LIFE CYCLE ASSESSMENT OF ADVANCED ANAEROBIC DIGESTION PROCESS CONFIGURATIONS FOR SEWAGE SLUDGE - A UK PERSPECTIVE

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SUMMARY: Over the past 10 years significant development has been made in advanced anaerobic digestion technologies for sewage sludge. These processes are now being implemented at large scale across the UK and within Thames Water. Although there are significant economic benefits to advanced anaerobic digestion (AD) processes, life cycle impact assessments have been limited in depth. This paper attempts to fill this gap in knowledge by comparing several process variants as part of a Life Cycle Assessment (LCA). Using operating data, a process model was created to calculate the economic and environmental impact factors of the options during the life of the operational plant. It was found that advanced AD processes have advantages over conventional AD but the increased energy input requirements of thermal pre-treatment make it less beneficial under some conditions. Cleaning up biogas to enable Gas to Grid (GtG) injection requires significant renewable incentives to be economic and environmental impact can be negative when compared with Combined Heat Power (CHP).

1. INTRODUCTION

The UK Water Industry currently generates approximately 800 GWh 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 disposal as the main driver (Davis 1996; Barber 2010).

Over the past 10 years significant development has been made in advanced anaerobic digestion processes, which improve energy yields from this resource which the industry has in abundance. These processes have and are now being implemented at large scale across the UK and within Thames Water (Riches 2010).

Many Life Cycle Assessment (LCA) studies pre-date these technological developments and are also questionable in depth (Lundin and Morrison 2002). Therefore, a new LCA has been conducted alongside economic studies to assess advanced anaerobic digestion and new technologies available to the UK water industry.

2. SLUDGE TO ENERGY TECHNIQUES

A comparison between several processes has been made, these are described below and include:

- Conventional AD with Combined Heat and Power (CHP);
- Conventional AD with Gas to Grid (GtG) technology;
- Advanced AD using thermal pre-treatment with CHP;
- Advanced AD using thermal pre-treatment with GtG.

Thames Water now owns and operates at full scale or demonstration scale all of these process variants described above and the LCA is based on operational data from these plants.

2.2 Conventional AD

Currently the most widely used method of sludge treatment is AD which can achieve the required sterilisation or pathogen kill to allow the sludge to be disposed of to land, under the current UK regulations. AD has the added benefit of reducing the volume of sludge for disposal 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, Baeyens et al. 2008). In a typical process, sludge is thickened then heated to approximately 36°C before entering the mixed digester tank, typical retention times range from 12 to 20 days. The final digestate is then dewatered to a cake of around 20% Dry Solids (DS) and transported off site, generally for agricultural land use (Suh and Rousseaux 2002).

2.3 Advanced AD

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

- Increased Biogas yields;
- Increased volatile solids destruction;
- Reduction in mass when compared with conventional digestion;
- Process allows increased organic loadings 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 the typically the rate limiting step of AD. Thermal Hydrolysis Process (THP) is the more widespread and the technology of choice for Thames Water to achieve future generation and carbon mitigation targets (TWUL

2009).

2.2.1 THP

THP involves using high temperature (165˚C) and pressure (7barg) to disrupt and solubilise sludge before being fed 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) pa (Cambi 2010).

However, the increase in biogas does not necessarily result in an overall net increase in energy yield. The process demands an input of high grade heat and additional electrical energy, when compared with conventional AD. The high grade heat demand typically outweighs the heat available from a CHP unit burning the biogas produced. All of the plants THP installations in the UK currently require a support fuel (typically natural gas) to maintain the process (Mills 2011).

2.4 Biogas Utilisation

The biogas produced in AD has traditionally been utilised in ~~a~~ spark ignition gas engine or dual fuel engine and converts 30 - 40% of the 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 forming CHP (Hawkes 2011). In the UK this form of generation is incentivised under the Renewable Obligation scheme which rewards generators with additional financial revenue.

A new technology, GtG, cleans up and injects all of the bio-gas 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%. Once upgraded the bio-gas requires the addition of propane and odourizer to be compliant with gas quality standards before final compression into the gas network (Greer 2010; Starr, Gabarrell et al. 2012). A disadvantage of this process is that heat is no longer supplied from a waste source and has to be supplied by either bypassing some of the biogas or purchasing supplementary natural gas, which is usually the preference.

3. LCA

Many studies in the past have conducted quite extensive LCA for sludge treatment techniques, but these have focused on traditional disposal routes for the wastewater treatment by product (Dalemo, Sonesson et al. 1997; Sonesson, Dalemo et al. 1997; Suh and Rousseaux 2002; Lundin, Olofsson et al. 2004). These typically include land fill, compost, incineration and land application after conventional AD. Most of these and similar studies were conducted during a period (1995-1999) when the EU was changing regulations relating to sewage sludge and member states where attempting to influence the direction of this strategy change with LCA studies.

The studies vary depending upon the country of origin. Studies available from Sweden or Switzerland where sewage sludge is a contentious issue and are biased toward incineration as both countries restrict agricultural application of sewage sludge

(Lundin, Olofsson et al. 2004; Houillon and Jolliet 2005). Lundin who reviewed many studies in this area 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 post Lundin's work in 2004 (Lundin, Olofsson et al. 2004).

Carballa in 2011 is the most recent and applicable to this area comparing AD pre-treatment methods (including THP) of sludge and kitchen waste. An issue with this LCA is that all the operational performance data is scaled from laboratory work conducted using 10 litre anaerobic digesters, considering an average size site would use 5,000m3 digesters the accuracy of these scaled results would not be considered without question by the industry. The study also excluded any impact from sludge handling post digestion (Carballa, Duran et al. 2011). In all papers reviewed there is limited detail on plant configuration which has a large impact on energy balance, operational economics and subsequently the environmental impact (Mills 2011).

GtG LCA studies in this area are limited. However, Jury finds biogas injection from energy crop fermentation to be environmentally competitive with natural gas (Jury, Benetto et al. 2010). Another study which compared different upgrading technologies, concludes that electricity use has the highest environmental impact (Starr, Gabarrell et al. 2012). There has been little research into the comparative impact of GtG and CHP.

3.1 Goal & Scope

There is a need to conduct a study that incorporates the advances in technology and that draws on operational experience and data. The goal of this study is to evaluate the relative environmental and economic impact of the configuration of advanced technologies, to inform decision makers in Thames Water, to identify any inconsistencies or anomalies and potentially lobby policy makers. The functional unit used is the dry mass of sludge; TDS. All sludge parameters and process assumptions are listed in Appendix A.

3.2 System Boundaries

Figure 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, Duran et al. 2011). A 15 year operational period is assumed as this is typically the lifetime for major components such as a CHP unit. The sludge and energy process itself will consume energy (electricity & natural gas) & chemicals (poly-electrolyte) which are included. On site there will also be emissions to air for CHP and gas boilers these are likely to be dominated by CO_2, SO_X and NO_X (Poeschl, Ward et al. 2012).

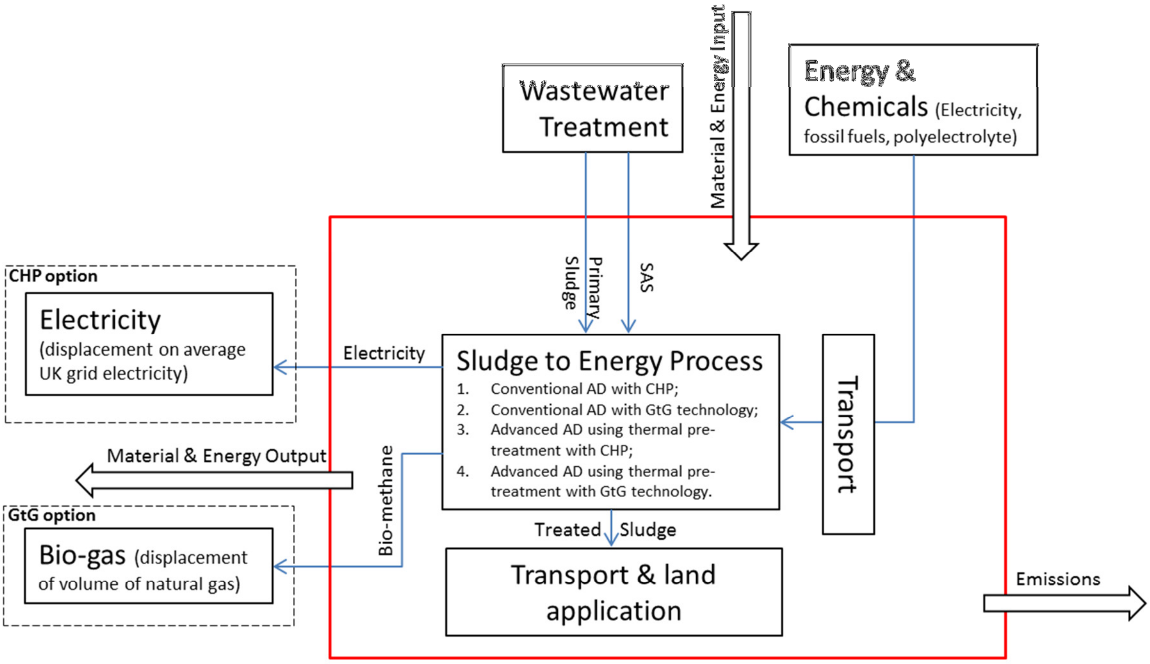

Figure 1. Overview of the System Boundaries

It is assumed that all digested sludge is transported an average of 30km and applied to agricultural land as this is the current practice in the UK for 60% of the UK's sludge (Andrews 2008). In addition to vehicle emissions, this activity will have air emissions (CH_4 & N_2O) associated with the continued decomposition of the biomass on the land (Inubushi, Goyal et al. 2000).

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 delivering and combusting the equivalent energy unit of natural gas. All assumptions used within the model are listed in Appendix A.

3.2.1 Exclusions

The process and upstream wastewater treatment has not been incorporated, as this will exist no matter what sludge to energy option is used. Returns from the sludge to energy plant are ignored in this preliminary model. The nutrient rich sludge should displace the use of commercially available fertilisers but practice is inconsistent and difficult to quantify, so the burden displacement has not been modelled. Problems associated with heavy metals and other non-biological sludge contaminants will be constant throughout all of the process variants so therefore has been discounted from the study.

3.3 Inventory

Table 1 shows the main output parameters which affect the LCA model.

It can be observed that THP generates more energy than the MAD options, but requires additional electricity and natural gas. This detrimental in the CHP configuration as the net energy output is less than all of the alternatives. The best configuration from a pure energy point of view is the THP GtG followed by the traditional MAD CHP scenario.

Table 1. Key Performance Parameters

Inventory Item	Units	MAD CHP	MAD GtG	THP CHP	THP GtG

Electricity consumption	kWh/TDS	144	274	288	489
Electricity generation	kWh/TDS	660	n/a	920	n/a
Bio-methane	kWh/TDS	n/a	1,661	n/a	2,564
Natural gas	kWh/TDS	0	600	520	910
Propane	kWh/TDS	n/a	350	n/a	530
Diesel	kWh/TDS	2.4	2.4	1.3	1.3
Net energy[1]	kWh/TDS	516	437	112	635
Polymer	kg/TDS	6.8	6.8	12.9	12.9
Sludge disposal volume	m^3/TDS	3.5	3.5	1.9	1.9

[1] Site only, ignores transport and consumables

Global warming potential (carbon dioxide equivalent emissions) has been the main focus of the study. However, acidification and photochemical ozone creation potential will also be large impacts, due to emissions of NO_X and SO_2 and these must be considered when applying for planning permission and obtaining/maintaining environmental permits.

3. RESULTS

The results have been divided and displayed as 6 discrete areas to aid analysis and focus any follow up work, these are:

- Displacement – burden displacement of grid electricity (CHP) or natural gas (GtG)
- Transport – impact associated with transporting digested dewatered sludge to land
- Plant emissions – stack emissions (CHP or GtG process) and consumption of electricity
- Heating – On site boiler plant stack emissions
- Land – Emissions from decomposing sludge on agricultural land (GWP only)
- Chemicals – Impact associated with polyelectrolyte supply chain

The lowest global warming impact can be seen from the MAD CHP configuration. Despite THP having almost 50% more energy production the benefit of increased displacement is masked by the increased energy requirements (electricity and heat) of the process.

The process with the highest global warming impact is the THP with GtG configuration and is also due to the plants high demand for electricity and heat.

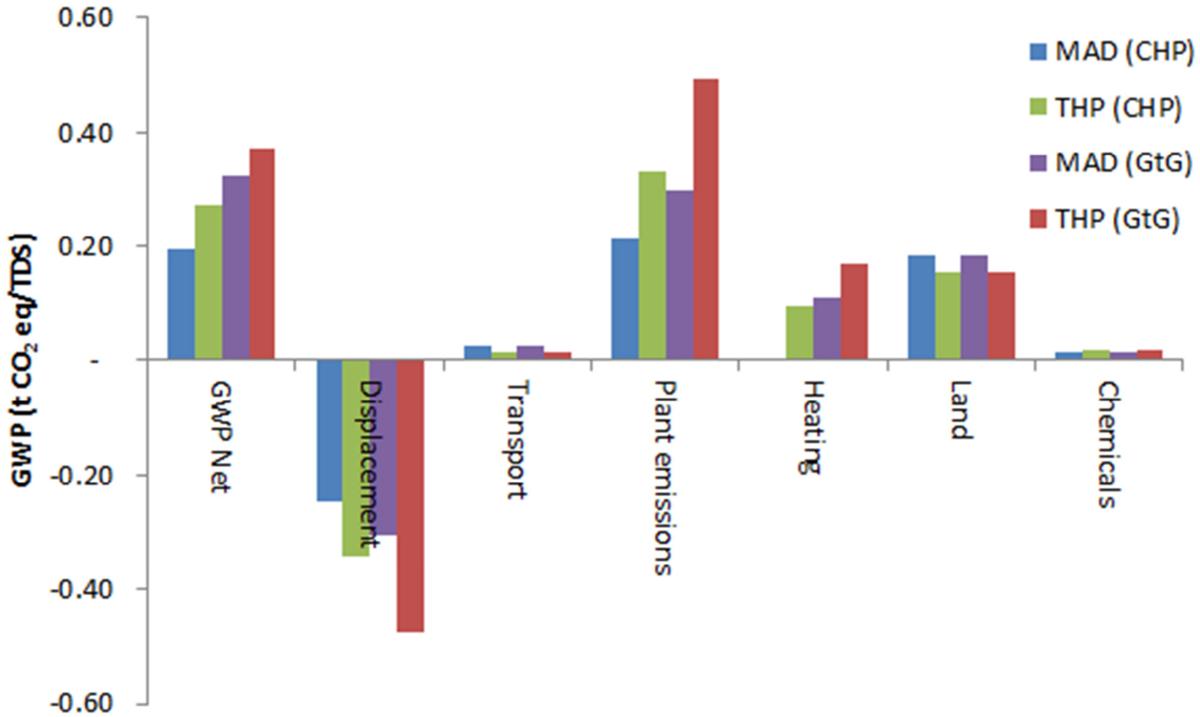

Figure 2. Global Warming Potential

The impact from Photochemical Ozone Creation Potential (POCP) & Acidification, Figure 3 and 4 respectively, are mainly driven by transport, electricity consumption and burden displacement. Overall the THP solutions are optimal because of the reduced transport due to smaller sludge volumes post process.

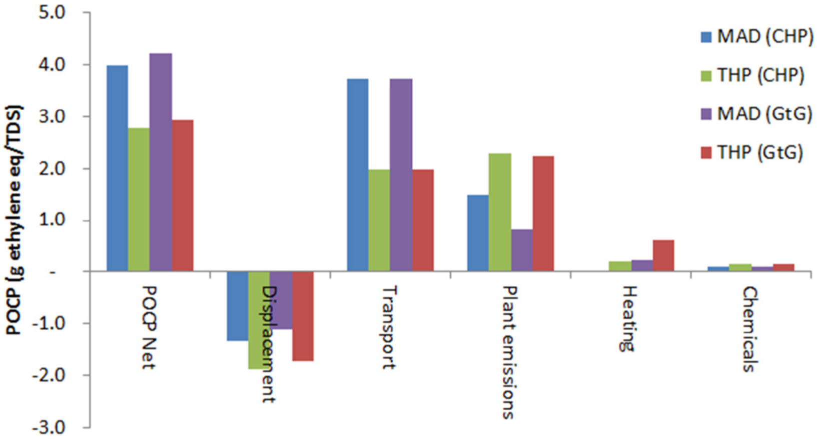

Figure 3. Photochemical Ozone Creation Potential

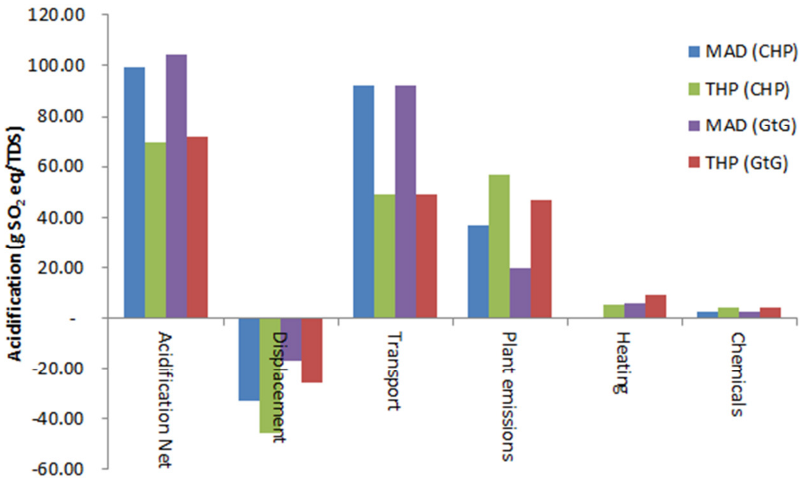

Figure 4. Acidification

4.2 Economics

The whole life cost was calculated, a technique used to inform investment decisions. The Net Present Value (NPV) takes account of capital expenditure, operational expenditure and inflation and can be seen plotted for each of the four options in Figure 5.

The RHI scheme, which supports GtG, providing the additional investment required for GtG and as a result the two GtG options have the best return on investment, with THP providing the superior solution.

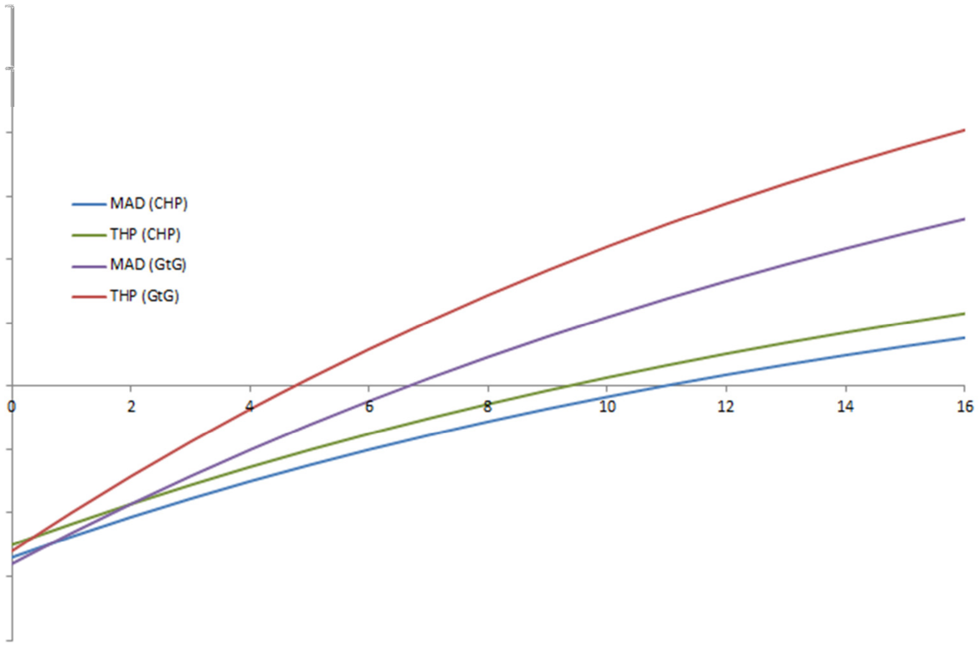

Figure 5. NPV over time (years) with full incentives

If the incentive schemes (ROCs and RHI) are removed economics look very different, as shown in Figure 6. It reveals that without the government incentive, which makes up over 60% of the revenue, GtG is not economically feasible. The two CHP options both remain profitable as the incentive makes up a small proportion of the revenue.

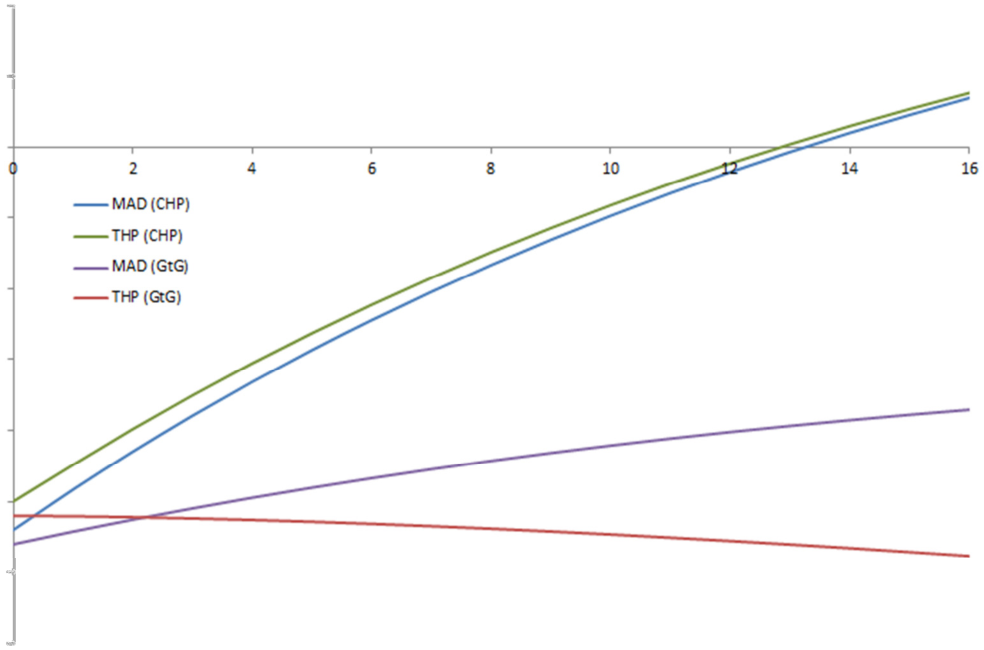

Figure 6. NPV over time (years) with no incentives

5. CONCLUSION

LCA shows there are clear differences between (a) the economic results and (b) GWP

(a) Shows THP with GtG as best option;
(b) Shows MAD with CHP as best, but THP with GtG as worst.

This analysis should open up opportunities for interesting debate on how the economics and incentives should be considered in relation to the outcomes they are aiming to achieve in relation to GWP / POCP / Acidification. In the short term THP with CHP appears to be reasonable compromise.

LCA provides a valuable insight into the 15 year capital investment needed for these processes, especially when the returns on investment have considerable dependency on government policies such as RHI and on fuel prices such as for natural gas, both of which may add considerably to overall risks. This study has clearly demonstrated the need for further detailed investigation, to enable greater understanding of these relationships, dependencies and levels of risk.

5. FURTHER WORK

- Continue modelling to include other impact factors (human toxicity & eutrophication);
- Expand model to include impact of wastewater return & sludge nutrient benefit;
- As the UK grid electricity mix changes it will impact the burden displacement, it is recommended that sensitivity analysis is conducted to quantify the effect;
- The analysis shows that GHG emissions from land application of sludge are significant and non-land disposal routes should be explored and developed.

APPENDIX A - ASSUMPTIONS

Table 2. Global Assumptions

Parameter	Units	Qty
Primary proportion	%	50
Primary VS content	%	80
SAS VS content	%	75
Bio-gas yield	M3/kgVS	1.0
Bio-gas CV	MJ/m3	23
Bio-gas CO2 content	%	30

Table 3. Process Specific Assumptions

Parameter	Units	Qty
MAD – combined feed DS	%	6.0
MAD – Primary VSD	%	60
MAD – SAS VSD	%	15
MAD – Process Electrical load	kW/TDS/d	6.0
MAD – Cake DS	%	21
THP – combined feed DS	%	16
THP – Primary VSD	%	63
THP – SAS VSD	%	55
THP – Process Electrical load	kW/TDS/d	12
THP – Steam requirements	kg/TDS	900
THP – Cake DS	%	32
CHP electrical efficiency	%	40
CHP electrical parasitic load	%	10
GtG Process Propane demand	% vol / vol	5
GtG Process Electrical Load	kW/m3	0.50

Table 4. LCA Assumptions

Emissions Factor	Units	Qty
Grid Electricity	tCO2eq/MWh	0.540
Natural Gas	tCO2eq/MWh	0.185
Sludge transport	gCO2eq/tkm	254
Sludge land emissions	tCO2eq/TDS	0.187
Chemicals (dewatering polymer)	kgCO2eq/kg	2.100

Table 5. Economic Assumptions

Parameter	Units	Qty
	REMOVED	

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