions have been taken from a combination of published sources and discussions with technical experts within Thames Water and other sources. These assumptions have provided a starting point and will be reviewed and revised as necessary as the research progresses. The process specific assumptions will vary depending on the site or processes in question; the economic assumptions are likely to be the most dynamic as they are subject to both the regulatory and commercial situations.

In summary the model calculates the following physical quantities which relate to cost:

- Process energy consumption (electrical and gas)
- Chemical consumption
- Volume of wet sludge cake transported to agricultural land
- Labour & Maintenance

And physical quantities that relate to income:

- Bio-gas production
- Electrical Generation
- ROCable output – the output that is eligible for renewable obligation certificates

The net OpEx is then produced by the subtraction of these costs from total incomes.

Thermal Hydrolysis Process – energy/heat balance

The model aims to ensure that heat use is appropriately accounted and calculates the amount of process steam that can be supplied by the CHP and the additional quantity that is required from another source. Figure 2 shows the total energy input to the process, both electrical and thermal, for THP and standard Mesophilic Anaerobic Digestion (MAD). It shows that THP uses additional electrical power over conventional MAD this is due to THP being a more complicated process with increased sludge handling i.e. more pumps and additional dewatering. The additional thermal energy required is 0.3 MWh/TDS; this is provided from a support fuel, natural gas in this case, representing 40% of the process steam energy.

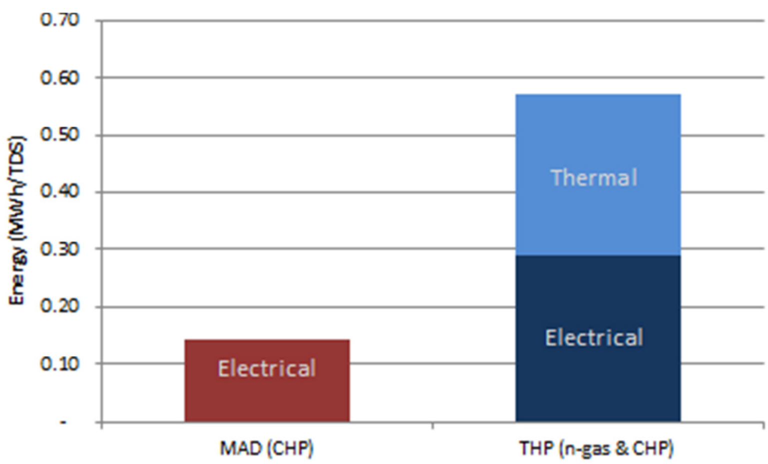

Figure 2 - Energy Input into the Process

Bowen observes a similar support fuel requirement for the Cardiff THP plant, which uses 0.33MWh/TDS or 46% of the steam energy (Bowen 2010). A Sankey diagram of the 84TDS/day process can be seen in Figure 3.

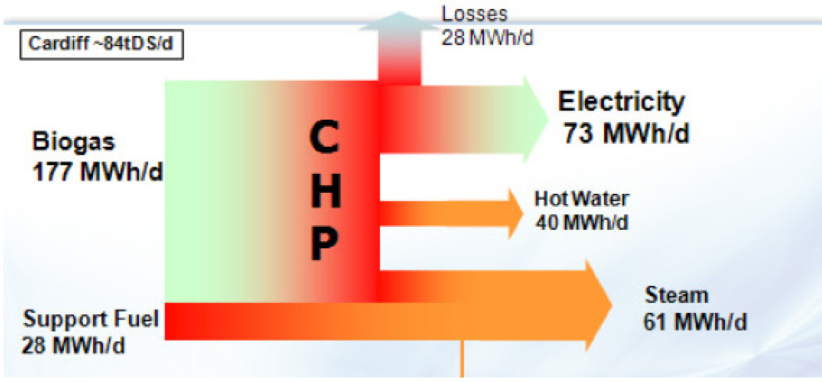

Figure 3 - Sankey Diagram from Cardiff THP Site (Bowen 2010)

Support Fuel Type

There are two options currently being used on operational THP plants across the UK, these are natural gas and biogas diversion, shown as Option A and B respectively in Figure 4. Option A is considered in the analysis above. Option B has been considered to compare the relative economics.

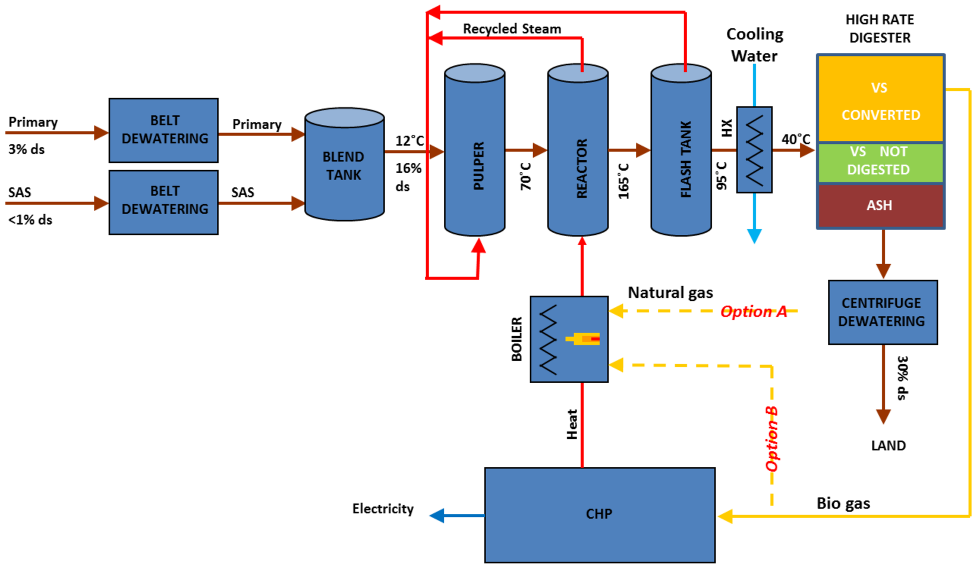

Figure 4 - THP with Support Fuel Options

The model was adapted to include an additional process module that satisfies the process heat requirements with bypassed biogas from the CHP. This does make solving the model slightly more complicated because the biogas bypassed reduces the engine size and waste heat available. The optimum bypass proportion was found by the process shown in Figure 5.

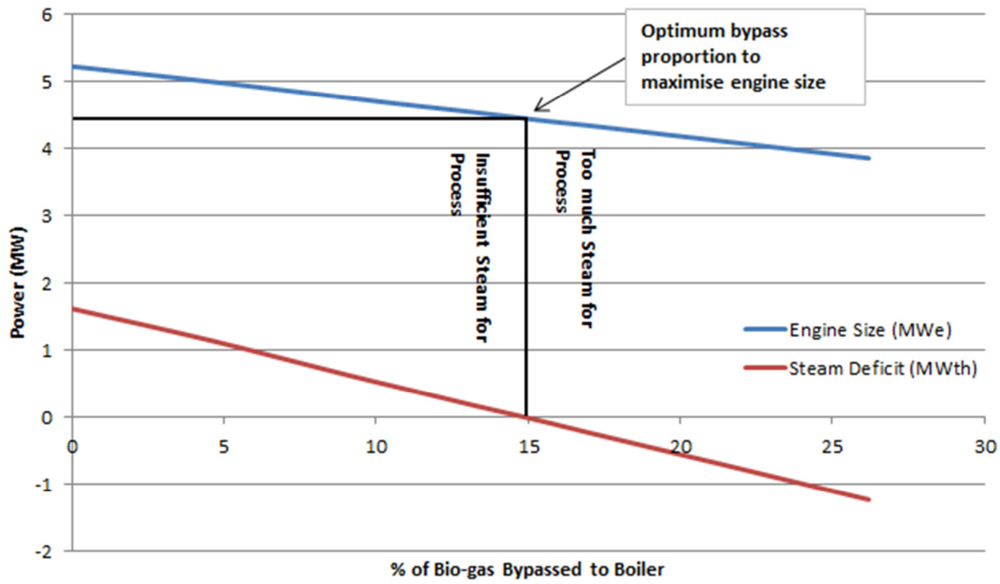

Figure 5 - Biogas Bypassed and Theoretical Engine Size

The impact on OpEx is significant, because the engine output is reduced and revenue is lost from the sale/offsetting of electricity and ROCs, Figure 6 shows the difference in the net OpEx. Based on Opex alone, it is recommended that natural gas is used as a support fuel instead of bypassing the more valuable bio-gas away from the CHP. However the CapEx for the engine is likely to be smaller for bio-gas bypassing and so the final recommendation will need to wait for the next level of analysis when CapEx will be included.

Logically there should be no real difference in which gas-fuel is used for which purpose (other than energy content / plant efficiency), but the economics of renewable incentives make this both difficult and changeable and means that additional flexibility may need to be built into plants in order to be able to always achieve profitability.

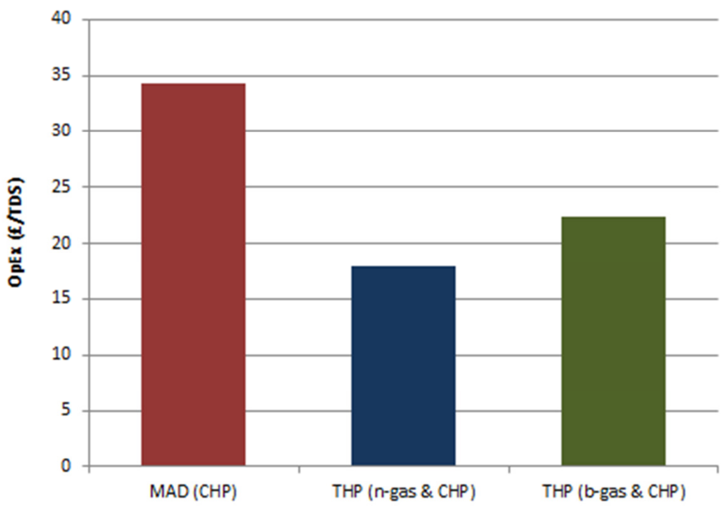

Figure 6 - Net OpEx comparrison

Engine type

The gas engine or CHP unit used within the scheme can make a difference to the overall energy balance and therefore the economics. This is because heat and electrical output vary depending upon engine design, size and manufacturer.

Spark ignition gas engines convert the fuel energy into the following:

Electrical Energy – The engines prime purpose is to generate shaft power to drive an alternator, typical conversion efficiencies from fuel to wire are 34-41%.

Exhaust Gas Heat – The exhaust gas is typically over 400degC and is one of the largest heat rejections on a CHP unit, and conversion can vary between 20% and 30% thermal efficiency [1].

Jacket Water Circuit Heat – The main cooling circuit/jacket cools the main engine block, in particular the cylinders and the valves, temperatures are typically below 100degC. However some manufactures do operate to limits close to 110degC (Caterpillar 2011) to prevent some undesirable effects when combusting bio-gas. Conversion of energy into jacket water heat is typically the same as the exhaust and can vary between 20% and 30%.

Oil cooler – This maintains the oil temperature within the operating limits; it is often in series with the jacket water circuit or the charge air cooler. Depending upon configuration temperatures can vary between 60 and 90degC and thermal conversion is <7%.

Charge air cooler – Cooling for turbo charged engines, also referred to as after cooler or intercooler on some engines. This cooling circuit cools the charged air before combustion, to reduce the air density concentrating oxygen and allowing more fuel to be burnt. Increasing the power output of the generator without increasing the frame size as a result all modern gas CHP units use a turbo charging stage. The heat rejection varies in temperature (40-90degC) and depends upon air emissions requirements, fuel quality and heat recovery configuration, thermal conversion could be as high as 5% efficient.

Losses – energy is also lost from the engine that is typically uneconomical to recover due to the grade and quantity available this includes radiated heat from the engine and alternator.

The key parameters to be considered for a THP CHP application are high grade heat rejection from the exhaust as this will generate the steam for the process and the electrical efficiency which is proportional to the revenue. Table 4 compares the key parameters for two similar sized engines from different manufactures Jenbacher (JMS 320) and Caterpillar (Cat 3516) based on their published data the main differences are that the Cat 3516 has a larger exhaust heat rejection at high temperatures but is less electrical efficient than the JMS 320.

[1] Assuming ambient temperature of 25degC as the base temperature.

Table 4 - Engine comparison (Caterpillar 2011; Jenbacher 2011)

Parameter	Units	JMS 320	Cat 3516	Delta or Comments
Exhaust gas temperature	˚C	435	485	50
Exhaust gas mass flow rate	kg/h	5876	6391	515
Density of exhaust gas	kg/Nm^3	1.265	*1.256**	**based on JMS 320 density*
Exhaust gas volume	Nm^3/h	4645	5052	407
Specific heat capacity of gas	kJ/kg/K	1.0	1.0	n/a
Temperature of gas after HX	˚C	190	190	*12.5barg steam required*
Total heat recovered	kW	400	524	124
High grade heat efficiency	%	15.1	18.6	3.6
Energy input	kW	2652	2808	156
Electrical output	kW	1063	1039	24
Electrical efficiency	%	39.9	37.0	2.9

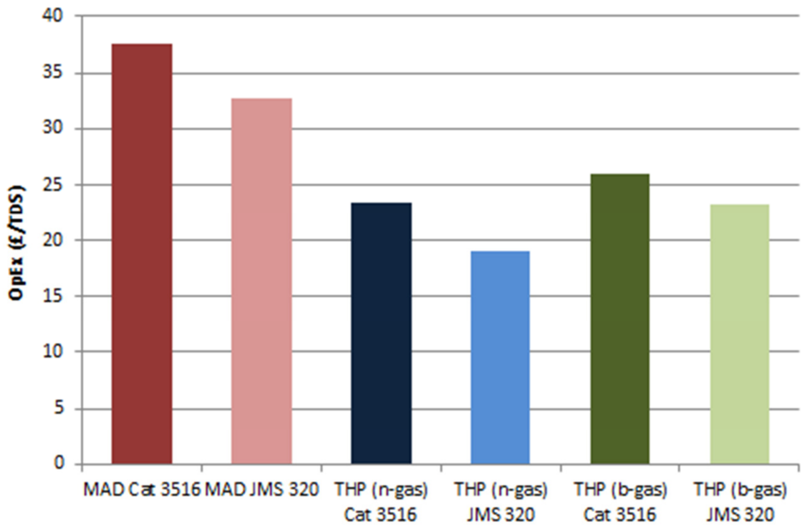

Figure 7 - Net OpEx comparison with two different CHP units

Despite the JMS320 requiring more support fuel its high electrical efficiency results in the lowest net OpEx across both THP configurations and conventional MAD. However, the benefit is less significant with the bio-gas bypass configuration when compared with the natural gas support fuel option. This is because less of the valuable bio-gas is being consumed by the engine and therefore the effect of the higher electrical efficiency is not as significant in improving revenue.

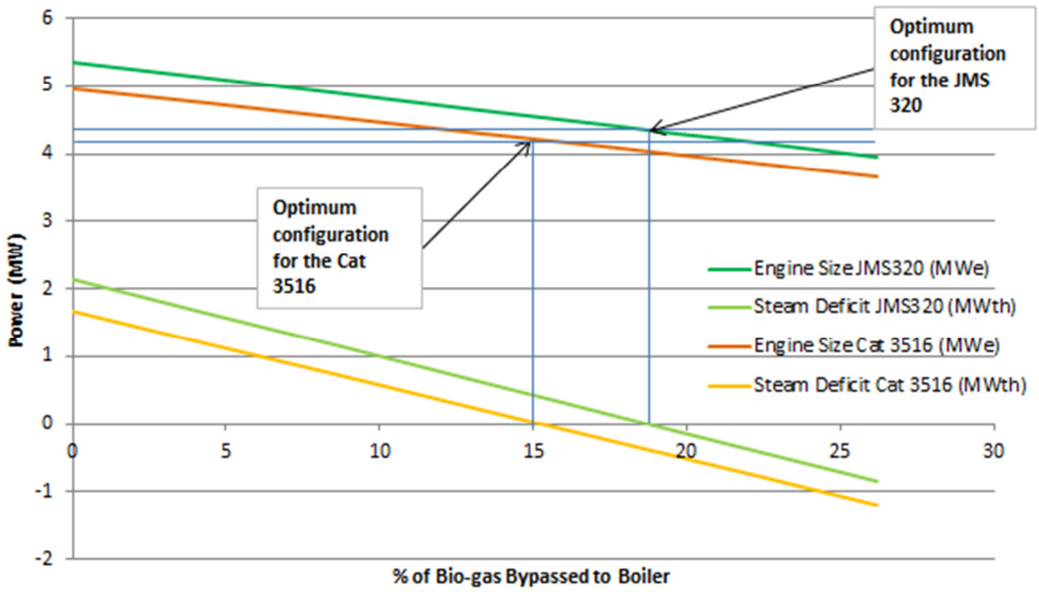

Figure 8 - Bio-gas bypass with different CHP units

Figure 8 quantifies the difference between the two engines set up for the bio-gas bypass option and shows each engine optimum configuration to maximise electrical output whilst satisfying the process requirements for steam. The Cat 3516 requires only 15% of the bio-gas to be bypassed but the engine output is 4.21MWe compared with 4.36MWe with the JMS 320 engine. Therefore, JMS 320 is the most economical solution, before CapEx is considered, as it generates the largest revenue.

Conclusion

Using THP as a sludge pre-treatment process before AD is a very affective when compared with conventional MAD. OpEx savings of approximately 35% can be expected, most of the improvements are from the reduced transport costs due to enhanced dewatering of the digested sludge. This is not therefore simply a financial benefit to water companies, it also contributes to a potentially significant reduction in lorry movements, with consequent savings in carbon emissions and impact to the local environment.

As the modelling and literature search has revealed THP cannot satisfy its steam requirements from waste heat recovered from the gas engines, at least a 40% deficit can be expected.

The steam deficit can be supplied using a support fuel such as natural gas or by bypassing bio-gas around the CHP into a boiler. The modelling has suggested that, if readily available, natural gas support fuel is preferable when considering the OpEx. Using natural gas instead of bio-gas reduces OpEx by 20%. This is however, a complex and dynamic relationship that is affected by both the regulatory situation in respect of ROCs and RHI, and also the economics of the varying commercial costs and value of energy.

The selection of gas engines for a THP scheme must consider the high grade heat rejection together with electrical efficiency. Despite the high electrical efficient engine needing additional support fuel or biogas bypass the overall economics favoured it due to the high electrical output which has a higher unit value than heat. The difference in OpEx between the two engines modelled is >20%.

THP offers the industry a step change in AD performance, but the heat balance of entire process must be considered carefully to optimise performance and the economic benefit. The use of THP and the selection and configuration of CHP requires considerable CapEx investment and it is therefore important that all of the technical, economic and financial opportunities and issues relating to energy and heat are properly understood.

As described above, this paper has presented some preliminary results from the first of a four year collaborative research project between Thames Water and the Centre for Environmental Strategy at the University of Surrey. It is intended that further research into this topic will be carried out as the research project progresses.

References

Andrews, A. (2008). "The wasted potential of anaerobic digestion in the water industry." from http://www.utilityweek.co.uk/news/news_story.asp?id=39692&title=The+wasted+potential+of+anaerobic+digestion+in+the+water+industry.

Bowen, A., Evans, B., Oliver, B., Evans, R., Merry, J. (2010). "Advanced Digestion at Cardiff and Afan; Dwr Cymru Welsh Water drive for lowest sustainable cost of sludge treatment and 15% reduction in carbon footprint." 15th Biosolids Conference 2010.

Cambi. (2010). "Cambi - Recycling Energy - Unleash the Power of Anaerobic Digestion." from http://www.cambi.no/wip4/detail.epl?cat=10636.

Caterpillar (2011). Technical Specification - Low Energy Gas Continuous 1030ekW 1278kVA 50Hz 1500RPM 400Volts.

Jenbacher (2011). Jenbacher gas engines technical specification - JMS320 GS-N.L.

McCabe, J., Eckenfelder, W. (1957). Biological Treatment of Sewage and Industrial Wastes. New York, Reinhold Publishing.

Merete, N. "The CAMBI Thermal Hydrolysis Process (THP) dramatically improving sludge digestion and dewatering."

Riches, S., Oliver, B., Brown, C., Allen, J. (2010). Delivery and Performance of the Great Billing Advanced Digestion Plant as part of Anglian Water's AMP4 Biosolids sub-programme. 15th European Biosolids and Organic Resources Conference, Leeds, Aqua Enviro Technology Transfer.

Glossary

SAS	Surplus Activated Sludge (also referred to as secondary sludge)
DS	Dry Solids Content (normally measured in %)
TDS	Tonne Dry Solids
VS	Volatile Solids
VSD	Volatile Solids Destruction
AD	Anaerobic Digestion
MAD	Mesophilic Anaerobic Digestion
THP	Thermal Hydrolysis Process
CHP	Combined Heat and Power
ROC	Renewables Obligation Certificates

[i] Sewage sludge has two main components – primary sludge, recovered from primary settlement tanks before biological treatment of the sewage effluent, and SAS which is a product of the activated sludge process, that is used to provide the main biological treatment for the effluent stream. While primary sludge generally has a high organic content and responds readily to dewatering and anaerobic digestion, SAS is lower in organics content and is much more difficult to dewater and digest. Most AD in the UK is carried out using combined sludge ie a mixture of primary and SAS.