

Unlocking the Full Energy Potential of Sewage Sludge

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Abstract

The UK water industry has huge, but as yet under-developed, potential to generate sustainable energy from the main by-product created in the treatment of wastewater. Sewage sludge is an energy rich sustainable biomass resource with a similar calorific value to woodchip.

Until recently, technologies and processes for further energy recovery have not been efficient or viable for large-scale use, but this research has shown that developments and innovations are now available and can realistically be brought into use. Using a combination of detailed techno-economic analysis and data from several large scale demonstration plants this research has shown that the renewable energy produced from sewage sludge in the UK could be significantly increased.

A typical conventional AD site will achieve 15% electrical conversion efficiency; this can be improved to 20% with the Thermal Hydrolysis Process (THP). Second generation THP developed during the project could boost recovery to 23% with other benefits such as reduced support fuel requirements and sludge transport volumes. By combining THP, sustainable thermal drying and pyrolysis, gross conversion efficiencies of 34% to electricity are achievable. All of the scenarios developed by the project have been proven to environmentally & economically sustainable and have been demonstrated at a large scale as part of this project.

A UK wide study in conjunction the Department of Energy & Climate Change showed that an economic deployment across the UK of second generation THP, followed by drying and pyrolysis, could generate to 2,216GWh or an additional 1,310GWh pa of renewable electricity from sewage sludge.

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Nomenclature

AD	Anaerobic Digestion
CHP	Combined Heat and Power
THP	Thermal Hydrolysis Process
LCA	Life Cycle Assessment
DS	Dry Solids
SAS	Surplus Activated Sludge
STW	Sewage Treatment Works
VSD	Volatile Solids Destruction
TDS	Tonnes Dry Solids
GtG	Gas to Grid (bio methane injection)
RO	Renewable Obligation
RHI	Renewable Heat Incentive
LG	Low Grade (heat – hot water)
HG	High Grade (heat – steam)
CV	Calorific value
WID	Waste Incineration Directive
GWP	Global Warming Potential
POCP	Photo Ozone Creation Potential
EP	Eutrophication Potential
AP	Acidification
ADP element	Abiotic depletion of elemental resources
ADP fossil	Abiotic depletion of fossil fuels
CRC	Carbon Reduction Commitment
IRR	Internal Rate of Return
OFWAT	Office for Water Industry Regulation in the UK
CapEx	Capital Expenditure
OpEx	Operational Expenditure

Throughout the document negative OpEx numbers relate to profitable conditions.

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Executive Summary

Background

The UK water industry has huge, but as yet under-developed, potential to generate sustainable energy in the form of biogas, heat, electricity and other fuels from by-products created in the treatment of wastewater. Sewage sludge is the main energy rich by-product of wastewater treatment and a sustainable biomass resource with a similar calorific value to woodchip. Approximately 70% of the UK's sewage sludge is treated using Anaerobic Digestion (AD) which does recover some energy, but the digested sludge is then mainly re-cycled to land and a large proportion of the energy which could be re-claimed is lost. Traditionally sludge has been seen as a waste product for which it has been necessary to achieve the cheapest possible 'treatment' and disposal at minimal risk. With the emphasis on disposal, little effort has traditionally been made to recovery energy, other than what could be done easily with main-stream processes. However, it is now well understood that increased energy recovery from sludge reduces exposure to raising energy prices and offers a significant mechanism for net carbon reduction within a carbon intensive industry (Palmer 2010).

Objectives

This project aimed to research, analyse, design and implement methods of increasing sustainable energy production from sewage sludge. The project has been structured to answer the following questions:

- How sustainable are existing processes?
 - Investigate and analyse existing energy recovery processes with techno-economic and environmental life cycle methods.
- What does the future look like?
 - Conceptualise, research, develop, test and demonstrate new approaches, processes and configurations for increased energy recovery.
 - Investigate and analyses future processes with techno-economic and environmental life cycle analysis (LCA).
- What is the UK potential?
 - Engage with policy makers to understand the barriers and work with them to find solutions to overcome them.
 - Model the UK potential.
 - Calculate the financial incentives, if any, required for the industry to implement best practice solutions.

Justification

The UK produces approximately 1.7 million dry tonnes of sewage sludge every year which has an energy content of 7.52TWh, currently only 10% is converted to electrical energy. This existing 10% is the very 'low hanging fruit', and it is expected that there is a 'level' at

which it becomes uneconomic or non-viable to achieve further conversion. If a 35% conversion efficiency were achievable across the UK, the water industry could generate 2,800GWh per year this is 10% of the current wind turbine output for all of the UK (equivalent to about 340 new 3.5MW offshore wind turbines). Unlike wind power sludge derived renewable energy is flexible and predictable and therefore greatly beneficial to the stability of the UK national grid which will be put under increased strain from more intermittent generators and a reduction in the availability of traditional thermal plant. The water industry would also achieve energy neutrality on many sites, reducing cost and uncertainty from volatile energy prices. This will help to mitigate\reduce increasing costs of wastewater treatment and will contribute to maintaining an environmentally and economically sustainable service to the water consumer.

How sustainable are existing processes?

Historically the industry has considered sludge a problem and a waste and existing processes and procedures are designed with this in mind, even relatively new technologies are optimised for and almost entirely focussed on disposal and not for energy recovery. It was therefore important to better understand these processes from an economic and environmental point of view, and to identify important design considerations that effect energy recovery. Existing mainstream sludge treatment processes that involve energy recovery can be summarised as:

- Conventional anaerobic digestion (AD)
- Advanced AD specifically the Thermal Hydrolysis Process (THP)
- AD with Gas to Grid (GtG) - injection of bio-methane instead of CHP
- Incineration with energy recovery

These processes are described below in more detail.

Conventional AD

Currently the most widely used method of sludge treatment. AD achieves the basic “sterilisation” or pathogen kill to allow the sludge to be recycled to agriculture. AD has the added benefit of reducing the dry mass and volume of sludge for disposal and producing a methane rich biogas which can be used as fuel in a combined heat power (CHP) plant. The most common variant is mesophilic AD; it is a complex biological process involving a diverse bacterial consortium (Appels et al. 2008). In a typical AD process each tonne of dry matter fed will produce 350m³ of biogas (65% methane) which generates up to 820kWh of electrical energy.

Advanced AD – Thermal Hydrolysis

AD is widespread and an effective sludge treatment technique for the water industry, but it does require a large footprint and relatively high capital investment. For this reason there are a number of process variations which have been developed and applied for the last 15 years. These all aim to improve the digestibility of sewage sludge, increasing the yield of gas and asset utilisation. The benefits of advanced AD (McNamara et al. 2012; Pickworth et al.

2006) can be summarised as:

- Increased biogas yields;
- Increased Volatile Solids Destruction (VSD);
- Reduction in total solids mass when compared with conventional digestion;
- Process allows increased loading (i.e. throughput) in existing assets reducing CapEx;
- Enhanced dewatering, reducing transport costs and increasing the quality of product.

The most developed and widely applied advanced AD technique is thermal hydrolysis (hydrolysis is typically the rate limiting step of AD). THP involves using high temperature (165°C) and pressure (6bar) to disrupt and solubilise sludge before feeding it to a conventional digester, resulting in increased methane production and a smaller volume of digestate (Kepp 2000). In a typical THP AD process each tonne of dry matter fed will produce 450m³ of biogas which would generate up to 1,100kWh of electrical energy. However, THP demands an input of high grade heat and additional electrical energy, when compared with conventional AD. The high grade heat demand outweighs the waste heat available from a CHP unit consuming the biogas produced, typically 350kWh of natural gas are required for every tonne of dry matter processed.

Gas to Grid

A new UK practice, Gas to Grid (GtG) aims to clean up and inject all of the bio-methane produced in AD into the gas network. The carbon dioxide and hydrogen sulphide are removed along with other contaminants the gas is then upgraded with the addition of propane and odorant to be compliant with UK gas quality standards before final compression into the gas network. A disadvantage of this process is that the heat required by the process is no longer supplied from a waste source (i.e. CHP) and has to be supplied by either burning some of the biogas or purchasing supplementary natural gas, which is usually the preference on financial grounds as the biogas attracts a large government incentive.

Incineration with Energy Recovery

Incineration involves the complete conversion of sewage sludge to oxidised end products such as carbon dioxide and other gases, water and ash. There are clear advantages to complete conversion which are high volume reduction, disinfection and the recovery of heat to produce steam which can drive turbines to produce electricity. However, high capital costs and adverse environmental effects limit the application of this process to large works with limited disposal options where the economics are more favourable (Metcalf and Eddy 2003b). Thames Water own and operate two sludge fluidised bed incinerators in East London and around the UK there are six similar plants that remain in operation. However, the trend across the UK is to shut these facilities down in favour of Advanced AD due to high operating costs and low electrical conversion efficiencies (AEA 2010; Bruno 2011).

Summary of Performance

The data shown in Table 1 are the result of literature research, studies and data capture from operational sites and extensive process and financial modelling including

environmental LCA, which has been published in the Waste Management Journal (Mills et al. 2011b, 2011a, 2012b, 2012a, 2014a).

Table 1 - Summary of Existing Processes

Performance	Units	Conv. AD	Advanced AD (THP) CHP	Advanced AD (THP) GtG	Incineration with energy recovery
Energy Yield (elec)	kWh/TDS	820	1100	n/a	880
Parastic energy - elec	kWh/TDS	90	150	290	496
Parastic energy - heat	kWh/TDS	0	370	920	0*
Solids Destruction	%DS	34	45	45	77
Carbon emissions	kgCO ₂ e/TDS	593	143	774	<i>not modelled</i>
Net OpEx	£/TDS	-33	4	76	-107
RE incentive proportion	%	19	19	61	39
CapEx	£M/100TDS	31.4	33.7	32.5	71.5
NPV after 20yrs¹	£M	11.6	17.1	27.2	<0

¹ - Assuming a base disposal cost of £150/TDS.

The results show that THP has clear advantages over conventional AD and incineration, (mainly reduced CO₂ emissions, improved NPV and increased energy generation) this supports the current trend in the industry to build THP. GtG looks very attractive financially if the generous incentive remains in place, but the carbon emissions are relatively high.

What does the future look like?

Answering this question allowed the project to make significant contributions to knowledge in the following areas:

- THP Development
- Sustainable Thermal Drying
- Advanced Energy Recovery

THP Development

The rapid application of THP in the UK and in Thames Water justified focusing significant project time on exploring and developing potential improvements to THP:

1. 2nd Generation THP
2. Utilising Steam Explosion during THP

2nd Generation THP - SAS only THP

This configuration employs the core THP process but as the name suggested only one sludge stream, Surplus Activated Sludge (SAS), is dewatered and thermally hydrolysed. The second sludge stream, primary sludge, bypasses THP and is instead fed directly into the digester. The advantages of this process are that the THP plant can be smaller and the resulting steam demand is reduced to an extent where no support fuel is required. The performance of the digestion is slightly reduced as the primary sludge has not been hydrolysed, but the benefit gained from the SAS hydrolysis is significant as it is difficult to digester conventionally. The performance of this process has been confirmed in laboratory trials and modelled in detailed as part of the project (Shana A et al. 2013). In a SASonly THP

AD process each tonne of dry matter fed will produce 420m³ of biogas which would generate up to 1,000kWh of electrical energy without the need for natural gas as a support fuel. A full scale plant of this kind is currently under construction in east London.

2nd Generation THP – Intermediate THP

This process configuration trialled at length at laboratory scale by Shana, effectively locates the THP in the middle of two digestion stages (Shana et al. 2011, 2012; Shana et al. 2013). This project built on the original research of Shana and worked closely with Shana to study and develop the process through modelling, design and development on a realistic scale pilot plant (Figure 2). This large pilot plant located in Basingstoke was designed as part of this project to verify and optimise the performance at a realistic scale to inform the design of any full scale application.

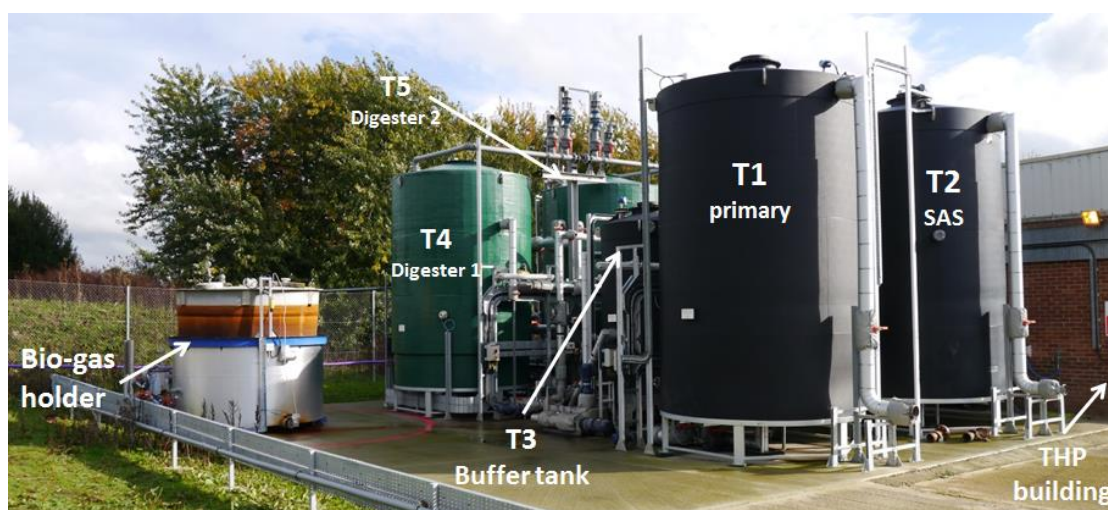


Figure 1 – The Sludge & Energy Innovation Centre, built to demonstrate I-THP (2m³ / day)

The first stage of digestion is a medium rate conventional digester which will obtain biogas from the readily available organic matter. The digested sludge now with a reduced mass is dewatered before thermal hydrolysis which can now be two thirds the size of a conventional plant. The second stage digester is a higher rate digester which produces more biogas. When combined with the first stage there is 10-15% improvement on conventional THP. A combination of this increased energy production and reduced THP size means that the process is heat self-sufficient (as with the SAS only THP configuration). The low grade heat from the CHP is sufficient to heat the first digestion stage. Each tonne of dry matter fed will produce 500m³ of biogas which will generate up to 1,200kWh of electrical energy without the need for natural gas as a support fuel.

Steam Explosion

In a steam explosion, biomass is exposed to saturated steam at temperatures between 160 and 260°C for a period of time. The pressure is then suddenly reduced, making the biomass undergo explosive decompression which shatters cell walls and reduces ‘particle’ size; it may also promote chemical reactions such as further hydrolysis (Perrault et al. 2015).

Recent developments in the design of THP plants driven by improvement in throughput have resulted in the steam explosion effect now being present during the hydrolysis reaction. As little research has been undertaken to understand and quantify the benefits to the process, the project commissioned a series of carefully designed laboratory experiments. The conclusion of which is that steam explosion has a positive effect, accelerating the production of biogas in AD post THP and potentially increasing the rate of digestion which may allow the reduction in asset size with CapEx savings.

Sustainable Thermal Drying

Anaerobic digestion cannot achieve full energy conversion, even with second generation THP only 57% of the potential energy in the sludge is converted into biogas. To access the considerable chemical energy remaining in the sludge after AD, it is concluded that the sludge should be dried to produce a solid fuel product (Flaga 2005; Niu et al. 2013). However, sludge drying in the UK has had a troubled past with several dust explosions and fires (HSE 2011) and expensive operating costs (Bowen et al. 2010). However, there are now new drying technologies that are safe, efficient and able to utilise waste heat.

Slough Paddle Dryer Demonstration

One of these technologies is the paddle dryer, which is very efficient and has minimal dust production. A demonstration was planned, funded and built that dried digested sludge cake at 20%DS to 95%DS to produce a granular fuel. This was then used beneficially as a supplementary fuel in the Crossness sludge incinerator. The dryer installation at Slough STW can be seen in Figure 2.



Figure 2 – The paddle dryer demonstration plant at Slough (4.5 Tonnes / day)

The trial was a great success, the dryer proved to be reliable, robust and efficient. When the granular fuel was used at Crossness the operations team were able to reduce or remove the natural gas support fuel, increase throughput and divert more steam for electricity generation. One of greatest achievements of this 2 year demonstration project was to change the attitude of the industry to consider post digestion energy recovery as safe and feasible (Mills et al. 2012c).

The drying technology described above has been instrumental in moving this project forward. However, the technology relies on medium grade heat (approx. 140-200°C) which competes with the need to raise steam for the process on THP sites and on a conventional AD site there is an insufficient quantity to make drying worthwhile.

Low Temperature Belt Dryer Application

An alternative approach to drying, developed and analysed as part of this project, utilises the low grade (90°C) heat which is readily available and unused on a THP site. The project has shown that by combining low temperature belt dryer (a recent development by the supply chain) and high DS dewatering all of the digested sludge on a THP site can be dried to at least 90%DS with only waste heat. The value of the fuel produced was confirmed during the Crossness trial, but what if it was possible to sell the fuel as an alternative to coal or wood chip? The economics are favourable, but to be able to do this the dried sludge needs to be given 'end of waste status' by the Environment Agency. Unfortunately a technical investigation, led by the project, involving detailed sample analysis concluded that under existing regulations it is not be feasible to obtain this status.

Advanced Energy Recovery

Once a dried product has been produced it opens up other options, such as pyrolysis and gasification which have a high energy conversion efficiency (greater than 85%) to a syngas which can then be used in CHP units (Ray R et al. 2012). Figure 3 shows a pyrolysis unit trialled with digested dried sludge as part of this project.



Figure 3 – A pyrolysis unit with a throughput of (15 Tonnes / day)

Combining AD, drying and pyrolysis has been explored by Cao and Pawłowski who conclude that maintaining AD as an initial recovery step leads to a more efficient overall energy recovery configuration (Cao and Pawłowski 2012). This research project has reinforced their conclusion. The main by-product from these processes is char, which is environmentally stable and can be used beneficially as a soil conditioner or potentially as a source for mineral recovery. Pyrolysis has the advantages over gasification, producing a relatively concentrated fuel gas which is more suitable for CHP (Bridgwater 2012; Domínguez A et al. 2006). This was confirmed during the project with comparative trials. Figure 4 shows the

energy flows for the advanced energy recovery configuration utilising pyrolysis (referenced to 1kgDS/hour).

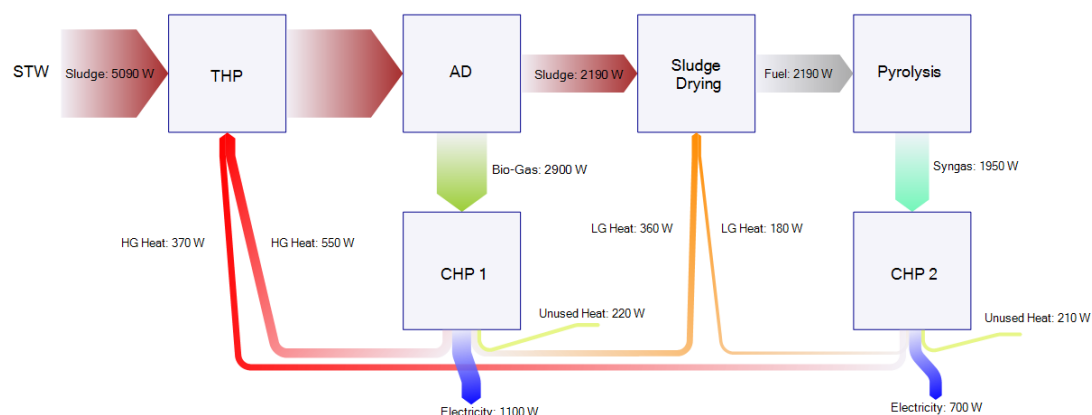


Figure 4 - Energy Flows for THP AD, CHP, Sludge Drying and Pyrolysis (1kgDS/hour) Electrical loads not shown

Each tonne of dry matter fed into this process configuration will produce 450m³ of biogas from AD then another 460m³ of syngas which would generate up to 1,800kWh of electrical energy in two independent sets of CHP units. As Figure 4 demonstrates the configuration is also now self-sufficient in heat.

Summary of Performance

The relative performance of the processes developed, demonstrated and modelled during this project are summarised in Table 2 (Mills et al. 2014a, 2014b), note all options utilise High DS dewatering.

Table 2 - Summary of Future Processes Opportunities Developed during this Research Project

Performance	Units	Conv. THP	THP with S.Exp	2 nd Gen THP SAS only	2 nd Gen THP I-THP	THP + Drying for fuel	THP + Drying + Pyrolysis
Energy Yield (elec)	kWh/TDS	1,100	1,160	1,020	1,210	950 (+2,380 fuel)	1,830
Parastic elec	kWh/TDS	150	150	150	200	340	580
Solids Destruction	%	45	45	42	50	45	77
Carbon emissions	kgCO ₂ e/TDS	143	137 ¹	154 ¹	138	-421	-614
OpEx	£/TDS	11	19	7	34	48	119
RE Incentive prop of revenue	%	19	19	19	19	16	32
CapEx	£M/100TDS	38.1	37.0	37.6	39.3	41.7	50.8
NPV after 20yrs	£M	13.7	19.1	17.1	20.9	22.7	31.8

¹ Based on Conventional THP and proportioned based on net efficiency.

If post digestion options are not considered then it has been shown that I-THP offers the best solution for energy recovery and financial return when compared with all other AD

options considered during the project. The effect of steam explosion is quite profound assuming there is a reduction in digester volume requirements.

Post AD drying creates very attractive environmental and economic solutions that almost double the renewable energy output and have a net carbon reduction benefit and significantly improved financial returns. The solid fuel option is attractive but is problematic in the UK due to legislation surrounding waste make it difficult to classify dried sludge as a fuel. The pyrolysis option is very encouraging with the best financial and technical case, this technology should be adopted across the UK. A full scale demonstration plant is designed and the business case built as part of this project and TW plan to have this facility operational by 2017.

What is the UK Potential?

A subproject was conducted with the Department of Energy and Climate Change (DECC). The study revealed that the UK could almost triple its renewable electricity output and generate 2,216 GWh pa from sewage sludge.

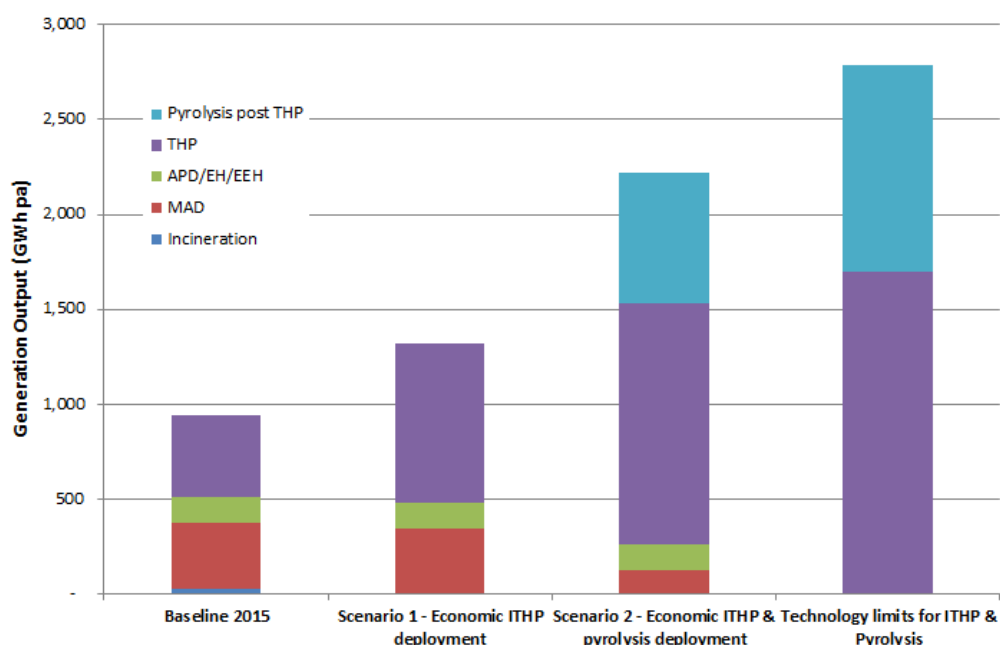


Figure 5 – UK Deployment potential of Energy from Sewage sludge technologies

Applying second generation THP and pyrolysis post digestion, the average levelised cost of generation is competitive with other forms of renewable electricity generation and therefore it is argued that existing incentives levels remaining in place for sewage sludge AD and pyrolysis.

Contributions to Knowledge

This ambitious research project has been very successful. The unique approach combined detailed techno-economic analysis and several large scale demonstration plants. This has made a bold statement to the industry and has blazed a path for others to follow. The key contributions can be summarised as:

1. Environmental & Economic LCA

The peer reviewed and published LCA study (Mills et al. 2014a) has genuine contribution to knowledge or novelty, because this is industry based research and much of the data used is not widely available to the academic community. Existing LCA studies of sewage sludge management options are limited to traditional techniques and do not consider advances in technology (such as THP and pyrolysis) or the impact of the system configuration, this project has addressed these gaps in knowledge. Examples of economic analysis of sludge management and energy recovery options are very rare in literature; this is the most extensive analysis published in this area to date.

2. THP Development

The project has developed I-THP, a new process, which has a clear contribution to knowledge. The fundamental science was undertaken by Shana a PhD student at the University of Surrey (Shana et al. 2011, 2012; Shana et al. 2013). This project has built on the original research and worked closely with Shana to study and develop the process through modelling, design and development on a realistic scale pilot plant built specifically for this purpose (Mills et al. 2014b). Additional laboratory work has also shown that steam explosion created during THP has a positive impact on AD performance. This and the I-THP work will be published in 2014 (draft paper within Appendix D).

3. Energy recovery concepts

The concepts researched, analysed, developed and trialled as part of this project are unique. In particular sustainable thermal drying followed by an advanced energy recovery step has not been explored in depth prior to this project (Mills et al. 2012c, 2014c).

4. UK potential

The analysis conducted in conjunction with DECC is unique and has revealed the huge potential the UK has to increase the renewable electricity generation from sewage sludge. Previous studies have not considered changes in technology or actively driven development of technology specific incentives within a government department. It is hoped that work will influence government policy to keep in place the mild subsidy to support investment (project report to be published on DECC website).

Conclusions

Until recently technologies and processes for further energy recovery from sewage sludge have not been efficient or viable for large-scale use, but this research has shown that developments and innovations are now available and can be brought into use. Using a combination of detailed techno-economic analysis and several large scale demonstration plants this research has shown that the renewable electricity produced from sewage sludge in the UK could be almost tripled.

Figure 6 aims to summarise the project journey which started top left with the existing processes. Conventional AD, THP and incineration were explored along with biogas utilisation in CHP or GtG. Incineration was dismissed relatively early mainly due to the economics along with GtG which should be avoided. THP provides large benefits so it was

explored in more detail and 2nd generation THP developed, particularly the ITHP process. Drying post digestion showed great promise unfortunately it is not currently practical with medium temperature dryers or any dryer technology on conventional AD site. However, when low temperature dryers are combined with THP the heat balance works. Drying to produce a fuel for a third party is currently restricted by legislation, but the process steps led the project to advanced energy recovery with pyrolysis post THP AD.

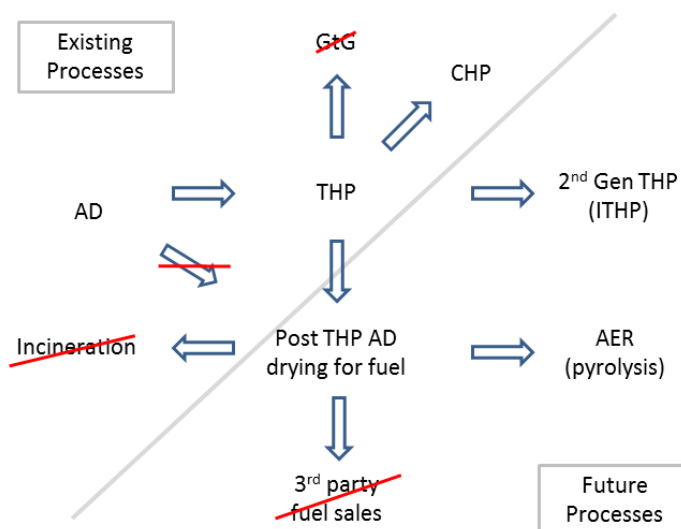


Figure 6 – Summary of Options Explored during the Project

A typical conventional AD site will achieve 15% conversion efficiency; a THP will improve this to 20%. ITHP boasts recovery to 23% with other benefits such as reduced support fuel requirements and sludge transport volumes. By combining THP, drying and pyrolysis a gross conversion 34% conversion efficiency to electricity is achievable and the economics and environmental impact change considerably for sewage sludge treatment with very attractive returns on investment. By economically deploying a combination of the technologies developed as part of this project the UK could generate 2,216 GWh pa of renewable electricity from sewage sludge.

Recommendations

- Incineration should not be considered as viable sludge to energy technology.
- GtG should be avoided the preference should CHP which has better synergies with application on sewage sludge to energy processes.
- Steam explosion clearly has a positive effect on THP, based on the laboratory tests, the economic analysis shows it would be worth exploring in more detail.
- The ITHP pilot plant should be operated until steady state is reached to ensure good data capture. Results should be modelled and conclusions published.
- Effort should be made to explore ways opportunities to utilise GRSF and overcome the barriers caused by waste legislation.
- A full scale advanced energy recovery plant should be built to demonstrate and prove the concept to the industry.

- In the UK renewable energy incentives should be maintained or enhanced for sewage sludge to energy technology to ensure future deployment predictions become reality.

1. Introduction

The UK water industry has huge, but as yet under-developed, potential to generate sustainable energy in the form of biogas, heat, electricity and other fuels from by-products created in the treatment of wastewater. Sewage sludge is the main energy rich by-product, a sustainable biomass resource with a similar calorific value to woodchip. 77% of the UK's sewage sludge is treated using Anaerobic Digestion (AD) which does recover some energy, but the digested sludge is then mainly re-cycled to land and a large proportion of the energy which could be re-claimed is lost (WaterUK 2010). Traditionally sludge has been seen as a waste product for which it has been necessary to achieve the cheapest possible 'treatment' and disposal at minimal risk. With the emphasis on disposal, little effort has traditionally been made into energy recovery, other than what could be done easily with main-stream processes. Across the UK only 10% of the potential energy is converted into useful energy typically electrical power, currently delivering in the order of only 1.5% UK's renewable electricity. The water industry could be responsible for delivering a larger proportion of the UK renewable target; whilst making significant economic and environmental savings to UK water companies such as Thames Water and its customers. It is also now well understood that increased energy recovery from sludge reduces exposure to raising energy prices and offers a significant mechanism for net carbon reduction within a carbon intensive industry (Palmer 2010).

This collaborative research and development project between the University of Surrey and Thames Water aimed to demonstrate what is feasible and show a risk adverse industry how it can unlock the full energy potential within sewage sludge.

1.1 Objectives

This project has researched, analysed, designed and implemented methods of increasing sustainable energy production from sewage sludge. The project was structured to answer the following questions; a flow chart for the project can be seen in Figure 7:

- How sustainable are existing processes?
 - Investigate and analyse existing energy recovery processes with techno-economic and environmental life cycle methods.
- What does the future look like?
 - Conceptualise, research, develop, test and demonstrate new approaches, processes and configurations for increased energy recovery.
 - Investigate and analyses future processes with techno-economic and environmental life cycle analysis (LCA).
- What is the UK potential?
 - Engage with policy makers.
 - Model the UK potential.
 - Calculate the financial incentives required for the industry.

The thesis has a section dedicated to answering each of these questions.

Project Lifecycle

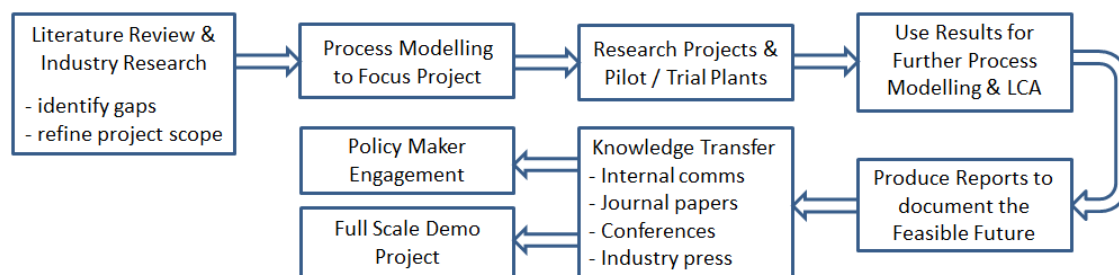


Figure 7 - Research Project Flow Chart

As displayed in Figure 7 an initial literature study was undertaken which explored and studied published material to understand what has already been achieved and where gaps in knowledge and technology existed. Using this and other data sources existing and future processes were modelled to help focus the research project and inform specific projects, pilot plants and trials.

One of the early barriers to change that was recognised is the 'scale' at which research is done, compared to the normal operational scale of a business like Thames Water, which produces 1,000 tonnes of dry sludge every day. In order for key decision makers to be provided with confidence to make necessary investments and changes, it was necessary to recognise that laboratory scale or small pilot scale demonstrations would not be adequate. One of the most successful features of this particular research has been to recognise this, and to develop processes for lab to bench to small pilot to large demonstration plant, including all of the steps to achieve funding and investment to design, build and operate the plants within the research project. It would have been possible to demonstrate principles at small scale, but it would not have been possible to overcome barriers to change within the business without planning for and demonstrating success at real-scale, both to key decision makers and to operatives. This is not a fundamental requirement for all research, but it has been in this case where the barriers to change were always going to be as difficult as the scientific and technical issues.

Results from these large scale activities refined the detailed process modelling, economic and environmental life cycle assessment and the results and conclusions have been published and disseminated in a variety of ways including at multiple conferences and in the industry press (Appendix B). This led to wider engagement with policy makers and a secondment project with the Department of Energy & Climate Change, an industrial fellowship from the 1851 Royal Commission and the birth of a new specialist conference (SludgeTech).

1.2 Industry Background

1.2.1 Wastewater Treatment

Wastewater treatment has been developed over the past 120 years employing a number of different techniques (Cooper 2001). The activated sludge process was developed in the

early 20th century; the first plant was commissioned in Davyhulme, Manchester in 1914 (Coombs 1992). This process now treats 91% of wastewater in the Thames Water region and >60% across the UK and is typically suited for larger sites where the economics and land constraints favour the intensified process. This project will explore energy recovery options based on wastewater treatment plant employing activated sludge, the configuration shown in Figure 8 and described below:

1. Preliminary treatment – grit and rag are removed from the wastewater (there are potential opportunities for energy recovery at this stage, but is not within this scope);
2. Primary treatment – removal of settleable solids from the waste water, typically this is through settlement in a tank with low velocities to allow the solids to sink to the bottom, this forms primary sludge that can be pumped, forming a separate sludge stream. The wastewater flows over a weir at the top of the tank and on to Secondary treatment. The settlement process typically removes around 60% of suspended solids and concentrates this up to less than 1% of the total flow;
3. Secondary treatment – removal of biodegradable organic matter, suspended solids not removed in primary treatment and soluble materials such as ammonia, phosphate and soluble carbon compounds. In an activated sludge plant an aeration basin is used, in which conditions are optimised for microorganisms which in turn:
 - a. Oxidise biodegradable constituents into acceptable end products;
 - b. Capture non settled solids and form a biological floc;
 - c. Transform or remove nutrients;

This stage of the process is mainly aerobic and requires the input of considerable quantities of air, generally using large compressor/blowers piped through to diffuser domes in the floor of the aeration basin.

4. After the biological treatment within the aeration basin, the wastewater enters the final settlement tanks, allowing the biological sludge mass to sink forming a sludge which can be pumped. More than 70% of this sludge is returned to the aeration basin to ensure sufficient sludge retention time in the process to accommodate the slowest growing micro-organisms. The surplus activated sludge (SAS) representing 50% of the flow now forms a second separate sludge stream;
5. The effluent from these final settlement tanks is generally allowed to flow to the water course. On some sites a tertiary treatment stage follows secondary treatment which is used to remove residual suspended solids (Metcalf and Eddy 2003a) and/or to achieve ever increasing standards required.

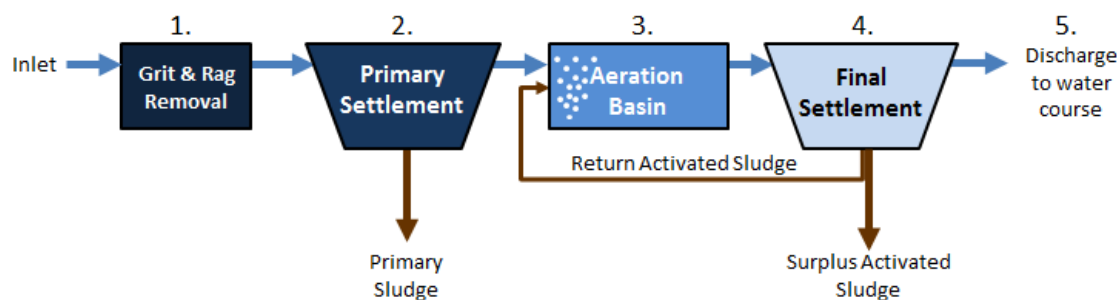


Figure 8 – Typical Configuration of an Activated Sludge Wastewater Treatment Process

To give an idea of scale of wastewater treatment, Figure 9 shows part of a STW in West London that treats sewage for a population equivalent of 1.8 million people.



Figure 9 – Picture of Mogden STW showing the final Settlement Tanks in the fore ground with Aeration Basins visible in the background (TWUL-i 2011)

1.2.2 Sewage Sludge

The sludge or waste bio-solids from the sewage treatment process (described above) has a very high water content and the dry solids concentration is typically less than 2%, SAS is less than 1%. The volatile content typically 77% by dry mass but the sewage treatment process design, catchment and sludge logistics have a large influence on the volatile solids (VS) content. For example if the wastewater treatment works has a very efficient primary settlement step and does not dose iron for phosphorus removal the sludge could have a VS content of 85% (Giacalone S et al. 2014). In contrast if the site has underperforming primary treatment with iron dosing and long sludge storage times the VS content could be less than 70%. VS content has an impact on the energy content of the sludge, which could range between 16-22MJ/kgDS (Lee 2010). A typical calorific value is 19MJ/kgDS which is comparable with woodchip a renewable fuel currently on the market for £100/tonne. Optimisation of existing treatment assets and procedures is very important to improve the energy recovery from sludge. But it is outside the scope of this EngD project as it is considered 'business as usual' for a water company.

Table 3 - Sludge Characteristics

	Primary Sludge		SAS	
Parameter	Range	Typical	Range	Typical
Dry Solids (%)	0.5-4.0	1.5	0.2-1.2	0.7
Volatile Solids (%)	65-87	77	65-87	77
Calorific Value (LHV) (MJ/kgDS)	16-22	19	16-22	19

Sludge requires further treatment before being safely returned to the environment. Historically treatment has mainly been designed to reduce pathogens before disposal to agriculture which is encouraged by the EU sewage sludge directive 86/278/EEC. Most sludge treatment processes have been designed to meet the Sludge Use in Agriculture Regulations 1989 (HMGovernment 1989). As a result process streams are not suitable for optimum renewable energy extraction, but instead are designed for least cost sludge disposal. Traditionally, only the simplest attempts have been made to recover energy such as biogas from digestion. Barber observes that *“currently, the Water Industry generates the majority of this Biogas [renewable energy] using infrastructure which was not designed for either, energy generation or carbon footprint reductions”* (Barber 2010). This is evident from Figure 10 which shows the potential energy available from the wastewater organics (not including screenings) of a 150,000 population equivalent (PE). The current recovery on a typical site with Anaerobic Digestion (AD). The recovery from the sludge into methane rich biogas is approximately 30% efficient with 70% of the energy remaining in the sludge after digestion. The biogas is then converted into electricity and heat in a gas engine, the heat is required for the AD process, which means that the only useable/saleable/profitable energy is the electricity. The electricity can displace purchased power for the sewage treatment works. Typically 50% displacement is possible on an STW using activated sludge.

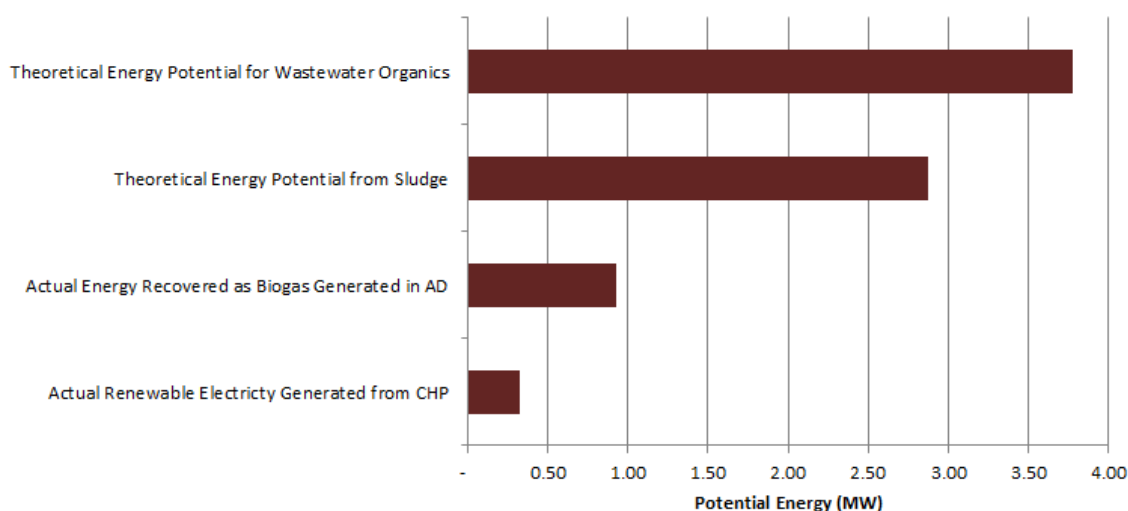


Figure 10 - Potential Energy from a typical (150,000 Population Equivalent - PE) Wastewater Plant with AD - adapted from (Pearce 2009)

2. How sustainable are existing processes?

Despite conflicting drivers several techniques have been deployed by the UK water industry that allows energy recovery from sludge, currently producing around 0.77 TWh pa of electricity from 1.7 M Tonne Dry Solids (TDS) pa of sewage sludge (Andrews 2008; DECC-ii 2011). The energy content of the sludge is approximately 4.7MWh/Tonne Dry Solids (TDS) (Lee 2010). Assuming this value is true for all 1.6 MTDS pa, the UK as a whole produces sludge with a gross energy content of 7.52 TWh pa. Only 0.77 TWh pa is converted to electrical energy resulting in a UK wide annual conversion efficiency of just 10%.

Thames Water produced 391,311 TDS pa of sewage sludge (June return to OfWat 2011) and generated 166GWh pa (TWUL-ii 2011) of renewable electricity in 2011. Which means TW has only a 9% conversion efficiency, generally the processes are more than 10% efficient but overall efficiency is reduced because a proportion of sludge is not processed through a recovery operation, generally on smaller remote sites.

The conversion, across the UK, is currently achieved using a combination of anaerobic digestion, advanced AD and incineration with energy recovery, these are described below.

2.1 Anaerobic Digestion

Anaerobic Digestion (AD) can achieve the required pathogen kill to allow the sludge to be disposed of to land, under the current UK regulations over 60% is recycled to agriculture (Kelessidis A. and Stasinakis A. 2012). AD has the added benefit of reducing the volume of sludge and producing a methane rich biogas which can be used as fuel. The most common variant is mesophilic anaerobic digestion (MAD); it is a complex biological process involving a diverse bacterial consortium (Appels et al. 2008) shown in Figure 10.

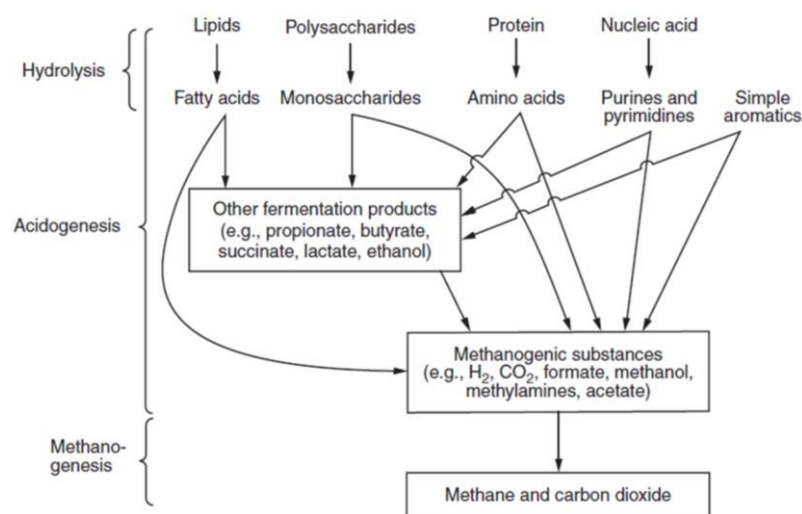


Figure 11 - Stages of Mesophilic Anaerobic Digestion (Tchobanoglous 1993)

Anaerobic Digestion Background

To understand the influencing parameters of AD it is important to state some key terminology and variables used to model and describe AD.

Dry Solids Content (DS) – dry matter content expressed as a percentage. The dry solids content affects total volume fed to anaerobic digestion because the dry matter is fixed. This is important as the because a thin sludge (or low DS) reduces the the hydraulic retention time and will also increase the heating requirements

Volatile Solids Content (VS) – typical sewage sludge includes both organic and inorganic matter and the volatile/organic content is measured on a mass basis and is expressed as a %, it is important as it determines the potential for a sludge to produce biogas in the anaerobic digestion process. The non-volatile/organic content, also referred to as ash or char is not digestible and is not destroyed in the AD process.

Volatile Solids Destruction (VSD) – is an important parameter used to measure AD performance and is the difference in VS before and after AD expressed as a % in inlet VS. VSD is dependent upon a number of parameters, the pre-treatment, AD conditions (including temperature and mixing), the type of sludge primary or secondary.

Specific Gas Production (SGP) – is the conversion rate of VS to biogas typically measured as m^3 of biogas/kgVS. (NB the main constituents of biogas are typically 60 to 65% methane and 30 to 35% carbon dioxide).

Organic Loading Rate (OLR) – indicates how much organic matter is being fed to the anaerobic digester the most common unit is kg of VS per m^3 of digester volume per day ($\text{kgVS}/\text{m}^3/\text{day}$). If the organic loading rate is too high the microorganisms can become unstable and the process can die, too low and the process will 'starve'. The mix of primary sludge to secondary is also important as the latter has a strong cellular structure which is harder and therefore takes longer to break down.

A conceptual mass balance can be seen in Figure 12 in which 1kg of sludge with an 80% VS content is processed through AD with a VSD of 60%, producing 480ltrs of biogas at a SGP of $1\text{m}^3/\text{kgVS}$. The resulting dry mass of the digestate is 520g as the ash content remains constant the VS content of the digestate is now 62%.

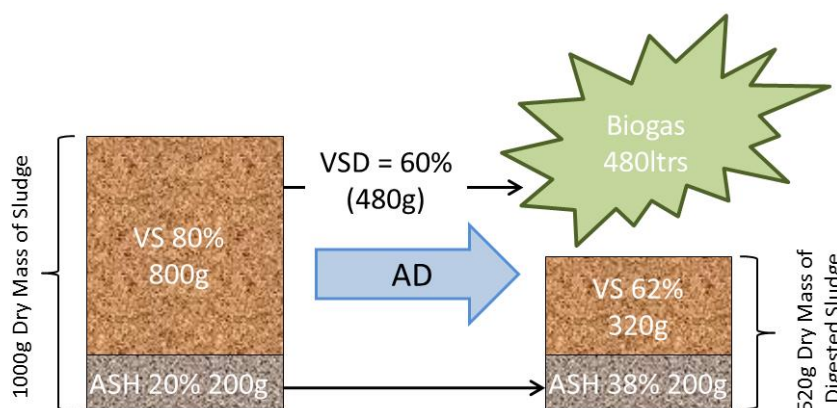


Figure 12 - Conceptual Mass Balance for AD

Two of the key parameters that have an influence on the performance of AD are the primary SAS ratio and hydraulic retention time. HRT is the average time the liquid and solids spend within the digester (the solids retention time is a preferable parameter but HRT is often used as it is easier to measure). An estimated relationship has been constructed from different sources below in Figure 13. It shows the influence of sludge type on the volatile solids destruction, SAS does not digest to the same extent as primary sludge.

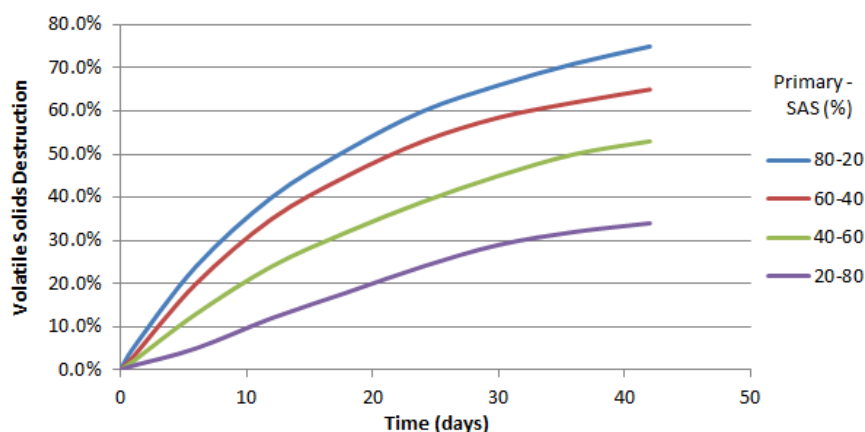


Figure 13 - Volatile Solids Destruction vs HRT [adapted from data from (Fountain 2008)]

Further background on AD is provided in Appendix D.

Anaerobic Digestion Typical Performance

In a typical process both sludge streams are thickened and combined before being heated to approximately 37°C inside a mixed digester tank with retention times of 12 to 30 days. The volatile solids destruction is approximately 40% which yields 350m³/TDS of biogas and translates to 30% dry mass reduction (Appels et al. 2008). The final digestate is then dewatered to a cake of around 20% Dry Solids (DS) and transported off site for agricultural land use (Suh and Rousseaux 2002).

Currently the most widely used method of sludge treatment is AD which achieves the required “sterilisation” or pathogen kill to allow the sludge to be recycled to land. AD has the added benefit of reducing the dry mass of sludge for disposal and producing a methane rich biogas which can be used as fuel in a combined heat power (CHP) plant. The most common variant is mesophilic AD; it is a complex biological process involving a diverse bacterial consortium (Appels et al. 2008). In a typical process, sludge is thickened then heated to 35-40°C before entering the mixed digester tank. The final digestate is then dewatered to a cake of around 20% Dry Solids (DS) and transported off site, generally for recycling on agricultural land (Suh and Rousseaux 2002). Figure 2 shows the energy flows for a typical configuration with a CHP unit (referenced to 1kgDS/hour).

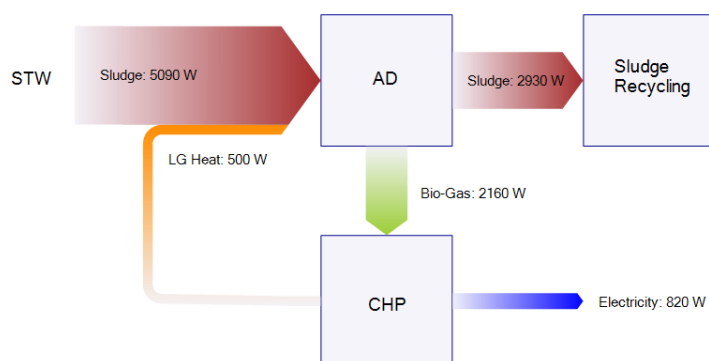


Figure 14 - Energy Flows for Conventional AD with CHP and Land Recycling (1kgDS/hour)

2.2 Advanced Anaerobic Digestion

Although AD is widespread and effective sludge treatment technique for the water industry, it has limitations. For this reason there are a number of process variations which have been under development and have begun to be applied during the last 10 years, these all pre-treat the sludge aiming to improve the digestibility, the benefits of advanced AD (McNamara et al. 2012; Pickworth et al. 2006) can be summarised as:

- Increased Biogas yields;
- Increased volatile solids destruction;
- Process allows increased organic loadings in existing assets reducing capital costs;
- Reduction in mass and enhanced dewatering characteristics reducing transport costs and increasing the quality of product for farmers.

The most developed advanced AD techniques are thermal and biological hydrolysis, as hydrolysis is the typically the rate limiting step of AD these variants attempt to reduce this bottleneck. The Thermal Hydrolysis Process (THP) is the most widespread and the technology of choice for Thames Water to reduce disposal volumes and increase value recovery from sewage sludge. The most common biological hydrolysis processes are acid phase digestion (APD) and enzymatic hydrolysis (EH) both offer a solution which is more economical to operate than conventional anaerobic digestion and some studies have shown it is cheaper to operate than THP on a typical wastewater treatment site (Mills et al. 2011a). However, operating experience at full scale has meant that APD is not the preferred option for Thames Water. This is due to the long retention times and inherent instability of APD & EH when compared with THP, which means that a shut down on an APD plant is likely to be measured in weeks instead of hours for a THP plant. THP is the strategic solution within Thames Water who have operated both APD and THP for more than 10 years at full scale, TW are now committed to building and operating 8 THP plants. For this reason the research has focused on THP as main tool for improving the performance of anaerobic digestion.

Conventional THP dewateres the combined sludge stream (primary and SAS) from about 3% Dry Solids (DS) to 16.5% DS before the first stage of the process. Across the world there are >40 full scale THP sites either in operation or construction that will process 800,000 Tonnes Dry Solids (TDS) pa (Cambi 2014). There are two main versions of THP supplied by Cambi

and Veolia although others are now attempting to provide rival technologies; Cambi THP remains the most dominant solution. The Cambi THP configuration consists of three main stages (Figure 13) and is described below.

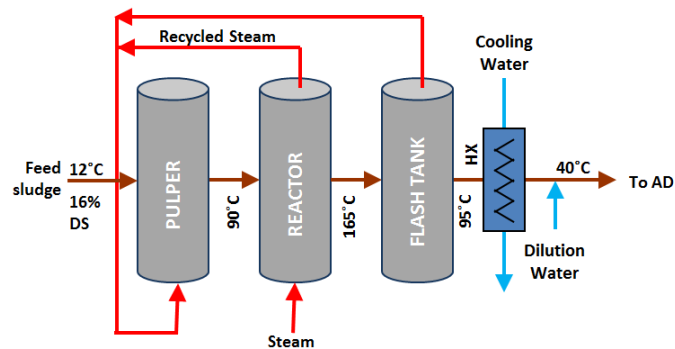


Figure 15 – Simplified Process Flow Diagram for Cambi THP

A pulper vessel receives the incoming sludge and acts as a preheating stage utilising the waste steam from the back end of the process. Typically this raises the sludge to 90°C before it is pumped forward into the reactor, which could be one or multiple units depending on the size of the plant. In the reactor the preheated dewatered sludge is heated to 165°C (6.5barg) and maintained for 30minutes. Once completed the pressure in the reactor is partly reduced to around 3barg by releasing the headspace of the reactor into the pulper. The sludge is then released using the pressure difference into the flash vessel, the last stage of the hydrolysis process, which is initially at atmospheric pressure. The steam released in the flash vessel, now around 2barg, is vented into the pulper to preheat the next batch of incoming thickened sludge. The hydrolysed sludge is pumped from the flash vessel and cooled and diluted to around 40°C and 10%DS before digestion. Biogas production is typically 450m³/TDS on a good site, which on most sites is combusted in CHP to produce electricity and high grade heat for use within the hydrolysis process. Volatile solids destruction (VSD) of around 60% is typical and with a conventional belt filter press cake of 32% dry solids (DS) can be achieved.

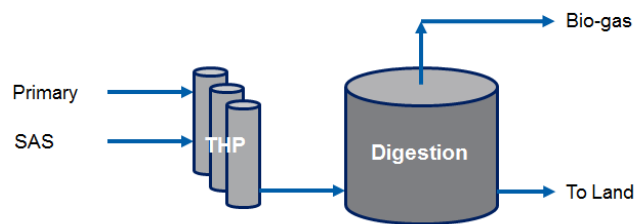


Figure 16 – Simplified Process Flow Diagram for Conventional THP

The THP process requires steam at approximately 12barg and unfortunately there is insufficient high grade heat from the CHP to meet all of the steam requirements (Kepp 2000). Wilson observes a support fuel requirement for the Cardiff THP plant, which was designed for 0.33MWh/TDS or 46% of the steam demand. A Sankey diagram of the 84TDS/day process can be seen in Figure 15 and shows the 28MWh of support fuel

requirement as designed (Wilson 2011). However, the operational performance is closer 0.51-0.53MWh/TDS (Merry and Oliver 2014).

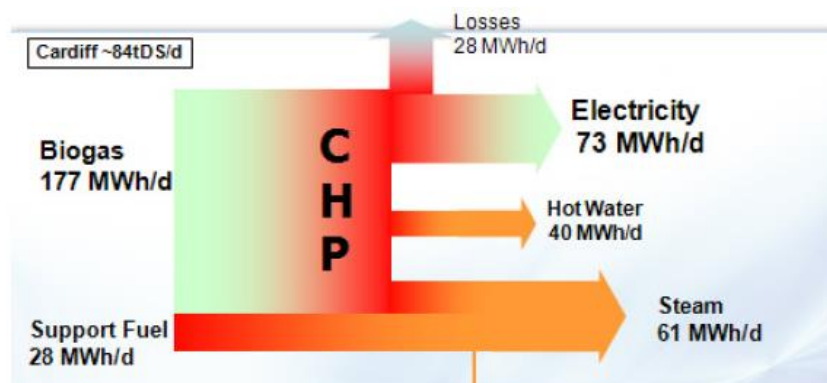


Figure 17 - Sankey Diagram from Cardiff THP Site as designed (Wilson 2011)

From the modelling it was shown that the additional steam energy required is 0.37 MWh/TDS (Mills et al. 2011b). Some of the differences in fuel requirements between the modelling and the Cardiff site referenced above can be explained by the low DS feed to the THP and high SAS content at Cardiff.

There are two options currently being used to provide the thermal energy on operational THP plants across the UK, these are natural gas and biogas diversion, shown as Option A and B respectively in Figure 16.

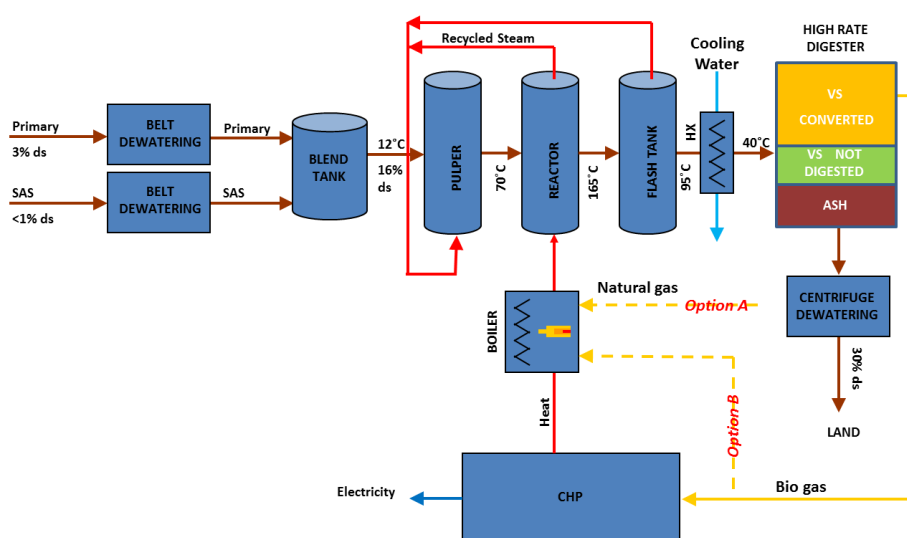


Figure 18 - THP with Support Fuel Options A and B

There is little difference in the CapEx between options A & B. It was found that Option A was most economic when considering OpEx this is because of the subsidised revenue is maximised by using all of the bio-gas in the CHP. Based on this it is recommended that natural gas is used as a support fuel instead of bypassing the more valuable bio-gas away from the CHP.

One of the benefits of this process study within this research project was the identification of potential anomalies and these were investigated further. In particular analysis was conducted to understand the best gas engine type. It was found that an engine with a high electrical efficiency was optimum despite this having a lower high grade heat rejection and therefore required more support fuel. The difference in OpEx between the two engines modelled was >20% (Mills et al. 2011b). Figure 17 shows the energy balance for the option A configuration.

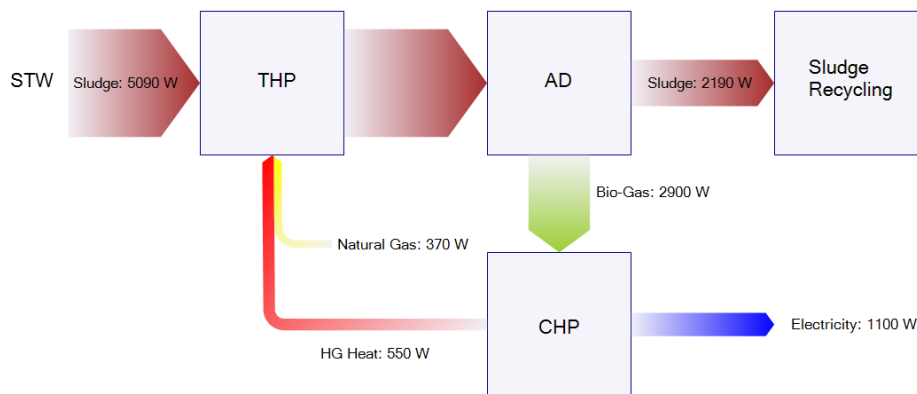


Figure 19 - Energy Flows for Option A (THP AD with CHP and Land Recycling (1kgDS/hour)) electricity input is not shown

2.3 Biogas Utilisation

The biogas produced in AD has traditionally been utilised in spark ignition gas engines or dual fuel engines which convert 35 - 42% of the chemical energy into renewable electricity. A proportion of the waste heat from the exhaust gas and the water jacket is recovered for utilisation by the process thus justifying the label CHP (Hawkes 2011). In the UK this form of generation is incentivised to varying degrees under the UKs Renewable Obligation (RO) Scheme which rewards generators of renewable energy with additional revenue.

A new UK practice, Gas to Grid (GtG) aims to clean up and inject all of the bio-methane produced in AD into the gas network and is financially supported under the Renewable Heat Incentive (RHI) (DECC 2011). A number of technologies are available to remove the carbon dioxide and hydrogen sulphide but water absorption is most commonly used in the UK. The resulting gas has a methane content of >99% (Ryckebosch et al. 2011) . Once cleaned the bio-gas requires the addition of propane and odorant to be compliant with gas quality standards before final compression into the gas network (Greer 2010); (Starr et al. 2012). Figure 18 shows the energy flows for a typical configuration (referenced to 1kgDS/hour).

Unlocking the Full Energy potential of Sewage Sludge

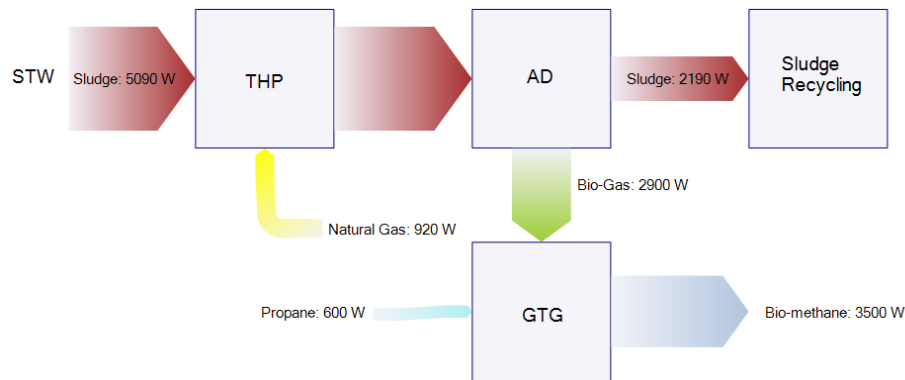


Figure 20 - Energy Flows for THP AD with GtG and Land Recycling (1kgDS/hour) electricity input is not shown

A disadvantage of this process is that the heat required by the process (e.g. THP or conventional AD) is no longer supplied from a waste source and has to be supplied by either burning some of the biogas or purchasing supplementary natural gas, which is usually the preference on financial grounds as the biogas attracts a large incentive. CHP is the more widely used and produces electricity, which is a very versatile form of energy - easily transportable to point of use, and with many applications that can use it. However, generation efficiency of electricity is at best only 42%. GtG has much higher conversion efficiencies than CHP (>95%). The relative environmental burden displacement and economics of CHP and GtG are compared in section 2.5.

2.4 Incineration with energy recovery

Incineration involves the complete conversion of sewage sludge to oxidised end products such as carbon dioxide and other gases, water and ash. There are clear advantages to complete conversion which are high volume reduction, disinfection and the recovery of heat to produce steam which can drive turbines to produce electricity. However, high costs and adverse environmental effects limit the application of this process to large works with limited disposal options where the economics are more favourable (Metcalf and Eddy 2003b). Thames Water own and operate two sludge fluidised bed incinerators in East London and around the UK there are six similar plants that remain in operation as shown in Table 4. These plants process about 10% of the total sludge produced across the UK.

Table 4 - Sewage Sludge Incinerators in England & Wales (Abbott 2004; EA 2009; Hand-Smith 1999; Smith 2008)

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 ¹
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 ²	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 Meadows	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

It is unlikely that many new sludge incinerators will be built due to the public perception and subsequent planning restrictions. These existing UK facilities were typically built to replace sludge dumping at sea which was banned in the UK and the EU in 1998 (EC 1998). The reaction to the changes enabled the high capital and operational costs to be justified (Werther and Ogada 1999). Some believe that much of the UK's sewage sludge incineration will be replaced with the more economic AD process by 2030 (AEA 2010) and the trend in Table 3 indicates this has begun, Yorkshire Water has announced plans to replace incineration assets with advanced AD processes it is estimated this will save £120/TDS in operational costs (Bruno 2011). The CapEx for a recent incinerator extension approached £94m for a throughput of 70TDS/day and the expected operating and maintain costs are approximately £100/TDS.

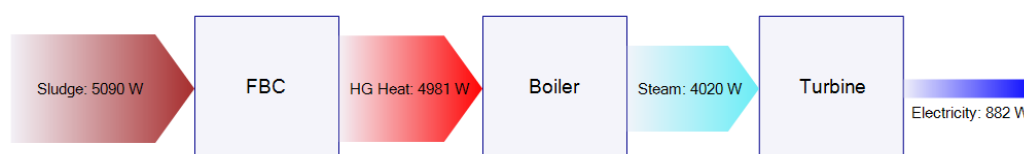


Figure 21 - Energy Flows for Fluidised Bed Incinerator with Energy Recovery (1kgDS/hour)

2.5 Environmental Life Cycle Assessment

There was a need to conduct an LCA study that incorporates the advances in technology. The goal of this study was to evaluate the relative environmental and economic impact of the configurations to inform decision makers across the industry and to identify any inconsistencies or anomalies in policy. Conventional MAD, THP with CHP and GtG were

¹ Throughput low due to plant being upgraded

² Plant mothballed

considered as these are very current technologies being adopted across the UK at full scale. Incineration was not considered in this study as it is not a desirable technology due to the economics and likely planning restrictions from any new build projects. The results of this study are given below and have been published (Mills et al. 2014a). All sludge parameters and process assumptions are detailed in the Waste Management journal paper within the Appendix. The functional unit used is the dry mass of sludge; Tonne Dry Solids (TDS).

Background literature

Many studies in the past have conducted extensive LCA for sludge treatment techniques, but these have focused on traditional disposal routes for the wastewater treatment by-product (sludge) (Dalemo et al. 1997; Lundin et al. 2004; Sonesson et al. 1997; Suh and Rousseaux 2002). These typically include land fill, compost, incineration and land application after conventional AD. The studies vary depending upon the country of origin. Lundin et al. reviewed many of these studies and observe a common difference which depends upon whether the organisation considers sewage sludge as a waste or a resource, this remains a feature in papers that postdate this paper. More recently there have been several Chinese studies, which have explored various off site recovery options for sludge as a fuel showing clear environmental and economic benefits for energy recovery (Q. Liu et al. 2011; B. Liu et al. 2013; Niu et al. 2013). The study by Carballa et al. (2011) is most relevant to the area of interest here in that it compared AD pre-treatment methods (including THP) of sludge and kitchen waste, it was found that pressurisation and chemical treatment most effective. An issue with the Carballa study is that all the operational performance data is scaled from laboratory work conducted using 10 litre anaerobic digesters. An average size site would use 5,000 m³ digesters so the accuracy of these scaled results would be considered questionable by the industry. The study also excluded any impact from sludge handling post digestion (Carballa M et al. 2011). LCA studies on GtG are few, but Jury et al. (2010) finds biogas injection from energy crop fermentation to be environmentally competitive with natural gas (Jury et al. 2010). The relative environmental burden displacement is less for the displacement of natural gas by biogas than the displacement of electricity from fossil fuels by electricity from biogas.

System Boundaries

Figure 23 shows the outline system boundary for all cases considered; it has been assumed that all process variants are assessed in operation only and the impact of construction and decommissioning are ignored as these emissions are likely to be insignificant in comparison (Carballa M et al. 2011). The 'sludge to energy' process itself will consume energy (electricity & natural gas) and chemicals (e.g. poly-electrolyte) which are included. On site there will also be emissions to air from CHP engines and gas boilers which emissions are dominated by CO₂, SO₂ Particulates, CO and NO_x emissions (Poeschl M et al. 2012).

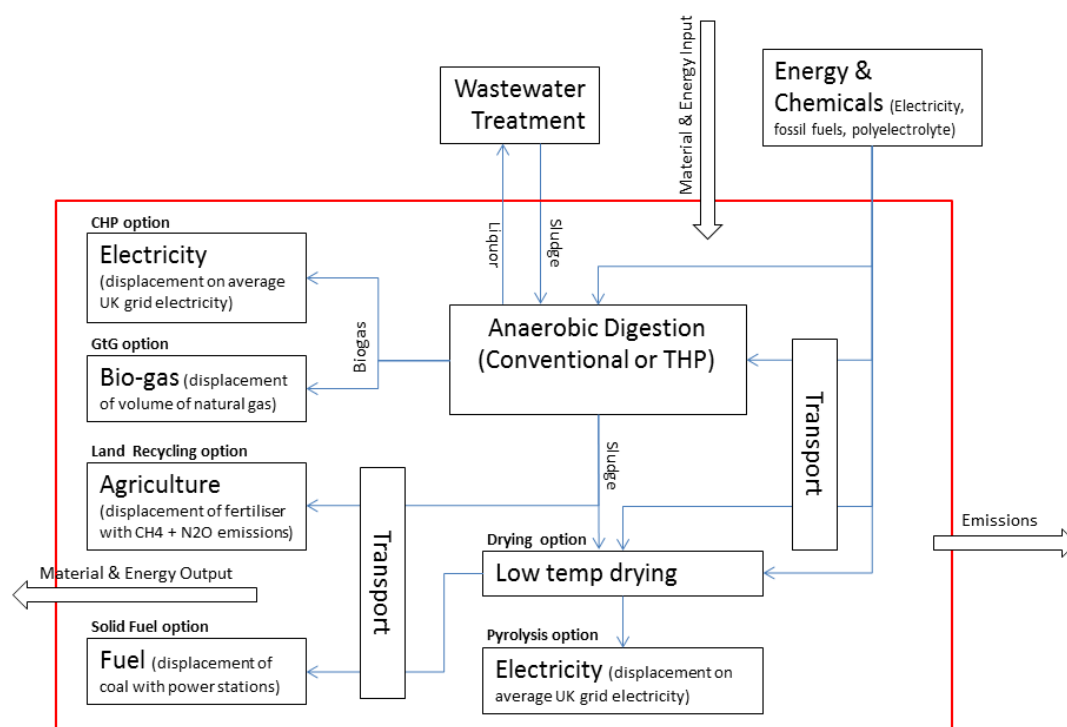


Figure 22 – Overview of System Boundaries

It is assumed that digested sludge is applied to agricultural land (this is the current practice in the UK for 60% of the UK's sludge (Andrews 2008)) and is transported an average of 60 km. In addition to vehicle emissions, this activity will have air emissions (CH_4 & N_2O) associated with the biodegradation of sludge cake in the soil (Kazuyuki et al. 2000). The Nitrogen and Phosphorus (N&P) content of the recycled sludge will be a credit to the system because it displaces industrially made fertilisers in this case Urea and Triple Superphosphate.

Electricity produced from CHP credits the system by displacing grid-produced electricity. Biogas injected under the GtG option also credits the system by displacing the burden associated with producing the equivalent amount of natural gas. Problems associated with heavy metals and other non-biological sludge contaminants have been discounted from the study. All assumptions used within the model are listed in Appendix A. The main assumptions are captured in Table 5.

Table 5. Main process assumptions

Parameter	Units	Value	Comment
Feed and pre-treatment			
PS VS	%	77	
SAS VS	%	77	
PS content in feed	%	60	
PS & SAS density	kg/ltr	1.0	
Thickened PS DS (AD feed)	%	6.0	
Thickened SAS DS (AD feed)	%	5.5	
PS thickener poly consumption	kg/TDS	1.5	
SAS thickener poly consumption	kg/TDS	2.5	
THP thickening combined DS	%	16.5	
THP thickening poly consumption PS	kg/TDS	3.0	
THP thickening poly consumption SAS	kg/TDS	7.0	
Raw PS dewatering DS for lime	%	32	
Raw SAS dewatering DS for lime	%	17	
Raw PS dewatering poly consumption	kg/TDS	4.0	
Raw SAS dewatering poly consumption	kg/TDS	9.0	
Lime consumption prop. cake volume	%	15	
Anaerobic Digestion			
MAD PS VSD	%	60	
MAD SAS VSD	%	20	
MAD PS OLR	kgVS/m ³ /d	3.0	
MAD SAS OLR	kgVS/m ³ /d	2.0	
MAD secondary digestion HRT	days	9	
THP AD feed DS (post dilution)	%	9	
THP PS VSD	%	65	
THP SAS VSD	%	50	
THP PS OLR	kgVS/m ³ /d	7.0	
THP SAS OLR	kgVS/m ³ /d	4.0	
Biogas, THP and CHP			
Biogas CV	MJ/m ³	23	
Ambient sludge temperature	°C	15	
AD temperature	°C	40	
Specific enthalpy of sludge	kJ/kg	4.18	
CHP Electrical efficiency	%	40	
CHP Electrical parasitic load	%	5	
CHP low grade heat efficiency	%	20	95°C
CHP high grade heat efficiency	%	19	10barg steam
Boiler efficiency	%	80	Steam boiler
THP steam demand / TDS of sludge	kg/TDS	0.95	(Merry and Oliver 2014)
Gas to Grid			
Propane consumption	V/V %	5	
Power consumption	kWh/m ³	0.3	
Dewatering & Drying			
MAD dewatering DS (normal / Bucher)	%	20 / 29	
THP dewatering DS (normal / Bucher)	%	31 / 44	
Conv. dewatering poly consumption	kg/TDS	8.0	
Bucher dewatering poly consumption	kg/TDS	10	

AD Electrical Load & Operator Labour			
MAD process load	kWh/TDS	90	60% of THP load
THP & SAS only THP process load	kWh/TDS	150	Joe Merry
MAD resource requirement	# / 30TDS/d	1.0	
THP (all configs) resource requirement	# / 30TDS/d	1.5	

Inventory

A commercial LCA package (GaBi) was used to construct a model for each of the 5 scenarios. Figures 12, 17 & 18 display high level summary Sankey diagrams for the energy flows in each scenario (note that electricity, road fuel and consumables are not shown but are included in these results). Table 1 shows the inventory for the main performance indicators which drive the life cycle impacts, grouped as energy outputs, inputs and digestate.

Table 6. Inventory of Key Performance Indicators for 1 TDS feed

Inventory Item	Units	Conv AD CHP	THP AD CHP	THP AD GtG
OUTPUTS				
Electricity generation	kWh	728	1,020	-
Bio-methane	kWh	-	-	3,230
INPUTS				
Electricity consumption	kWh	135	179	199
Natural gas	kWh	0	370	907
Propane	kWh	-	-	546
Diesel	kg	7.3	3.7	3.7
Polymer	kg	9.2	14.0	14.0
DIGESTATE				
Sludge disposal	Wet tonnes	2.3	1.4	1.4
N&P Benefit	kg	254 / 156	150 / 92	150 / 92

Environmental Life Cycle Analysis Results

The software used (GaBi) in this study can allow a number of different impacts to be analysed, for this study the following were deemed important:

1. GWP-Global Warming Potential (excluding biogenic) (kgCO₂ – Equiv.)
2. POCP-Photo Ozone Creation Potential (kg Ethene – Equiv.)
3. EP-Eutrophication Potential (kg Phosphate – Equiv.)
4. AP-Acidification Potential (kgSO₂ – Equiv.)
5. ADP element - Abiotic Depletion Potential (elements kg Sb – Equiv.)
6. ADP fossil - Abiotic Depletion Potential (fossil MJ)

Figure 21 displays the normalised results for the six impacts calculated as part of the study; negative values are environmentally beneficial and positive values represent environmental

burdens. The largest impact area is ADP fossil which is negative (beneficial), this is due to all the processes displacing fossil fuel use. Conventional AD performs better than THP (CHP & GtG) and the pyrolysis options, because it has relatively low parasitic energy and chemical demand. The drying to fuel scenario is best due to the direct displacement of hard coal. The GWP impacts follow a different trend and are discussed in detail later due to their regulatory and financial significance.

The next most significant emissions are 'local' (AP & POCP) and reveal a slightly different picture that suggests that the GtG scenario has the least impact, due to the low direct emissions associated with the production of bio-methane, compared with a CHP exhaust. Unsurprisingly the scenarios with CHP units have the largest impact, due to the exhaust emissions (Dust, CO, NO_x, SO₂ and VOCs). ADP elements and EP are insignificant in comparison and are therefore not discussed further.

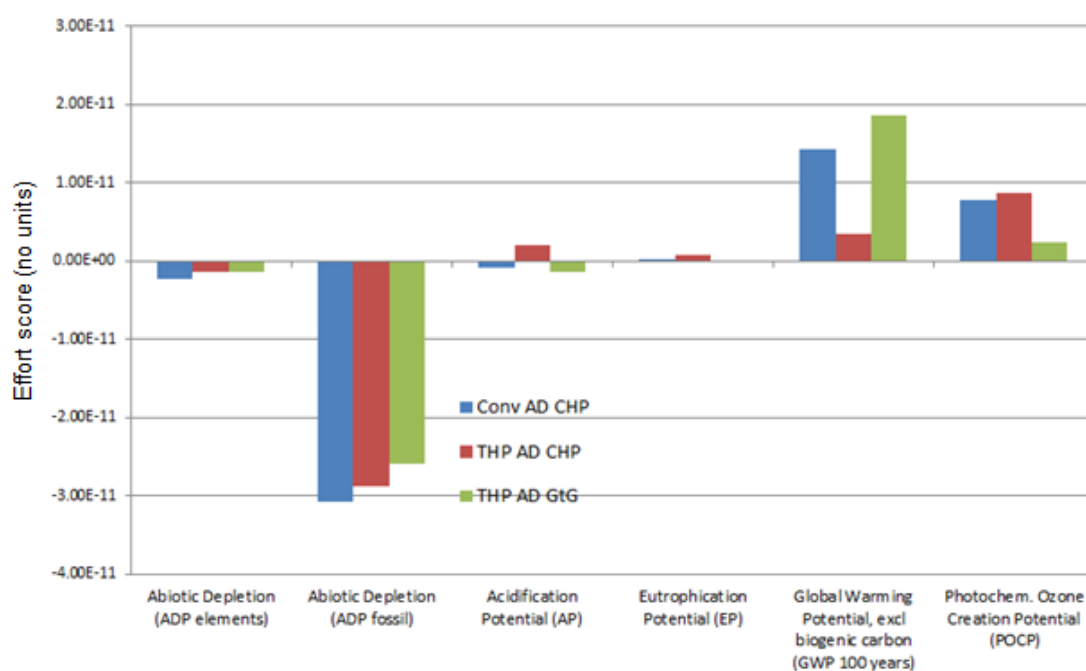


Figure 23 – Life Cycle Impacts per TDS Normalised using the 'CML2001 – Nov.2010' Method

Using a weighting for each impact the net environmental impact can be calculated for each scenario and this is shown in Table 6. Using this metric all the scenarios have a net environmental impact and the worst performer is the GtG scenario. THP with CHP has environmental benefits over conventional AD with CHP.

Table 7 - Weighted Net Impact using the 'CML 2001 – Dec. 07, Experts IKP (Northern Europe)' Method

Conv AD CHP	THP AD CHP	THP AD GtG
9,250	6,110	10,500

GWP is considered the most important impact to water companies, as it is a reportable output to the regulator OFWAT and it also costs millions of pounds annually in taxes such as

the Carbon Reduction Commitment (CRC). Figure 22 shows the results for GWP of the scenarios described previously. The net GWP for each scenario is shown as the black column with a data label, the emissions have also been categorised into six key process steps to improve analysis, shown as discrete columns.

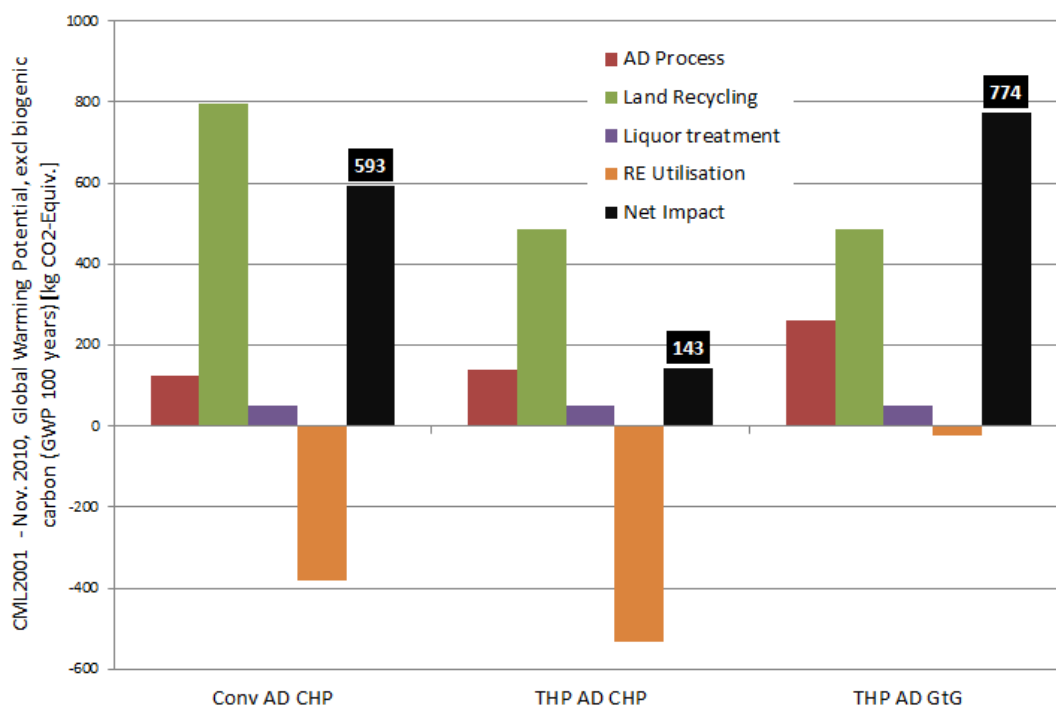


Figure 24 – Global Warming Potential for 3 Options

The results show that the move from conventional AD with CHP to THP is beneficial, despite the parasitic fuel requirements, mainly natural gas support fuel for steam generation. The GtG option performs very badly for two reasons: firstly, the beneficial impact of injecting bio-methane into the gas grid is not as great as displacing electricity, and, secondly, the process requires a large 'top up' with propane gas and natural gas to maintain the steam demand for the THP plant. The emissions of CH₄ and N₂O from recycled sludge on agricultural land are significant and dominate Figure 22.

2.6 Economic Analysis

2.6.1 OpEx

A process model was created which consists of the following main modules or functions (the structure of which is shown in Figure 23, all assumption in Appendix A):

1. Process inputs - containing 4 main parameter groups:
 - a. Sludge feed (throughput (tDS/day), %PS, %VS content)
 - b. CHP type (efficiencies (elec, HG & LG heat))
 - c. Dewatering (%DS output, polymer (kg/tDS))
 - d. Resource requirements (FTE/tDS/day)
2. AD Process – uses process input parameters and process variant information (i.e. MAD or THP AD) to calculate key outputs such as biogas and digestate. The performance

calculation is split into two parts, PS and SAS. Each part has an assumed: %DS feed, %VSD, gas yield (m^3/kgVSD), organic loading rate ($\text{kgVS}/\text{m}^3/\text{d}$), thickening polymer consumption (kg/tDS). These two parts produce outputs which are combined to give results on the combined performance: VSD, DSD, digestate (mass and VS, DS content), gas yield (m^3/day , m^3/tDS), polymer consumption (kg) and digester volume required (m^3). These parameters are either used in other process modules or used in the OpEx and CapEx calculations. The module also calculates a number of parameters to aid error checking this includes parameters such as organic loading rate ($\text{kgVS}/\text{m}^3/\text{d}$) and HRT (days).

3. Bio-gas use, CHP – uses the gas yield from the previous module and the technical input assumptions to calculate: engine size (MWe), ROCable output (MWh/d), low and high grade heat output (MWh/d) used in the CapEx and OpEx calculations.
4. Bio-gas use, GtG – uses the gas yield from the previous module and process specific assumptions to calculate the bio-methane output to the grid (m^3) and the required inputs such as: propane and electrical power (MWh/d) used in the CapEx and OpEx calculations.
5. Heat Demand – this module sits between the 'AD process' and the 'bio-gas use' modules and effectively solves the heat balance to ensure the process has sufficient heat and that if additional support fuel is required it is quantified. Natural gas is assumed as the support fuel of choice and the requirement is used in the OpEx calculations.
6. Digestate disposal – a relatively simple module it takes the digestate mass from the 'AD process module' and using the dewatering parameters (%DS and polymer consumption) calculates the volume of cake and the polymer required used in the OpEx & CapEx calculations.

Following the process model a number of key parameters are carried forward into the OpEx module and combining these with unit cost assumptions the following costs/revenues are calculated:

Cost bases:

- Electricity use (MWh/d)
- Labour (FTE's)
- Polymer (kg/d)
- Digestate volume (m^3/d)
- Maintenance (% of CapEx – explained later)

Revenue bases:

- Electricity generated (MWh/d)
- Electricity eligible for ROCs (MWh/d)

The output is a net OpEx position which can be used to compare processes and in combination with the CapEx, explained next, used in full financial analysis of each process.

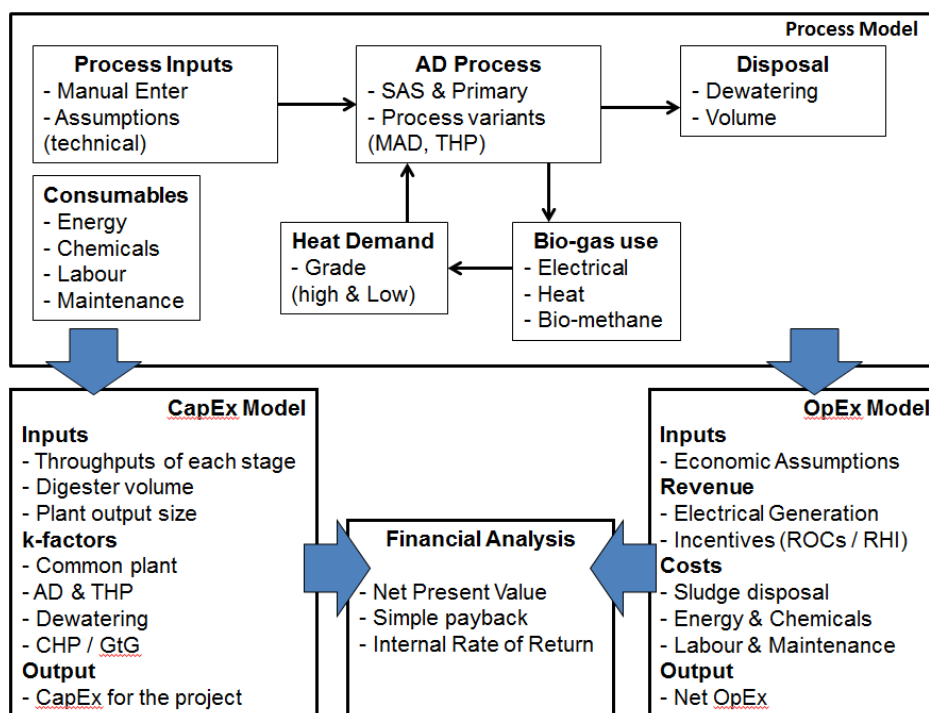


Figure 25 – Process model structure

2.6.2 CapEx

The content of Table 7 is the result of combining a number of sources of data to produce a cost estimate for various process configurations on a typical green field site. These are generalised values, they are not site or project specific. Over-heads are estimated for this comparative study and are not necessarily representative of those used within Thames Water. Using common chemical engineering CapEx estimation techniques, the non-linear nature of CapEx can be normalised and calculated for each scenario with Equation 1 (Sinnott 2009).

$$\text{CapEx} = k \times S^{0.6} \quad (1)$$

Using cost data at various scales (S) and an exponent value of 0.6 (average value for similar installations) a series of k -values were calculated (Table 7).

Table 8 – Sludge to Energy Process – CapEx model

Component	CapEx (£)	Size	Unit	k-Value
Pre-treatment & thickening	2,654,662	100	TDS/d	167,498
AD	5,779,416	22,000	m ³	14,336
THP	5,890,325	100	TDS/d	371,654
Dewatering & Cake Storage	3,812,236	60	TDS/d	326,805
Odour Treatment	665,165	100	TDS/d	41,969
CHP & Electrical	5,535,458	5,000	kWe	33,402
Control & Instrumentation	789,402	100	TDS/d	49,808
General	2,031,665	100	TDS/d	128,189
SUB TOTAL	27,158,329			
Contractor Management (20%)	5,431,666			
Client Overheads (10%)	3,258,999			
TOTAL	35,848,994			
ADDITIONAL OPTIONS (before Contractor and Client Overheads)				
GtG (CHP eq output 2.5kW/m ³ /h)	4,620,716	5,000	kWe	33,402

2.6.3 Analysis

Using and adapting the data in Table 7 the total CapEx for each scenario was obtained; with the OpEx information from the previous section, the economic feasibility of each process scenario was calculated. Table 8 summarises the financial situation and the resultant NPV with and without government incentives for a 100TDS/day plant for each scenario. A discount factor of 8% was used and the life of the plant was assumed to be 20 years. All other assumptions can be found in Appendix A. The financial benefit that UK water companies exploit from the increasing the regulated capital value (RCV) of the company asset base has not been factored into the analysis.

Table 9 - Financial performance of each process scenario assuming a 100tDS/day plant

Scenario	CapEx (£m)	OpEx w incentives (£/tDS)	NPV and Payback with incentives		NPV and Payback without incentives	
			£m	years	£m	years
Conv AD CHP	31.4	-29.0	12.1	7.1	9.2	8.4
THP AD CHP	33.7	7.3	17.3	5.9	13.4	7.0
THP AD GtG	32.5	79.2	28.8	3.9	-0.7	22.3

The results show that the GtG option has the best NPV and payback followed by THP CHP. However, when the incentives are removed the NPV becomes negative for the GtG option, which means the investor would not see a return on the investment within the operational life of the plant.

THP is superior to conventional MAD CHP although there is not a significant difference, this maybe the case but what is not apparent from financial analysis is the benefit bought from

a superior sludge cake. The product is preferred by farmers and as such reduces disposal risk from land not being available for recycling sludge. In addition THP allows for much larger throughput on the same footprint, on urban treatment sites land is limited so conventional AD, with large anaerobic digesters with their associated large footprint, is simply not feasible. Land purchase was not included in the CapEx calculations as most sites are already congested.

In reality an organisation has limits on the total borrowing, debt and the gearing which can affect the feasible options, which is why it is very important to always analyse and show CapEx, OpEx and whole life costs, so that good decisions can be made.

Financial Sensitivity analysis

This was carried out to understand the relative financial performance of the three scenarios. The effect of digester CapEx and digestate disposal were modelled.

Digester CapEx

This is an important parameter to understand as the unit cost can vary considerably. If the site has existing digester assets which is often the case little or no spend is required to achieve the appropriate digester volume particularly for THP sites, in contrast some construction methods and/or site conditions will increase the cost of construction. Therefore, the effect of the unit cost was varied from 0 to 2 times the base case shown in Table 6. The results of this are shown in Figure 24, the x-axis displays the unit costs varying from 0-2 times the base case, to help quantify and give context the cost for a 4,000m³ digester is shown in. As you would expect, reducing the cost of digesters increases the rate of return for all scenarios. An interesting effect was seen which shows that below 0.3 times conventional MAD with CHP is more attractive financially than THP CHP. THP with GtG follows a similar relationship to THP CHP, but has a better IRR on average 8% more.

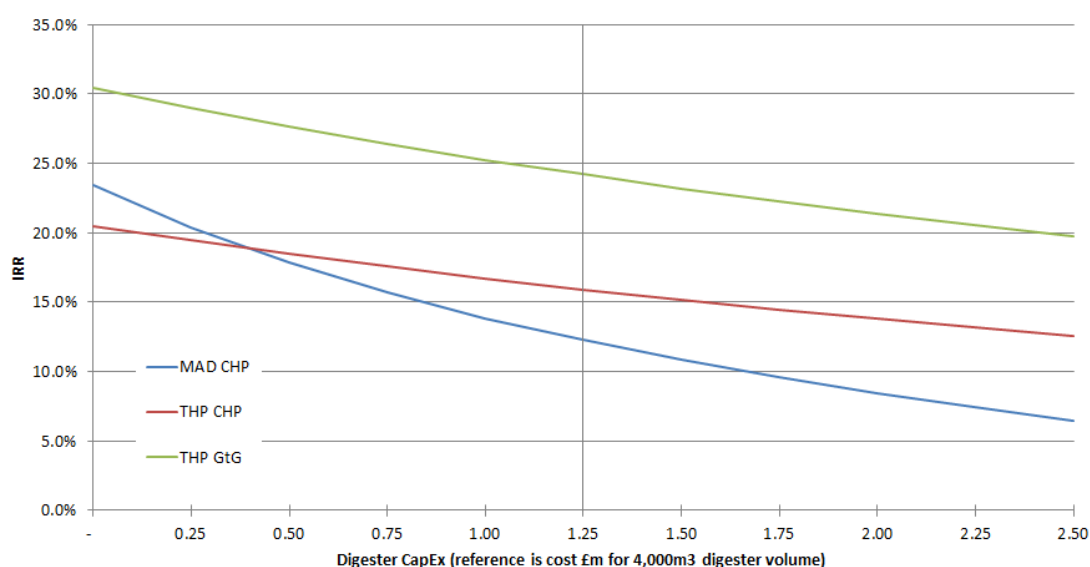


Figure 26 - Effect of Digester CapEx on IRR

Digestate disposal cost

This is an important parameter as it can also vary significantly depending upon location, proximity to suitable agriculture, regulations. In the UK land recycling of digestate is common practice so variation in disposal cost may vary between £10-35 per wet tonne. However, in some countries like the Netherlands sewage sludge recycling to land is not permitted and therefore disposal of the digestate post digestion is very expensive up to and over £100 wet tonne. Therefore, a range of 0.1 - 5 times the base case was selected for the sensitivity analysis, translating to £2-100 per wet tonne. To ensure that this analysis was meaningful the 'do-nothing' treatment cost also had to vary. The 'do-nothing' base case assumed £150/tDS which is typical for a 'liming operation'. Liming is a non-digestion, chemical stabilisation option which is low CapEx and high OpEx. It does not reduce the mass or sludge for disposal on the contrary it increases it but CapEx on large long retention time assets is avoided. Therefore, the 'do nothing' unit cost was varied by $X^{0.6}$, where X is the multiplier on the disposal cost varied from 0.1 - 5 translating to a 'do-nothing' treatment cost of £38 - £394 per tDS.

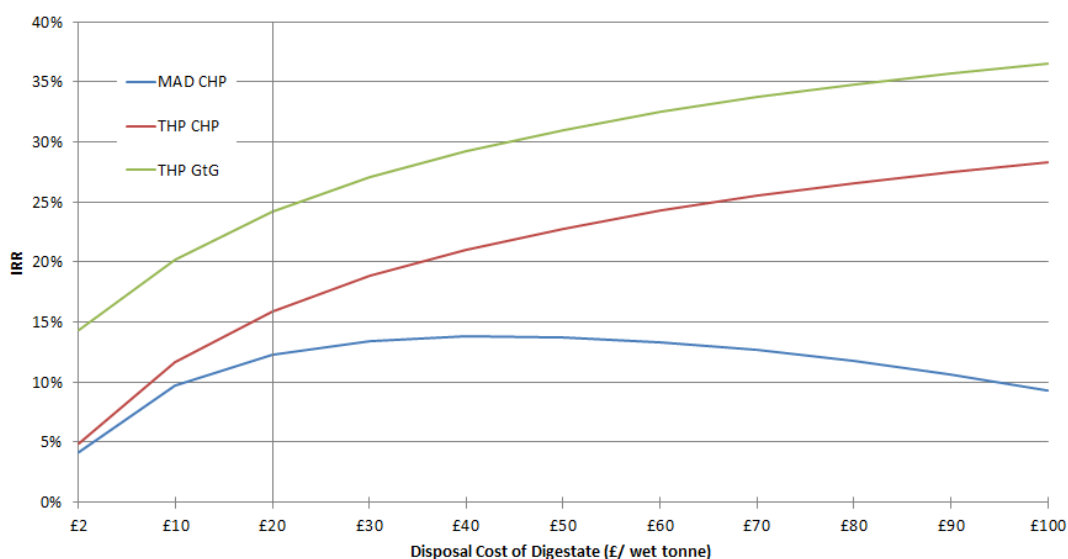


Figure 27 - Effect of digestate disposal cost on IRR

It can be seen that from Figure 25 THP with GtG remains the superior option, with THP and CHP following the same curve but around 8% IRR less attractive. Both respond positively to the increased disposal cost; unlike the conventional MAD option, above £40 wet tonne the IRR reduces with an increase in disposal cost.

2.7 Summary of existing processes

The existing processes analysed in this study have shown there are clear differences between what is available, table 9 aims to summarise and conclude this work.

Table 10 - (Table 1 repeated) Summary of Existing Processes

Performance	Units	Conv. AD	Advanced AD (THP) CHP	Advanced AD (THP) GtG	Incineration with energy recovery
Energy Yield (elec)	kWh/TDS	820	1100	n/a	880
Parastic energy - elec	kWh/TDS	90	150	290	496
Parastic energy - heat	kWh/TDS	0	370	920	0*
Solids Destruction	%	34	45	45	77
Carbon emissions	kgCO ₂ e/TDS	593	143	774	<i>not modelled</i>
OpEx	£/TDS	-33	4	76	-107
RE incentive proportion	%	19	19	61	39
CapEx	£M/100TDS	31.4	33.7	32.5	71.5
NPV after 20yrs	£M	11.6	17.1	27.2	<0

The results show that THP has clear advantages over conventional AD and incineration and supports the current trend in the industry to build THP. THP development forms a large part of this project and can be seen in section 3.1.

Incineration is a very costly to build and operate and has a poor net energy yield also in reality does require significant quantities of support fuel. Incineration has no real future in the industry other than in extreme situations where there are considerable problems with recycling sludge to agricultural land. Conventional AD is an efficient energy recovery processes with the lowest parasitic energy demand.

GtG should probably be avoided due to the relatively poor environmental performance when compared with the CHP options. The main reductions in benefit can be attributed to the use of liquid propane to adjust the CV of the gas before final injection into the local gas network. Also there is additional electricity consumption required to pressurise the gas before injection into the local gas network. This varies depending upon the gas pressure local to the site; the modelling assumed medium pressure. GtG is also not favourable due to the high financial risk posed by proportionally high renewable incentives. These may be removed or adjusted before a project could be commissioned and accredited and therefore represents a large investment risk. Upgrading biogas to a bio-methane suitable for transport fuel might be a better solution, requiring fewer incentives due to the relatively high price of transport fuels and displacing a carbon intensive fuel would be more environmentally beneficial, this is commonly seen in the EU. However, there may be a point in the future where the electricity grid carbon intensity maybe reduced to a level where the production of bio-methane for grid injection would be favourable environmentally over the more traditional electricity production. GtG was not been explored further by this project after the environmental and economic LCA.

3. What does the future look like?

Answering this question represented the majority of the EngD project and can be summarised as three main activities which are described and analysed in detail in this section:

1. THP Development
2. Sustainable Thermal Drying
3. Advanced Energy Recovery

3.1 THP development

The present technology was initially developed 15-20 years ago and now a number of new developments are underway, to refine the application of this effective process.

3.1.1 SAS only THP

This THP variant employs the same process but only the SAS stream is dewatered and thermally hydrolysed. The thickened primary sludge bypasses THP and is instead fed directly into the digester. The advantages of this process are that the THP plant can be smaller and the resulting steam demand is reduced to an extent where no support fuel is required. The performance of the digestion is slightly reduced as the primary sludge has not been hydrolysed. The digester configuration is also slightly more complicated in the UK, due to the requirement to extend the retention time to maintain a sufficient pathogen kill; this is achieved by further a series of digesters or a second stage.

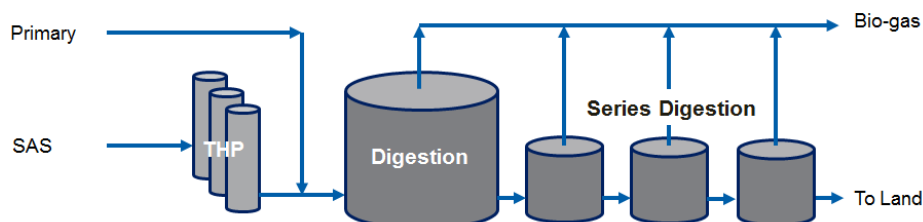


Figure 28 – Simplified Process Flow Diagram for SAS only THP

The performance of this process has been confirmed in laboratory trials (Shana A et al. 2013). The two findings from this work are that on average 421m³/TDS of biogas can be produced and the volatile solids destruction is around 54%, dewatering tests simulating a conventional belt filter press showed that 28%DS can be achieved. A full scale SAS only THP plant is being built at Thames Water's Long Reach WWTP and will be operational in 2015.

Unlocking the Full Energy potential of Sewage Sludge

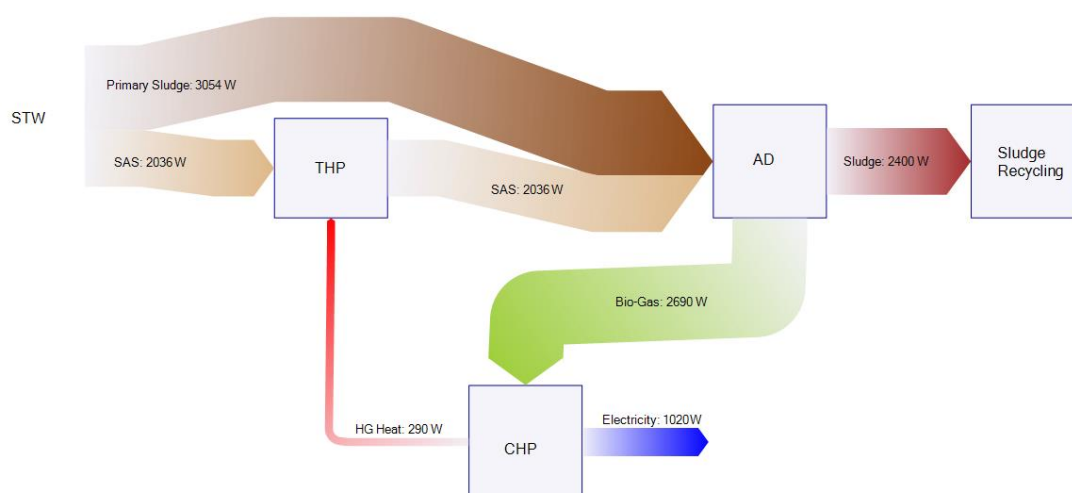


Figure 29 - Energy Flows for SASonly THP AD and Land Recycling (1kgDS/hour) electricity input is not shown

3.1.2 Steam Explosion

Steam explosions were patented in 1926 by Mason et. al as a method pre-treatment for biomass (Stelte 2013). Steam explosions fall into the category of a physio-chemical pre-treatment and can be carried out with or without the addition of an acid catalyst. In a steam explosion, the biomass is exposed to saturated steam at temperatures between 160 and 260°C for a period of time. Typically periods are between 5 and 15 minutes, depending upon the operating conditions chosen. The pressure is then suddenly reduced, making the biomass undergo explosive decompression, which shatters cell walls and reduces 'particle' size; it may also promote chemical reactions such as further hydrolysis.

The Cambi THP system is such that the hydrolysed sludge undergoes a steam explosion during the period of transfer from the reactor vessel to the flash tank (Horn et al. 2011). By altering the pressure of the reactor before sudden decompression the steam explosion effect can be increased. The aims of a laboratory study were to better understand and quantify this effect and verify claims that increased gas yield could be achieved.

Experimental Procedure

The study into the steam explosion effect was undertaken using a small scale thermal hydrolysis rig. Steam explosion conditions were changed by altering the flash pressure from the reactor into the flash tank. The changes to the hydrolysed sludge were measured using a small batch digestion (2ltr) rig.

A mixture of primary sludge and SAS (60:40 ratio by dry mass) from Reading STW (with lamella primary settlement and secondary treatment with Biological Nutrient Removal) was used, with a VS content of approximately 78%. It was dewatered manually to a cake of around 13-14%DS.

Thermal Hydrolysis

The small scale THP rig consists (Figure28) of a 20L reactor vessel, a 50L flash tank, a steam boiler operating at 9 barg, and actuated valves on the reactor and flash tank discharges.

The rig also has pressure instrumentation on the reactor and flash tank with high frequency data logging.

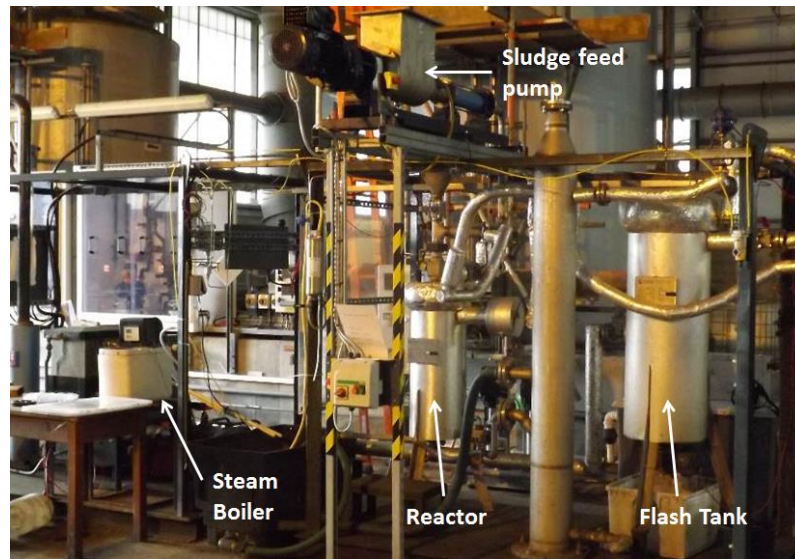


Figure 30 – Picture of the Small scale pilot THP at Reading STW

On start-up of the plant, steam was introduced into the reactor in order to pre-heat the vessel and avoid condensation. After 2 hours of continuous heating, the steam was flashed into the flash vessel, the condensate drained and the valves repositioned. Sludge was then fed into the reactor using a progressive cavity pump located above the reactor. Once complete the reactor was loaded with sludge, all the valves were closed and steam introduced to the sludge to preheat it. Once 6.0 barg was reached, the pressure was held at 6.0 barg for five minutes as a preheating step to attempt to ensure the sludge temperature is uniform. After the 5 minute preheat, the reactor was maintained accurately at 6.0 barg for 30 minutes to complete the hydrolysis. As shown in figures 29, 30 & 31 the reactor pressure was then changed prior to the flash. This was achieved by bleeding off some of the steam in the headspace of the reactor with a small valve; this process took 2-5 minutes. Three pressures were trialled 3.0, 4.5 & 6.0 barg. Once the correct pressure was met the actuated valve between the reactor and the flash tank was opened fully. The flash vessel was also open to atmosphere so as to maximise the steam explosion effect. Figures 29, 30 & 31 show the typical pressure relationships in the reactor and flash tanks for the 3 flash scenarios 3.0, 4.5 and 6 bar respectively.

Unlocking the Full Energy potential of Sewage Sludge

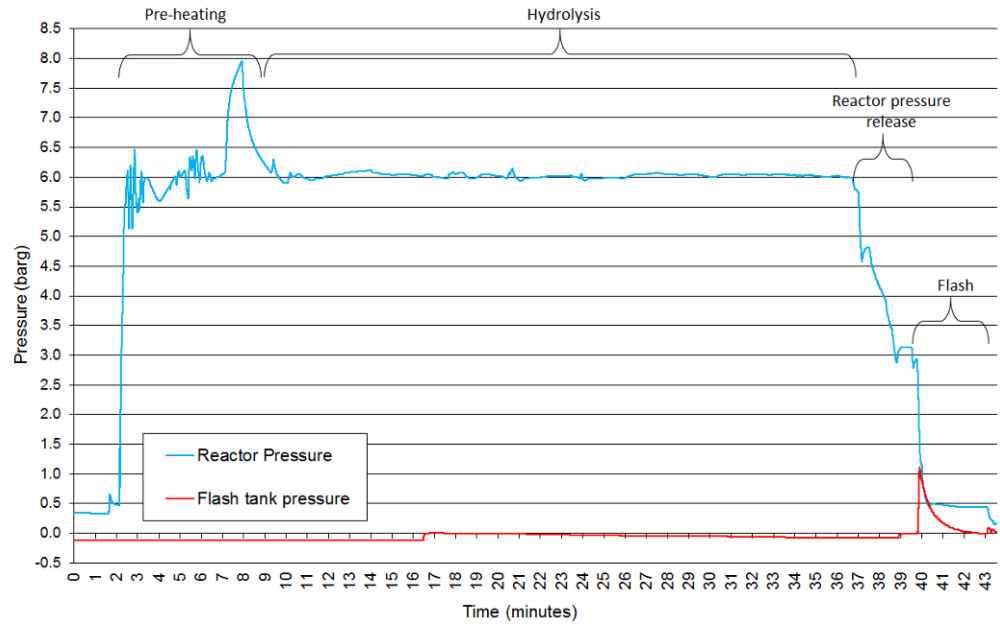


Figure 31 – Pressure within Reactor and Flash tank for 3.0barg Flash Conditions

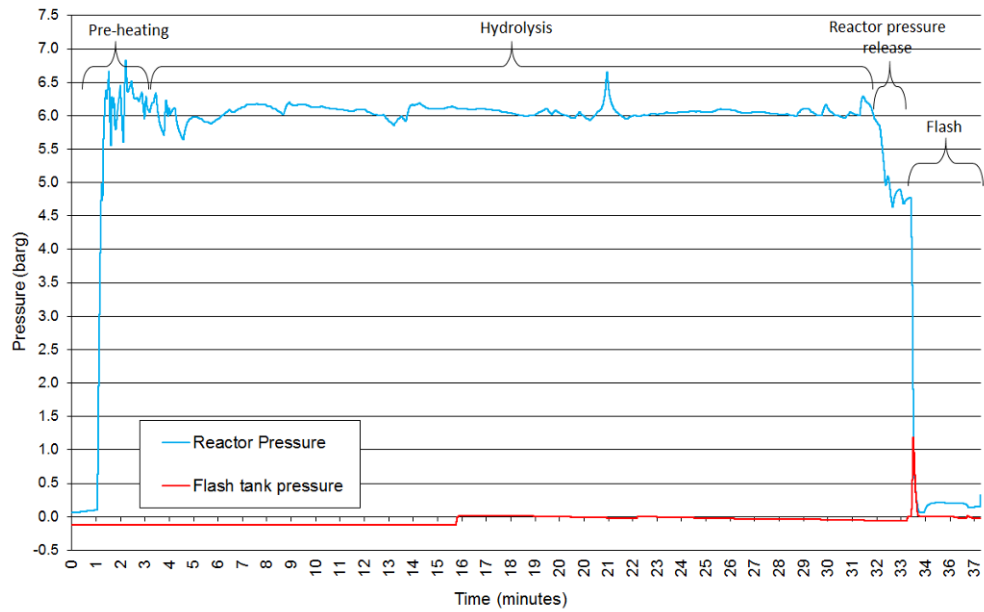


Figure 32 – Pressure within Reactor and Flash tank for 4.5barg Flash Conditions

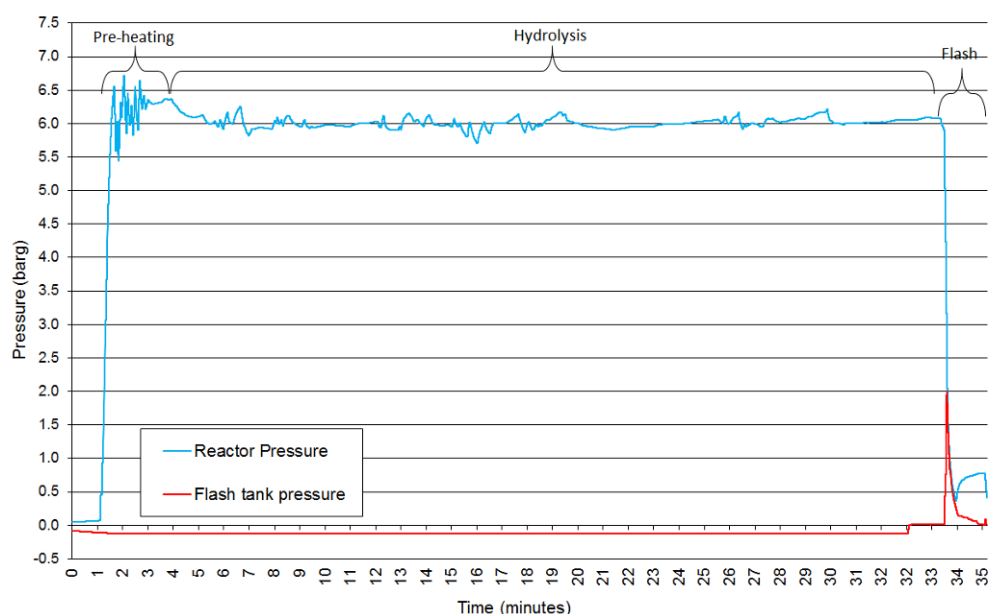


Figure 33 – Pressure within Reactor and Flash tank for 6.0 barg Flash Conditions

The sludge feed and the hydrolysed sludge, collected from the base of the flash tank, was analysed for VS, DS and VFA. Sewage sludge is composed of complex biodegradable matter which must be solubilised and broken down into smaller monomers before being assimilated by bacterial cells (Gunnerson C and Stuckey D 1986). For this reason soluble carbohydrate, protein and lipid analysis was also undertaken to understand if steam explosion has a measurable effect on improving the degradation of the biomass prior to digestion.

Proteins, carbohydrates and lipids analysis

Proteins were measured using the method documented by (Lowry et al., 1951) in two stages. It is worth noting that this method is used for analysis of extractable proteins, but it is not a method for analysing total proteins. During the first stage of the analysis, Soluble Microbial Products (SMP) were measured to provide information on mainly substrate related proteins, plus to some extent lysed microbial biomass related proteins. During the second stage, Extra-cellular Polymeric Substance (EPS) were measured. EPS represents the lysed microbial biomass proteins. Extractable total proteins were reported as the sum of SMP and EPS expressed in mg/l.

Extractable carbohydrates related SMP and EPS were measured in a two stage process using the Phenolic – sulphuric acid method (Dubois et al. 1956) and reported as a sum of SMP and EPS expressed in mg/l.

Lipids analysis involved samples heated (80°C) with hydrochloric acid, followed by subsequent extraction with diethyl ether and petroleum ether (40°C-60°C). The solvent was evaporated and the residue (lipids) were determined gravimetrically.

Batch Digestion Experiment

A batch digestion experiment as also undertaken using an Automatic Methane Potential Test System (AMPTS) rig designed by 'Bioprocess'. Twelve x 2ltr digesters were used for the experiment, located within a heated water bath and mixed with mechanical stirrers operating on timers. The biogas produced is stripped of CO₂ with sodium hydroxide and the remaining CH₄ is fed to the flow cell array which has a 10ml resolution using liquid displacement. Data is stored in the unit, and can be exported into a spreadsheet.

The batch reactors were seeded using TW Chertsey STW digested sludge (a THP digestion site). The DS and VS of hydrolysed feed sludge were used to calculate the organic load to each batch reactor. To ensure comparable and consistent results, all the batch reactors had the same organic loading of 6.88kgVS/m³/day and a 3:1 seed:feed VS ratio was maintained. Precision timing has to be employed when preparing the digestion mixtures to prevent premature unmeasured gas production. The batch digestion was maintained for 14days and the VS, DS and VFA undertaken on the digested sludge.

Results

In total two successful experiments were undertaken after many failed attempts which refined the technique. In particular the precise timing required for initiating the AMPTS to prevent unmeasured bio-gas production at the start of the experiment. The first results are presented in Table 10 show the average VS and steam lost during thermal hydrolysis itself.

Table 11 - Average Volatile and Steam loss during THP

Parameter	THP feed	Flashed @3.0barg	Flashed @4.5barg	Flashed @6.0barg
DS (%)	13.14	11.96	11.62	9.35
VS (%)	79.83	79.60	78.95	78.05
Steam in sludge (%)	-	11.32	13.90	36.24
VFA (mg/l)	2494	2179	1537	1401
VS loss (%)	-	0.29	1.11	2.23

It can be observed that the higher flashing pressures invoke a higher VS and VFA loss, presumably into the flash tank exhaust gas. Fortunately on a full scale plant these volatiles are returned to the pulper stage and are therefore not lost to digestion, but in this experiment they were not recovered. However, the higher flash pressures have the opposite effect on the condensation of steam in the sludge which is increased at high pressures. This is likely to be subtlety only observed at this scale due to the experimental set up.

Two batch digestion experiments were undertaken and the cumulative and rate of gas production of these is shown below. Note that 3 batch digesters were used for each flash pressure condition and results from some of these digesters have been removed due to equipment failure, a mean average is displayed.

The first experiment shows a clear relationship between the flash pressure and increased gas production both cumulative and rate (Figure 32 & 34).

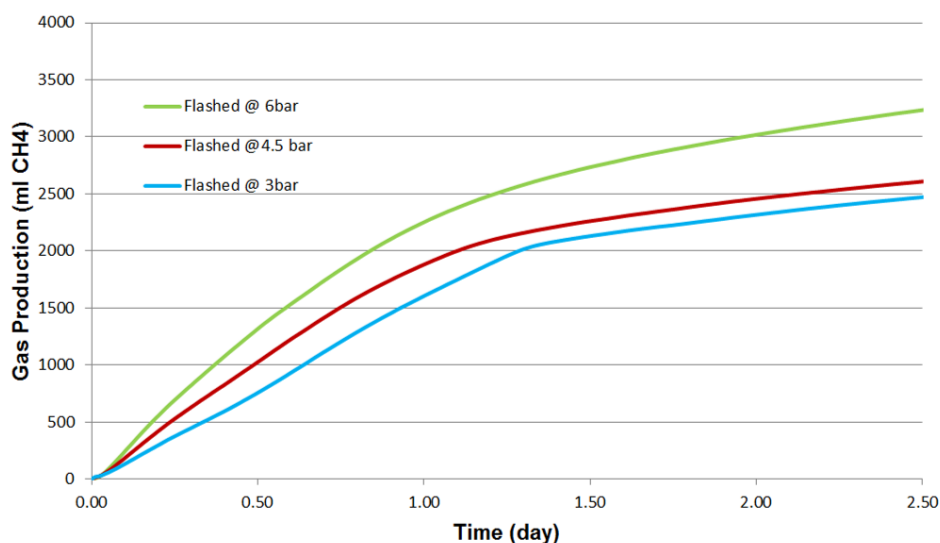


Figure 34 - Cumulative Gas Production - experiment one

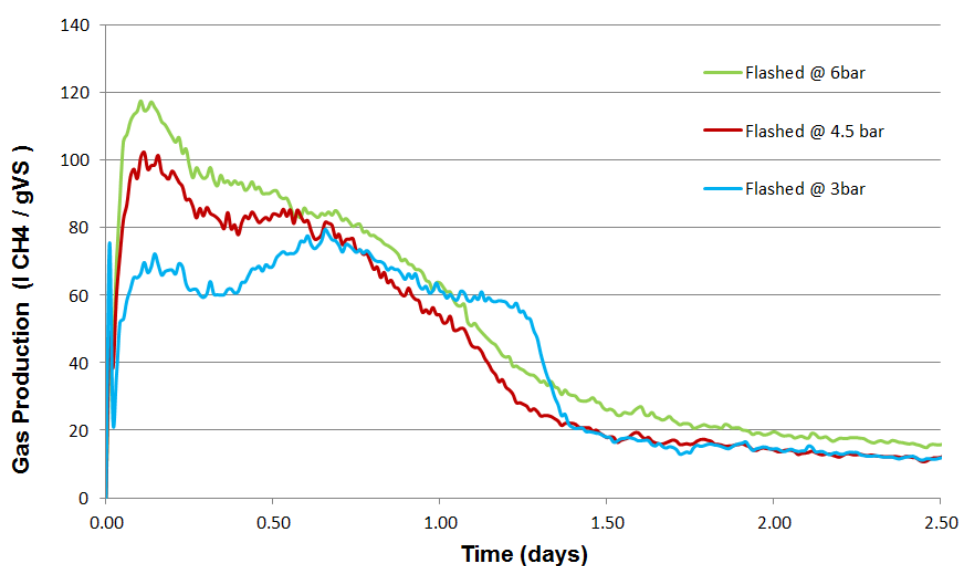


Figure 35 - Gas Production Rate - experiment one

The compositional analysis (Figure 34) also shows a clear relationship that the higher flash pressure increases the soluble carbohydrate and protein, showing enhanced hydrolysis of sludge organic matter content. These soluble carbohydrates and proteins will be readily taken up by successive acidogenic, acetogenic and methanogenic bacteria, and will be ultimately converted to biogas.

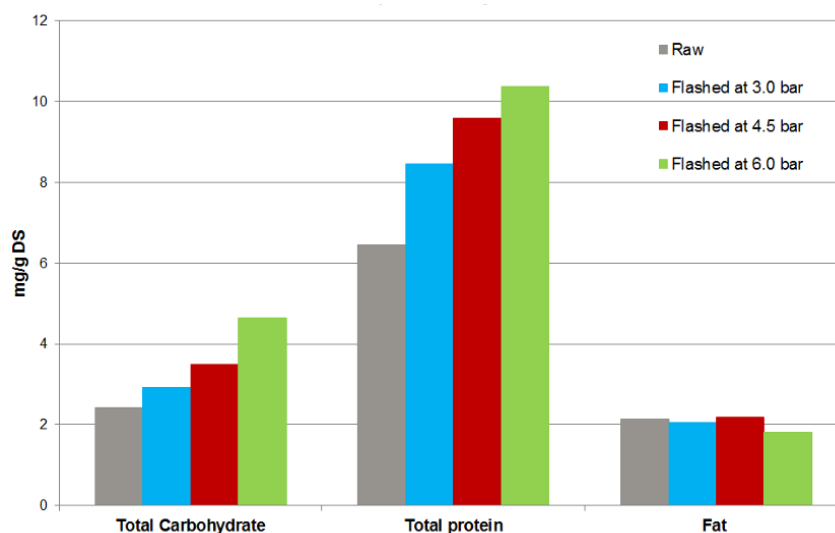


Figure 36 - Compositional Analysis - experiment one

The second experiment was set up to understand the repeatability of the first experiment. In summary, although a similar trend was seen, the extent is not as pronounced as in the first experiment. There is little difference in the instantaneous gas production within the first day and a difference is only seen on the second day. However, despite the slow start, the cumulative gas production shows an advantage in the high flash pressures.

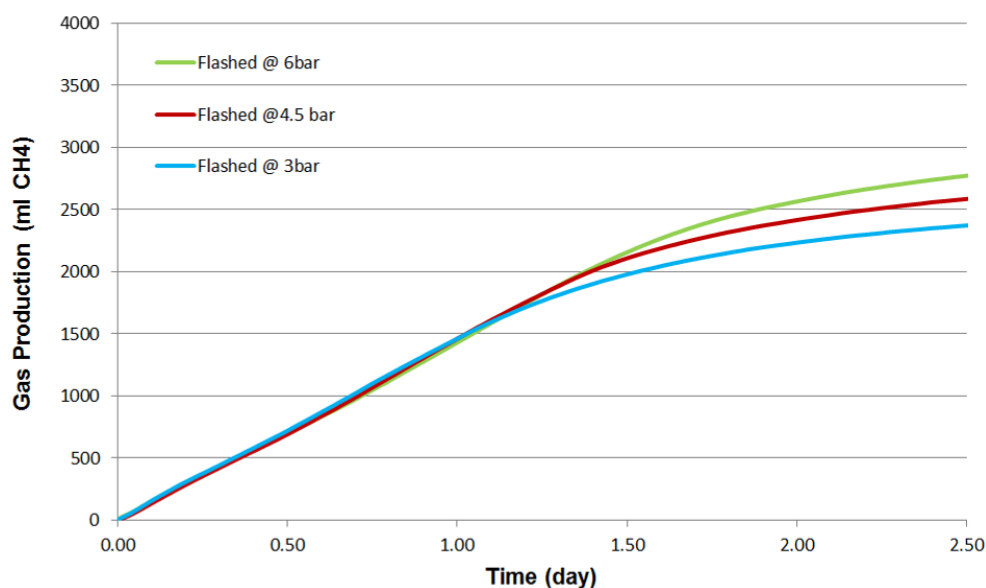


Figure 37 - Cumulative Gas Production - experiment two

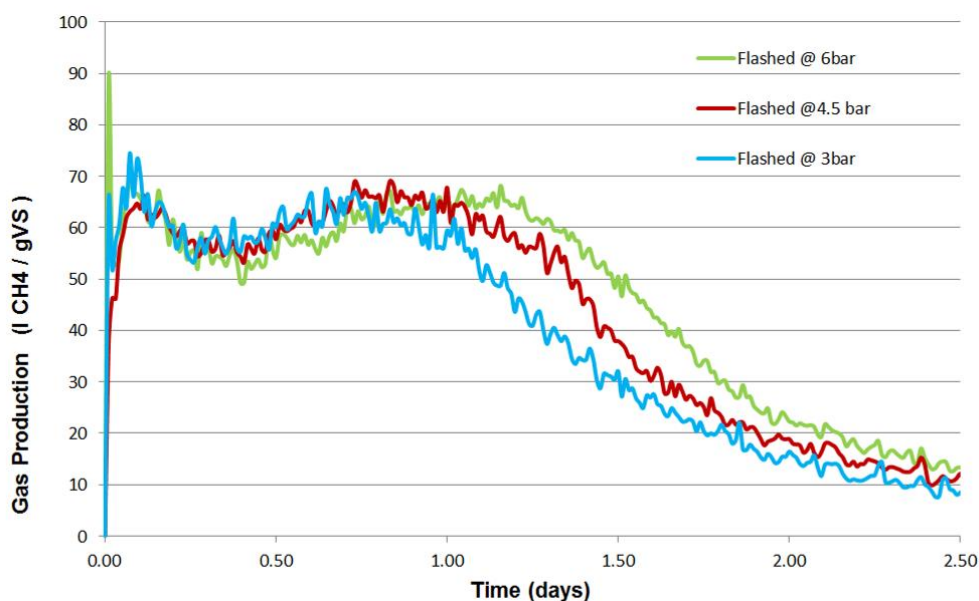


Figure 38 - Gas Production Rate - experiment two

For this second experiment VS, DS VFA and pH were analysed for in the digestate and the feed these results are shown in Table 11. The higher gas yield suggests an increase in specific gas production per unit of volatile solid destroyed; the VS content post AD for all scenarios was similar despite the input VS being reduced at the higher flash pressures, which produced more biogas and faster. VFAs post AD was observed to be larger in the higher flash pressure scenarios; this may due to enhanced hydrolysis of lipids as stated by (McNamara et al. 2012).

Table 12 – Batch AD performance

Parameter	Chertsey Seed	Flashed @3.0barg	Flashed @4.5barg	Flashed @6.0barg
DS to AD (%)	3.56	10.98	11.42	9.89
DS post AD (%)	-	4.2	2.8 ³	3.4
VS to AD (%)	57.2	80.2	79.2	77.5
VS post AD (%)	-	60.1	61.0	61.0
VFA feed to AD (mg/l)	186	2179	1537	1401
VFA post AD (mg/l)	-	127	152	167

A basic but reliable drainage test was conducted using filter paper. The method used 250ml of each sample of the hydrolysed sludge mixed with 50 ml of polymer and stirred for 30 seconds manually. It is then put into a filter paper and gently pressed through a filter paper

³ This result is likely to be incorrect considering the input DS.

for 20 seconds. The amount of water collected is then measured using a beaker the results of 4 repeat tests revealed a strong trend. 99ml, 77ml, 58ml of water is released respectively from 3.0, 4.5 & 6.0 barg. It was observed that the samples from the higher flashing pressures blinded the filter paper more quickly. It can be hypothesised that this is because the higher flashing pressures invoke more violent steam explosion effect and greater disintegration therefore resulting in a smaller particle size which clogs the filter paper more quickly reducing the volume of water collected. The smaller particle size provides a larger surface area for the anaerobic bacteria to interact with the substrate, improving the rate of the digestion reactions. Combined with the increased concentration of soluble protein and carbohydrate at higher flashing pressure this explains why the batch digestion tests showed increase in the rate and total methane production.

This study showed that the steam explosion improves the performance of digestion, by producing more bio-gas at a faster rate; it also has the added advantage of reducing the THP cycle time increasing throughput of a fixed unit and/or reducing the cost of a new installation. The increased rate of digestion may also justify increasing the rate of feed of the digester and reducing the physical digester volume required.

Financial implications of steam explosion

This preliminary experiment has shown that the steam explosion effect looks to be effective for sewage sludge it is therefore worth quantifying the potential benefits financially to justify any further work. The three main advantages of steam explosion can be summarised as:

1. Increased gas yield leading to more power generation.
This has been shown to be true in the small batch experiment that between a 12-22% increase in gas yield can be expected from using steam explosion over the conventional approach. This experiment needs to be repeated and also verified at larger scale and with a continuous digester. However, it is worth calculating the benefit from this apparent financial effect so a conservative assumption of just 5% gas yield has been used in the modelling. It has been assumed that the VSD is unchanged but the bio-gas yield has increased per unit of VS matter destroyed. The change in gas yield is 23m³/tDS
2. Reduced THP cycle time reducing the size of the THP plant for the same unit of throughput.
By applying the steam explosion effect the end of the reactor cycle is shortened because the pressure reduction stage doesn't need to happen saving approximately 15mins or around 20%. For the modelling it is assumed that by applying the steam explosion a 20% saving can be made to the THP CapEx for a 100tDS/day plant this is around £740,000
3. Increased loading rate possible in the digestion
The increased rate of biogas is evident from the data in both experiments, it is not unreasonable to therefore suggest that an increased rate of digestion is also a result, this obviously would require further work to prove. For this modelling exercise it has been assumed that an additional 5% can be achieved in loading rate taking us from 5.4kgVS/m³/day from 5.8kgVS/m³/day.

The results of these three changes are summarised in Table 12, it can be concluded that based on these assumptions listed above that the steam explosion effect has a large impact on the economics. A combination of reducing the CapEx and increasing the OpEx improves the IRR by 1.6%.

Table 13 – Economic Impact of Steam Explosion on Conventional THP

	CapEx (£m)	OpEx (£/tDS)	IRR
Without Steam Explosion	33.7	5.1	15.9%
With Steam Explosion	32.7	13.4	17.5%

This is the first laboratory scale investigation that has shown significant potential benefits and has highlighted the need for further in-depth research in the future.

3.1.3 I-THP

This process configuration trialled at length at laboratory scale by Shana (Shana et al. 2011, 2012; Shana et al. 2013; Shana A et al. 2013), effectively locates the THP in the middle of two digestion stages. The first stage of digestion is a medium rate conventional digester which will obtain biogas from the readily available organic matter, the digested sludge now with a reduced mass is dewatered before thermal hydrolysis which can now be two thirds the size of a conventional plant.

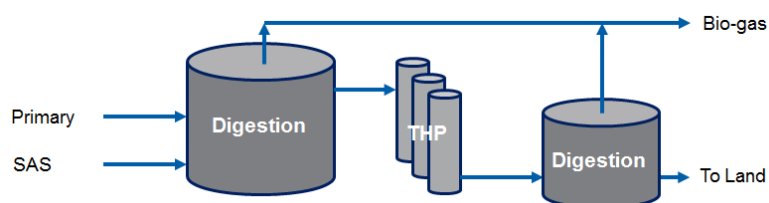


Figure 39 - Simplified Process Flow Diagram for ITHP

The THP stage is conventional other than it now processing digested sludge and differences in rheology are currently being investigated at the Sludge & Energy Innovation Centre, Basingstoke along with the general performance of this process. The second stage digester operates at a high loading rate which produces more biogas. When combined with the first stage the total gas production is approximately 500m³/TDS a 10% improvement on conventional THP and has a corresponding VSD of 65%, producing up to 1200kWh/TDS of electrical energy. A combination of this increased energy production and reduced THP size means that the process when combined with CHP unit is self-sufficient in heat. The low grade heat from the CHP jacket cooling water is sufficient to heat the first digestion stage and the exhaust gas is sufficient to make the steam for the THP assuming a steam consumption of less than 1.0 tonne of steam / TDS. Figure 38 shows the energy balance for the system.

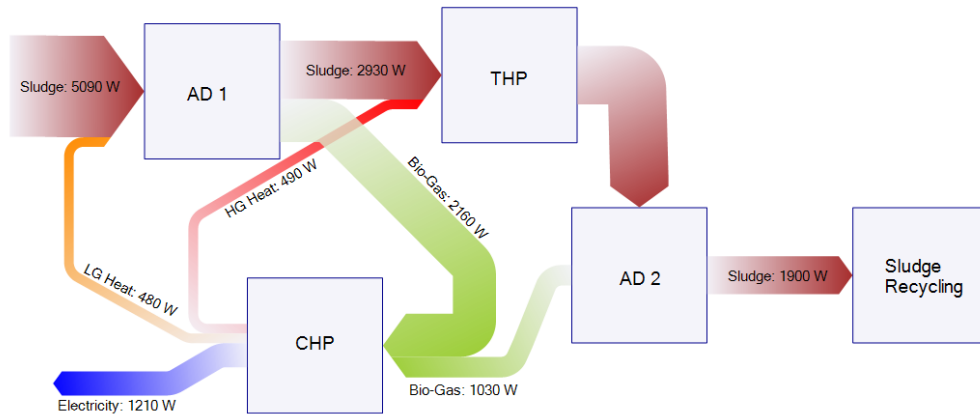


Figure 40 - Energy Flows for I-THP AD and Land Recycling (1kgDS/hour) electricity input is not shown

3.1.4 ITHP Pilot Plant

The successful work undertaken by Shana justified the construction of a realistic scale plant which is developing the design and engineering knowledge required to build a full scale plant. The process flow diagram of the ITHP pilot plant is shown in Figure 39 and photograph of the plant is shown in Figure 40.

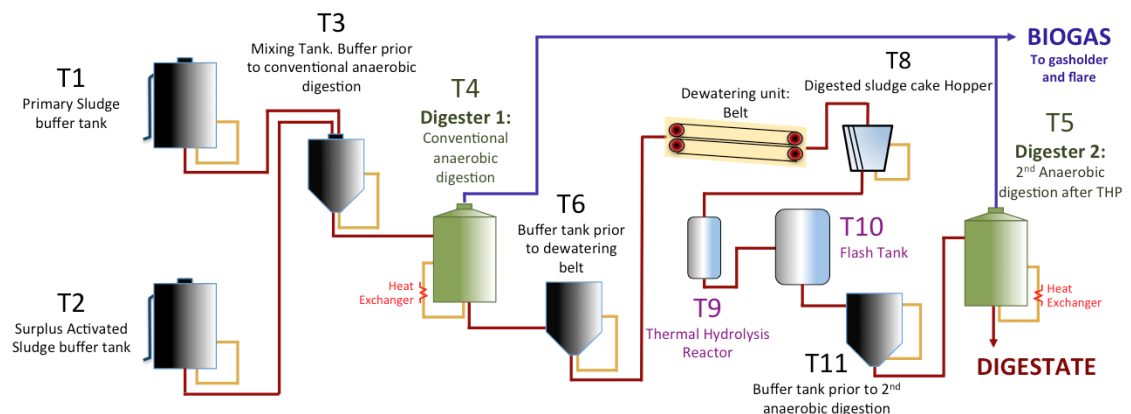


Figure 41 – ITHP Pilot Plant Process Flow Diagram

The plant is not connected to the Basingstoke STW in terms of sludge stream so sludge is delivered in road tankers and the two 18m³ import tanks (T1 & T2) at the front end allow flexibility of feed. Typically, T1 is used for PS and T2 for SAS. In order to keep the sludge mixed, each tank is fitted with recirculation and air mixing (5min/h). Every day, the two types of sludge can be mixed at different ratios (based on dry mass) into the blending tank (T3). T3 is also fitted with a recirculation line and air mixing in order to keep the sludge mixed and avoid stratification. A macerator is in series with the recirculation loop and is designed to break up rag which could block pumps and pipework downstream.

On an hourly basis, a controlled volume of sludge is added to the first digester (T4), based on a set Organic Loading Rate (OLR) calculated with measured DS and VS of the feed sludge.

Both digesters are kept at a set temperature controlled by an automatic valve in the hot water supply to a tubular heat exchanger. The volume and composition of bio-gas produced is measured and the gas is continuously transferred into a gas holder and then flared. Every hour (and around twenty minutes after feeding), the same volume of sludge is pumped out of the first digester and transferred into a holding tank (T6). The volume of sludge in the digester is kept constant by level controller that ensures the volume in and out of the digester is equal.

Twice (or more) a week, digested sludge from T6 is dewatered on a belt filter press using a liquid polymer, the unit achieves 23%DS consistently, this cake is then transferred into a hopper (T8) where it is diluted with hot water to about 16%DS. The diluted and heated cake is recirculated for about 25min to ensure it is well mixed, when the pressure in the cake pump drops below a minimum set point (indicative of 16%DS) the cake is pumped forward into the hydrolysis reactor (T9), where it is thermally hydrolysed. High pressure steam (10bar) from the steam boiler is injected into the reactor at several points at the base of the reactor, bringing the sludge to 6.5 barg. The sludge is kept under those conditions for 30mins before being “flushed” in a matter of seconds into the flash tank (T10). Once hydrolysed, the sludge is transferred into the buffer tank (T11). The tank is insulated in order to keep as much heat as possible and also fitted with a dilution line (final effluent at ambient temperature) to bring the DS down to between 7-10%DS to overcome potential viscosity problems in the second stage of digestion (T5).

A set volume of hydrolysed digested sludge is transferred to the second digester (T5) on an hourly basis. This volume is driven by the set OLR calculated with measured DS of the feed sludge in T11 but the VS measured pre hydrolysis, this is because VS measurement of hydrolysed sludge is not representative. The same volume is also pumped out of the digester (20min after the feed) and some is collected periodically for further analysis. The volume and composition of the biogas produced is measured and the gas is transferred into the common gas holder.

It is worth noting that although the pilot plant is considerably more realistic than the laboratory set up there are some features that differ from full scale application. These are mainly associated with the THP plant which is operating intermittently when compared with a full scale site which would be operating batches continuously. This means that on the pilot plant the recycling of steam from the flash tank to a ‘pulper’ vessel is not feasible, this has two impacts. Firstly the steam consumption will be higher because there is no heat recovery; secondly the sludge now has to be heated with hot dilution water before the reactor which means it is less than the desired 90°C. This has an adverse effect on the rheology of the sludge which will differ from full scale and will mean that some of the parameters\conditions experienced will not be transferable for full scale. In addition the lack of a ‘pulper’ vessel also means that the volatile organic vapour released during the flash is lost to atmosphere and not returned to the pulper where it is condensed, the same effect seen in the steam explosion experiment. The VS content in the feed to the second stage of digester is therefore reduced and the performance of the second digester would arguably improve at full scale.

On line flows, levels, temperatures and pressures of the process are recorded and stored. In addition manual sampling of sludge is undertaken at least 3 times a week directly on site and analysed as detailed in Table 13:

Table 14: ITHP pilot plant - Laboratory analysis

Sludge Type	Analysis
Primary sludge (T1)	DS, VS
Secondary Sludge (T2)	DS, VS
Combined Sludge (T3)	DS, VS
First Stage Digested Sludge (T4)	DS, VS, VFA, Alkalinity, pH
Dewatered Cake (Belt Press)	DS
Diluted Cake (T8)	DS, VS
Hydrolysed Sludge (T11)	DS, VS
Second Stage Digested Hydrolysed Digested Sludge	DS, VS, VFA, Alkalinity, pH

Sludge samples are collected and stored in a fridge at 4°C. Analysis of this sludge was undertaken using the following methods:

- Dry Solids (%DS w/w) – analysed using a LECO automated thermogravimetric analyser at 105°C.
- Volatile Solids (%VS w/w – analysed using a LECO automated thermogravimetric analyser (post DS analysis) at 550°C.
- Volatile Fatty Acids (VFA mg/l):
 1. Titration. Done three times a week onsite and on the same day of gathering samples. The methodology does not involve centrifugation, thus the analysis is done directly on 5ml of sludge diluted in 50ml of deionised (DI) water. Duplicates are done for the feed and triplicates for digested sludge samples.
 2. Gas chromatography with Flame Ionization Detector. Done once a week at Thames Water laboratory facilities. This method allows for speciation of VFA and involves a pre-centrifugation of the samples at 4,000RPM for 15 minutes.
- Alkalinity – (mg/l CaCO₃ EQ) sludge is diluted tenfold, and shaken for 15 minutes. This is then centrifuged to remove particles and the supernatant is analysed by a Konelab Aquakem.
- pH – measurement is conducted by a pH meter and automated sample changer.

The biogas composition from each digester is also measured at least three times a week for methane, carbon dioxide and oxygen.

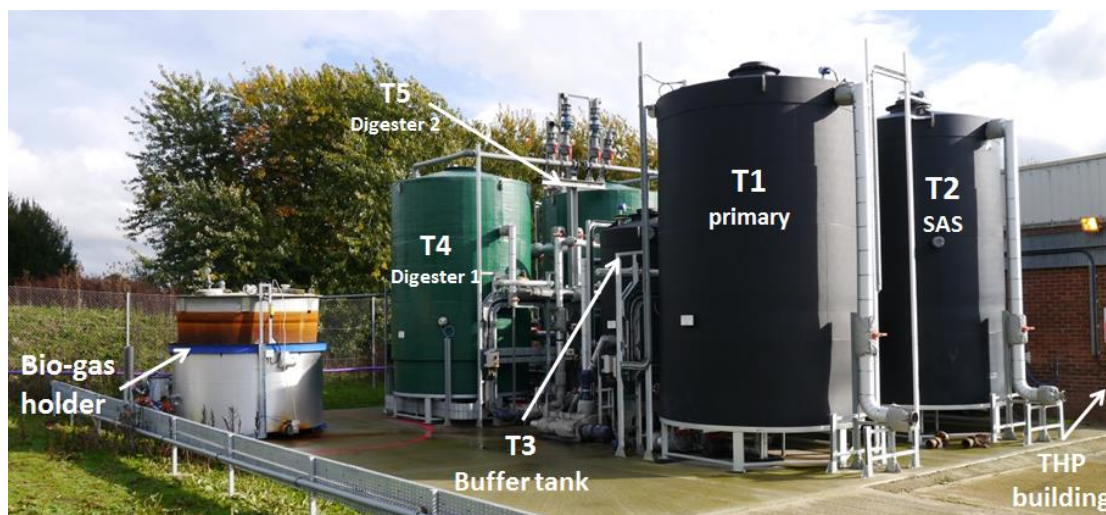
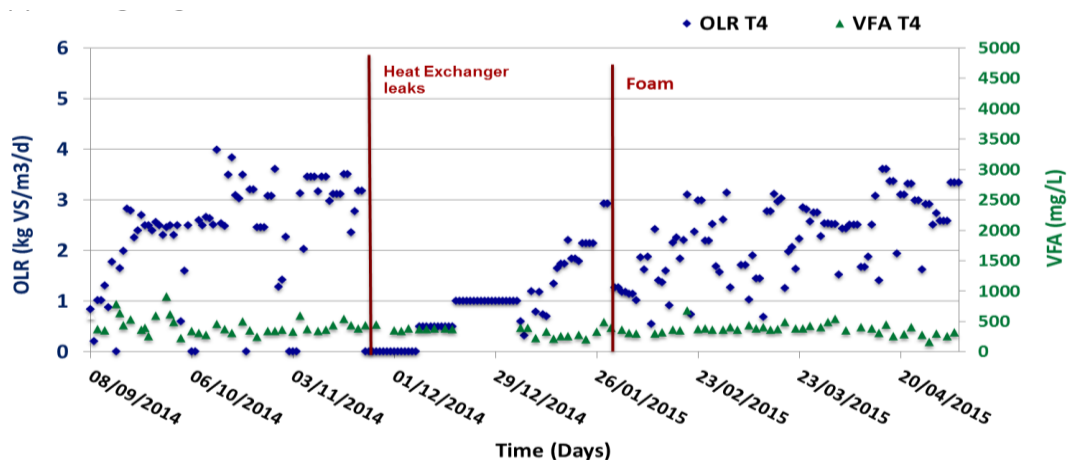


Figure 42 – ITHP pilot plant at Basingstoke STW (Figure 1 repeated)

Results – Digestion Stability

Figure 41 shows the OLRs for digester 1 and 2 with their respective VFA concentrations for the period from September 2014 to April 2015. Digester 1 needed to be ramped up on two occasions due to several leaks in the heat exchanger line during the winter period (beginning to mid December 2015). The digester was ramped up again in January 2015, which was shortly followed by a blockage in the anti-foam line allowed for foam to build up in the digester causing it to go into the gas line. After these two events, no further issues were observed in either digester. Digester 2 has never experienced observable foam issues. The OLR for each digester was 3kgVS/m³d on the first stage and to 4.5kgVS/m³d for the second stage, which corresponds to an HRT of 11.0 and 11.4 days respectively.

Improvements to digester 2 feeding consistency have resulted in clear improvement in the gas production. A stable feed and therefore OLR is maintained by strict control in DS going in to the THP and the buffer tank where sludge is diluted to a consistent 7%DS. Digester 1 shows higher variability due to the variation in DS on delivery. The variability is both due to dilution from atmospheric moisture and control of the feed pump to T3.



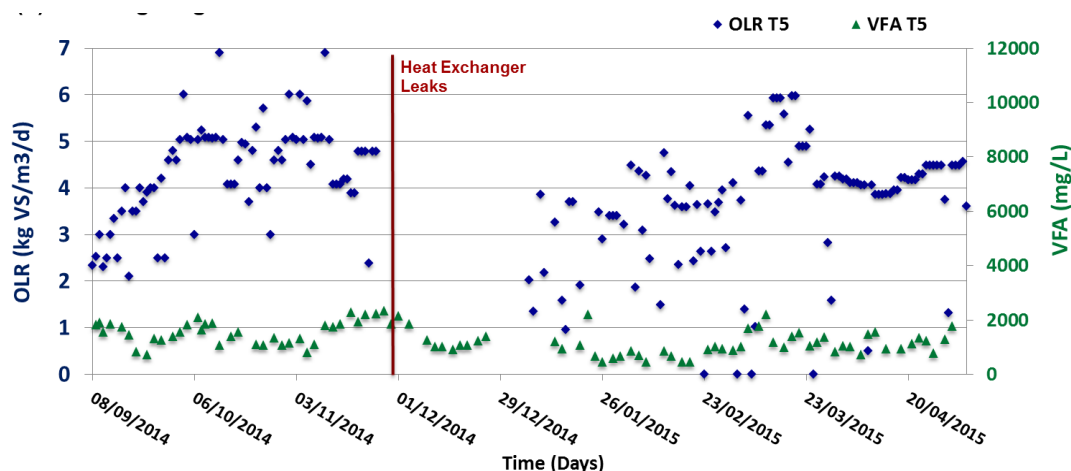


Figure 43 – OLR and VFA of digester 1 or T4 (top) and digester 2 or T5 (bottom)

VFA concentrations were stable in both digesters for the entire period, an average of 370 ± 70 mg/L in digester 1 and 1448 ± 478 mg/L with slight rises in digester 1 during ramp up periods. Alkalinity also remained very stable for both digesters with average values of 3461 ± 257 mg/L and 4878 ± 620 mg/L in digesters 1 and 2 respectively. VFA/Alk ratios were within acceptable levels for digester 1 at 0.11 ± 0.02 (Tchobanoglous 1993). Digester 2 showed a VFA/Alk ratio of 0.32 ± 0.13 . Ammonium stayed below 3000 mg/L in both digesters, with an average of 854 $\pm$ 96 mg/L in digester 1 and 1678 $\pm$ 246 mg/L in digester 2. Therefore, all stability parameters indicate good digestion taking place.

Results – Digester Performance (SGP and VSD)

During the period presented in Figure 41 the plant had a number of issues which resulted in an unrepresentative data set for the period up to 26th January 2015 for SGP and VSD. Rag blockages have been a big issue, blocking the feed pumps and the inhibiting the digester feed. The PS:SAS ratio in the feed was also difficult to control. Heat exchanger leaks also had an impact on the digesters, with a considerable drop in temperature. During this period, the average total gas yield was a very low 330 ± 23 m³/tDS and a VSD of $45 \pm 3\%$. In October 2014, it was discovered that effective hydrolysis was not taking place (explained in a subsequent section), which had impacted the VSD and SGP in digester 2. Additionally, poor mixing in digester 2 was identified as a possible cause of low VSD in the second phase. A lithium tracer test in this digester indicated a 20% reduction in the active working volume (WV). The THP issues were resolved and the feed in digester 2 was dropped from 9% to 7% DS and WV increased from 5.5 to 6 m³. Furthermore, the 50:50 PS:SAS ratio was changed to 60:40 to mimic the lab scale work by Shana. Figure 42 shows a reliable dataset for SGP and the VSD, in which the majority of the issues explained above had been resolved.

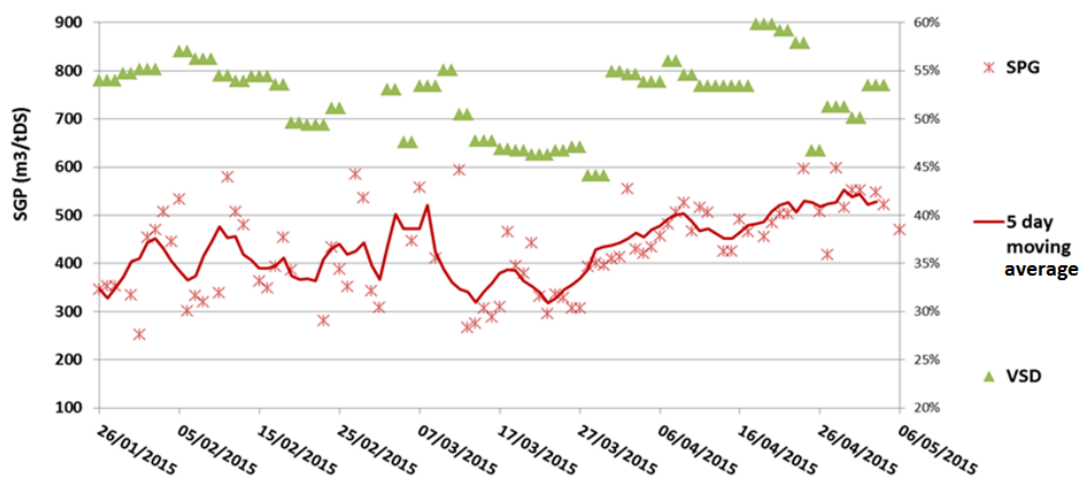


Figure 44 - SGP & VSD for combined plant

The variability in SGP observed during the months of January to March 2015 coincides with a ramp up period for both digesters and the more irregular feeding due to rag issues in the feed pumps to the blend tank (T3) from T1 and T2 and a number of rejected deliveries of poor quality sludge (e.g. very low DS, PS with high levels of SAS, septic smell). Since March 2015 a stable feed has been maintain to digester 2 as shown by the stable OLR in Figure 41. This corresponds with a great improvement in SGP which was an average of 501 ± 53 m³/tDS for the period of April – May 2015. The VSD for the stable period of April – May 2015 is averaging $55 \pm 5\%$ and is lower than expected, but the VSD is unlikely to respond to the improvements until at least 3 HRTs.

A bench scale automated digester was set up to further understand the reactivity of the second stage digester and closely monitor its gas production. The system is a 50L digester fed in a semi-continuous fashion. The current set up is for $4\text{kgVS}/\text{m}^3/\text{d}$ to mimic digester 2 (T5). Every 3 seconds it records gas production, gas composition, temperature and pH. This allows continuous observations of key parameters in a more controlled environment.

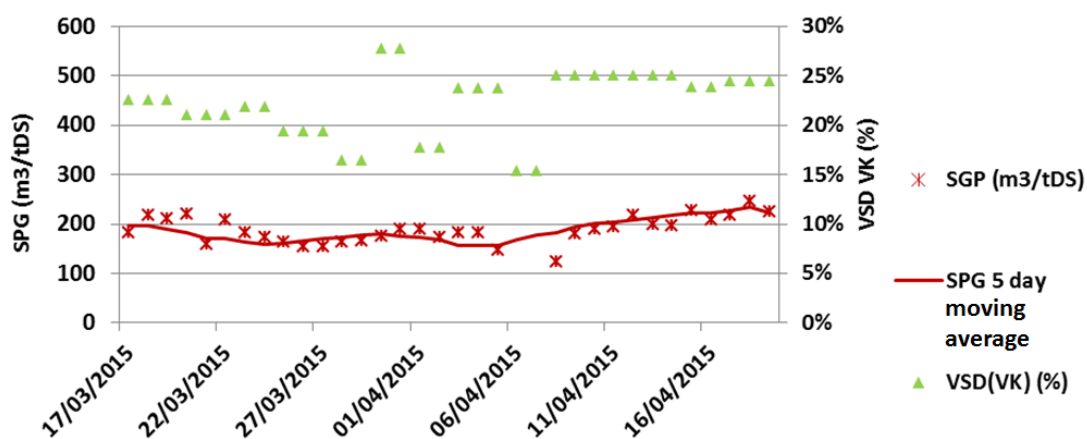


Figure 45 –SGP and VSD in the bench scale digester mimicking digester 2

For the period displayed in Figure 43 the bench scale digester had stable VFA with an average of $1050 \pm 89 \text{ mg/L}$, pH of 7.47 ± 0.04 , and methane production of $65 \pm 2.5\%$ indicating good digestion. As can be observed in Figure 43, the SGP averaged $189 \pm 27 \text{ m}^3/\text{tDS}$ fed in the second stage, with values above $200 \text{ m}^3/\text{tDS}$ in the most recent period. VSD is currently 23%. This is close to the findings by Shana et al., (2012), where the SGP for the second stage was $240 \text{ m}^3/\text{tDS}$ and VSD was 30% with a corresponding specific gas production is $1.2 \text{ m}^3/\text{kgVS}$ destroyed.

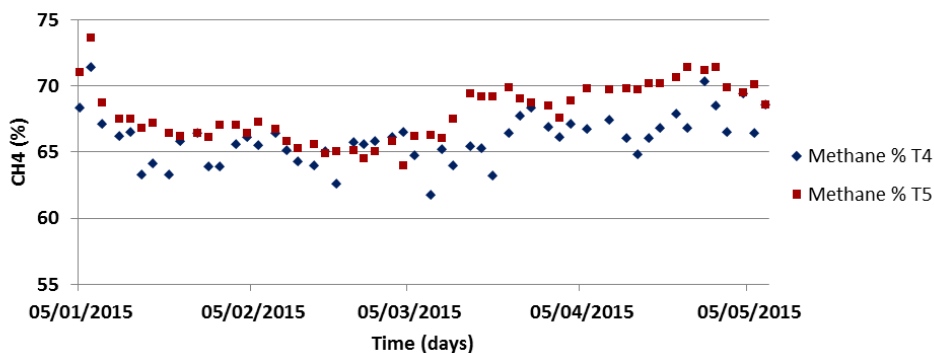


Figure 46 – Methane content of the biogas from digester 1 & 2

The average methane content on digesters 1 & 2 in the biogas for the entire period studied (September 2014 – April 2015) was $67 \pm 3\%$ and $69 \pm 2\%$ for digester 1 and 2 respectively (Figure 44), digester 2 being consistently higher in the second stage.

Optimising THP Conditions

The THP reactor (T9) has a pressure transmitter installed at the top of the vessel and a temperature probe at the bottom of the vessel which is 200ltr with a working volume of 150ltrs. It had been observed that during every batch the pressure transmitter shows 6.5 barg (the control system uses pressure as the set point) whilst the temperature measured did not reach 165°C the corresponding temperature expected at this pressure. Instead temperatures of only $50\text{--}80^\circ\text{C}$ were observed, initially it was assumed that the temperature probe in the reactor was malfunctioning as full scale installations do not use temperature instruments in the reactor because they are unreliable. However, with the poor SGP and VSD, this assumption was challenged. The temperature measurement was tested and was found to be correct concluding that the THP was indeed operating at low temperatures and was ineffective, explaining the poor digester performance.

The feed to the reactor was changed as one theory was that the sludge feed to the reactor was too thick which was preventing the steam fully penetrating the sludge the effect is referred to as 'rat-holing'. When 'rat-holing' occurs the steam, injected at the base of the reactor, passes straight through the sludge and into the headspace raising the reactor pressure without significantly raising the temperature of the sludge. To test this theory the sludge feed was over diluted to less than 15%DS whereas it was typically 16%DS before. The resulting temperature/pressure profiles in the reactor for the two conditions can be seen in Figure 45, the green line is temperature in the reactor, blue is pressure in the reactor the red line is the pressure in the flash tank.

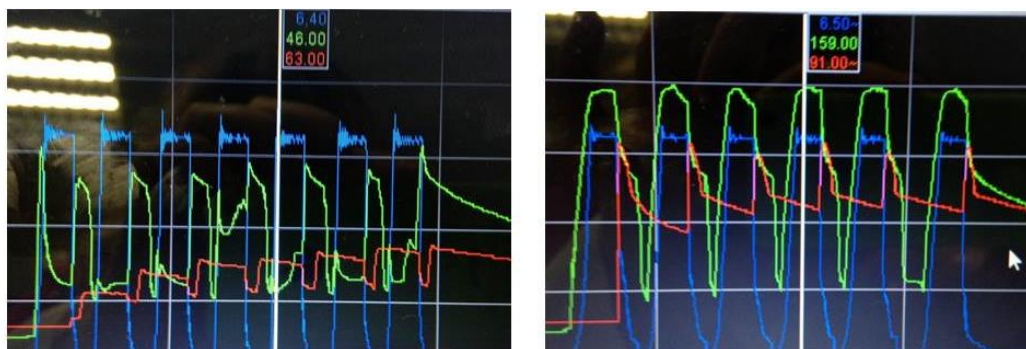


Figure 47: Temperature & pressure in reactor and pressure flash tank (left at 16%DS, right at <15%DS).

The change in DS resulted in a clear increase in temperature within the reactor now reaching 159°C. The cycle time is also increased which is encouraging as it suggests that steam was fully penetrating and heating the sludge. Other physical observation supported this theory firstly the hydrolysed sludge in the reservoir tank before digester 2 (T11) was warmer and secondly the odour had become stronger, suggesting that additional organic volatiles are being released. Although this is a marked improvement in the reactor temperatures 6.5barg corresponds to 165°C on the saturated steam curve and the best measured was 159°C. This was possibly due to the inert gases (mainly nitrogen and carbon dioxide) in the reactor which would make it impossible to reach 165°C at 6.5barg. So headspace venting was implemented during the hydrolysis cycle to remove these gases. This was achieved by installing a control valve on the top of the reactor which opened for a short period during the initial steam injection. The results of all of these trials can be seen in Figure 46, which shows that with 12%DS feed and headspace venting a reactor temperature of 162°C can be achieved. Note the difference in cycle times between the high DS feed and the low DS feed scenarios.

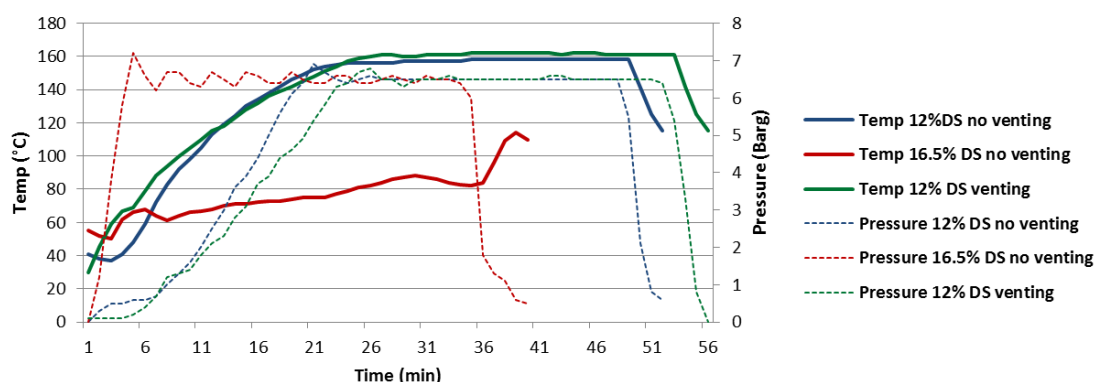


Figure 48: Temperature & pressure in reactor at different DS feed and with headspace venting

3.1.5 Second Generation THP Assessment

The 3 THP variants described (Conv THP, SASonly THP and I-THP along with conventional AD) were modelled. All assumptions can be seen in Appendix A. Note that all processes have been modelled at the upper limit of their performance utilising high efficiency CHP units with an electrical efficiency of 40%. Table 14 displays the technical performance of the 4 processes modelled.

Table 15 - Technical Performance Provide ref for AD, THP & SASonly THP

Parameter	Units	Conventional MAD	THP	SAS only THP	I-THP
VS Destruction	%	44%	59%	55%	65%
DS Destruction	%	34%	45%	42%	50%
Disposal Volume	m ³ /TDS	3.3	1.8	2.1	1.5
Gas Yield	m ³ /TDS	339	454	421	503
Gas yield	MWh/tDS	2.16	2.90	2.69	3.21
Elec Efficiency (gross)	%	15.4%	20.6%	19.1%	22.7%
Elec Efficiency (net)	%	13.7%	17.8%	16.3%	19.1%
Electrical Output	MWh/tDS	0.82	1.10	1.02	1.21
Support Fuel	MW/tDS	-	0.37	-	-
Net Electrical Output	MWh/tDS	0.73	0.95	0.87	1.02
Digester volume for 100TDS/d	m ³	46,350	14,300	26,250	29,000
Digester vol. efficiency	MWh pa/m ³	0.65	2.82	1.36	1.55

It can be seen in Table 20 that THP, SAS only THP and I-THP all have advantages over the conventional MAD (Mills et al. 2014a). THP and SAS only THP are similar in performance although SAS only THP doesn't require support fuel, and reduction in performance is small 80kWh-elec/TDS compared with conventional THP. The ITHP process is very impressive showing a clear step change over conventional THP using no support fuel and producing 10% more biogas than THP, achieving a net efficiency of 19.1%, however it does require greater digestion capacity. The digester volume efficiency, is the electrical output per unit of digester volume (MWh pa/m³ of digester volume), reveals the huge advantage of THP has over conventional MAD. For a conventional THP plant each m³ of digester volume generates an annual 2.82MWh of electrical energy, compared with just 0.65MWh for a conventional MAD. The second generation THP scenarios (SASonly THP and ITHP) perform better than MAD but have reduced digester volume efficiency when compared with THP. Another important parameter which affects the OpEx for the process is the disposal volume post digestion, again all of the THP options reduce the disposal volume and therefore the cost. I-THP performs the best because of the increased VSD, which reduces the mass and the improved dewatering further reduces the volume. SASonly THP has a larger volume than both THP and ITHP because VSD is smaller and the dewatering is reduced comparatively.

3.2 Sustainable Thermal Drying

Anaerobic digestion cannot achieve full energy conversion, even with second generation THP only 57% of the potential energy in the sludge is converted into biogas. To access the considerable chemical energy remaining in the sludge after AD, it is proposed that the sludge should be dried to produce a solid fuel product (Flaga 2005; Niu et al. 2013). Wessex Water has built a such a dryer installation that will produce a product that *"...will be disposed of as a fuel to a third party."* (Jones 2008). This project is relatively unique because the sludge is not being treated as a waste although they have used the word 'dispose'

which suggests it is at cost. Sludge drying in the UK has had a troubled past with several dust explosions and fires (HSE 2011) and expensive operating costs (Bowen et al. 2010). These issues are mainly associated with direct drying equipment particularly the hot air drum dryer type which creates a lot of dust within a rotating drum operating with air at over 400°C.

3.2.1 Sold fuel production trial

There are new drying technologies that are claimed to be safe, efficient and able to utilise waste heat. One of these technologies is the paddle dryer, which is very efficient and has minimal dust production. It was therefore important to demonstrate that this technology could be operated safely and efficiently whilst creating a granular renewable solid fuel (GRSF) product which has an inherent value as a fuel.

The trial project had specific goals, these are:

1. Prove that viable solid fuel can be manufactured from sewage sludge;
2. Prove that viable solid fuel can be used within existing combustion plant for support;
3. Prove that the dryer plant is a practicable solution;
4. Understand the energy balance and operational economics in STW context;
5. Apply for 'end of waste' status for the fuel;

The basis of the scientific work was to test the hypothesis that the dried digested sludge was effective at reducing the support fuel requirement in the incinerator. The main driver which allowed for the short term business justification for the project is the desire to improve the operation of the two Sludge Power Generators (SPGs) in East London which Thames Water own and operate. Beckton and Crossness SPGs process 200TDS/day and 110TDS/day respectively, both consume large quantities of natural gas to maintain combustion inside 5 fluidised bed incinerators (2 at Crossness and 3 at Beckton). Crossness consumed 1.1 million m³ of natural gas in 2011, which represented 12% of the thermal input. Burning natural gas has several impacts to the OpEx of the SPG:

1. The SPGs are thermally limited and so burning natural gas reduces the volume of sludge cake that can be burnt reducing throughput and forcing sludge to go elsewhere;
2. Natural gas also consumes some of the oxygen content in the combustion air, potentially further reducing the sludge throughput;
3. Natural gas is costly (£319k in 2011):
4. Renewable Obligation incentive is reduced proportionally to the natural gas consumed. If over 10% by energy comes from a non-renewable source the incentive is significantly reduced, this is explained in Figure 47.

Unlocking the Full Energy potential of Sewage Sludge

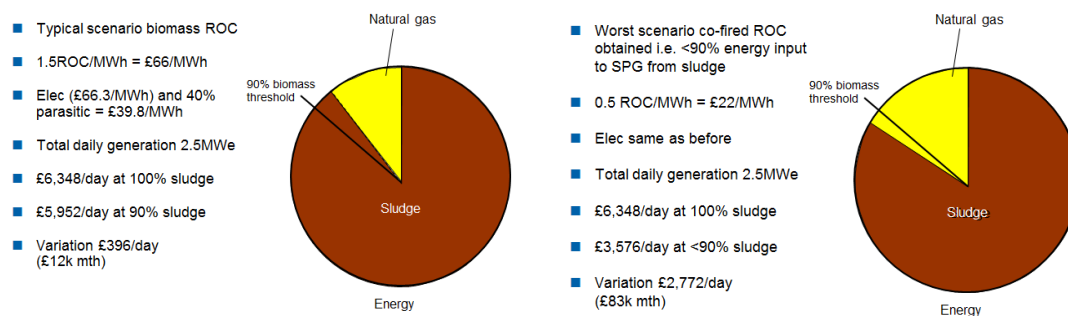


Figure 49 - Natural Gas influence on ROC income, left – typical, right – worst case

If the natural gas consumption exceeds 10% of the thermal energy input to the SPG (monthly average), the renewable incentive (ROCs) drop from 1.5ROC/MWh (£66/MWh) to 0.5ROC/MWh (£22/MWh). Factoring in sale of electricity the revenue generated using 100% sludge (i.e. no natural gas) was £6,348/day (£190k/month). If >10% natural gas was consumed the revenue was just £3,587/day (£107k/month) a difference of £83k/month or 44%. Assuming the fuel displaces the equivalent energy content of natural gas, 1 TDS of digested dried sludge from Slough with an average energy content of 14,000MJ will displace 250m³ of natural gas at 56MJ/m³. Based on this assumption the energy and financial savings are calculated as shown in Figure 48.

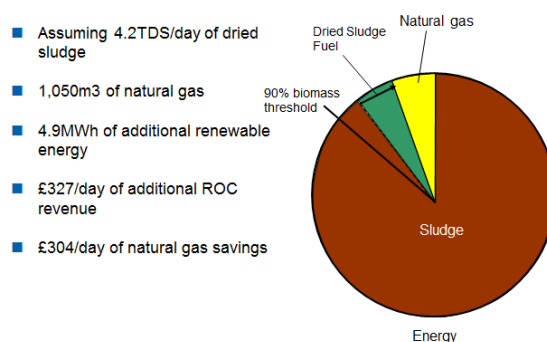


Figure 50 - Benefit from Dried Sludge for the typical case

It is assumed that the SPG is operating with biomass ROCs as co-fired status is not guaranteed and could not be claimed as part of the business justification. The trial relies on the supply of free heat at Slough STW where spare biogas produced in AD has historically been flared.

Table 16 - Business Justification for trial (typical scenario)

Activity		OpEx £k pa
Slough Operation (Labour)	0.8 FTE	(27) cost
Slough Operation (Electricity)		(35) cost
Slough Operation (Maintenance)	5% of capital	8 cost (n/a for initial 24month defect period)
Slough Cake Land Disposal Savings	21wT/day @ £18/wT	139 saving
Transport of dried sludge to Crossness SPG	£250/trip @ 1/week	(13) cost
Crossness Nat Gas Savings	383,250m ³ @ 29p/m ³	111 saving
Increase in ROC revenue	1,789MWh @ 1.5ROC/MWh	118 revenue
Total Savings		285 net saving

Simplistically the net OpEx savings, shown in Table 15, of £285k equates to a payback period of about 5 years on the CapEx for the dryer, which justified the construction of the demonstration dryer plant at Slough STW.

3.2.1.1 The Demonstration Sludge Dryer

The demonstration drying process consisted of five key areas (Figure 49):

1. Sludge cake storage and feed system
2. Sludge Dryer
3. Product cooling and handling
4. Off Gas system
5. Thermal oil heating system

A 25m³ sludge cake hopper, with an agitator, provides 24 hours storage, at full throughput, of sludge cake at 20%DS; the sludge is pumped with a progressive cavity pump to the dryer, the pump is controlled through a variable speed drive so that the flow rate to the dryer can be controlled. The dryer consists of two counter rotating heated paddles in a trough; the paddles agitate the sludge whilst driving off the water. The sludge travels along the dryer by displacement as water is removed and becomes progressively drier before exiting the trough via a weir at the far end of the machine. The dried sludge or product is then cooled to below 45degC in a screw conveyor with a water jacket. Finally the cooled product enters a drag conveyor which lifts the product and drops it into 1m³ fabric bags, these bags are then ready for transportation to the Crossness SPG. The plant can produce approx. 4.5TDS/day at full throughput. A photograph of the plant can be seen in Figure 50.

Unlocking the Full Energy potential of Sewage Sludge

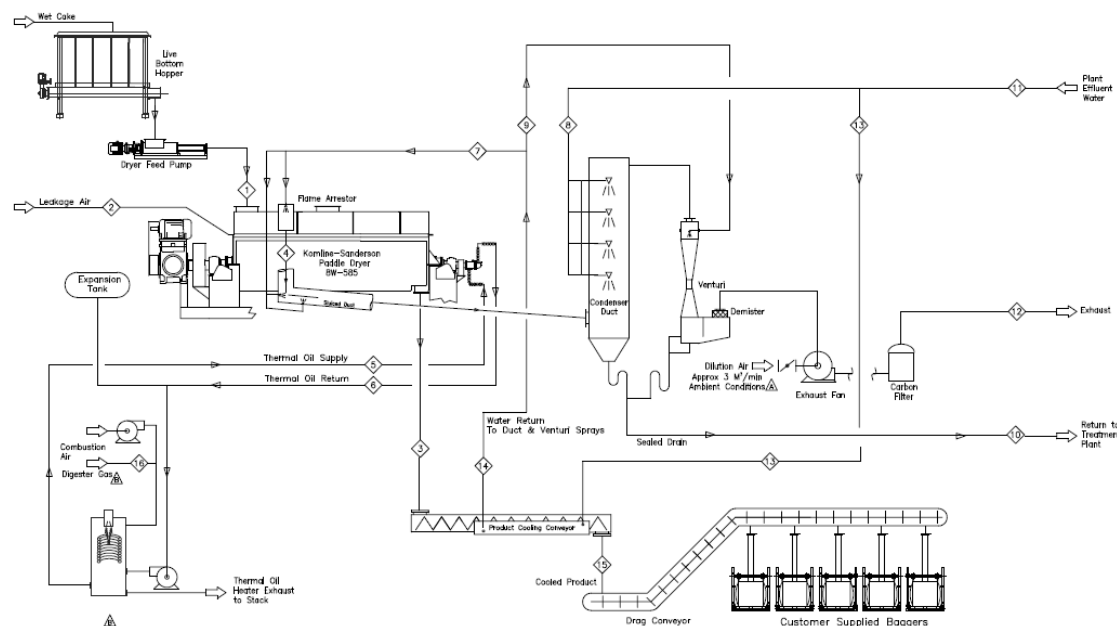


Figure 51 - Process Flow Diagram - Slough Dryer



Figure 52 - Slough Dryer under Construction

The production of odours is a significant problem for all methods of sludge treatment. One of the main criteria for selection of this particular dryer is that it is totally enclosed. The 'off-gases' that are evaporated from the sludge can therefore be captured and treated.

The off gas from the dryer is drawn by an exhaust fan; the off gas consists of a small amount of solids, water vapour and leakage air. The gas first enters a condensing spray tower which cools the gases and condenses the water vapour which is then drained away; this is followed by a venturi separator which is designed to remove any remaining particles and these are washed to a drain. Down stream of the exhaust fan is an activated carbon filter designed to remove odour before the air is vented to the local atmosphere.

All of the heat required for drying was sourced from a thermal oil heater that consumed spare biogas previously flared on site. The thermal oil was supplied to the dryer at around 190degC at full throughput.

The dryer efficiency was calculated to be 3.1 MJ/kg H₂O removed, this is among the best values found in the literature which has confirms and supports the reasoning for selecting this particular type of dryer. Table 17 shows the relative efficiencies of various dryer technologies.

Table 17: Efficiencies of other type of dryer for industrial applications (Devki 2006)

Dryer Type	Typical Heat loss sources	Typical Specific Energy Consumption (MJ/kg of H ₂ O evaporated)
Indirect Rotary	Surface	5.5
Cascading Rotary	Exhausts, leaks	4.8
Cross circulated tray / oven / band	Exhaust, surface	12.0
Cross circulated shelf / tunnel	Exhaust, surface	9.0
Through circulated tray / band	Exhaust	8.5
Vacuum tray / band / plate	Surface	6.5
Drum	Surface	7.5
Fluidised / Sprouted bed	Exhaust	8.0
Pneumatic conveying / Spray	Exhaust	5.5
Two stage	Exhaust, surface	5.0
Cylinder	Surface	6.5
Stenter	Exhaust	8.5

Experience

The dryer has proven to be very reliable, robust and effective, although a few teething problems have had to be overcome.

Odour is a problem that characterises all drying technologies. The off-gas from full-scale units located on STWs is generally treated by diffusing it in the aeration lanes, which act as biological scrubbers. This solution was not implemented at Slough STW because it was not considered cost-effective for a pilot plant. Unfortunately the Granular Activated Carbon (GAC) utilised for odour control has not performed. However, providing the condenser spray tower was maintained the odour reduction from absorption was acceptable.

The automated control uses a Proportional-Integral-Derivative (PID) control loop to maintain temperatures throughout the dryer, which has proven to be unstable. Figure 51 highlights the diverging trends in the sludge temperatures along the dryer. This form of instability generally leads the dryer into a controlled shutdown and due to the long duration (9 hours) of these cycles it has proven to be difficult to tune the PID control. For the short term the loop has been switched off and manual control initiated which is monitored daily.

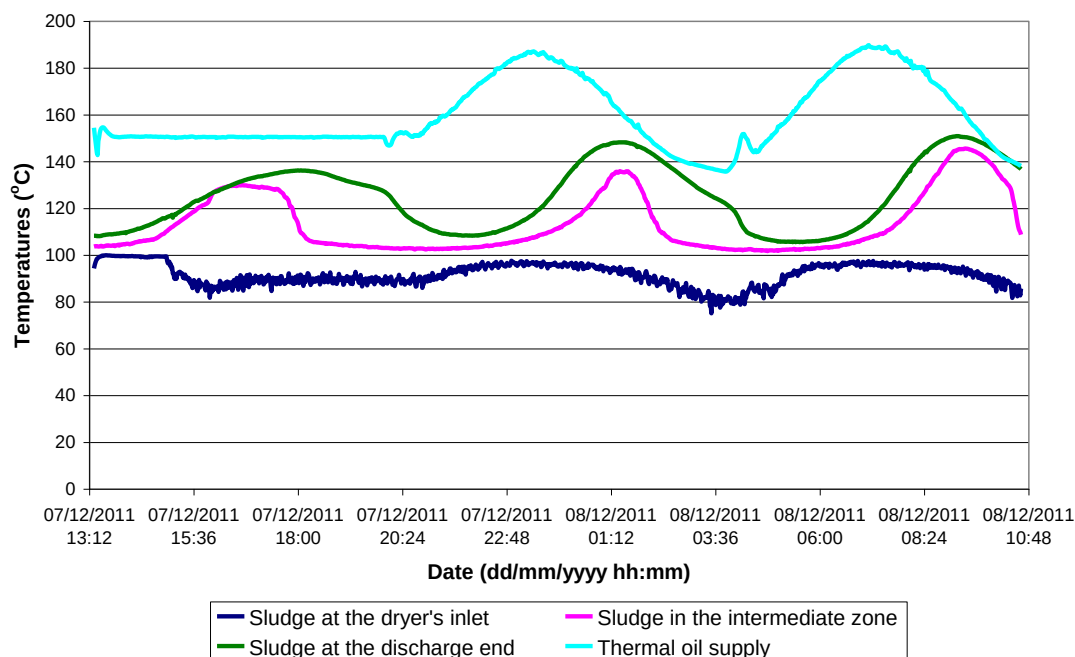


Figure 53: Example of diverging trends in the temperatures along the dryer and in the temperature of the thermal oil supply (i.e. the control input) with the PID controller engaged

A key point to this drying project being different to others is that it is sustainable because it does not use fossil fuel for heat, and the end of product is utilised to displace fossil fuel. So an assessment of the entire site and resulting mass and energy balance was made throughout the trial period. A model was produced to assess the integration of the dryer on site. This soon identified a potential pinch point on site, relating to the existing operational plant. The primary sludge thickening is not performing and as a result is affecting the biogas available to the sludge dryer. The model quantified the effect and showed that refurbishment of the thickeners is necessary. Figure 52 shows the effect that improving the performance and therefore the primary dry solids from 2% to 6%DS has on AD hydraulic retention time (HRT), volatile solids destruction (VSD), spare biogas and the resulting drier throughput.

If the thickeners do not function properly, the sludge feed to the digesters contains too much water and not enough biomass, which affects the process in two ways. The additional water results in consumption of additional biogas for heating, while the reduction in biomass results in a shorter retention time resulting in a lower destruction of organics and therefore a reduced biogas production.

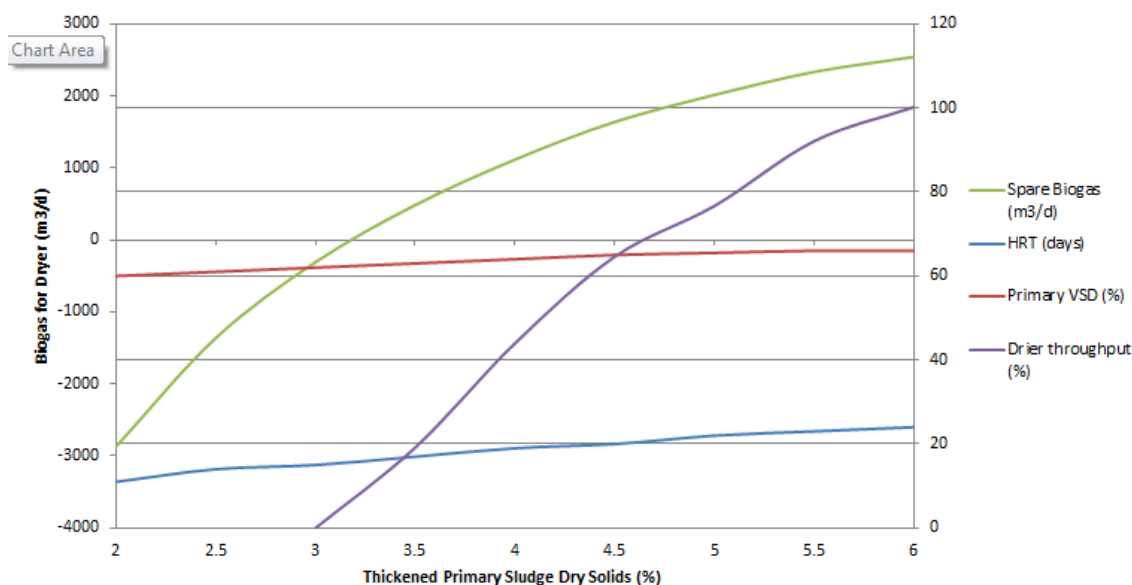


Figure 54 – The Modelled Impact of Primary Sludge Thickener Performance

The model has shown that biogas for the dryer is not available until a DS of 3% or more is produced in the thickeners. At 5%DS the dryer will be able to function at 80% of the designed throughput. Improvements on site are underway to achieve consistent dry solids feed to the digesters.

The drying of digested sludge is not considered to be the optimum configuration. SAS is very problematic for AD as it does not digest or dewater readily when compared with primary sludge. It requires more than 4 times the digester volume per unit of mass and there is also evidence to suggest that SAS limits performance of primary sludge in AD (Winter 2010). Therefore, if SAS or a proportion was separated pre AD and dried this would benefit the AD process by improving HRT, VSD and freeing digester throughput capacity for increased imports from satellite sites. A further benefit is that dried SAS would have a higher CV 18-20MJ/kg instead of 14MJ/kg for digested sludge and therefore potentially a superior fuel to be used in the SPGs. It is important for this demonstration trial to prove the viability of being able to consistently produce a fuel (GRSF) and that the dryer is reliable and effective. It is worth noting that other types of dryer are now available since this trial that are able operate at lower temperatures and utilise more abundant sources of genuinely waste heat (see section 3.2.3).

3.2.1.2 The Solid Fuel Trials

The 5 fluidised bed combustors at Beckton and Crossness (Figure 53 - left) are of the same design only differing in throughput. The Crossness process consists of the following steps:

1. Dewatering: plate presses take undigested sludge from 3%DS to 30%DS;
2. Fuel conveyors: several sets of drag and screw conveyors transfer the sludge cake to a storage silo and then on to a single feed point on the combustors;
3. Combustors (Figure 53 – right): a 4.4m diameter bubbling fluidised bed with an air flow of about 20,000 m³/hr, combust approximately 2 TDS/hr, natural gas support fuel is used to maintain the bed temperature between 750-850°C;

4. Heat Recovery: the exhaust gases, at about 900-1,000°C, then pass through a waste heat recovery boiler to raise steam (40Barg) which is used to pre-heat combustion air to maintain bed temperatures, excess steam is used to drive a (5MWe) steam turbine;
5. 1st stage Gas Cleaning: the fly ash and mercury is removed in a cyclone with activated lignite coke dosing;
6. 2nd stage Gas Cleaning: bag filters remove the final residue followed by a NaOH scrubber to remove SO₂.



Figure 55 - left - Crossness SPG, right - 1 of 2 Fluidised Bed Incinerators

Goal 2 of the project aimed to prove that the dried sludge fuel (GRSF) can be used within SPG's as a support fuel. This is very important as it is one of the main business justifications for the demonstration project. Due to the planning constraints on the Crossness SPG only three short trial windows were allowed.

Phase-1 of the trial involved manually feeding dried product into the wet sludge cake at Crossness pre combustion. Initially low feed rates were applied (1.1% by dry mass (0.3% by volume, 0.8% by energy content) slowly building up to 8.7% by dry mass (2.6% by volume, 6.6% by energy content). This manual trial determined that the feed rate envelope for the automatic feed equipment which was needed for phase-2 of the trial.

The GRSF was fed into a modified screw conveyor which normally transports indigenous sludge cake from a silo and drops it on to a drag conveyor. The drag conveyor feeds a paddle feeder which throws the cake into the combustion chamber and onto the fluidised bed, Figure 54 is a representation of the arrangement.

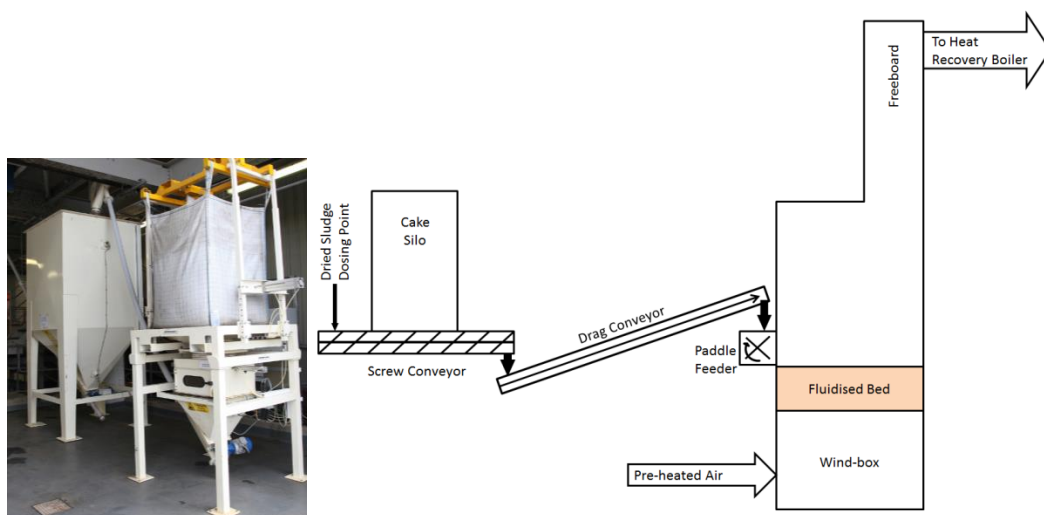


Figure 56 – left – Auto Feed Equipment, right - Simplified PFD showing dried sludge feeding point

The screw conveyor was selected as it would mix the dried sludge granules with the wet cake and thereby minimise any issues arising from dust cloud formation.

Before and during the trial key parameters within the SPG were being logged at a high frequency. These included temperatures (such as bed, wind box, pre-heat, and freeboard), steam production, gas consumption, emissions, feed rates and turbine output.

Results

During phase-1 the gas consumption reduced in stream 2 (the trial stream) whilst in comparison stream 1 did not change and also required larger volumes of gas to maintain combustion temperatures by pre-heating the combustion air with a gas burner.

The GRSF clearly had an impact on the combustion temperatures. Figure 55 shows data collected from day 2 of phase-1, during the 150kgDS/hr & 200kgDS/hr feed the average bed temperature increased by 30degC at the same time the freeboard temperature rose by 40°C. The wind box temperature was able to be dropped from 300°C to 230°C during the feeding, resulting in significant benefits to the process in terms of parasitic steam and/or natural gas consumption.

Unlocking the Full Energy potential of Sewage Sludge

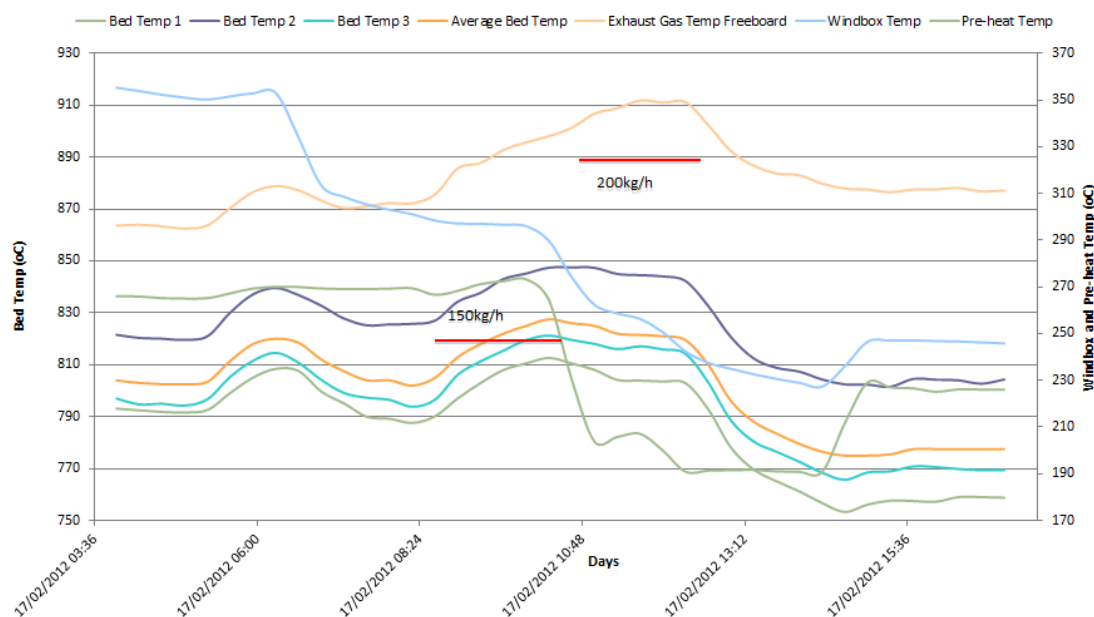


Figure 57 - Combustion Temperatures

This result is most significant as it was not predicted the GRSF would have quite this effect on combustion. The GRSF looks to be improving the combustion within the bed and as a result it appears that more heat is being released into the bed. During the trials the operators were able to reduce the combustion air pre-heat in response to the higher bed temperatures. This allowed more steam to be fed to the steam turbine for electricity generation as less is being used for combustion air heating. It has also allowed more sludge cake to be fed into the bed as thermal capacity has been increased; Figure 56 aims to demonstrate visually what was observed, the next section quantifies what was observed.

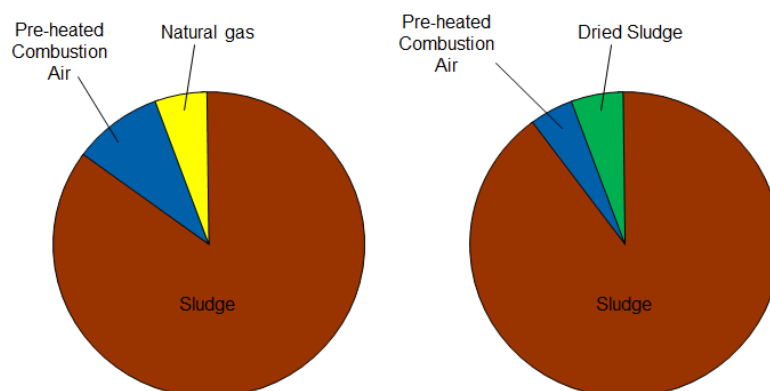


Figure 58 - Conceptual Thermal Energy Balance of Crossness, left - without GRSF, right - with GRSF

Quantification

The two SPGs have historically not performed as designed and unfortunately it has been difficult to maintain optimum conditions within the combustors. The difference between bed temperature and freeboard temperature is often large ($>200^{\circ}\text{C}$) this requires support fuel to keep the bed warm, reduction in sludge feed and water injection into the freeboard to prevent damage to equipment from excessive temperatures. This is a common observation in sewage sludge combustion and can be attributed to incomplete combustion

of particles in the bed producing CO which is combusting in the freeboard (Anthony 1995). Werther and Ogada go on to claim this is an advantage of Fluidised Bed Combustion (FBC) technology referring to the freeboard as a “*post-combustion chamber*” (Werther and Ogada 1999). Mathematical modelling of sewage sludge, a complex fuel, also confirms that “*released volatile matter burns in the freeboard in a flameless fashion*” (Urciuolo et al. 2012). However the reality of operating a FBC in this manner restricts the throughput of sludge and affects the efficiency of the plant.

From the data captured in phase-1 it was suggested/theorised that the addition of the dried sludge is altering the combustion characteristics within the FBC; increasing the heat released in the bed and reducing freeboard combustion, this in turn has resulted in the reductions in natural gas support fuel used and air pre-heat required. An in-depth model of a FBC combustor concluded that “*a range of 60/40 to 90/10 [bed/freeboard] depending on the fuel particle distribution*” can be expected (Yang et al. 2008). It was therefore logical to attempt to prove/quantify whether the dried sludge had shifted the bed/freeboard combustion ratio. However it is much more difficult to do this with an operational asset due to the number of unknowns and an attempt to do this with a simplified heat balance was inconclusive. However, the resultant energy inputs to the SPG, calculated during the exercise were very revealing. Figure 57 displays the two conditions (i.e. with and without GRSF) and it clearly shows the beneficial impact expected and conceptualised earlier in the report. With the GRSF feed a clear reduction in natural gas consumption, increased sludge feed and reduced combustion air pre-heating can be observed.

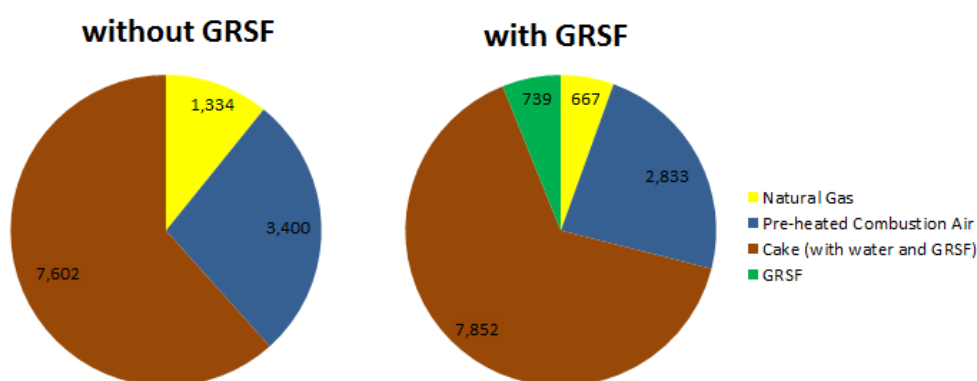


Figure 59 - Energy Inputs into the Incinerator during the Trial (kW)

This trial was very successful and clearly displayed the benefit of adding dried sludge to the SPG. If the concept was scaled up to feed both SPGs 10% dried sludge (65TDS/day) the net OpEx benefit would be approximately £2m pa. This would reduce the annual net OpEx for both sites by around 15% and bring the unit cost of operation to around £90/TDS from £107/TDS previously. Significant investment in drying plant would have been required and unfortunately the arrival of the ‘Bucher Press’ (explained in section 3.2.3) and THP on both SPG sites meant that this was not an attractive or strategic option and is not being pursued.

3.2.2 End of Waste (EoW)

Goal 5 of the trial was to understand whether the fuel would have commercial viability outside Thames Water and to do this it must lose the ‘waste’ badge. The European Waste

Framework Directive 2008 defines Waste as “... any substance or object which the holder discards or intends or is required to discard”. Therefore almost everything is a waste after use, luckily sewage sludge for land recycling is treated differently in the UK as a separate Act exists to allow it to safely be recycled to land under the “Sludge (Use in Agriculture) Regulations 1989”. But if we want to try and utilise the sewage sludge as a solid fuel the WFD is then effective and very restrictive, stipulating that the fuel is only used in a unit that is compliant with the Waste Incineration Directive. Because of the cost complying with WID, these facilities typically require a gate fee for waste which they incinerate, this economic model does not work for sewage sludge. This is because the cost of the drying operation is not fully compensated for by the savings made by displacing the costly sludge cake disposal operation. Further economic benefit is required from the sale of the fuel for a project to be economically viable.

However, there is another way, which involves achieving something called “End of Waste” for the GRSF. Article 6 of the WFD states:

“Certain specified waste shall cease to be waste within the meaning of point (1) of Article 3 when it has undergone a recovery, including recycling, operation and complies with specific criteria to be developed in accordance with the following conditions:

- (a) the substance or object is commonly used for specific purposes;*
- (b) a market or demand exists for such a substance or object;*
- (c) the substance or object fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products;*
and
- (d) the use of the substance or object will not lead to overall adverse environmental or human health impacts.”*

An expert was engaged who advised that the following key criteria would need to be considered in determining EoW :

- 1. Product specification:** The GRSF must be a recovered secondary product or raw material which meets a consistent specification;
- 2. Comparator fuel(s):** There must be a clearly defined ‘comparator’ virgin fuel, or preferably a range of different virgin fuel comparators;
- 3. Markets and application of GRSF:** There must be a defined and readily available market for the GRSF as a fuel, or at least what the WFD refers to as ‘demand’ for the product;
- 4. Compliance with technical requirements and legislation:** The GRSF must meet all technical requirements for the type of fuel which it is to take the place of, as well as any existing legislative and other product standards applicable to that type of fuel;
- 5. Application of the fuel:** There must be no material differences in the way that the GRSF is used as against how the relevant comparator fuels are used in the relevant plants; and

6. Comparative Environmental impact / pollutant composition: The GRSF must not produce a materially greater environmental (or human health) impact when used in the relevant plants than would have been the case with the relevant comparator fuels.

Using information on comparator fuels sourced from the Phyllis 2 database (ECN 2012), it was shown that GRSF has a calorific value similar to straw, miscanthus and wood chip.

Historic digested sludge data from Slough STW and the wider Thames region allowed in-depth comparison of fuel characteristics of GRSF and SAS against fuel specifications for waste wood and coal shown in Table 18. SAS was investigated as compared with digested sludge GRSF as it was believed that SAS will contain less contamination due to its location in the process.

Table 18: Comparison of selected fuel characteristics for coal, waste wood and GRSF (Firth 2014)

Parameter	Unit	Typical coal	Waste wood ¹	Slough GRSF mean	Slough SAS mean
Moisture	% weight	8.2 – 10.3	10 - 25	3.1	-
Carbon	% weight	40.4 - 46.6	38.3	4.3	5.7
Hydrogen	% weight	-	4.9	4.3	4.41
Nitrogen	% weight	-	4	4.5	4.15
Sulphur	% weight	0.92 – 1.73	0.1	2.19	1.49
Chlorine	% weight	-	0.1	0.16	0.18
Oxygen by difference	% weight	-	39.5	17.2	29.9
Ash	% weight	15.2 - 23.1	5	37.65	30.35
CV (LHV)	MJ/kg ar	22.4 - 24.0	14.3	13.7	-
DAF CV²	MJ/kg ar	33.8 - 34.9		24.2	23.7
DAF VM³	%	36.1 -39.7		92.7	91.8

¹ The waste wood specification was provided by a major biomass customer and is based on a combination of desirable fuel characteristics, physical characteristics and achieving compliance with emission limits.

² Dry Ash Free (DAF) calculated Calorific Value of combustible fraction of fuel

³ DAF Volatile Matter refers to the components of the fuel, except for moisture, which are liberated at high temperature in the absence of air. The ratio of VM to fixed carbon gives an indication of ignition properties

The data in Table 20 demonstrates that:

- The moisture content of GRSF is low particularly in relation to biomass fuels such as waste wood.
- GRSF has a CV broadly comparable with wood waste but below typical coals.
- The ash content of GRSF (37%) and SAS (30%), are high compared with wood (5%) and coal (23%). The consequences of the elevated ash concentrations are a lower CV fuel due to percentage of incombustible material, high volumes of ash for disposal, physical attrition of the combustion plant and possibly boiler fouling depending on the melting characteristics of the ash.
- Chlorine and sulphur concentrations in the GRSF and SAS are elevated compared to coal and waste wood.

The analysis of metal concentrations in coal is not routinely undertaken by fuel suppliers and therefore detailed analysis was commissioned of both fuel characteristics and metal concentrations for a number of “typical” coals used by UK power stations. The results of this analysis are provided as a range rather than individual values.

A direct comparison is challenging due to the range of characteristics and attributes of virgin fuels. Comparison data for metals concentrations in coal and waste wood was compiled and this is used for comparison with GRSF, SAS and historic digested sludge data in Table 19, where it can be concluded that:

- The concentration of copper and zinc in GRSF are comparable with historic digested sludge data from Slough STW.
- The concentration of copper and zinc in GRSF are above the concentrations desirable for waste wood fuel and the actual concentrations in coal.
- The copper and zinc concentration in Slough SAS are lower than in GRSF and this difference is supported by the lime treated SAS data.
- The concentration of cadmium and mercury in GRSF and SAS are below the waste wood limits whereas nickel is above the threshold but less than the concentration in typical coals.

Table 19: Comparison of metal limits for GRSF, SAS, waste wood and coals (Firth 2014)

Parameter (mg/kg dry weight basis)	Historic Sludge ¹ mean	Historic Sludge ¹ maximum	Slough GRSF mean	Slough SAS mean	TW SAS Mean	Waste Wood	Typical Coal Range ²
Cadmium	0.98	2.2	0.9	0.3	0.6	5	0.1 - 0.4
Zinc	683	942	590	181	310	150	11 - 40
Vanadium			11	6		n/a	32 - 88
Lead	60	138	58	13	34	500	5 - 54
Copper	650	915	647	353	192	80	12 - 52
Chromium	45	110	74	18	17	50	11 - 58
Nickel	20	33	38	14	12	5	19 - 127
Antimony	-	-	8.9	3.8	-	-	2.1 - 8.6
Cobalt	-	-	3.7	2	-	-	3.4 - 27.5
Manganese	-	-	208	109	-	-	32 - 234
Thallium	-	-	0.12	0.1	-	-	3.7
Tin	-	-	74.5	20.9	-	10	5.7
Arsenic	5	7.6	5.6	5.4	3.3	40	10.2 - 53.9
Mercury	1.3	2.4	1.0	0.29	0.70	1	< 0.1
Bromine	-	-	53	-	-	-	-
Iodine	6.4	12	1.0	-	-	-	-
Molybdenum	-	-	8.6	3.9	3.4	-	-
Silver	-	-	13.9	5.2	-	-	-

¹ Historic data relates to Thames Water sludge analysis 2008 – 2012

² Typical coal range values supplied by Hargreaves (UK coal supplier)

End of Waste Investigation Conclusions

The achievement of EoW for GRSF would allow TW to access different and wider markets, and thereby provide the potential for a sound financial basis for investment in new plant and infrastructure for its production. This part of the study has focused on providing baseline information on the quality of the GRSF and also on fuel which could be produced from surplus activated sludge (SAS), to advance the EoW assessment. The conclusions can be summarised as:

- Sludge data from STW across the TW region indicates that SAS contains lower concentrations of metals than the digested sludge and the Slough GRSF.
- The concentration of metals in SAS from Slough STW is lower than input digested sludge and the Slough GRSF.
- When comparing GRSF to virgin fuels, the main issues are lower calorific values, increased metal concentrations and ash content.
- SAS appears to have lower metal concentration and similar or better fuel characteristics than GRSF.

The main conclusion is that GRSF is unlikely to achieve End of Waste status, SAS derived fuel may have a better chance but still contains high concentrations of ash, zinc and copper. For these reasons it was decided not to pursue this avenue of investigation further.

3.2.3 Low temperature dryers

The successful dryer demonstration project at Slough created a solid fuel product, GRSF, using medium temperatures (150-200°C), but at these temperatures the application within the industry is restricted. The demonstration site had excess biogas which is rare and was a result of some recent process improvements; the CHP unit is scheduled to be replaced in the near future to consume the additional gas production. Relying on excess biogas on sites to operate dryers is an unrealistic strategy of adoption of post digestion drying. However, the medium temperature dryers can also utilise exhaust heat from the CHP. On a conventional MAD site the digester heating requirement is large and if the exhaust heat was used for drying the remaining thermal energy from the engine jacket water would be insufficient to satisfy the digester heating. So this application is also not practical, unless significant improvements are made to the digester feed thickening system, which reduces the volume of sludge to be heated.

The low temperature belt dryers can utilise heat sources as low as 50°C whilst having efficiencies comparable with the paddle dryer technology. Little literature exists on the applications of low temperature sludge drying. The majority of work published is related to medium temperature drying. Belt dryers were initially used for the drying of sugar beet in the 1980s, before the technology was proven for use in the wastewater industry. The application of belt dryers for drying sludge expanded in the 1990s as a safe alternative technology, after numerous explosions using drum dryers. Belt dryers were initially used for low temperature drying, but the size of the plant, combined with the high residence time required and odour problems, meant that medium temperature drying became increasingly adopted (Roediger and Bogner, 2009). More recent trends are favouring the low

temperature applications particularly the belt type and the technology has developed to be more efficient, cost effective and with a smaller footprint.

The operation of the low temperature belt dryer begins with the sludge cake extruded onto a series of belts, through which warm air is blown. The equipment is simple, but because of low temperatures, they are typically large units to allow for sufficient retention time to dry the product. The sludge moves through the dryer on the belts, which may involve several (2 or 3) belts aligned above each other to reduce the dryer footprint. The drying air is heated with 'water to air' heat exchangers; the air is recirculated several times to increase the thermal efficiency typically 0.8-0.9MWh/tonne of H₂O removed which translates to 2.9-3.2MJ/kgH₂O. There is almost no agitation of the sludge so there is little to no dust generation reducing the risk of explosion and in fact some the units don't even require an ATEX rating. However the increased air flow and circulation requirement do require additional electrical load which is typically 80kWh/tonne of H₂O removed.

Low temperature belt dryers can use hot water as heat source as low as 50°C, but temperatures nearer 90°C are more common as this is the heat grade that can be extracted from a CHP unit and jacket water and oil cooler circuits. There are a number of applications in the EU working with this exact configuration Figure 58 shows an installation in Germany visited during the project (Winter et al. 2013).



Figure 60 - Low Temperature Belt Dryer in German (Huber)

As discussed previously the use of waste heat for drying is critical to the economic and environmental sustainability of a project. On a conventional MAD site it is very difficult to find surplus heat from the CHP as the volume of sludge to be heated before digestion is large and as such all of the available heat is used to heat the digester feed sludge. The heat balance does not have sufficient spare heat to dry the digestate.

The heat balance on a THP site is very different, on a THP site only the high grade heat is required to generate steam and as discussed a deficit exists in the conventional THP configuration. However, the lower grade jacket water and oil cooler CHP circuits are not utilised apart from boiler water preheating which is a small proportion of the total steam energy requirement.

Figure 59 shows the low grade heat balance for a system utilising a low temperature belt dryer to dry the entire digestate output from a conventional THP plant, the cake DS feed to the dryer is a critical variable and a range of 20-50% was investigated. Negative values indicate that the dryer heat demand exceeds that available from the CHP and would require natural gas support fuel in a boiler. Positive values are obviously the opposite and an excess of waste heat exists. At 32%DS, a typical design standard for THP cake dewatering, the system would require support. At 44%DS the system is self-sufficient, but requires a step change in dewatering performance; luckily during this project this is exactly what happened.

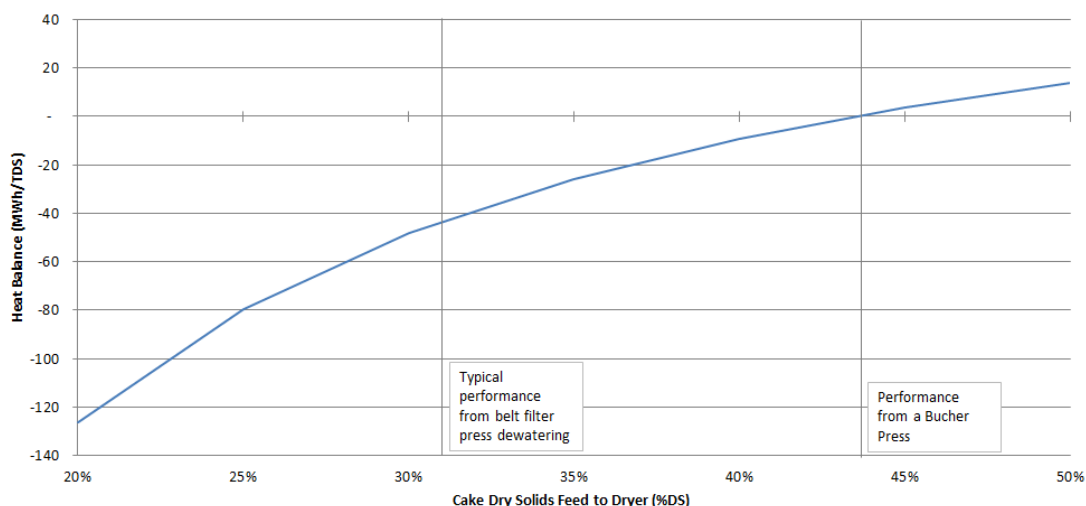


Figure 61 - Low Grade Heat Balance on a THP site utilising a low temp dryer

Bucher Press

The Bucher press is a machine which has for the last 20 years been used in the beverage industry for fruit-juice and wine production. The device uses a large piston with permeable internal straws or socks which wick away the liquid fraction when the piston is compressed, leaving the pulp which is discharged at the bottom of the press.



Figure 62 – Bucher Press

The company (Bucher) found that competitors from the wastewater dewatering industry were starting to take a larger market share of the beverage industry, so Bucher took a decision to trial the press with sewage sludge. The results showed that 30% more water

could be removed with this technology compared to traditional technology; this was verified by Thames Water (Huppert et al. 2011). The device uses a unique mechanical configuration combined with sophisticated process control sequence to achieve more contact time with the filtration membranes. Figure 63 shows the results from the Thames Water verification trials. Along the x-axis different sludge's are shown which relate to VS destruction. On the left hand side poorly digested sludge and high SAS content raw sludge on the right hand side advanced digested sludge from THP. The blue line is the performance expected from traditional dewatering technology performance (typically a belt filter press or a centrifuge) the red line is the Bucher press results which show an additional 30% water removal consistently.

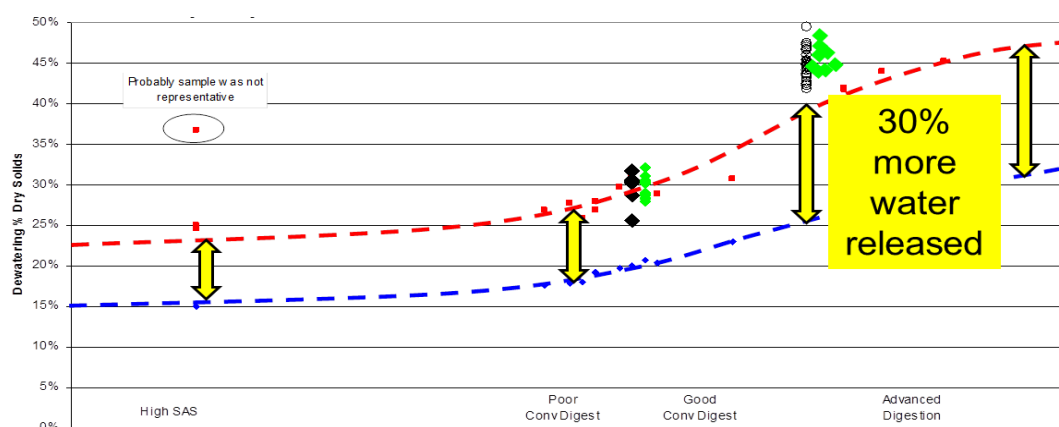


Figure 63 – Thames Water trials of the Bucher Press relative to traditional technologies (Fountain 2012)

The Bucher press is more expensive than traditional technologies, but the OpEx savings from reduced transportation and reduced CapEx for onsite storage (cake pad and barn) more than compensates for the additional CapEx required for the equipment. Thames Water has invested in 19 units across 4 sites employing THP.

Bucher and low temperature belt dryers on a THP site

The combination of THP with abundant low grade waste heat, the Bucher press and low temperature belt drying create a system which is self-sufficient in heat. Figure 64 displays the energy flows for this configuration, note it is assumed that no losses occur within the dryer.

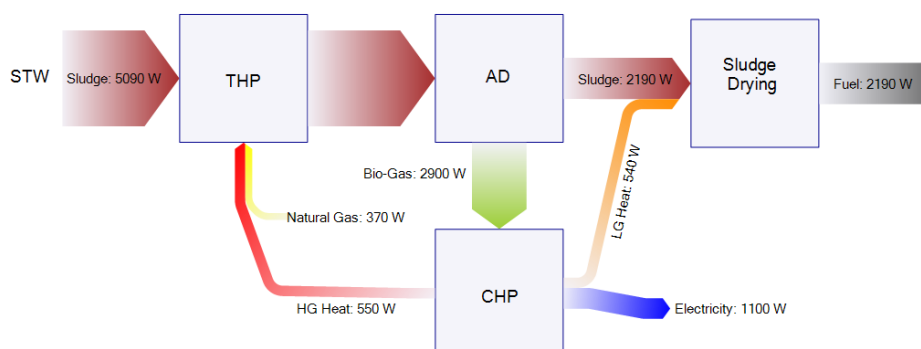


Figure 64 - Energy Flows for THP AD and Sludge Drying to Fuel (1kgDS/hour) electricity input is not shown

The configuration is very attractive as it displaces the expensive and risky land recycling operation and creates a potentially revenue generating operation. The economics and sustainability are explored in section 3.5.3 including technical and economic sensitivity surrounding key parameters.

3.3 Advanced Energy Recovery

Once a dried product has been produced it opens up other utilization options, such as pyrolysis and gasification technologies which have a high energy conversion efficiency (greater than 85%) to a syngas or fuel gas which can then be used in CHP units (Ray R et al. 2012). Combining AD, drying and pyrolysis has been explored by Cao and Pawłowski who concludes that maintaining AD as an initial recovery step leads to a more efficient overall energy recovery configuration (Cao and Pawłowski 2012). Attempts have been made to operate pyrolysis and gasification in the past using raw (undigested) sludge cake (Kasakura and Hiraoka 1982). For a number of reasons only a few of these technologies have been taken up at full scale. The general waste industry favours the mass burn approach as it is perceived this presents less risk to the investor (Malkow 2004). That said but there are many examples of advanced thermal conversion plants operating typically on wood or agricultural waste (Nexterra 2014). Yorkshire Water in the north of the UK are now operating a gasification technology on a mix of raw (undigested) sewage sludge and woodchip (YW 2013). In the UK the government have heavily supported a move from mass burn technologies to 'advance thermal conversion' technologies for waste to energy projects – this has driven innovation in the sector and many start-up companies and technologies were perceived to be either near or market ready. Thames Water conducted a large market study as part of a procurement exercise to understand the state of the art and which companies could potentially build a demonstration facility (UK-Tenders 2013). The tender had 42 responses which were shortlisted to 5 companies or technologies. The relative efficiencies of the shortlist technologies are shown in Figure 63 numbers assumed a feed of 90%DS digested sludge with a CV of 14MJ/kgDS.

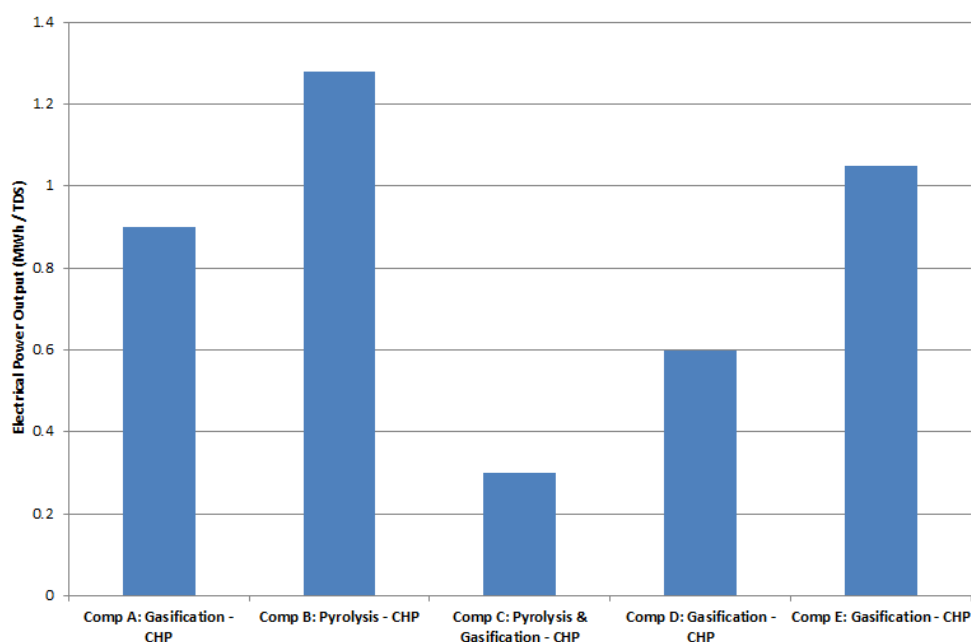


Figure 65 – Electrical Power Output from top tender returns

It can be seen that the pyrolysis option from Company B has the best conversion efficiency, closely followed by Company E and then A both using gasification technologies. All of the shortlisted technologies utilised the gas in a CHP unit which achieves a much greater electrical efficiency when compared with steam turbine based options. Company D produced a syngas with a very low CV which reduced the electrical output relative to others. Company C utilised much of the syngas in the process for heating, reducing the fuel available for electricity production. A number of parameters including economic were assessed, Company B and E were taken forward to pilot scale trials.

3.3.1 Pyrolysis

“Pyrolysis is the thermal decomposition of biomass into a range of useful products, either in the total absence of oxidizing agents or with a limited supply that does not permit gasification” (Basu 2010b). The useful products consist of gases and solid char, some of the gases condense to form liquids like oil. Pyrolysis is the initial thermochemical reaction with heat and O_2 before gasification where enough O_2 is added to make H_2 , H_2O & CO_2 and combustion where enough O_2 is added to make H_2O & CO_2 . There are many designs for pyrolysis systems some have been more successful than others; critical parameters are the pyrolysis temperature, the residence time and the initial heating rate (Meier et al. 2013).

Company B has a pyrolysis product which operated at relatively high temperatures ($>800^\circ C$) and retention times (>60 seconds) which can be controlled very accurately as the system is electrically heated and the dried sludge is mechanically transported through the reactor which can also be controlled. The process cannot be categorised as slow or fast pyrolysis and is unique. The advantage of these conditions is that very high pyrolysis ratios can be achieved ($>90\%$) and relatively high CV syngas $11-20 MJ/m^3$ is obtained. This is a higher CV than results from gasification (Bridgwater 2012; Domínguez A et al. 2006).

3.3.2 Gasification

Gasification and combustion are closely related thermochemical processes but with one important difference. Gasification packs energy into chemical bonds to produce gases such as hydrogen and carbon monoxide, whereas combustion breaks these bonds to release all of the chemical energy as heat (Basu 2010a). Unlike pyrolysis during gasification oxygen or an oxidant is present in the reaction which results in 'partial combustion', this means that a well-designed gasification system should be autothermic if the fuel's moisture and energy content are within limits. Typical gasification temperatures range from 500-1000°C and most system arrangements such as the downdraft or fluidised bed have residence times of <20 seconds. Syngas CV is typically in the range of 4-8MJ/m³ as nitrogen is introduced with air and this dilutes the syngas and typically some fuel, e.g. methane combusts to self-sustain the heat balance (Palmer et al. 2013).

Company E's technology also used a unique system which involved firstly preparing the fuel into a solid briquette which could be fed into a gasification chamber. The briquette is required to be a very specific size and density to ensure correct fluidisation. This process is more expensive to build, maintain and operate which takes the business case justification more difficult due to a longer pay pack period, see the next section.

3.3.3 Pilot trials

Companies B & E were provided with several tonnes of anaerobically digested dried sewage sludge from a low temperature belt dryer for in house pilot trials as part of the procurement process. The sludge feed sourced from Spain had the following characteristics displayed in Table 20.

Table 20 – Dried Feed Sludge Characteristics supplied to both trial units (Company_E 2014)

Units		
Dry Solids Content	%	84.3
Volatile Solids Content	% dry basis	60.5
Fixed Carbon	% dry basis	4.5
Total Sulphur	% dry basis	1.37
Chlorine	% dry basis	0.20
Carbon	% dry basis	36.0
Hydrogen	% dry basis	5.36
Nitrogen	% dry basis	5.66
Oxygen by difference	% dry basis	16.4
Flourine	mg/kg	123
CV (LHV)	MJ/kgDS	16.34

The sludge was sourced from Malaga in Spain from a conventional STW with primary settlement and activated sludge, which is comparable with a typical UK site. Importantly the site has anaerobic digestion and low temperature belt dryers which produce a product

which is representative chemically and physically to the configuration being modelled and developed.

Pyrolysis and gasification can be set up to produce a variety of products including oil, gas and solid materials like char. As described previously both of these technologies produce a syngas the composition of each syngas is shown in Table 21 which was sampled during the trials and analysed.

Table 21 - Pyrolysis (Company_B 2014) vs Gasification (Company_E 2014) – Gas Composition

	Units	Company B	Company E
Hydrogen	vol %	23	10
Carbon Monoxide	vol %	24	16
Methane	vol %	30	16
Ethane	vol %	1.5	-
Proportion combustible	vol %	78	42
Carbon Dioxide	vol %	19	13
Oxygen	vol %	0.1	0.4
Moisture	Vol %	22 ¹	4
Nitrogen	vol %	3.3	41 ²
Syngas CV (LHV)	MJ/m ³	17.6	8.2

¹ likely to be a feature of the gas cleaning system not the pyrolysis unit.

² Determined by balance.

It can be seen from these results that the pyrolysis process contains a higher proportion of combustible gases (78%) than the gasifier (42%). Relative to gasification the pyrolysis process also produces larger concentrations of the gases with higher combustion enthalpies and also includes a small quantity of ethane. The combination of these factors means that the pyrolysis process produces a syngas with twice the calorific value of the gasifier. This is mainly due to the gasifier requiring combustion air which dilutes the syngas and also reduces the combustible gas content as a proportion is converted to heat to maintain the process autothermic. However, the gasifier will have a larger syngas flow rate as a result of the combustion air it was measured as 1,444 m³/TDS during the gasifier trials whereas the pyrolysis process only produced 804m³/TDS. A high flow rate does mean that downstream gas handling and cleaning system will have to be larger. Gas contamination post cleaning for both process trialled were very efficient and produced a gas suitable for high efficiency gas engines, details of gas contamination is not included in this report.

A high level comparison that considers the most important parameters including gas CV, flow rate, electrical demand and char production can be seen in Table 22.

Table 22 - Pyrolysis (Company_B 2014) vs Gasification (Company_E 2014) - Energy Conversion

	Units	Company B	Company E
Throughput	tDS/hr	1.35	1.35
Feedstock energy	MJ/kgDS	16	16
Feedstock energy	MW	6	6
Syngas CV	MJ/m ³	17.6	8.2
Syngas flow rate	m ³ /tDS	804	1444
Syngas energy	MW	5.3	4.4
Conversion efficiency	%	89	74
Electrical Output @ 40% electrical efficiency	MWe	2.13	1.78
Parasitic Electrical	MWe	0.58	0.49
Net Electrical Output	MWe	1.55	1.29
Net Efficiency	%	26	22
Char &/or ash yield	kg/hr	527	499
CapEx of AER unit only	£m	3.6	7.0
Payback of AER unit only	yrs	2.0	5.2

The results in the table reveal a clear advantage to the pyrolysis technology; it has higher conversion efficiency at 89%, compared with 74% from the gasification process. Despite the pyrolysis unit requiring more parasitic power, mainly required for heating, the process has a net electrical output of 26% compared with 22% using the gasifier. While the gasifier does not require additional power for heating the dried sludge fuel it requires significant power for gas conveying through the process to enable fluidisation in the gasifier. Conversely the pyrolysis unit is operated at ambient pressure with syngas propagation providing the motive force for gas flow through the unit and downstream cleaning.

The gasifier is also more expensive £7m vs only £3.6m for the pyrolysis and simple economic comparison of the each unit in isolation (i.e. does not include dryers, installation and engines which are needed to make the unit work) shows that the pyrolysis process from Company B has a payback of 2.0 years vs 5.2 years. Therefore on the basis of the above data the gasification process was dismissed and pyrolysis process was studied further.

3.3.4 Configuration and Analysis

Now that an Advanced Energy Recovery process has been tested and key performance parameters proven, the deployment of pyrolysis post drying and the overall sludge to energy process can be explored and understood.

The full process which embeds the pyrolysis unit can be seen in Figure 65 which shows the main energy flows, referenced to 1kgDS/hour, for the configuration which builds on the scenario explored in section 3.2.3. The pyrolysis process obviously follows the low temperature belt dryers, the syngas is then utilised within a second gas engine (CHP 2). CHP 1 is a gas engine running on biogas from anaerobic digestion. Heat from both CHP 1 & 2 is

split into high grade (HG) which is used to raise steam for THP and low grade (LG) which is used for the sludge drying. It should be noted that unlike previous scenarios involving conventional THP there is no requirement for support fuel because the combination of HG heat output from CHP1 & 2 is sufficient to raise all the steam required for THP. This is a major achievement.

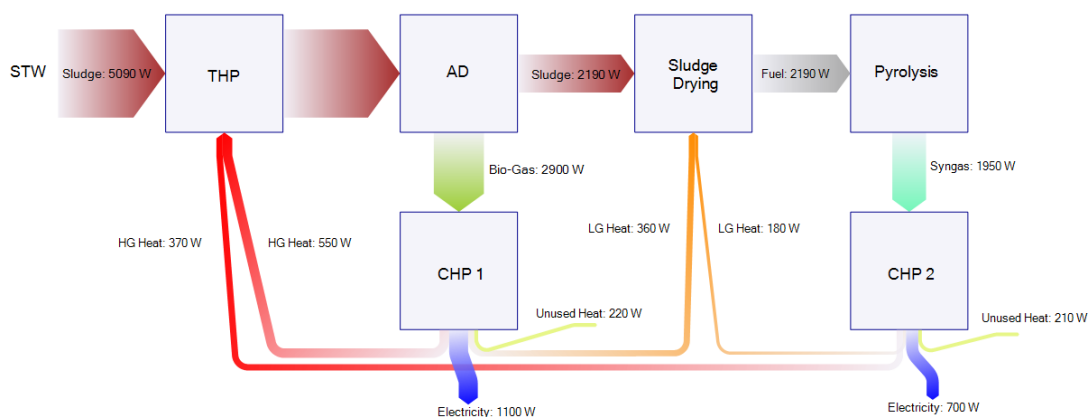


Figure 66 - Energy Flows for THP AD, CHP and Sludge Drying and Pyrolysis (1kgDS/hour) Electricity input not shown

The low temperature dryer as shown in Figure 64 is also operating on only waste heat and does not require any supplementary fuel. This does assume a 45%DS cake feed utilising the Bucher press, discussed in section 3.2.3. The previous analysis did show how sensitive the configuration was to the feed dry solids content, so it was necessary to better understand the sensitivity of the heat balance for this configuration to variation in cake feed dry solids. Before this is displayed it is important to explain that there are a number of options for heat configuration, these are summarised in Table 23 and explained below.

Table 23 - Options for CHP heat utilisation

	CHP 1	CHP 2	Comments
Option 1	LG to dryer HG to THP	LG to dryer HG to dryer	THP needs support fuel.
Option 2	LG to dryer HG to THP	LG to dryer HG to THP	Reduced / no THP support fuel. Very integrated system.
Option 3	LG not used HG to THP	LG to dryer HG to dryer	THP needs support fuel. Dryer, pyrolysis and CHP2 isolated from main process other than feed.

Option 1 allocates all of the CHP heat in the dryer other than CHP1 high grade which raises steam for THP, this means that support fuel is still needed for THP.

Option 2 is shown in Figure 65 and allocated the LG heat from both CHPs for the dryer and HG heat for the THP, resulting in no THP support fuel. This does mean that the system is very integrated and needs to be on the same site.

Option 3 may suit a scenario where the THP and AD is separate from the drying and pyrolysis process as CHP2 LG & HG heat is combined for the drying stage.

In order to understand how the cake feed dry solids effects the heat balance of the 3 options above, the process model (explained later) was used. The digested cake dry solids and feed to the dryer was varied from 20 to 50%DS. The dryer throughput was maximised with the available waste heat but not supplemented with a an external source, therefore any excess sludge was assumed to be land recycled. The results can be seen in Figure 65.

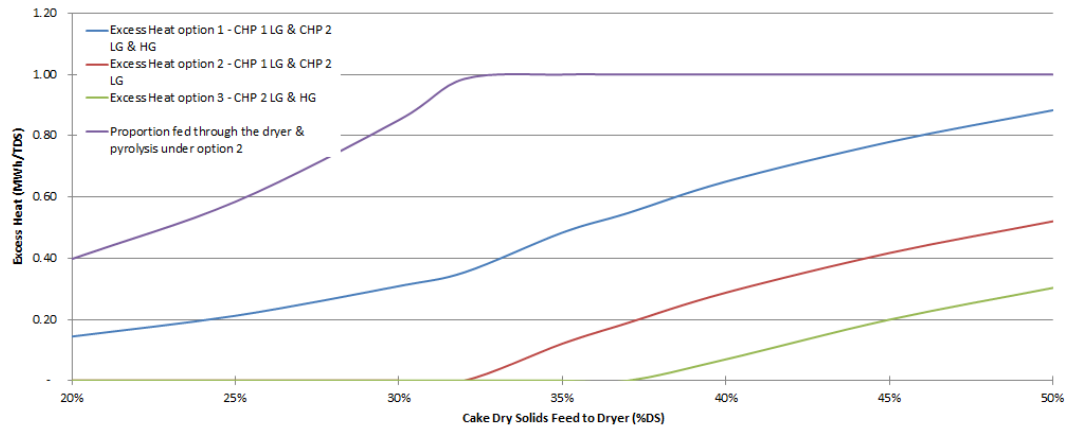


Figure 67 - Excess heat available vs Cake Dry Solids Feed to Dryer

Option 1 has excess heat even with a cake feed of 20%DS, considering that 32%DS should be expected, from THP sludge dewatered using conventional dewatering equipment, most of this heat will be wasted. The system starts to be balanced at a cake feed of 33%DS, which would suggest that a conventional THP site with conventional dewatering performing well, should be considered for AER post AD. Option 3 needs the highest cake feed DS (37%DS) of the 3 options, so this option would need Bucher press dewatering to process the entire throughput.

Figure 65 shows that for the additional electrical generation from AER post AD is in the order of 700W at a feed rate of 1kgDS/hr. This would take the gross electrical efficiency for the process from 20%, with THP only, to 34%. The net position (i.e. after parasitic load is subtracted) is equally impressive achieving 26%, compared to just 18% with THP without AER.

3.4 Environmental Life Cycle Analysis

The goal of this study is to evaluate the relative environmental and economic impact of the configurations to inform decision makers across the industry and to identify any inconsistencies or anomalies in policy. Conventional MAD, THP with CHP and GtG where considered in the previous section, in this section the two additional scenarios explored and developed with this project have been analysed. Developments in THP where not explored as these processes have advantages/disadvantages over conventional THP and the impact of from marginal gains or losses on environmental impact are obvious.

As before the functional unit used is the dry mass of sludge; Tonne Dry Solids (TDS). All sludge parameters and process assumptions are detailed in the Waste Management journal paper within the Appendix.

3.4.1 System Boundaries

Figure 68 shows the outline system boundary; it has been assumed that all process variants are assessed in operation only and the impact of construction and decommissioning are ignored as these emissions are likely to be insignificant in comparison (Carballa M et al. 2011). The 'sludge to energy' process itself will consume energy (electricity & natural gas) and chemicals (e.g. poly-electrolyte) which are included. On site there will also be emissions to air from CHP engines and gas boilers which emissions are dominated by CO₂, SO₂ Particulates, CO and NO_x emissions (Poeschl M et al. 2012).

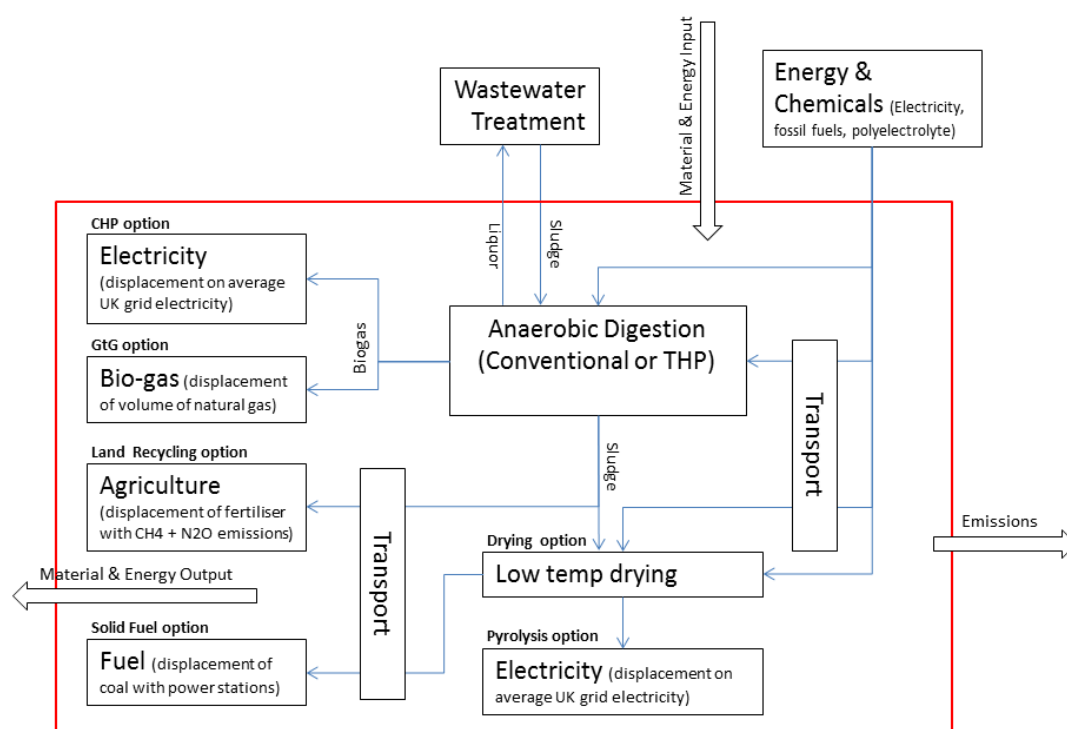


Figure 68 – Overview of System Boundaries

It is assumed that digested sludge is applied to agricultural land (this is the current practice in the UK for 60% of the UK's sludge (Andrews 2008)) and is transported an average of 60 km. In addition to vehicle emissions, this activity will have air emissions (CH₄ & N₂O) associated with the biodegradation of sludge cake in the soil (Kazuyuki et al. 2000). The Nitrogen and Phosphorus (N&P) content of the recycled sludge will be a credit to the system because it displaces industrially made fertilisers in this case Urea and Triple Superphosphate.

Electricity produced from CHP credits the system by displacing grid-produced electricity. Biogas injected under the GtG option also credits the system by displacing the burden associated with producing the equivalent amount of natural gas. All assumptions used within the model are listed in Appendix A. Problems associated with heavy metals and other non-biological sludge contaminants have been discounted from the study.

3.4.2 Inventory

A commercial LCA package (GaBi) was used to construct a model for each of the scenarios. Figures 12, 17, 18, 62 & 64 display high level summary sankey diagrams for the energy flows in each scenario (note that electricity, road fuel and consumables are not shown but

included in these results). Table 24 shows the inventory for the main performance indicators which drive the life cycle impacts, grouped as energy outputs, inputs and digestate.

Table 24 - Inventory of Performance Indicators for 1 TDS feed (note numbers differ slightly to others quoted)

Inventory Item	Units	Conv AD CHP	THP AD CHP	THP AD GtG	THP AD CHP + Drying for Fuel	THP AD CHP + Drying, Pyrolysis & CHP
ENERGY OUTPUTS						
Electricity generation	kWh	728	1,020	-	1,020	1,820
Bio-methane	kWh	-	-	3,230	-	-
Solid Fuel	kWh	-	-	-	2,260	-
INPUTS						
Electricity consumption	kWh	135	179	199	210	443
Natural gas	kWh	0	370	907	370	370
Propane	kWh	-	-	546	-	-
Diesel	kg	7.3	3.7	3.7	0.8	0.4
Polymer	kg	9.2	14.0	14.0	14.0	14.0
DIGESTATE \ CHAR						
Sludge disposal	T	2.3	1.4	1.4	-	-
N&P Benefit	kg	254 / 156	150 / 92	150 / 92	-	-
Char	kg	-	-	-	-	220

3.4.3 Environmental Life Cycle Analysis Results

The software used (GaBi) in this study can allow a number of different impacts to be analysed, for this study the following were deemed important:

1. GWP-Global Warming Potential (excluding biogenic) (kgCO₂ – Equiv.)
2. POCP-Photo Ozone Creation Potential (kg Ethene – Equiv.)
3. EP-Eutrophication Potential (kg Phosphate – Equiv.)
4. AP-Acidification (kgSO₂ – Equiv.)
5. ADP element - Abiotic depletion (elements kg Sb – Equiv.)
6. ADP fossil - Abiotic depletion (fossil MJ)

Figure 69 displays the normalised results for the six impacts calculated as part of the study; negative values are environmentally beneficial and positive values represent environmental burdens. The largest impact area is ADP fossil which is negative (beneficial), this is because all the processes displace fossil fuels. Conventional AD performs better than THP (CHP & GtG) and the pyrolysis options, because it has relatively low parasitic energy and chemical demand. The drying to fuel scenario is best due to the direct displacement of hard coal. The GWP impacts follow a different trend and are discussed in detail later due to their regulatory and financial significance.

The next most significant emissions are 'local' (AP & POCP) and reveal a slightly different picture that suggests that the GtG scenario has the least impact, due to the low direct emissions associated with the production of bio-methane, compared with a CHP exhaust. Unsurprisingly the scenarios with CHP units have the largest impact, due to the exhaust emissions (Dust, CO, NO_x, SO₂ and VOCs). ADP elements and EP are insignificant in comparison and are therefore not discussed further.

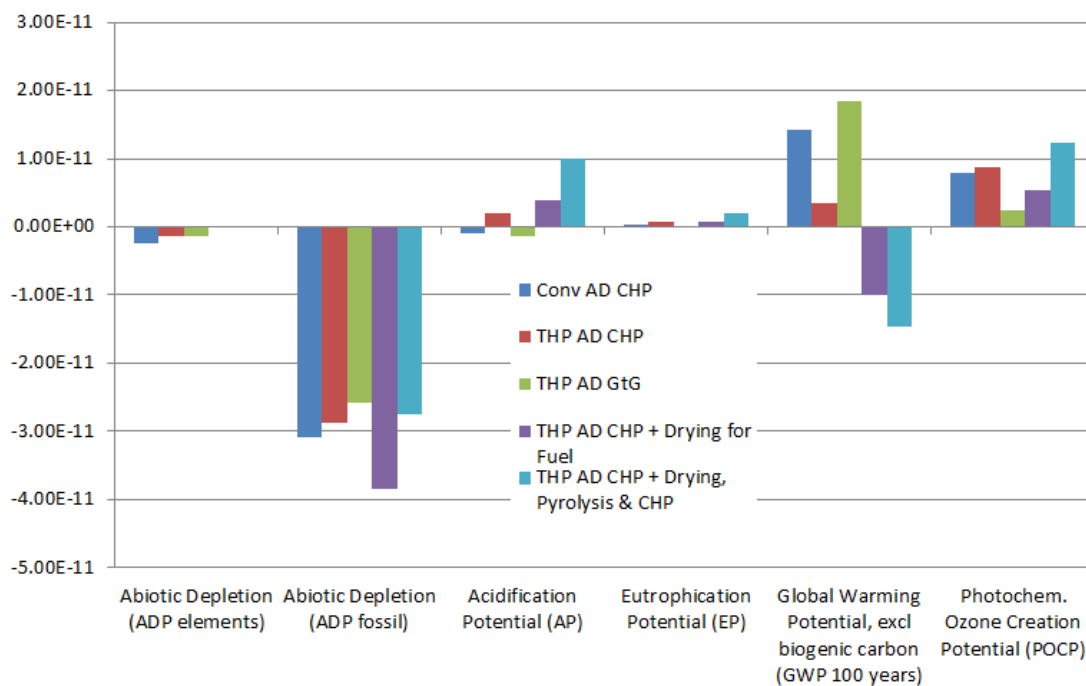


Figure 69 – Life Cycle Impacts per TDS, Normalised using the CML2001 – Nov.2010 method

Using a normalisation method, CML2001, the net environmental impact is shown in Table 25, revealing that drying for fuel production is optimal followed by the pyrolysis option, the worst performer is the GtG scenario. THP with CHP has environmental benefits over conventional AD with CHP.

Table 25 - Weighted Net Impact using the 'CML 2001 – Dec. 07, Experts IKP (Northern Europe)' Method

Conv AD CHP	THP AD CHP	THP AD GtG	THP AD CHP + Drying	THP AD CHP + Pyrolysis CHP
9,250	6,110	10,500	478	2,240

GWP is considered the most important impact to water companies, as it is a reportable output to the regulator OFWAT and it also costs millions of pounds annually in taxes such as the Carbon Reduction Commitment (CRC). Figure 68 shows the results for GWP of the five scenarios modelled. The net GWP for each scenario is shown as the black column with a data label, the emissions have also been categorised into six key process steps to improve analysis, shown as discrete columns.

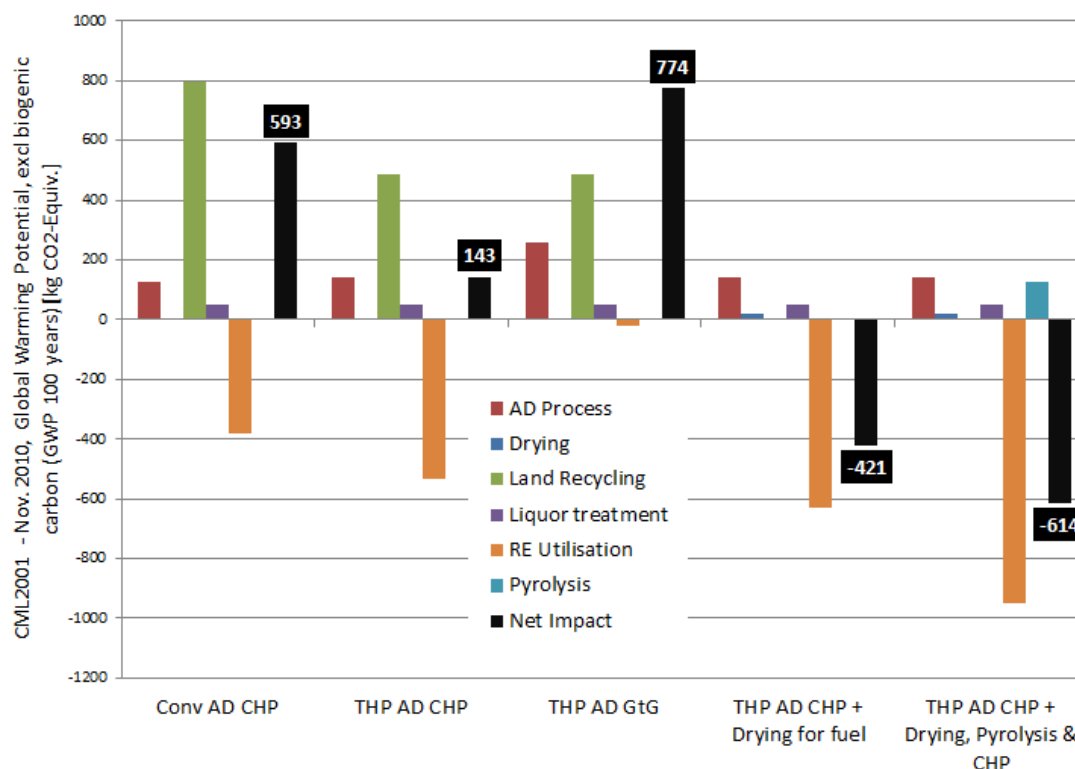


Figure 70 – Global Warming Potential per TDS for 5 Options modelled

The two future options which avoid land displacement therefore result in a net benefit in GWP. In addition both these options achieve improved energy recovery, especially the pyrolysis option which has approximately doubled the electrical output (a carbon intensive burden) of the process when compared with conventional AD. It can be concluded from these results that the future technologies developed as part of this project offer a considerable advantage over the existing techniques, especially when considering GWP. However, the pyrolysis option does this at a greater potential detriment to the local environment.

3.5 Economic Analysis

3.5.1 OpEx

The process model discussed in section 2.6 was also used to model the future processes. The following additional modules or functions were included in the extended model, shown in Figure 69 and described below:

1. Drying – the model assumes low temperature belt dryer technology described previously. This function contains assumptions on the dryer thermal efficiency (MWh/m³ H₂O) and electrical demand which is typically 10% of the thermal energy demand. The model is driven by the mass of digested sludge cake (wet T/d). The sludge is dried to 90%DS from a starting point derived from the previous module, producing an evaporative capacity (m³ H₂O/hr) which informs the CapEx calculation and the heat demand (MWh/d). The evaporative capacity fixes the proportion of the sludge dried

determined by the scenario and the waste heat available which is discussed in more detail below:

- a. For the 'drying to fuel' scenario the function assumes that all of the digested sludge will be processed. The dryer function firstly uses all of the waste heat available from the biogas CHP engine and then if required it is supplemented with natural gas to match demand; the cost of gas is accounted for in the OpEx calculations. The energy content of the solid sludge fuel is calculated using the VS content of the sludge post digestion, a conversion factor of 25 MJ/kgVS was used which is an average from historical data (Lee 2010). The solid fuel product is assumed to be sold at £20/TDS.
 - b. For the 'pyrolysis' function heat is available from both CHP plants as described in section 3.3.4 and option 2 is the preference. An iteration step is used to maximise the dryer throughput using waste heat only. The pyrolysis CHP output is dependent upon the dryer and the dryer is dependent upon the pyrolysis CHP output, hence the iteration requirement. If there is insufficient heat the dryer throughput is reduced and sludge that is not dried is recycled to land, the OpEx model takes account of this additional cost. However, the analysis in section 3.3.4 showed that cake only bypasses the dryer when the cake dry solids are low.
2. Pyrolysis – as before the energy content of the sludge was calculated using the VS content of the dried sludge post AD. The energy content and mass of the sludge drives the pyrolysis function which uses a simple conversion ratio to derive the syngas energy output (MWh/d). The char output (t/d) is a function of the VS content and mass flow rate. The mass of char is used in the OpEx calculation as a cost for disposal. The energy consumption is calculated using known conversion factors (390kWh/TDS) driven by the throughput of the unit.
 3. Syngas use, CHP 2 – as with the biogas CHP, the syngas from the pyrolysis module and the technical input assumptions are used to calculate: engine size (MWe), ROCable output (MWh/d), low and high grade heat output (MWh/d) and these are used in the CapEx and OpEx calculations.

Following the process model a number of key parameters are carried forward into the OpEx module and combining these with unit cost assumptions (shown in Appendix A) the following costs/revenues are calculated:

Costs:

- Electricity use (MWh/d)
- Labour (FTE's)
- Polymer (kg/d)
- Char disposal (t/d)
- Digestate volume (t/d)
- Maintenance (% of CapEx)

Revenue:

- Sale of solid fuel (MWh/d)
- Electricity generated (MWh/d)
- Electricity eligible for ROCs (MWh/d) at 0.5 ROC
- Electricity eligible for ROCs (MWh/d) at 1.8 ROC

The output is a net OpEx position which can be used to compare processes and in combination with the CapEx, explained next, used in full financial analysis of each process.

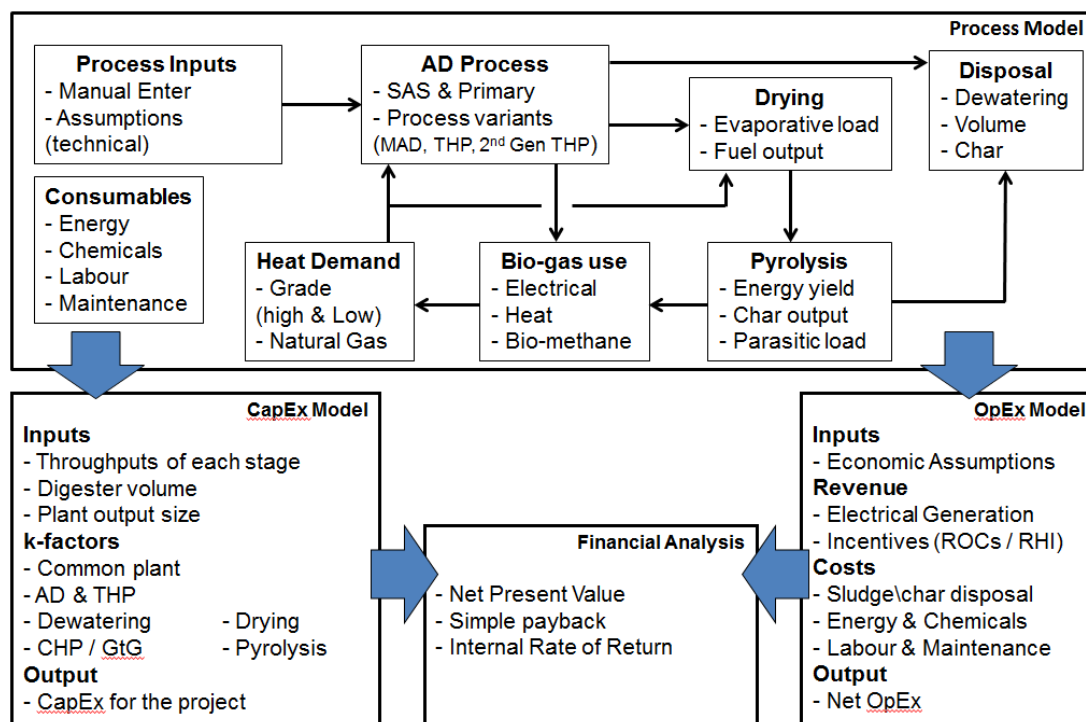


Figure 71 – Process model structure which includes Future Process scenarios

The results of the future process scenarios are shown below in Table 26. Concentrating initially on the second generation, the SASonly THP option has a similar OpEx to conventional THP but the savings in natural gas do not compensate for the reduced overall energy efficiency. ITHP is the superior THP scenario with best OpEx because of contributions from increased energy yield, natural gas savings and reduced land recycling costs.

It can also be seen from the results that there are significant advantages to post digestion drying options. Drying for fuel production increases the net OpEx by 110% over ITHP the best performing digestion option.

Combining drying with pyrolysis is a step change in economics, for every TDS processed the operator would make £116 in profit or a 300% increase over ITHP. The dramatic change is driven by the high energy efficiency of the entire process and the high value of the renewable electricity from pyrolysis generated power which receives 1.8ROC/MWh compared with 0.5ROC/MWh for the AD produced power.

Table 26 - OpEx performance of the processes

Parameter	Units	MAD existing process	THP existing process	SAS only THP	ITHP	Drying post THP AD	THP + drying + pyrolysis
Net OpEx	£/TDS	-20.8	8.7	6.2	29.0	45.3	114.8
Electricity use	£/TDS	-8.55	-14.3	-14.3	-18.5	-19.2	-39.4
Labour	£/TDS	-3.65	-5.48	-5.48	-5.48	-6.21	-7.31
Maintenance	£/TDS	-39.6	-36.1	-38.0	-39.7	-38.7	-46.2
Polymer	£/TDS	-25.5	-30.2	-28.5	-30.6	-30.2	-30.2
Natural gas	£/TDS	-	-12.8	-	-	-12.8	-
Disposal	£/TDS	-40.0	-22.0	-27.7	-19.3	-	-19.5
Electricity generation	£/TDS	78.1	104.8	97.1	115.4	104.8	171.5
Renewable Energy incentives	£/TDS	18.5	24.8	23.0	27.3	24.8	81.7
Sale of Fuel	£/TDS	-	-	-	-	21.9	-
Energy Efficiency (net)	%	15.6%	20.3%	18.6%	21.7%	19.2%*	29.6%
Electrical Output	MWh/TDS	0.82	1.10	1.02	1.21	1.10	1.81

* doesn't include solid fuel energy output

The financial benefit associated with the regulated capital value (RCV) of the investment has not been accounted for; this would improve the financial benefit.

3.5.2 CapEx

The CapEx was calculated using the k-factors in Table 6 with the additional options shown in Table 27 for the dryer, pyrolysis plant and CHP. As the post digestion recovery options rely upon the Bucher press dewatering performance, the analysis has assumed that all scenarios including conventional AD utilise the Bucher which has increased CapEx (double the conventional dewatering CapEx).

Table 27 – Future Sludge to Energy Process Options – CapEx for components (before overheads)

Component	CapEx (£)	Size	Unit	k-Value (£)
Bucher Press and Cake Storage	7,311,781	60	TDS/d	626,805
Drying Plant	3,121,326	3,200	kgH ₂ O/hr	24,618
Pyrolysis Plant	5,238,923	60	TDS/d	449,109
Pyrolysis CHP & Electrical	4,841,808	4,000	kWe	33,402

Table 28 shows the resulting CapEx for each scenario and the main items that contribute to the CapEx. Conventional MAD has the lowest CapEx despite a very large digester volume, but has the smallest CHP and no THP plant. SASonly THP is the cheapest of the THP variants because both the THP & CHP plant are smaller, ITHP has the highest cost because it requires the largest digester volume and CHP unit, but savings are made with the THP plant over the conventional configuration. Post THP AD Drying has only a small additional cost over the cost of the conventional THP configuration. The pyrolysis option adds 30% to the

cost of the conventional THP configuration because the of the large additional CHP unit (>3MWe) and the pyrolysis plant.

Table 28 – CapEx for the future processes and main key parameters for a 100TDS/d plant

Parameter	Units	Conv MAD	THP	SAS only THP	I-THP	Drying post THP AD	THP + drying + pyrolysis
CapEx	£m	36.3	38.1	37.6	39.3	41.2	50.3
Digester volume	m ³	46,345	14,300	27,400	28,600	14,300	14,300
THP size	TDS/d	-	100%	40%	66%	100%	100%
CHP size	MWe	3.6	4.8	4.5	5.3	4.8	8.1

3.5.3 Analysis

Net Present Value (NPV) analysis was carried out by combining the CapEx and OpEx results, assuming a 20year asset life and a discount factor of 6%. The results of this exercise can be seen in Table 30 which includes the conventional AD and THP for comparison. Internal Rate of Return (IRR) and a simple payback calculation were also carried out and are also displayed in Table 29.

Table 29 - Financial Performance of all Processes with Bucher Press

Parameter	Units	Conv AD	THP	SAS only THP	I-THP	THP AD + drying to fuel	THP + drying + pyrolysis
Net OpEx	£/TDS	-16.5	10.8	7.2	34.0	70.6	114.8
NPV after 20years	£M	13.7	17.6	17.1	20.9	26.1	31.8
IRR	%	12.5%	14.7%	14.7%	16.6%	19.0%	18.6%
Simple payback	years	7.3	6.3	6.4	5.8	5.1	5.2

The general trend shows that the more efficient processes generate a better financial return. There is little difference between the conventional THP and SAS only THP. I-THP shows a large improvement over conventional THP and SAS only THP, because of the improved OpEx position which more than justifies the additional CapEx. Both the post digestion energy recovery options perform very well and show a step change, both with an IRR of 19%.

Sensitivity analysis

It is important to understand the relative financial performance of the scenarios when certain parameters are changed. The global parameters included in the sensitivity analysis were:

- Digester CapEx
- Sludge disposal unit cost
- Post digester dewatering performance

Digester CapEx

This is an important parameter to understand as the unit cost can vary considerably. If the site has existing digester assets which is often the case little or no spend is required to achieve the appropriate digester volume particularly for THP sites. In contrast some construction methods and/or site conditions will increase the cost of construction. Therefore, the effect of the unit cost was varied from 0 to 2 times the base case shown in Table 6, the results of this are shown in Figure 70 the x-axis displays the unit costs varying from 0-2 times the base case. To help quantify and give context the cost for a 4,000m³ digester is £1.25m and is shown by the vertical line. As you would expect, reducing the cost of digesters increases the rate of return for all scenarios. An interesting effect was seen which shows that below £0.5M the conventional MAD with CHP is more attractive financially than SASonly THP and THP CHP. SASonly THP and THP CHP seems to be least effected by the effect of digester CapEx and has the smallest gradient of all the AD only configurations. Both drying options have shallow gradients which can be explained because AD CapEx component is a smaller than the AD only options.

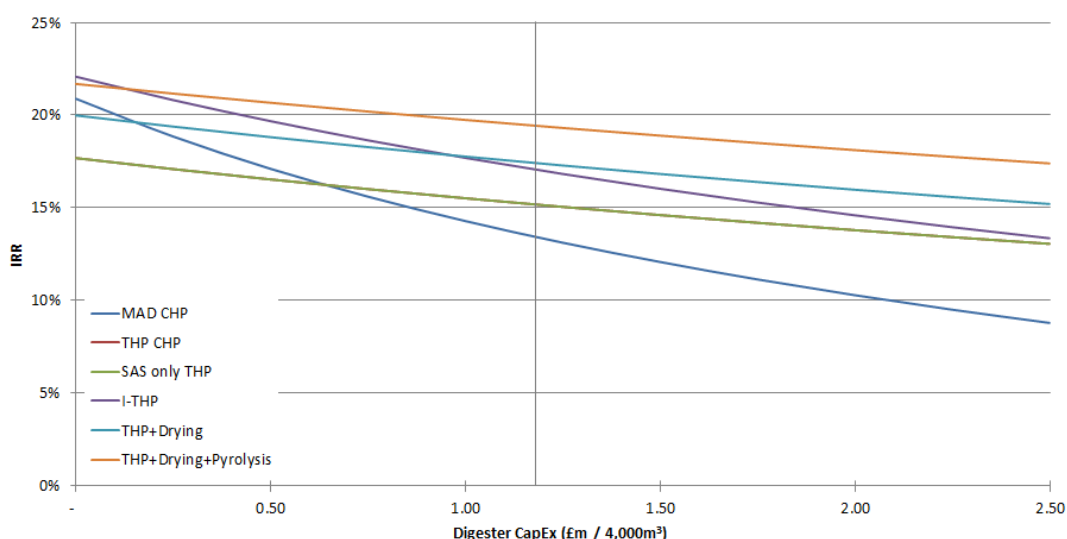


Figure 72 - Effect of Digester CapEx on IRR of investment in various technologies from base case

Sludge Disposal

This is an important parameter as it can also vary significantly depending upon location, (i.e. proximity to suitable agriculture) and the regulations. In the UK land recycling of digestate is common practice and variation in disposal cost may vary between £10-35 per wet tonne. However, in some countries like the Netherlands sewage sludge recycling to land is not permitted and therefore disposal of the digestate post digestion is very expensive up to £60 wet tonne. Therefore, a range of 0 - 3 times the base case was selected for the sensitivity analysis, translating to £0-60 per wet tonne. To ensure that this analysis was meaningful the 'do-nothing' treatment cost also had to vary. The 'do-nothing' base case is assumed as lime treatment which over the same range varies from £56 – 348 / TDS.

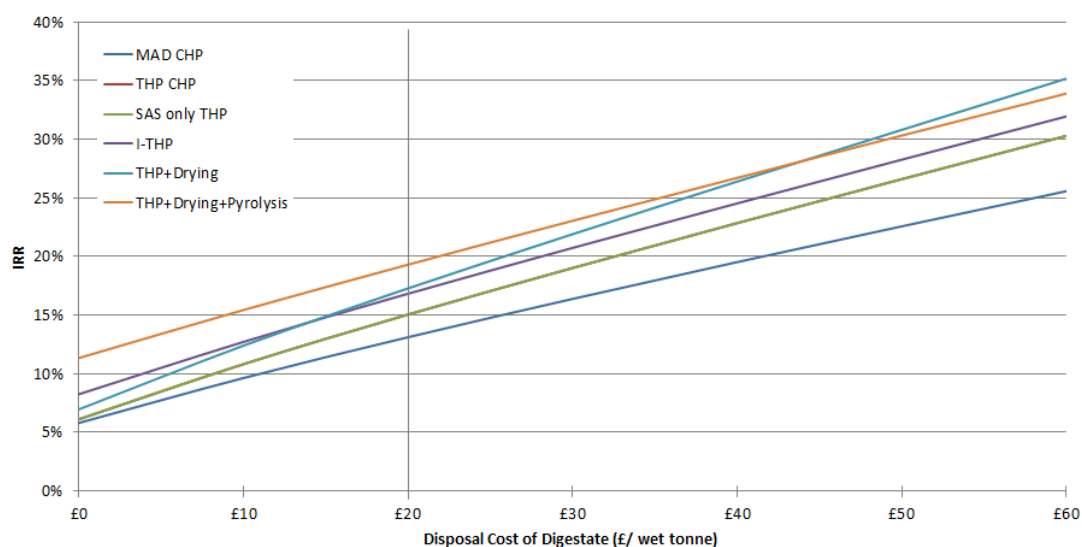


Figure 73 - Effect of digestate disposal cost on IRR of investment in various technologies from base case

It can be seen from Figure 71 that increasing disposal cost has a positive effect on the IRR for all of these processes. All options other than pyrolysis are not financially attractive if the disposal is free. The post digestion recovery options both perform well over the entire range. The drying to fuel scenario has the steepest gradient of all the options and as a result at the lower ends of the range is ranked 3rd but at the high end is 1st. All of the digestion options follow a similar relationship and I-THP remains the best option over the range.

Dewatering performance

This is a very important parameter to vary as it drives the disposal cost for the digestion only options. For the options involving drying it will affect the size and cost of the dryer and the heat demand. It is not unreasonable to expect variation in performance from dewatering from 0.6 – 1.1 of the assumed base value in the standard model. For all scenarios it has been assumed that the Bucher press is deployed and that the cake output dry solids displayed in Table 30 is achieved under optimum conditions.

Table 30 – Base values for dewatering performance from AD processes

	Conv AD	THP	SAS only THP	I-THP
Cake Dry Solids	30%	45%	38%	47%

The results of the sensitivity analysis on the IRR can be seen in Figure 74. All of options modelled are affected by the reduced performance in dewatering, most notably the drying for fuel option, which becomes economically unattractive below 90%, which translates to 41%DS, this is because natural gas has to be consumed to maintain the dryer throughput.

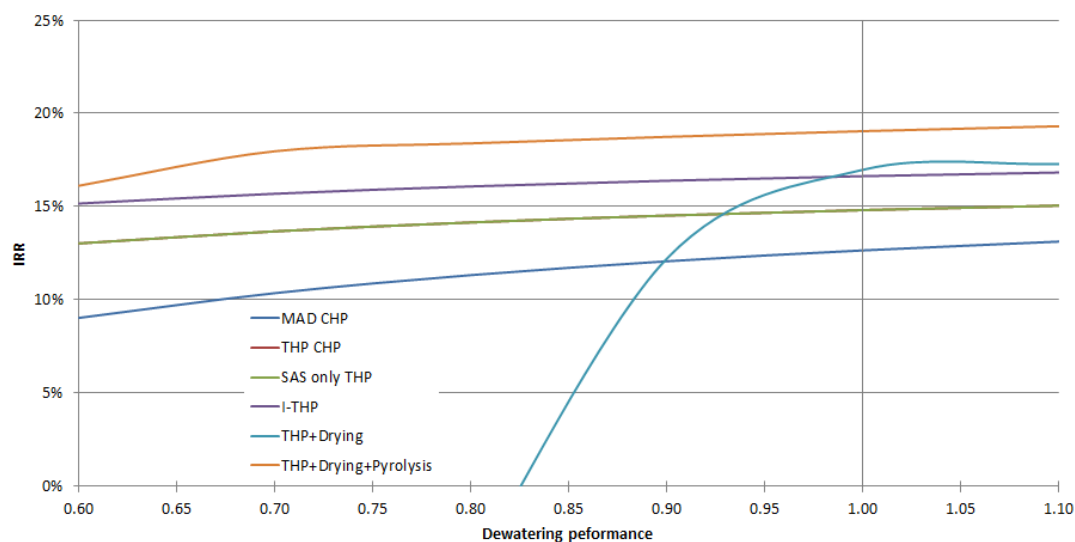


Figure 74 - Effect of Dewatering Performance

Renewable energy incentives

It is important to understand the sensitivity of an investment to the renewable energy incentives. Table 31 shows the financial analysis of the 6 scenarios with and without the incentives in place. In the standard model all of the AD generated electricity receives 0.5ROCs (£22/MWh) and the electricity generated from pyrolysis receives 1.8ROCs (£81/MWh).

Table 31 - Financial performance of each process scenario with CHP and Bucher assuming a 100tDS/day plant

Scenario	CapEx	OpEx with incentives	NPV and Payback with incentives		NPV and Payback without incentives	
	£m	£/tDS	£m	years	£m	years
Conv AD	36.3	-16.5	13.7	7.3	10.8	8.7
THP AD	38.1	10.8	17.6	6.3	13.7	7.5
SASonly THP AD	37.6	7.2	17.1	6.4	13.5	7.5
I-THP AD	39.3	34.0	20.9	5.8	16.6	6.7
THP AD + Drying	41.7	70.55	26.1	5.1	22.2	5.7
THP AD + Drying + Pyrolysis	50.8	114.6	31.8	5.1	19.0	7.3

With incentives removed all of the schemes maintain a positive NPV. However conventional AD does not have a desirable return and THP and SASonly THP would be border line. The I-THP and THP + Drying option are the best performing followed by the pyrolysis scenario.

Renewable Solid Fuel Price

The main reason the drying option performs well financially without the incentives is because the fuel sale is a large part (30%) of the revenue, Figure 73 shows the sensitivity of investment to the fuel price. It shows the fuel price can actually be negative (i.e. a gate fee)

and the plant remains financially viable, which corresponds to 12% IRR or about a 7.5 year simple payback. However without the incentives the fuel price must be neutral or positive.

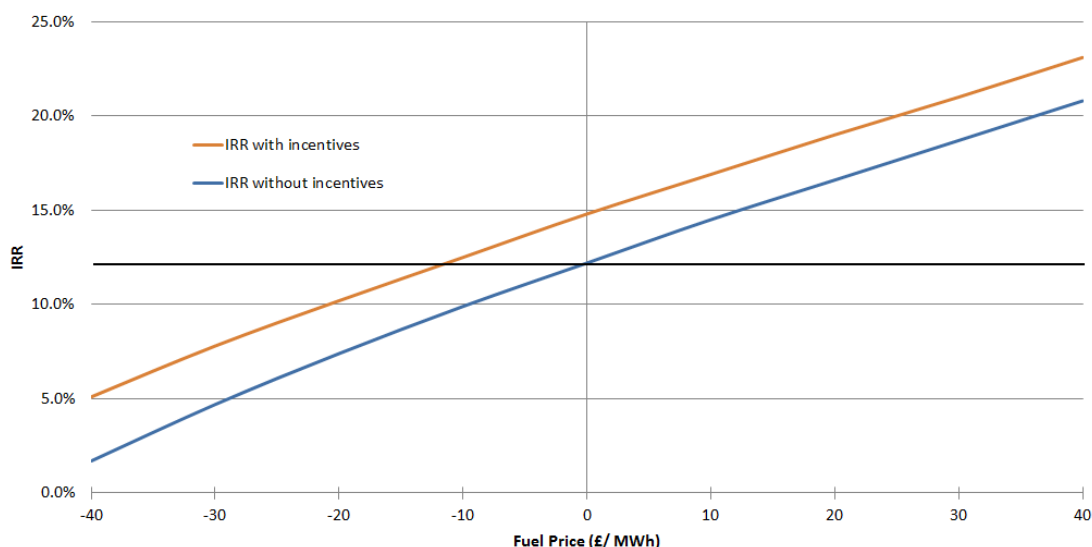


Figure 75 - Impact of fuel price on IRR

3.6 Summary of future processes

Table 32 aims to summarise the performance of the future processes modelled and/or developed as part of this project. There is some evidence that shows steam explosion having a positive effect on THP (based on the laboratory tests); the economic analysis shows it should be worth exploring in more detail. SASonly THP offers a lower CapEx alternative that provides most of the benefits that THP offers. ITHP recovers the most energy from sewage sludge and most efficiently (i.e. no support fuel), but it requires additional CapEx. The overall investment (NPV) is superior to all other AD based options. However, the ITHP pilot plant has yet to reach steady state and perform as expected based on laboratory results. All of the technical process modelling and economic analysis is based on the performance observed in the laboratory under stable conditions. All AD based options are economically robust to changes in digestion CapEx and digestate disposal costs. Renewable energy incentives are required to maintain conventional AD as economically feasible and without incentives THP and SASonly THP would be difficult to justify. All AD based options show an improvement in GWP and environmental impact over conventional MAD, but there are only minor differences between THP variants as it is basically the same process.

Table 32 – (Table 2 repeated) Summary of Future Processes Opportunities Developed during this Research Project

Performance	Units	Conv. THP	THP with S.Exp	2 nd Gen THP SAS only	2 nd Gen THP I-THP	THP + Drying for fuel	THP + Drying + Pyrolysis
Energy Yield (elec)	kWh/TDS	1,100	1,160	1,020	1,210	950 (+2,380 fuel)	1,830
Parastic elec	kWh/TDS	150	150	150	200	340	580
Solids Destruction	%	45	45	42	50	45	77
Carbon emissions	kgCO ₂ e/TDS	143	137 ¹	154 ¹	138	-421	-614
OpEx	£/TDS	11	19	7	34	48	115
RE Incentive prop of revenue	%	19	19	19	19	16	32
CapEx	£M/100TDS	38.1	37.0	37.6	39.3	41.7	50.8
IRR	%	12.5	14.7	14.7	16.6	19.0	18.6
NPV after 20yrs	£M	13.7	19.1	17.1	20.9	22.7	31.8

¹ Based on Conventional THP and proportioned based on net efficiency.

The post AD drying options perform incredibly well technically, environmentally and financially. The Bucher press is essential in making the drying options feasible as without the waste heat is insufficient, particularly with the drying only option. Issues with classifying dried sewage sludge as fuel via 'end of waste' do restrict the potential application, but this work shows the potential benefit if the legislation were to change. Combining drying with pyrolysis post THP AD provides the best solution for the UK, with the best overall environmental, technical and economic outcome.

4. What is the UK potential?

This section is very important as it frames the rest of the project and shows where it could lead if its recommendations were widely adopted in the UK.

4.1 UK Renewable Energy Policy

The Electricity Act was implemented in 1989 to privatise the industry, within this legislation the Non Fossil Fuel Obligation (NFFO), originally set up to support nuclear power, was instigated. The auction based system opened the market to renewable generators, and although the early system had many short falls and targets were never met, this early legislation built a small but successful renewables industry, mostly based around landfill gas and biomass generation (Simmonds 2002). In 2002 the industry was reformed again and the Renewables Obligation (RO) replaced the NFFO. The targets RO were more aspirational and the incentives more encouraging, (generators receive about £45/MWh). The RO scheme was banded in 2009 to ensure emerging technologies are more supported than mature types. Sewage sludge AD receives 0.5ROC/MWh or about £22MWh. Going forward the RO will be replaced with Feed in Tariffs (FiTs) and Contract for Difference (CfD). Despite operating differently, these incentives remain roughly the same for each MWh generated using sewage sludge and other biomass fuels.

4.1.1 Biomass and sewage sludge

Figure 74 shows how biomass generation has grown since 1990, the growth in landfill gas is quite incredible, and the response to co-firing from 2002 onwards is credit to the RO scheme that generally has received criticism for not delivering (Gross 2010; Woodman and Mitchell 2011). The success in these other industries has not been replicated in the water industry and sludge power generation is dwarfed in comparison; sludge has seen only 105% growth since 1990 compared with 1,696% growth seen in landfill gas (DECC-ii 2011).

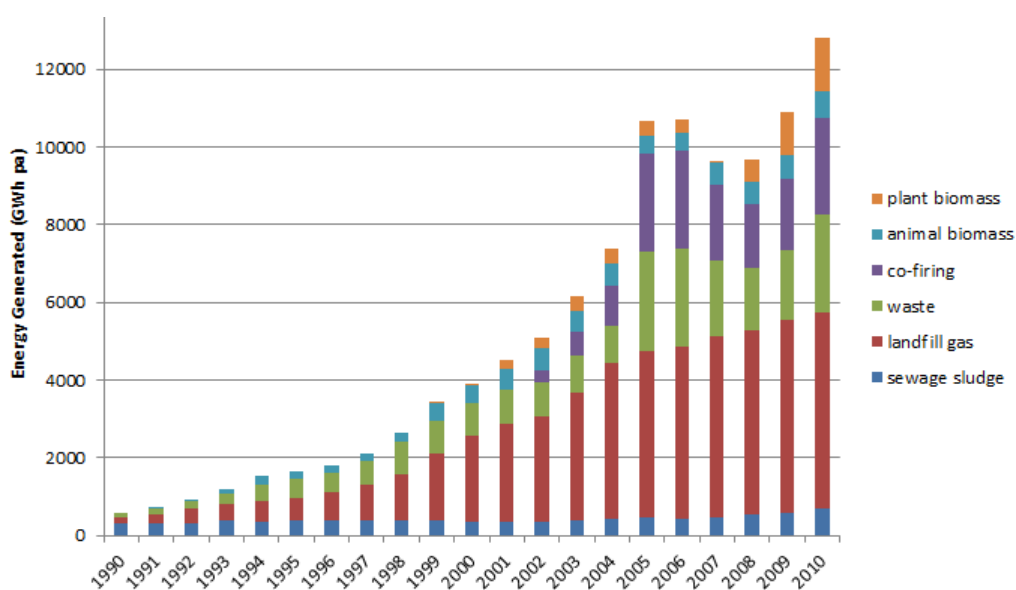


Figure 76 - Renewable Electricity from Biomass in the UK, source data from (DECC-ii 2011)

The lack of growth from sewage sludge generation could be blamed, at least in part, on the complexity of the regulation in the water industry. An independent analysis for DECC claims constraints on cash flow result in low payback on investment mainly due to financial restrictions from regulation (AEA 2010), although there are signs that regulatory change is coming to resolve some of these constraints (OFWAT 2011). This work by AEA in part has justified the reduction in support for sewage sludge generation which now receives half the RO subsidy it received in 2010. The basic analysis for DECC does not consider the current and potential advances in technology that would increase the invest-ability of future schemes.

4.2 Energy Potential in the UK

This lack of detailed understanding of the water industry by DECC presented an opportunity and thanks to the support from Royal Commission of 1851 a secondment project was delivered to DECC which aimed to:

- Provide detail on current practice in sludge to energy across the UK.
- Model the deployment of current and future technologies across the UK.
- Understand the sensitivity of deployment to the renewable energy incentives.

4.2.1 Current Practice

Data of the UK 'sludge to energy' asset base was collected through WaterUK. This consisted of data on sludge production, existing processes and generation assets. The data collection survey did not receive a 100% returns so using OFWAT data gaps in the data where filled. The UK water industry has 158 sites which have sludge to energy technology situated on them the size of which ranges from 4TDS/d to 300TDS/d. The data showed the UKs annual sludge production is around 1.75 MtDS and that approximately 80% is utilised in an energy recovery technology. The total installed generation capacity on these 158 sites is approximately 150MWe generating 761GWh pa of electrical power in 2014 along with a single gas to grid plant. The collected data suggests that an estimated 906GWh will be generated in 2015 due to a number of new sites being commissioned mainly on Thames Water sites.

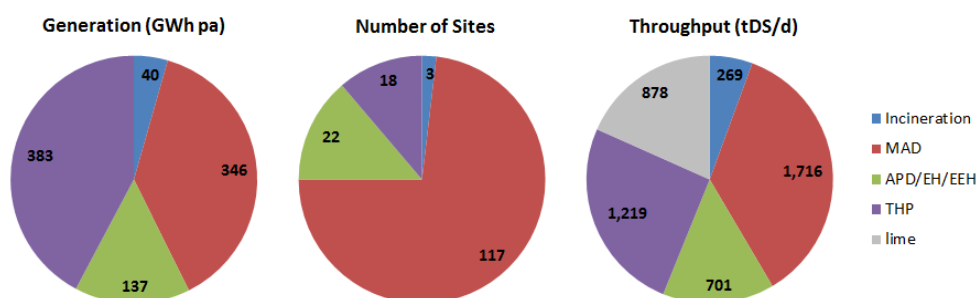


Figure 77 - Generation technologies by output, number of sites and throughput for the 2015 baseline

Figure 75 shows the split of the AD technology by power generation output, sites and throughput, it shows the dominance of THP which has the largest output (400GWh pa) from just 18 sites, the average site size is 68tDS/d with a 2.5MWe generator. There are a total of 117 traditional MAD sites generating at total of 340GWh pa. The average site is

smaller just 15tDS/d with a 300kWe generator. The advanced biological AD (APD, EH & EEH) produce 137GWh pa across 22 sites and are an average size of 32tDS/d with a 700kWe generator. Incineration has the smallest output (40GWh pa) across just 3 sites with an average throughput of 90tDS/d.

4.2.2 Modelling

A model was created using the collected data on the existing 158 generation sites processing 80% of UK sludge. The remaining 20% was assumed to be processed through a liming operations, information on liming operations was not requested and is difficult to ascertain as many are temporary. For the model a normal size distribution was applied to the remaining 880tDS/d across 26 liming sites ranging from 155 to 7 tDS/d in size.

The baseline data for these 184 sites was then used to model a number of scenarios, for DECC, those of most interest to this project were:

1. All existing MAD, lime and incinerator sites upgraded to THP.
2. All existing MAD, lime and incinerator sites (over 10tDS/d) upgraded to THP with pyrolysis and pyrolysis installed post THP on existing THP sites (over 10tDS/d).
- Both scenarios were also modelled with ITHP instead of conventional THP.

For each site the throughput and current technology is listed and using predetermined assumptions (Appendix A) the digestate mass, generation output, revenue and OpEx for each site is calculated. Depending upon the scenario and existing technology a decision is made by the model to whether the site is considered for an upgrade. The model then calculates for sites selected for consideration the new generation output, new OpEx position and CapEx required to upgrade the site. This allows the economic metrics to be calculated including IRR, NPV and payback period so that the viability of each investment can be assessed and sites/projects screened with undesirable payback periods (over 9.5 years). The model then returns the economic deployment for each scenario and provides a new total throughput, generation output, number of sites upgraded, CapEx and OpEx changes from the new investment. The model also allows the user to change the financial incentives for renewable energy for each technology scenario. This was particularly useful in informing DECC on the impact of changing future incentives on the deployment of various technologies.

Finally it was also requested that 'levelised cost' was calculated so a comparison can be drawn with other generation technology. Levelised cost is the discounted cost of generating electricity at the generator terminals. It includes the 'CapEx', the discount factor, 'r', and 'OpEx' over the life of the project, 't', in years. The equation excludes any revenue but includes the savings on disposal (sludge displacement), 'DispOpEx', over the life of the plant.

$$Levelised\ Cost = \frac{\sum_{t=1}^n \frac{[CapEx_t + OpEx_t - DispOpEx_t]}{(1+r)^t}}{\sum_{t=1}^n \frac{E_t}{(1+r)^t}}$$

4.2.3 Results

Figure 76 displays the results of the deployment modelling for scenarios 1&2 utilising conventional THP. In addition the technology limit is shown, assuming 100% of UK's sludge was processed with THP followed pyrolysis with no deployment or economic restrictions.

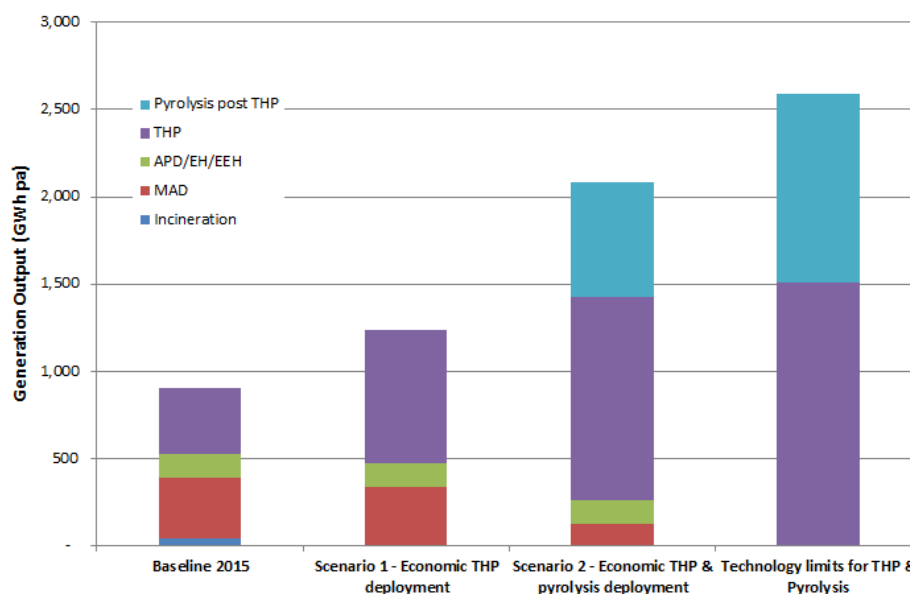


Figure 78 - UK Deployment potential of Energy from Sewage sludge technologies

It can be seen that a dramatic increase in generation is technically feasible, from a baseline of 906GWh the technological limit of THP followed by pyrolysis is 2,591 GWh pa. When the economic filter is applied under scenario 2, the output is 2,084 GWh pa and under scenario 1 the output is 1,237 GWh pa.

Analysing the scenario 1 in more detail (Figure 77) it can be seen that incineration has now been replaced by THP and all of the lime sites have been converted. In this scenario a total of 29 sites are developed for a CapEx of £558m and an average IRR of 10.7%.

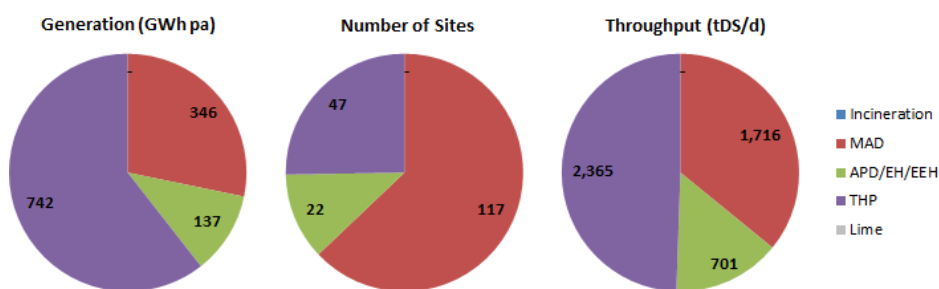


Figure 79 - Generation technologies by output, number of sites and throughput under Scenario 1

Analysing scenario 2 in more detail (Figure 78) it can be seen that incineration has now been replaced by THP as with scenario 1, along with 34 MAD sites and 82% of the lime sites have been converted to THP & pyrolysis. In this scenario a total of 67 sites are developed for a CapEx of £1,584m and an average IRR of 11%. As subsequent analysis has shown the

combination of THP and pyrolysis is a more attractive investment than THP alone. This is the reason why the so many more sites are developed in scenario 2.

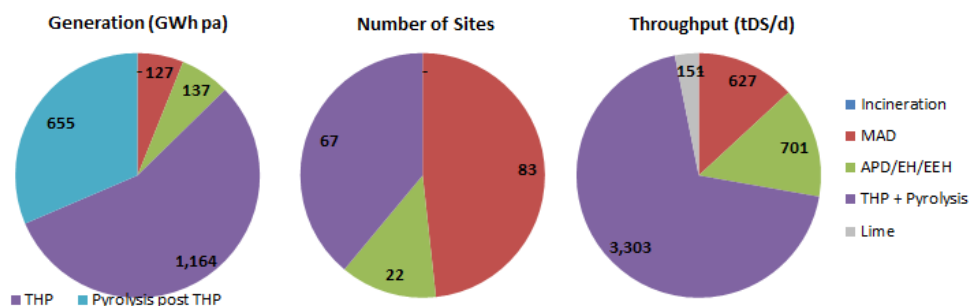


Figure 80 - Generation technologies by output, number of sites and throughput under Scenario 2

ITHP was also modelled for both scenario 1&2 the process improves both the generation output and the economic case. For scenario 1 the total UK generation is now increased to 1,321 GWh pa utilising ITHP across the same 29 sites an increase 95GWh pa and the IRR is now 12.1%. Scenario 2 is also improved the total generation output is 2,216GWh pa with an improvement in IRR at 11.3%.

When the renewable energy incentives are set to zero the deployment is dramatically reduced as shown in figure 79, which reveals only 57GWh pa is gained in scenario 1 and 113GWh in scenario 2.

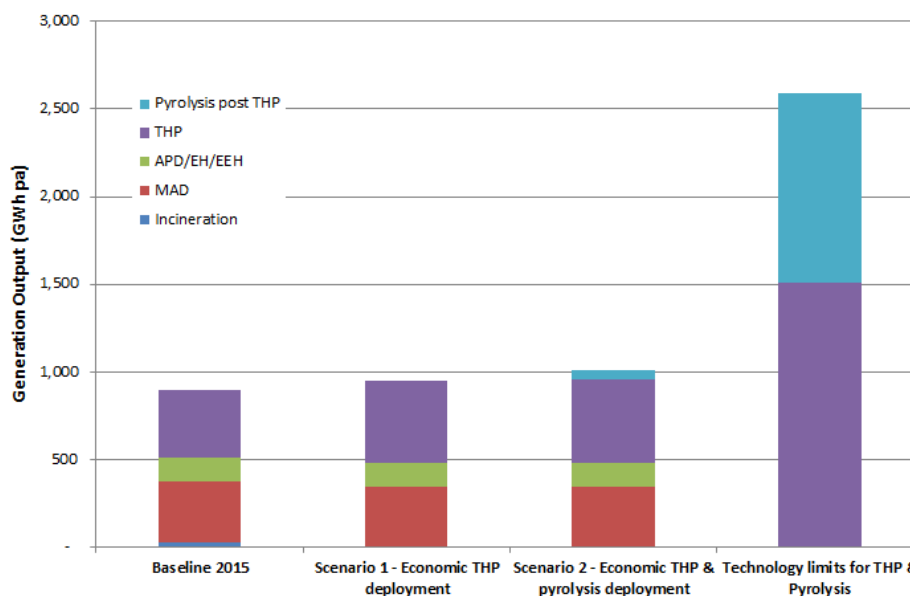


Figure 81 - UK Deployment potential of Energy from Sewage sludge technologies without energy incentives

This small deployment increase is mainly from the incinerator sites with high operational costs where the business case stands without the energy incentive. Based on this analysis it can be concluded that a level of incentive is essential for significant future deployment of sewage sludge to energy technology in the UK.

To help policy makers decide on an appropriate incentive mechanism, levelised cost is used. Figure 80 shows the levelised cost for the options explored in the economic deployment model. It can be seen that all but the pyrolysis bolt on option are competitive with other renewable technologies such as biomass or wind.

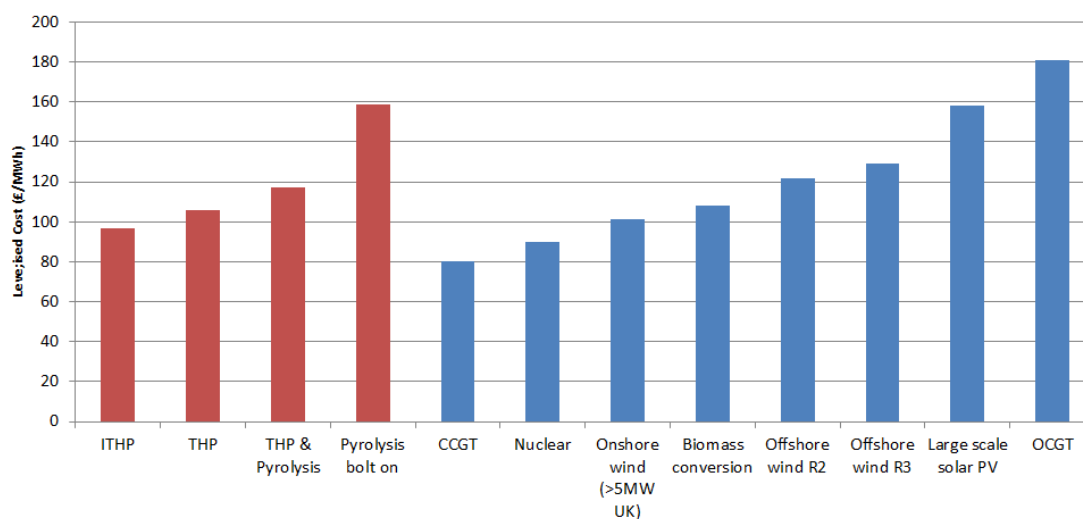


Figure 82 – Levelised cost of generation for sewage sludge and other technologies

4.2.4 Conclusion

This analysis has revealed that it is economically feasible for the UK to increase its renewable electricity generation from sludge to 2,216GWh pa by applying ITHP and pyrolysis post digestion or an additional 1,310GWh pa. The levelised cost of generation is competitive with other forms of renewable electricity generation and therefore it is argued that existing or equivalent incentives should remain in place for sewage sludge to energy processes.

5. Conclusion

The main objectives of this research project were to investigate & develop technologies and processes, physically and analytically to produce results that contribute to knowledge and move the water industry forward. This has been achieved. Until recently technologies and processes for further energy recovery have not been efficient or economically viable for large-scale use, but this research has shown that developments and innovations are now available and can realistically be brought into use. Using a combination of detailed techno-economic analysis and several large scale demonstration plants this research has shown that the renewable electricity produced from sewage sludge in the UK could be substantially increased to 2,216GWh pa or an additional 1,310GWh pa.

5.1 How Sustainable are Existing Processes?

The project has proven that THP has clear technical, economic and environmental advantages over conventional AD and incineration and supports the current trend in the industry to build THP. It should be said however that conventional AD is an efficient energy recovery processes with a low parasitic energy demand.

Incineration is a very costly to build and operate and has a poor net energy yield. Also in reality it does require significant quantities of support fuel. Incineration has no real future in the industry other than in extreme situations where there are considerable problems/costs with recycling sludge to agricultural land.

Utilising the biogas generated in AD in CHP is the preference due to the demand for heat on site and the insulation provided by the relatively high value of electricity. GtG should probably be avoided due to the poor environmental performance and financial risk posed by proportionally high renewable incentives. These may be removed or adjusted before a project could be commissioned and accredited and therefore represents a large investment risk. Upgrading biogas to a bio-methane suitable for transport fuel might be a better solution, requiring fewer incentives due to the relatively high price of transport fuels and displacing a carbon intensive fuel would be more environmentally beneficial, this is commonly seen in the EU. However, there may be a point in the future where the electricity grid carbon intensity maybe reduced to a level where the production of bio-methane for grid injection would be favourable environmentally over the more traditional electricity production.

5.2 What does the future look like?

THP is a very effective proven technology and should be the base for further advances in AD based energy recovery. Steam explosion clearly has a positive effect on THP based on the laboratory tests conducted as part of the project and the economic analysis shows it should be explored further and exploited. SASonly THP offers a lower CapEx alternative that provides most of the benefits that THP delivers. ITHP is the most efficient AD based energy recovery option. It does require additional CapEx but the overall investment is superior to all other AD based options. The Thames Water ITHP pilot plant has yet to reach a period of

sustained steady state. All of the technical process modelling and economic analysis is based on the performance observed in the laboratory under stable conditions.

All of the future AD based options are economically robust to changes in digestion CapEx and digestate disposal costs. Renewable energy incentives are required to maintain conventional AD economically feasible and without incentives THP and SASonly THP would be difficult to justify. All AD based options show an improvement in GWP and environmental impact over conventional MAD, but there are only minor differences between THP variants as it is basically the same process.

The post AD drying options, for fuel production or prior to pyrolysis, both perform incredibly well technically, environmentally and financially. The drying trials at Slough were instrumental in returning confidence to the industry which has had a troubled past with sludge drying. The scale of the Slough demonstration unit also proved that fuel could be beneficially utilised in the large incinerators. Unfortunately, the paddle drying technology used is not suitable for large scale application because of its medium grade heat demand. But the low temperature dryer technology is perfectly suited to utilise low grade waste heat available on a THP plant. The Bucher press is essential in making the low temperature drying options feasible as without it the waste heat is insufficient to provide full drying.

The drying for fuel option is very promising but issues with classifying dried sewage sludge as fuel via 'end of waste' do restrict the potential application. This work does show the potential benefit if the legislation were to change. Combining drying with pyrolysis post THP AD provides the current optimum solution, with the best overall environmental, technical and economic outcome.

5.3 What is the UK potential?

This bottom up analysis, with DECC, of the UK sewage sludge asset base has revealed that the UK could almost triple its renewable electricity generation from sewage sludge by applying second generation THP (ITHP) and drying with pyrolysis post THP AD. The average levelised cost of generation is competitive with other forms of renewable electricity generation.

5.4 Summary of Conclusions

Figure 81 aims to summarise the project journey which started top left with the existing processes. Conventional AD, THP and incineration were explored along with biogas utilisation in CHP or GtG. Incineration was dismissed relatively early mainly due to the economics along with GtG which should be avoided. THP provides large benefits so it was explored in more detail and 2nd generation THP developed, particularly the ITHP process. Drying post digestion showed great promise unfortunately it is not currently practical with medium temperature dryers or any dryer technology on conventional AD site. However, when low temperature dryers are combined with THP the heat balance works. Drying to produce a fuel for a third party is currently restricted by legislation, but the process steps led the project to advanced energy recovery with pyrolysis post THP AD.

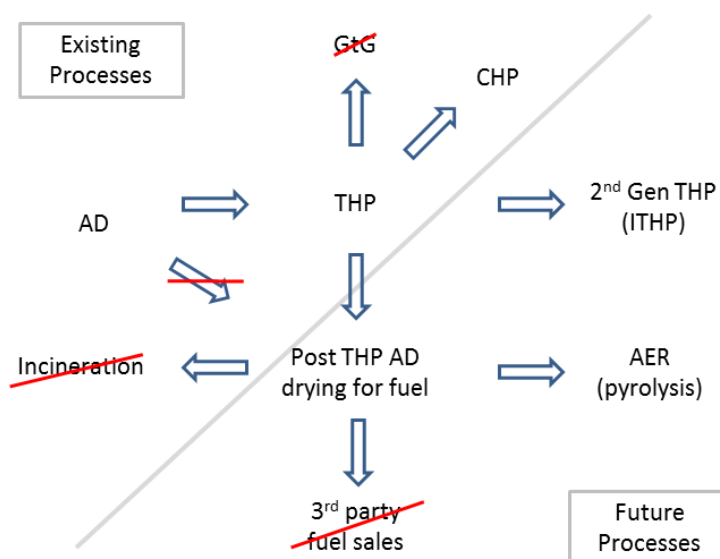


Figure 83 – Summary of Options Explored during the Project

A typical conventional AD site will achieve 15% conversion efficiency; a THP will improve this to 20%. ITHP boasts recovery to 23% with other benefits such as reduced support fuel requirements and sludge transport volumes. By combining THP, drying and pyrolysis a 34% gross conversion efficiency to electricity is achievable with a positive environmental impact and very attractive returns on investment. By economically deploying a combination of the technologies developed as part of this project the UK could generate 2,216GWh pa an additional 1,310GWh pa.

6. Recommendations for Future work

- Incineration should not be considered as a viable sludge to energy technology.
- GtG should be avoided; the preference should be CHP which has better synergies with application on sewage sludge to energy processes.
- Steam explosion clearly has a positive effect on THP, based on the laboratory tests, the economic analysis shows it would be worth exploring in more detail.
- The ITHP pilot plant should be operated until steady state is reached to ensure good data capture. Results should be modelled and conclusions published.
- Effort should be made to explore opportunities to utilise GRSF and overcome the barriers caused by waste legislation.
- A full scale advanced energy recovery plant should be built to demonstrate and prove the concept to the industry.
- Renewable energy incentives should be maintained or enhanced for sewage sludge to energy technology to ensure future deployment predictions become reality.

7. References

- Abbott, J. (2004), 'Yorkshire Water's Sewage Sludge Incinerators upgrade at four plants to meet Directive', *Wastewater Treatment & Sewerage*, 2004, 37-39.
- AEA (2010), *UK and Global Bioenergy resource – Annex 1 report: details of analysis* (Oxford).
- Andrews, A. 'The wasted potential of anaerobic digestion in the water industry', <http://www.utilityweek.co.uk/news/news_story.asp?id=39692&title=The+wasted+potential+of+anaerobic+digestion+in+the+water+industry>, accessed 4/03/2012.
- Anthony, E. J. (1995), 'Fluidized bed combustion of alternative solid fuels; status, successes and problems of the technology', *Progress in Energy and Combustion Science*, 21 (3), 239-68.
- Appels, L., et al. (2008), 'Principles and potential of the anaerobic digestion of waste-activated sludge', *Progress in Energy and Combustion Science*, 34 (6), 755-81.
- Barber, W.P. (2010), 'Factors Influencing Energy Generation from Municipal Sludge Digestion', *15th European Biosolids and Organic Resources Conference* (Leeds: Aqua Enviro Technology Transfer).
- Basu, P. (2010a), 'Chapter 5 - Gasification Theory and Modeling of Gasifiers', in Prabir Basu (ed.), *Biomass Gasification and Pyrolysis* (Boston: Academic Press), 117-65.
- (2010b), 'Chapter 3 - Pyrolysis and Torrefaction', in Prabir Basu (ed.), *Biomass Gasification and Pyrolysis* (Boston: Academic Press), 65-96.
- Bowen, A, et al. (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*.
- Bridgwater, A. V. (2012), 'Review of fast pyrolysis of biomass and product upgrading', *Biomass and Bioenergy*, 38 (0), 68-94.
- Bruno, B. (2011), 'Incineration vs Thermal Hydrolysis', *16th European Biosolids and Organic Resources Conference* (Leeds: Aqua Enviro Technology Transfer).
- Cambi (2014), 'Cambi - Recycling Energy - Unleash the Power of Anaerobic Digestion', <<http://www.cambi.no/wip4/detail.epl?cat=10636>>, accessed 04/03/2014.
- Cao and Pawłowski (2012), 'Sewage sludge-to-energy approaches based on anaerobic digestion and pyrolysis: Brief overview and energy efficiency assessment', *Renewable and Sustainable Energy Reviews*, 16 (3), 1657-65.
- Carballa M, Duran C, and Hospido A (2011), 'Should We Pretreat Solid Waste Prior to Anaerobic Digestion? An Assessment of Its Environmental Cost', *Environmental Science & Technology*, 45 (24), 10306-14.
- Company_B (2014), 'Sewage sludge trials findings & authorised sampling results for Thames Water'.
- Company_E (2014), 'Report to Thames Water on the Gasification Trials of Densified Sewage Sludge'.
- Coombs, E.P. (1992), 'Activated Sludge Ltd - The Early Years', *Published privately by C.R. Coombs, Bournemouth, Dorset, UK*.
- Cooper, P. F. (2001), 'Historical aspects of wastewater treatment', in Piet N. L. Lens Piet Lens, Grietje Zeeman, Gatzke Lettinga (ed.), *Decentralised sanitation and reuse: concepts, systems and implementation* (IWA Publishing).
- Dalemo, M., et al. (1997), 'ORWARE – A simulation model for organic waste handling systems. Part 1: Model description', *Resources, Conservation and Recycling*, 21 (1), 17-37.

- DECC-ii (2011), 'Renewable sources used to generate electricity, heat and for transport; electricity generation from renewable sources', in *DUKES_2011_Long_Term_Trends* (ed.).
- DECC (2011), 'Renewable Heat Incentive', in *Department_for_Energy_&_Climate_Change* (ed.), (London: DECC), 34-42.
- Devki (2006), *Best Practice Manual: Dryers* (Devki Energy Consultancy).
- Domínguez A, Menéndez J, and J, Pis (2006), 'Hydrogen rich fuel gas production from the pyrolysis of wet sewage sludge at high temperature', *Journal of Analytical and Applied Pyrolysis*, 77 (2), 127-32.
- Dubois, M., et al. (1956), 'Colorimetric method for determination of sugars and related substance', *Analytical Chem*, 28 (93), 350-56.
- EA (2009), 'England and Wales - Incineration Inputs and Capacity 2009 (Excel, 69KB) ', in *Environment Agency* (ed.).
- EC (1998), 'Commission of European Communities. Council Directive 91/271/EEC of 21 March 1991 concerning urban waste-water treatment (amended by the 98/15/EC of 27 February 1998).'
- ECN 'Phyllis2 Database for biomass and waste', <<https://www.ecn.nl/phyllis2/>>, accessed 1/07/2014.
- Firth, W. (2014), 'A technical assessment of dried sewage sludge for end of waste requirements', (Sustainable Resource Solutions).
- Flaga, A. (2005), 'Sludge Drying', (Krakow: Institute of Heat Engineering and Air Protection, Cracow University of Technology).
- Fountain, P (2008), 'Sludge Workshop 2008 - Getting the most from Digestion', (Senior Consultant - Thames Water).
- Giacalone S, Winter P, and Smith S (2014), 'Anaerobic Digestion, there is still room for improvement', in *Aquaenviro* (ed.), *19th European Biosolids & Organic Resources Conference & Exhibition* (Manchester: Aquaenviro).
- Greer, D. (2010), 'Gas Quality Considerations: Fundamentals of Biogas Conditioning and Upgrading', *BioCycle Energy*.
- Gross, R (2010), 'Time to stop experimenting with UK renewable energy policy', (Imperial College Centre for Energy Policy and Technology).
- Gunnerson C and Stuckey D (1986), 'Anaerobic digestion – principles and practices for biogas systems', *The World Bank, Washington, DC, USA*, World Bank Technical Paper 49.
- Hand-Smith, G (1999), 'INCINERATION Sludge disposal: the future of high-tech sludge incineration', *Wastes Management*, March 1999, 41-42.
- Hawkes, A.D. (2011), 'Techno-economic assessment of small and micro combined heat and power (CHP) systems', in Robert Beith (ed.), *Small and micro combined heat and power (CHP) systems* (1 edn.; Oxford: Woodhead Publishing Limited), 60-68.
- HMGovernment (1989), 'The Sludge (Use in Agriculture) Regulations 1989', (1989 no. 1263: HM_Government).
- Horn, Svein J., et al. (2011), 'Screening of steam explosion conditions for glucose production from non-impregnated wheat straw', *Biomass and Bioenergy*, 35 (12), 4879-86.
- HSE (2011), 'Health & Safety Executive - Operational Circular 847/9: Sewage Sludge Drying Plant', in *Field_Operations_Directorate* (ed.).
- Huppert, M., et al. (2011), 'Top range dewatering of digested and THP sludge with Bucher HPS press in the UK', in *aquaenviro* (ed.), *16th European Biosolids & Organic Resources* (Leeds).
- Jones, D (2008), 'Bristol (Avonmouth) STW: £35m scheme increases electrical self generation at sludge centre', *UK Water Projects Online: Wastewater Treatment & Sewerage*, 2008 (1), 75-77.

- Jury, C., et al. (2010), 'Life Cycle Assessment of biogas production by monofermentation of energy crops and injection into the natural gas grid', *Biomass and Bioenergy*, 34 (1), 54-66.
- Kasakura, T and Hiraoka, M (1982), 'Pilot plant study on sewage sludge pyrolysis—I', *Water Research*, 16 (8), 1335-48.
- Kazuyuki, I, et al. (2000), 'Influences of application of sewage sludge compost on N₂O production in soils', *Chemosphere - Global Change Science*, 2 (3-4), 329-34.
- Kelessidis A. and Stasinakis A. (2012), 'Comparative study of the methods used for treatment and final disposal of sewage sludge in European countries', *Waste Management*, 32 (6), 1186-95.
- Kepp (2000), 'Enhanced stabilisation of sewage sludge through thermal hydrolysis – three years of experience with full scale plant', *Water science and technology*, (42), 89 - 96.
- Lee, K. (2010), 'Calorific Value Analysis 2010', (Thames Water, Research & Development).
- Liu, Beibei, et al. (2013), 'Life cycle GHG emissions of sewage sludge treatment and disposal options in Tai Lake Watershed, China', *Science of The Total Environment*, 447 (0), 361-69.
- Liu, Qiang, et al. (2011), 'Life cycle assessment of an industrial symbiosis based on energy recovery from dried sludge and used oil', *Journal of Cleaner Production*, 19 (15), 1700-08.
- Lundin, M., et al. (2004), 'Environmental and economic assessment of sewage sludge handling options', *Resources, Conservation and Recycling*, 41 (4), 255-78.
- Malkow, Thomas (2004), 'Novel and innovative pyrolysis and gasification technologies for energy efficient and environmentally sound MSW disposal', *Waste Management*, 24 (1), 53-79.
- McNamara, P. J., et al. (2012), 'The effect of thermal hydrolysis pretreatment on the anaerobic degradation of nonylphenol and short-chain nonylphenol ethoxylates in digested biosolids', *Water Research*, 46 (9), 2937-46.
- Meier, D, et al. (2013), 'State-of-the-art of fast pyrolysis in IEA bioenergy member countries', *Renewable and Sustainable Energy Reviews*, 20 (0), 619-41.
- Merry, J and Oliver, B (2014), 'A Comparison of read AD plant performance: Howden, Bran Sandsm Cardiff and Afan', *19th Biosolids & Organic Resources Conference & Exhibition* (Manchester: AquaEnviro).
- Metcalf and Eddy (2003a), 'Wastewater Treatment', *Wastewater Engineering* (4th edn.: McGraw Hill).
- (2003b), 'Treatment, Reuse, and Disposal of Solids and Biosolids', *Wastewater Engineering* (4th edn.: McGraw Hill).
- Mills, N., et al. (2011a), 'Optimising Sustainable Energy Production within the Water Industry', *University of Surrey EngD Conference* (Guildford).
- (2011b), 'The Influence of Heat Balance on the Economics of Advanced Anaerobic Digestion Processes', *16th Biosolids & Organic Resources Conference & Exhibition* (Leeds: AquaEnviro).
- (2012a), 'Preliminary Life Cycle Assessment of Advanced Anaerobic Digestion Configurations', *University of Surrey EngD Conference* (Guildford).
- (2012b), 'Life Cycle Assessment of Advanced Anaerobic Digestion Process Configurations for Sewage Sludge - A UK Perspective', *4th Symposium of Energy from Waste* (Venice: Elsevier, Journal of Waste Management).
- (2012c), 'Granular Renewable Solid Fuel Trials in a Fluidised Bed Incinerator', *17th Biosolids & Organic Resources Conference & Exhibition* (Leeds: AquaEnviro).
- (2014a), 'Environmental & economic life cycle assessment of current & future sewage sludge to energy technologies', *Waste Management*, 34 (1), 185-95.

- (2014b), 'Second Generation Thermal Hydrolysis Processes', in Water & Environment Federation (ed.), *Biosolids & Residuals* (Austin, Texas, USA: WEF).
- (2014c), 'Advanced Energy Recovery', *19th Biosolids & Organic Resources Conference & Exhibition* (Manchester: AquaEnviro).
- Nexterra (2015), 'Nexterra - gasification technology projects',
<<http://www.nexterra.ca/files/projects.php>>, accessed 17/01/2015.
- Niu, D, et al. (2013), 'Greenhouse gases emissions accounting for typical sewage sludge digestion with energy utilization and residue land application in China', *Waste Management*, 33 (1), 123-28.
- OFWAT (2011), 'Sustainable sludge – project update', in Office for Water Supply (ed.), (London).
- Palmer, S.J. (2010), 'Future Challenges to asset investment in the UK water industry: the wastewater asset investment risk mitigation offered by minimising the principle operating cost risks', *International Water Association: Journal of Water and Climate Change*, 1 (1), 17-35.
- Palmer, S.J., Maclaren, J., and Ord, J. (2013), 'Advanced Energy Recovery from sewage sludge a comparative technology study', in Aquaenviro (ed.), *18th European Biosolids and Organic Resources* (Manchester).
- Pearce, P. (2009), 'A Framework Strategy For Energy - Wastewater, Identification of Research Needs', (Research & Development, Thames Water Utilities Limited).
- Perrault, A., et al. (2015), 'Steam Explosion of Sludge in the THP process', *SludgeTech 2015* (University of Surrey, Guildofrd).
- Pickworth, B., et al. (2006), 'Maximising biogas in anaerobic digestion by using engine waste heat for thermal hydrolysis pre-treatment of sludge', *Water Science and Technology*, 54 (5), 101-08.
- Poeschl M, Ward S, and Owende P (2012), 'Environmental impacts of biogas deployment – Part I: life cycle inventory for evaluation of production process emissions to air', *Journal of Cleaner Production*, 24 (0), 168-83.
- Ray R, Taylor R, and Chapman C (2012), 'The deployment of an advanced gasification technology in the treatment of household and other waste streams', *Process Safety and Environmental Protection*, 90 (3), 213-20.
- Ryckebosch, E., Drouillon, M., and Vervaeren, H. (2011), 'Techniques for transformation of biogas to biomethane', *Biomass and Bioenergy*, 35 (5), 1633-45.
- Shana A, Fountain P, and Mills N (2013), 'SAS only THP with series digestion – More options for energy recovery', in AquaEnviro Technology Transfer (ed.), *18th European Biosolids & Organic Resources Conference & Exhibition* (Manchester, UK).
- Shana, A., et al. (2011), 'Application of an Innovative Process for Improving Mesophilic Anaerobic Digestion of Sewage Sludge', *16th European Biosolids and Organic Resources Conference* (Leeds: Aqua Enviro).
- (2012), 'A Study Of The Impact Of An Innovative Intermediate Thermal Hydrolysis Process On The Performance Of Anaerobic Sewage Sludge Digestion Process', *IWA World Congress on Water, Climate and Energy* (Dublin, Ireland).
- Shana, A., et al. (2013), 'The impact of intermediate thermal hydrolysis on the degradation kinetics of carbohydrates in sewage sludge', *Bioresource Technology*, 137 (0), 239-44.
- Simmonds, G (2002), 'Regulation of the UK Electricity Industry', (Bath: Centre for the Study of Regulated Industry - University of Bath).
- Sinnott, R., Towler, G. (2009), 'Costing and Project Evaluation', *Chemical Engineering Design: SI edition* (5 edn.; Oxford: Butterworth-Heinemann), 247.
- Smith, A (April 2008), 'Jobs go as Severn Trent closes Coleshill plant', *Birmingham Mail*
<<http://www.birminghammail.net/news/solihull-news/2008/04/04/jobs-go-as->

- [severn-trent-closes-coleshill-plant-97319-20721573/>](#), accessed 16th September 2012.
- Sonesson, U., et al. (1997), 'ORWARE – A simulation model for organic waste handling systems. Part 2: Case study and simulation results', *Resources, Conservation and Recycling*, 21 (1), 39-54.
- Starr, K, et al. (2012), 'Life cycle assessment of biogas upgrading technologies', *Waste Management*, 32 (5), 991-99.
- Stelte, W (2013), 'Steam explosion for biomass pre-treatment', (Danish Technological Institute).
- Suh, Y and Rousseaux, P (2002), 'An LCA of alternative wastewater sludge treatment scenarios', *Resources, Conservation and Recycling*, 35 (3), 191-200.
- Tchobanoglous, G., Thesen, H., Vigil, S.A. (1993), 'Integrated Solid Waste Management - Engineering Principles and Management Issues', (McGraw-Hill Book Company, New York).
- TWUL-i 'Mogden Sewage Treatment Works',
<[, accessed 17/01/2015.](http://www.thameswater.co.uk/cps/rde/xchg/corp/hs.xsl/13550.htm#>, accessed 1.3.2011.</p>
<p>TWUL-ii (2011), 'Thames Water Annual Performance Report 2010/11', (Thames Water).</p>
<p>UK-Tenders (2015), 'FA1142 - Advanced Energy Recovery from Sludge, Thames Water Utilities Limited', <<a href=)
- Urciuolo, M., et al. (2012), 'Fluidized bed combustion and fragmentation of wet sewage sludge', *Experimental Thermal and Fluid Science*, 43 (0), 97-104.
- WaterUK (2010), 'Recycling of Biosolids to Agricultural Land', (Water UK).
- Werther, J. and Ogada, T. (1999), 'Sewage sludge combustion', *Progress in Energy and Combustion Science*, 25 (1), 55-116.
- Wilson, S. (2011), 'The Successful Implementation and Optimisation of Advanced Digestion for Dwr Crmru Welsh Water', *16th European Biosolids and Organic Resources Conferences* (Leeds: Aquaenviro).
- Winter, P. (2010), 'Parallel digestion of secondary and primary sludge', *15th European Biosolids and Organic Resources Conference* (Leeds: Aqua Enviro Technology Transfer).
- Winter, P., Mills, N., and Pearce, P. (2013), 'Low Temperature Belt Dryer - EU site visit report', (Thames Water - Innovation).
- Woodman, B. and Mitchell, C. (2011), 'Learning from experience? The development of the Renewables Obligation in England and Wales 2002–2010', *Energy Policy*, 39 (7), 3914-21.
- Yang, Y, Sharifi, Vida, and Swithenbank, Jim (2008), 'Mathematical modelling of sewage sludge incineration in a bubbling fluidised bed with special consideration for thermally-thick fuel particles', *Waste Management*, 28 (11), 2245-58.
- YW (2015), 'MP congratulates Yorkshire Water on aiming for energy-neutral sewage treatment works ', <[117](http://ywpublicaffairs.blogspot.co.uk/2013/06/mp-congratulates-yorkshire-water-on.html>, accessed 13th January.</p>
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