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Environmental & economic life cycle assessment of current & future sewage sludge to energy technologies

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ABSTRACT

The UK Water Industry currently generates approximately 800 GW h pa of electrical energy from sewage sludge. Traditionally energy recovery from sewage sludge features Anaerobic Digestion (AD) with biogas utilisation in combined heat and power (CHP) systems. However, the industry is evolving and a number of developments that extract more energy from sludge are either being implemented or are nearing full scale demonstration. This study compared five technology configurations: 1 – conventional AD with CHP, 2 – Thermal Hydrolysis Process (THP) AD with CHP, 3 – THP AD with bio-methane grid injection, 4 – THP AD with CHP followed by drying of digested sludge for solid fuel production, 5 – THP AD followed by drying, pyrolysis of the digested sludge and use of the both the biogas and the pyrolysis gas in a CHP.

The economic and environmental Life Cycle Assessment (LCA) found that both the post AD drying options performed well but the option used to create a solid fuel to displace coal (configuration 4) was the most sustainable solution economically and environmentally, closely followed by the pyrolysis configuration (5). Application of THP improves the financial and environmental performance compared with conventional AD. Producing bio-methane for grid injection (configuration 3) is attractive financially but has the worst environmental impact of all the scenarios, suggesting that the current UK financial incentive policy for bio-methane is not driving best environmental practice. It is clear that new and improving processes and technologies are enabling significant opportunities for further energy recovery from sludge; LCA provides tools for determining the best overall options for particular situations and allows innovation resources and investment to be focused accordingly.

1. Introduction

The UK Water Industry currently generates approximately 800 GW h pa of electrical energy from sewage sludge, a renewable by-product from wastewater treatment. This recovery of energy has until recently been mainly conducted using two methods: Anaerobic Digestion (AD) and incineration with energy recovery, both developed and deployed with achieving efficiencies in sludge disposal as the main driver (Barber 2010; Davis 1996). Incineration has not been considered in this study, as in the UK it is in decline due to very high operating costs.

Over the past 10 years significant development has been made in Anaerobic Digestion processes, which improves energy yields from this renewable resource, sewage sludge, which the industry has in abundance. These advanced processes have and are now being implemented at large scale across the UK and within Thames Water (Riches et al., 2010). At the same time drying sludge post digestion has been common place across Europe for over 20 years, especially in Germany where dried sludge is frequently used in coal-fired power stations and cement kilns (Fytili and Zabaniotou 2008; Kelessidis and Stasinakis 2012; Werther and Ogada 1999). Advanced energy recovery processes such as syngas pyrolysis and gasification are fast becoming feasible options post drying (Cao and Pawłowski 2012).

Life Cycle Assessment (LCA) studies on sewage treatment options pre-date these technological developments and are also questionable in depth as they do not consider process configuration in sufficient detail (Margareta Lundin and Morrison 2002). Therefore, a new LCA has been conducted alongside economic studies to assess advanced Anaerobic Digestion configurations and post drying recovery options.

2. Sludge to energy techniques

A comparison between several processes has been made and these are listed below:

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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
OpEx	Operational Expenditure
CapEx	Capital Expenditure
IRR	Internal Rate of Return
OFWAT	Office for Water Industry Regulation in the UK

1. Conventional AD with Combined Heat and Power (CHP) and land recycling of the digestate to agriculture (Conv. AD CHP).
2. Thermal Hydrolysis Process (THP) AD with CHP and land recycling of the digestate to agriculture (THP AD CHP).
3. THP AD with bio-methane injection or Gas to Grid (GtG) and land recycling of the digestate to agriculture (THP AD GtG).
4. THP AD with CHP, drying for fuel (THP AD CHP + Drying for fuel).
5. THP AD with CHP, drying and pyrolysis with CHP (THP AD CHP + Drying, Pyrolysis and CHP).

2.1. Conventional AD

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, encouraged by the EU sewage sludge directive 86/278/EEC and governed by the Sludge Use in Agriculture Regulations 1989. 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. 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, typical retention times range from 12 to 30 days. The final digestate is then dewatered to a cake of around 20%[1] Dry Solids (DS) and transported off site, generally for recycling on agricultural land (Suh and Rousseaux 2002). Fig. 1 shows the energy flows for a typical configuration with a CHP unit (referenced to 1 kgDS/h).

2.2. Advanced AD – THP

AD is widespread and an effective sludge treatment technique for the water industry, but it has limitations, particularly coping with Secondary Activated Sludge (SAS). Generally, installations have poor energy recovery and require large assets that are very capital intensive. 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 capital costs.
- Enhanced dewatering characteristics reducing transport costs and increasing the quality of product for farmers.

The most developed and widely applied AD techniques are thermal and biological hydrolysis, as hydrolysis is typically the rate limiting step of AD. Thermal Hydrolysis Process (THP) is the most widespread and the technology of choice for Thames Water to achieve future generation and carbon mitigation targets (TWUL 2009).

THP involves using a high temperature (165 °C) and pressure (7 barg) for 30 min to disrupt and solubilise sludge before feeding it to a conventional digester. The process also homogenises the sludge so that it is more digestible resulting in increased methane production and a smaller volume of digestate (Kepp 2000). Across the world there are 23 full scale THP sites either in operation or construction that will process 445,000 Tonnes of Dry Solids (TDS) p.a. (Cambi 2010).

However, the increase in biogas yield does not necessarily result in an overall net increase in energy per tonne digested. THP demands an input of high grade heat and additional electrical energy, when compared with conventional AD. The high grade heat demand typically outweighs the additional heat available from a CHP unit burning the biogas produced. All of the THP installations in the UK currently require additional support fuel (typically natural gas) to maintain the process (Mills 2011). Fig. 2 shows the energy flows for a typical configuration (referenced to 1 kgDS/h).

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 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)

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[1] Using centrifuge dewaterer, 30% DS achievable with more advanced technologies.

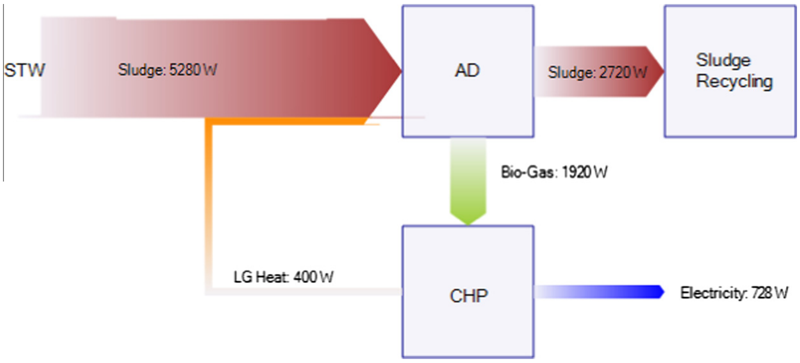

Fig. 1. Energy flows for conventional AD with CHP and land recycling (1 kgDS/h).

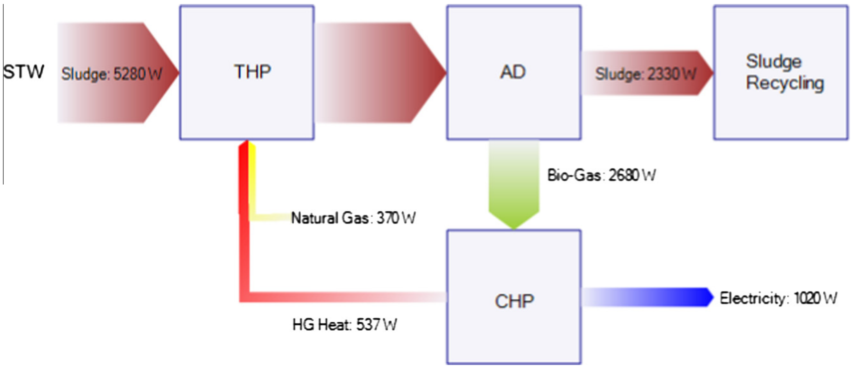

Fig. 2. Energy flows for THP AD with CHP and land recycling, CHP losses not shown (1 kgDS/h).

(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 and Diane, 2010; Starr et al., 2012). Fig. 3 shows the energy flows for a typical configuration (referenced to 1 kgDS/h).

A disadvantage of this process is that the heat required by the process (e.g. THP) 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. GtG LCA studies are few, but Jury et al. finds biogas injection from energy crop fermentation to be environmentally competitive with natural gas (Jury et al. 2010). 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%) but 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. This study aims to compare GtG and CHP as there has been no published material.

2.4. Drying post AD

To access the considerable chemical energy remaining in the sludge after AD, the sludge can either be burnt or be dried to produce a solid fuel product (Flaga, 2005; Niu et al., 2013). However,

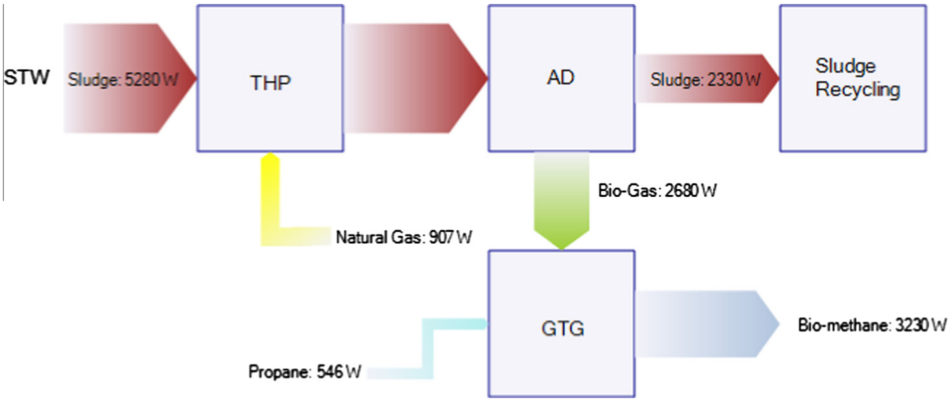

Fig. 3. Energy flows for THP AD with GtG and land recycling (1 kgDS/h) electricity input is not shown.

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 fuelled with fossil fuels, particularly the hot air drum dryer type which can create a lot of dust within a rotating drum with hot air at over 400 °C. This kind of dryer is inefficient and with current increased energy prices prohibitive economically. There are new drying technologies that are safe, efficient and able to utilise low grade waste heat. Low temperature belt dryers mainly developed in Germany or Spain are operational across Europe. The technology consists of a large perforated belt, inside a chamber where hot air (60–120 °C) heated with hot water is circulated up through the sludge which is extruded onto the belts at 20–40%DS; the dryer produces a 90%DS product.

2.4.1. Fuel production

This study has shown that it is technically feasible using a low temperature dryer to dry all of the digested sludge from a THP AD plant. If the THP digested sludge is dewatered to at least 42%DS it is feasible to dry the entire site output to 90%DS as there is sufficient waste low grade heat available from the CHP which is the rejected from the engine jacket at 80–100 °C (labelled 'LG Heat' on Fig. 4). Fig. 4 shows the energy flows for the configuration modelled as part of this study (referenced to 1 kgDS).

Within the EU dried sludge has been used as a fuel in coal fired power stations as the calorific value (CV) is benefical. Use of dried sludge as a fuel is a concept which Thames Water and others aspire to implement in the UK (Jones, 2008; Mills, 2012a). However, unlike in Germany where Regulations are more flexible, dried sludge would need either to be combusted in a Waste Incineration Directive (WID) compliant power station. Or be given 'end of waste' status, high concentrations of copper, zinc and ash relative to comparator fuels make this a challenge, but by controlling the feed sludge quality, by varying the blend ratio of primary and activated sludge, these issues could be resolved.

One of the potential draw-backs of deploying more advanced energy recovery processes (discussed in Section 2.4.2) is that they all essentially take place on the same site, in order to utilise process heat and avoid moving large quantities of wet sludge from site to site. However, some sites can have significant restrictions on land use, electricity export or planning restrictions. In some cases (as discussed in this section) site specific LCA may show it is more efficient to dry the fuel to 90% DS and then transport it to where it can be used most efficiently.

2.4.2. Advanced energy recovery

Once a dried product has been produced it opens up other utilisation options, such as pyrolysis and gasification technologies which have a high energy conversion efficiency (greater than 85%) to a syngas which can then be used in CHP units (Ray et al. 2012). Fig. 5 shows the energy flows for the configuration modelled as part of this study (referenced to 1 kgDS/h).

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). The only remaining byproduct from these processes is bio-char, which is environmentally stable and can be used beneficially as a soil conditioner or potentially as a source for mineral recovery. Under the right conditions pyrolysis has advantages over gasification producing a concentrated syngas which is as it more suitable for CHP (Bridgwater, 2012; Domínguez et al., 2006). In this scenario the waste heat from the pyrolysis CHP has not been utilised due to the added complexity of downstream reliance on upstream process heat. However, it is quite feasible to use the high grade exhaust heat to produce steam for the THP plant and displace natural gas support fuel.

3. Environmental life cycle analysis

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 observes 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 post-dating this paper (Lundin et al., 2004). 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 (Liu et al., 2011, 2013; Niu et al., 2013). The study by Carballa et al. is most applicable 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 this LCA is that all the operational performance data is scaled from laboratory work conducted using 10 l anaerobic digesters. An average size site would use 5000 m^3 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 et al. 2011).

3.1. Goal and scope

There is a need to conduct an LCA study that incorporates the advances in technology and subtleties in configuration especially those incorporating a drying step. The goal of this study is to evaluate the relative environmental and economic impact of the configurations

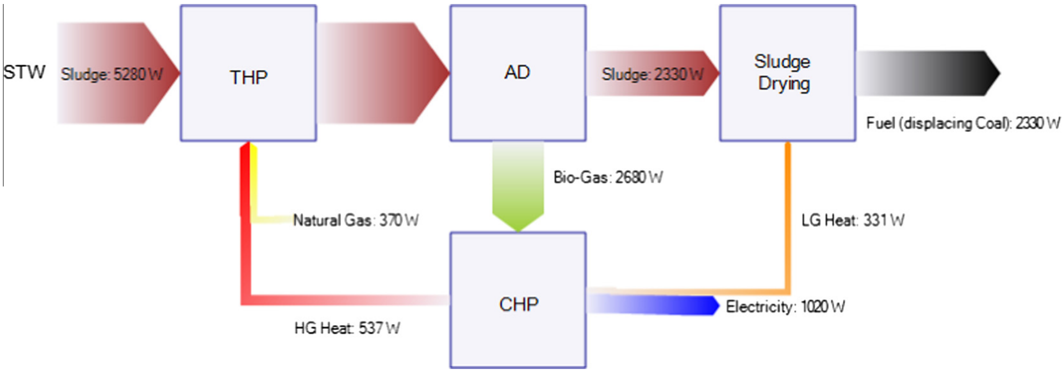

Fig. 4. Energy flows for THP AD, CHP and sludge drying for fuel production (1 kgDS/h) CHP losses not shown.

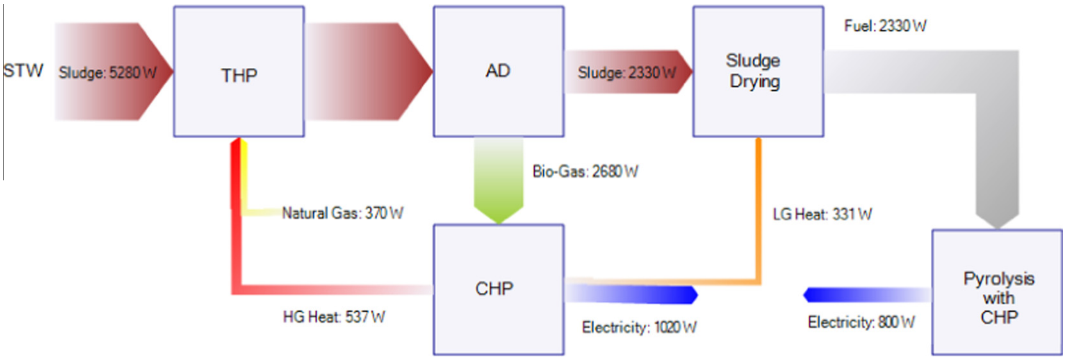

Fig. 5. Energy flows for THP AD, CHP and sludge drying and pyrolysis (1 kgDS/h) CHP Losses not shown.

to inform decision makers across the industry and to identify any inconsistencies or anomalies in policy. The functional unit used is the dry mass of sludge; Tonne Dry Solids (TDS). All sludge parameters and process assumptions are listed in Appendix A.

3.2. System boundaries

Fig. 1 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 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 CO_2, SO_2 Particulates, CO and NO_X emissions (Poeschl et al., 2012).

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 and N_2O) associated with the biodegradation of sludge cake in the soil (Inubushi 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.

3.3. Inventory

A commercial LCA package (GaBi) was used to construct a model for each of the 5 scenarios. Figs. 1–5 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 1 shows the inventory for the main performance indicators which drive the life cycle impacts, grouped as energy outputs, inputs and digestate/char (see Fig. 6).

4. Results

4.1. Environmental life cycle analysis

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) ($kgCO_2$ – Equiv.)
2. POCP – Photo Ozone Creation Potential (kg Ethene – Equiv.)
3. EP – Eutrophication Potential (kg Phosphate – Equiv.)
4. AP – Acidification ($kgSO_2$ – Equiv.)
5. ADP element – Abiotic Depletion (elements kg Sb – Equiv.)
6. ADP fossil – Abiotic Depletion (fossil MJ)

Fig. 7 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, NOx, SO_2 and VOCs), the pyrolysis option performs the worst of the five as it has the largest CHP output. ADP elements and EP are insignificant in comparison and are therefore not discussed further.

Using a normalisation method the net environmental impact is shown in Fig. 8, revealing that drying for fuel production is optimum followed by the pyrolysis option, the worst performer is the GtG scenario. THP with CHP has environmental benefits over conventional AD with CHP.

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). Fig. 9 shows the results for GWP of the five 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.

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 CH_4 and N_2O from recycled sludge on agricultural land are significant and dominate Fig. 9. The two

Table 1
Inventory of key performance indicators for 1 TDS feed.

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	1020	–	1020	1820
Bio-methane	kWh	–	–	3230	–	–
Solid Fuel	kWh	–	–	–	2260	–
INPUTS						
Electricity consumption	kWh	135	179	199	210	443
Natural gas	kWh	0	370	907	370	370[a]
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

[a] Could be reduced if the heat balance was optimised between THP and the pyrolysis CHP.

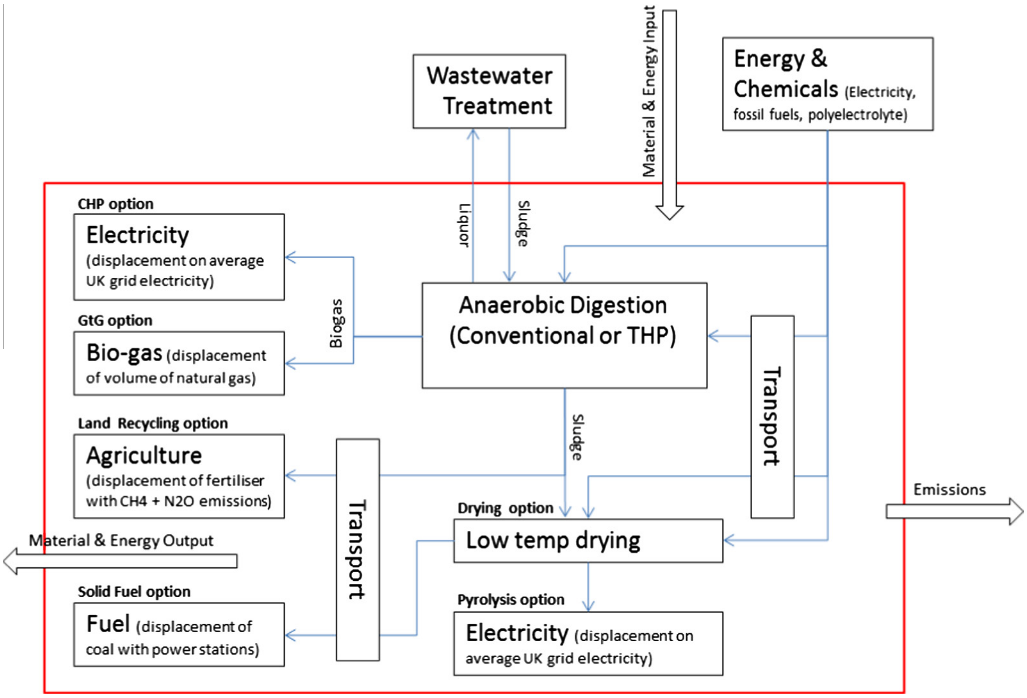

Fig. 6. Overview of system boundaries.

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 offer a considerable advantage over the existing techniques, especially when considering GWP. However, the pyrolysis option does this at the potential detriment to the local environment.

4.2. Economics

Previous work has extensively modelled the Operating Expenditure (OpEx) of each of the processes described in the LCA study (Mills 2012b). However, for various reasons Capital Expenditure (CapEx) models for these processes had not been built.

The content of Table 2 is the result of combining a number of sources of data to produce a cost estimate for various process configurations on a typical 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 Eq. (1) (Sinnott and Towler, 2009).

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

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 2).

Using and adapting the data in Table 2 the total CapEx for each scenario was obtained; with the OpEx information from previous work (Mills 2012b), the economic feasibility of each process scenario was calculated. Table 3 summarises the financial situation and the resultant Internal Rate of Return (IRR) with and without

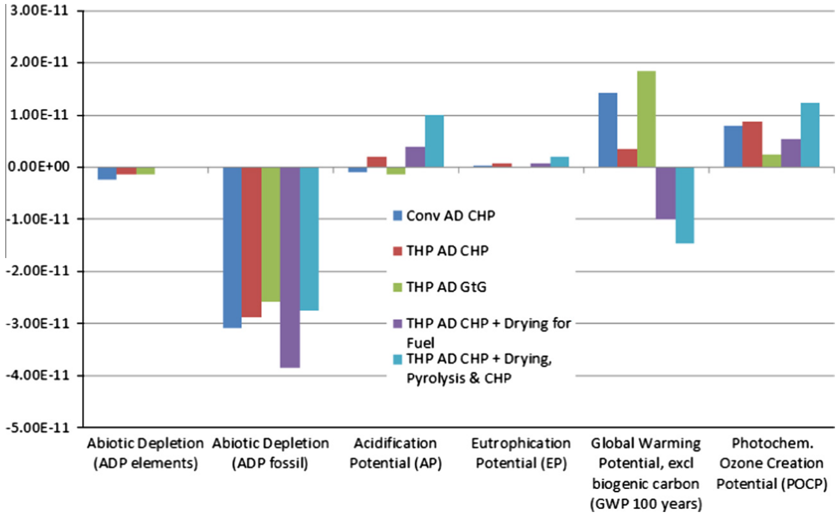

Fig. 7. Life cycle impacts normalised (CML2001 – November 2010) of the five energy recovery scenarios.

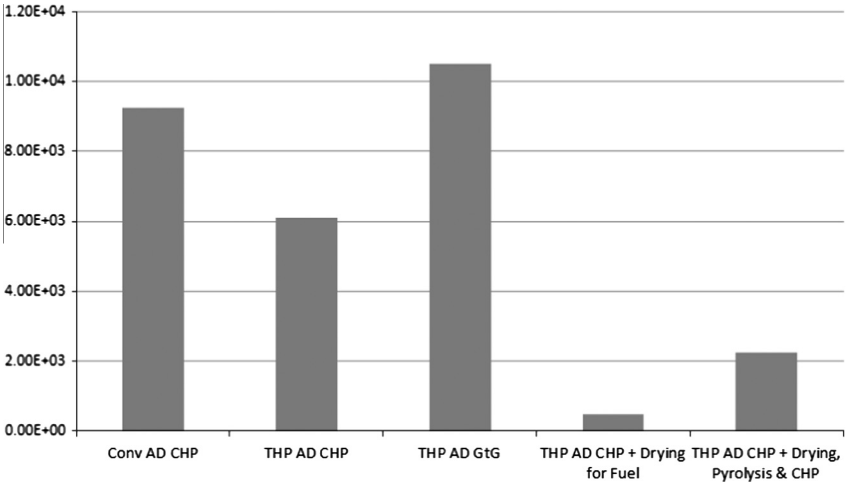

Fig. 8. Weighted net impact CML 2001 – December 07, experts IKP (Northern Europe) method.

government incentives for a 100 TDS/day plant for each scenario, general financial assumptions can be found in Appendix A.

The results show that the GtG option has the best IRR followed by pyrolysis and then the drying for fuel scenario. However, when the incentives are removed the IRR 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.

Conventional AD and THP appear to be comparable financially, 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. 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.

4.3. Summary of results

Combining the various environmental and economic results presents a challenge for decision makers, it was therefore deemed sensible to combine these results. Table 4 shows the results of a scoring exercise where each scenario was ranked and scored between 1 and 5, 5 being best for the following performance indicators:

- Net environmental impact, because this is the intellectually most satisfactory.
- GWP, because it is reportable to OFWAT, the UK water Regulato.
- IRR with incentives, because this represents commercial reality.
- IRR without incentives, because some of the current incentives seem out of proportion and therefore at risk of change.

This study has assessed the sustainability of these different scenarios as a balance of economic and environmental impact. However, the third remaining sustainability impact (Brundtland, 1987), societal, has not been explored in this case as it has been considered that the social impact is broadly neutral across all scenarios.

The results in Table 4 show THP AD with CHP has advantages over Conventional AD and supports the current shift from conventional AD to THP AD in the UK and the future strategy of many UK & International wastewater companies.

Most notable is that the drying post AD options are good solutions both environmentally and economically and these should be

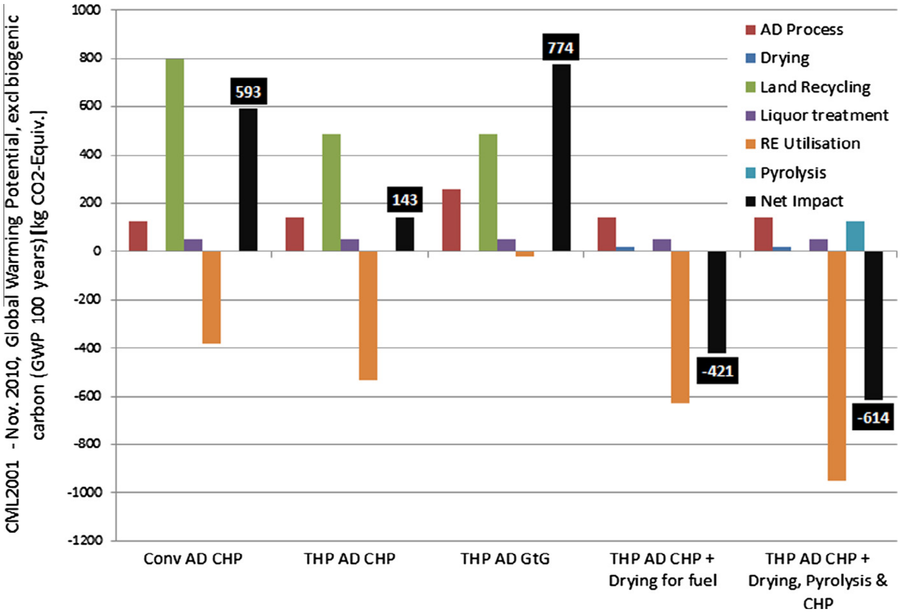

Fig. 9. Global warming potential (exc biogenic) for 5 energy recovery options.

Table 2
Sludge to energy process – CapEx model.

Component	CapEx (US$)	Size	Unit	*k*-value (US$)
Pre-treatment and thickening	4,114,727	100	TDS/d	259,622
AD	8,958,095	22,000	m^3	22,221
THP	9,130,003	100	TDS/d	576,064
Dewatering and cake storage	5,908,967	60	TDS/d	506,548
Odour treatment	1,031,005	100	TDS/d	41,969
CHP and electrical	8,579,959	5000	kWe	51,773
Control and instrumentation	1,223,573	100	TDS/d	77,202
General	3,149,081	100	TDS/d	198,694
Sub total	42,095,410			
Contractor management (20%)	8,419,082			
Client overheads (10%)	5,051,449			
Total	55,565,941			
Additional options (before contractor and client overheads)				
GtG (CHP eq output 2.5 kW/m^3/h)	7,162,110	5000	kWe	43,217
Drying plant	4,838,055	3200	kgH_2O/h	38,158
Pyrolysis	8,120,331	60	TDS/d	696,118
Pyrolysis CHP	7,504,802	4000	kWe	51,773

Table 3
Financial performance of each process scenario.

Scenario	OpEx with Incentives (US$ pa)	OpEx without Incentives (US$ pa)	IRR with incentives (%)	IRR without incentives (%)
Conv AD CHP	6,902,150	4,582,575	10.60	4.05
THP AD CHP	8,486,250	5,714,075	12.75	5.98
THP AD GtG	10,975,550	2,828,750	18.92	−2.81
THP AD CHP + drying for fuel	10,070,350	7,298,175	14.39	8.48
THP AD CHP + drying, pyrolysis and CHP	14,143,750	8,429,675	17.46	7.64

Table 4
Combined ranking of scenarios.

Scenario	Net impact	GWP	IRR with incentives	IRR without incentives	Combined total
Conv AD with CHP	2	2	1	2	7
THP AD with CHP	3	3	2	3	11
THP AD with GtG	1	1	5	1	8
THP AD, CHP & drying	5	5	3	5	18
THP AD, CHP, drying & pyrolysis with CHP	4	4	4	4	16

considered by the UK water industry as the next logical steps in unlocking the full energy and financial potential of sewage sludge.

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. Conclusion

The study has found that both the post AD drying options performed well but the option used to create a solid fuel to displace coal was the most sustainable solution economically and environmentally, closely followed by the pyrolysis configuration.

Application of THP improves the financial and environmental performance compared with conventional AD.

Producing bio-methane for grid injection is attractive financially but has the worst environmental impact of all the scenarios, suggesting that the current UK financial incentive policy for bio-methane is not driving best environmental practice. However, as the electricity grid is decarbonised there will come a point at which it is environmentally beneficial to produce bio-methane for grid injection instead of electricity some sensitivity analysis would be logical next step.

It is recommended that an enhanced pyrolysis option is explored that utilises the waste heat from the pyrolysis CHP in the THP plant.

It is clear that new and improving processes and technologies are enabling significant opportunities for further energy recovery from sludge; LCA provides tools for determining the best overall options for particular situations and allows innovation and investment resources to be focused accordingly.

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Appendix A. Assumptions

See Tables A1–A8.

Table A2
AD & THP process assumptions.

Parameter		Source
Thickening – electrical demand	60 kW h/TDS	Estimate
Thickening – polyelectrolyte consumption	2.2 kg/TDS	Estimate
Input:output – dry solids	1%:5%DS	Estimate
THP – electrical demand	50 kW h/TDS	Estimate
THP pre dewatering – polymer demand	5 kg/TDS	Estimate (50% increase)
THP pre dewatering input:output DS	5%:16.5%DS	Estimate
THP steam demand @12barg	1 kg/kgDS	TW asset standard
AD electrical demand	40 kW h/TDS	Estimate
Dewatering – electrical demand	50 kW h/TDS	Estimate for Bucher press
Dewatering – polymer demand	10 kg/TDS	Estimate
Polymer GHG emissions	2 $\text{kgCO}_2\text{e/T}$	Estimate
Liquor treatment energy demand	1.05 kW h/m^3	Venkatesh and Brattebø (2011)

Table A3
Land recycling assumptions.

Parameter		Source
Average journey distance	120 km (100 km THP)	Estimate
Average journey load and utilisation	22 t, 50%	Estimate
N & P concentrations	5%, 3%	Estimate
Land area for spreading	1 m^3/kg wet	Estimate
CH$_4$ emissions	0.02 kg/TDS	UKWIR (2012)
N$_2$O emissions	0.00011 kg/TDS	(as above)

Table A4
CHP Assumptions.

Parameter		Source
CV of biogas	23 MJ/Nm^3	TW typical
CHP electrical efficiency	38%	Estimate
CHP high grade heat efficiency	18%	Estimate
CHP low grade heat efficiency	20%	Estimate
Bio-gas leaks (CH4)	2%	Estimate
CO$_2$ (biotic) exhaust emissions	175 g/kW h	Estimate (13% exhaust gas)
CO exhaust emissions	986 mg/kW h	Borkowski (2007)
Dust exhaust emissions	164 mg/kW h	Poeschl et al. (2012)
NO*x* exhaust emissions	821 mg/kW h	Borkowski (2007)
NMVOCs emissions	136 mg/kW h	Diesel_net (2006)
SO$_2$ emissions	439 mg/kW h	Borkowski (2007)

Table A5
Bio-methane injection assumptions.

Parameter		Source
Electrical demand	0.05 kW h/m^3	Estimate
Propane required	17% or 0.101 kg/m^3	Calculation to meet CV (delivered by tanker)
CO2 (biotic) emissions	105 g/kW h	35% of biogas @ 1.9 kg/m^3
CV of grid ready bio-methane	37 MJ/m^3	NG (2005)

Table A1
AD process specific assumptions.

Parameter	Conv. AD. & CHP.	THP AD. & CHP.	THP AD. & GtG	Source
Bio gas yield	300 m^3/TDS	420 m^3/TDS	420 m^3/TDS	Typical
Solids destruction	30%	40%	40%	Typical
Cake dry Solids	30%DS	42%DS	42%DS	Bucher Press

Table A6
Sludge drying and fuel assumptions.

Parameter		Source
Electrical demand	55 kW h/TDS	Klein manufacturer[a]
Low grade heat demand	550 kW/TDS	Klein manufacturer[a]
Final dry solids	90%DS	Estimate
Journey distance	100 km	Estimate
Journey load and utilisation	22 t, 50%	Estimate
CV of dried sludge	14 MJ/kgDS	TW typical
CV of UK hard coal	36 MJ/kg	GaBi database

[a] Heat demand of 7.0 kW h/kgH_2O from 42% to 90% and electrical 0.7k W h/kgH_2O from 42% to 90%.

Table A7
Pyrolysis assumptions.

Parameter		Source
Electrical demand	400 kW h/TDS	Estimate
Bio-char mass	380 kg/TDS	Estimate (TW ash content)
Syn-gas conversion efficiency	3500 kW h/TDS	Estimate (90% @ 14 MJ/kgDS)

Table A8
Financial assumptions.

Parameter		Source
Electricity cost	£75/MW h	Typical average delivered power cost
ROC value[a]	£45/MW h	DECC
Polymer value	£2/kg	Typical
Natural gas	£29/MW h	DECC
RHI incentive value	£65/MW h	DECC
Sludge recycling	£18/wet T	Typical
Maintenance	3% of CapEx	Typical
Discount rate	8%	Typical for regulated industry
Value of dried sludge fuel product	60£/TDS	60% price of waste wood chip
Dollar to pound exchange rate	1.55 US$/£	www.xe.com, accessed 10/08/13
Base case sludge cost	£150/TDS	Displacement of lime disposal

[a] AD CHP receives 0.5 ROC/MW h and pyrolysis CHP receives 2.0 ROC/MW h.

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