

Strategic Carbon Technology

How to use sludge to your advantage

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Dave Auty

- 22 years in sludge and still happy as a....
- Always something new
- Carbon

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Carbon Factoids

- 18% of global carbon footprint is due to meat production (40% of global methane)
- A beef calf = 5000 kgCO₂epa in its lifetime
- Same as fossil fuel use by average UK citizen per year
- Running the average UK diesel on waste vegetable oil derived biodiesel saves 2000 kgCO₂epa
- Same as a return flight to New York

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This Presentation

- Carbon in context of sludge strategies
- Consider impact of sludge treatment technologies
- How we did this (and why it's not easy)
- What we found

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Carbon in Context

- **Reporting requirement**
- **Cost**
 - Shadow Price
 - Market value
 - Relatively small now, but one to watch?
- **Climate Change**
 - Raw dried to agriculture emits 24 kgCO₂epa per person
 - Average UK citizen fossil fuel footprint 5000 kgCO₂epa

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Sludge Strategies

- Need to be kept up to date
- Periodic reviews
- Strategic Direction Statements and Business Drivers

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Technologies

- Wide ranging – 34 technologies studied
- Groups
 - Sludge Minimisation
 - Cannibal
 - Ozonation – Biolysis
 - Enzymatic Conditioning

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Acid Phase Hydrolysis

PROCESS	Function	Hydrolysis - Enhanced Digestion	
	Input	Primary sludge - Waste Activated Sludge	
	Concept	Acid Phase Hydrolysis as pre-treatment to anaerobic digestion	
STATE OF DEVELOPMENT		Developed	
BACKGROUND	<p>The acid phase hydrolysis process is a pre-treatment stage that is installed in front of conventional anaerobic digestion. Its function is to provide optimum conditions for the groups of bacteria which break down constituents of sludge into volatile fatty acids which are then converted to biogas in the subsequent anaerobic digestion plant. Loading rates are approximately 20 kg/m³/d corresponding to retention times between 1.5 and 2.5 days. It is claimed that combining acid phase with conventional digestion results in: improved destruction of volatile solids; increased biogas production and improved pathogen deactivation. There is one operational site in the UK at Swindon, however, the technology has been used in various combinations in the United States for several decades</p>		
DESCRIPTION AND WORKING PRINCIPLE	<p>Thickened sludge is heated to 35°C prior to entry into acid phase digestion system</p> <p>Sludge is fermented for approximately 2 days. Volatile fatty acid concentrations are approximately 8000 mg/l which causes pH to drop to approximately 5.5 prior to entry into traditional anaerobic digestion plant.</p> <p>Acidified sludge is then further digested in traditional anaerobic digestion with loading rates up to 3.75 kg VS/m³.d</p>		
PERFORMANCE		MESOPHILIC DIGESTION (MAD)	ACID PHASE DIGESTION
(SOURCE – INTERNAL REPORT)	Loading rate kg VS/m ³ .d	2.60	3.00 overall (~ 20 in acid stage + 2.6 in MAD)
	Pathogen kill (log reduction)	0.5 – 1.5	Typically 1 log higher than MAD
	Volatile solids destruction	45%	45% + 10% approx
	HRT (d)	15	< 2 (acid phase) + 15 (MAD)
OPERATIONAL EXPERIENCE	<p><i>Swindon STW.</i></p> <p>Swindon STW is a 220,000 population equivalents site with conventional preliminary and primary treatments and activated sludge treatment with biological nitrogen and phosphorous removal. The sludge stream consists of separate mechanical thickening of primary and surplus activated sludge using drum and gravity belts respectively, sludge blend tank, acid phase digester (APD), three mesophilic anaerobic digesters, three unheated secondary digesters and belt filter press dewatering. The APD was built at Swindon STW and commissioning started in 2003. The main aims of the installation of the APD were: to improve the quality of the final product; to provide extra digestion capacity; and to investigate process reliability.</p> <p>During operation, issues occurred with the re-circulating centrifugal pump on the APD heating system preventing effective heat transfer to the sludge in the APD tank. The centrifugal pump was not able to pump sludge containing a high proportion of gas. The mixture of sludge and gas resulted in separation of gas from sludge leading to gas locking in the impeller. The gas tended to fill up the body of the pump resulting in cavitation and loss of pumping capacity. The plant has been operating much more reliably than before with this arrangement since 2004.</p> <p>To date, it has been shown that APD results in improved compliance by about 1 log and the final product E. coli kill has been generally of the order of 10¹²/gds. The VS destruction was in the range of 40-45% and biogas composition was 60 – 63% methane. An estimate of the daily gas production from the APD</p>		

CAPITAL AND OPERATING COST	Approximate Capital Cost:	Not available			
	Approximate O&M Cost:	Not available			
REFERENCE INSTALLATIONS	There are 8 full-scale reference installations in Europe and USA.				
	REFERENCE	THROUGHPUT	COMMISSIONED		
	Swindon STW	4,800t/DS/yr	2004		
	DuPage County, USA	4,380t/DS/y	1994		
	Oslo, Norway	14,600t/DS/y	1997		
	Elmhurst, USA	1,825t/DS/y	2000		
	Inland Empire Utilities USA	14,600t/DS/y	2000		
	Rockaway WWTF, New York City New York	5,475t/DS/y			
	Backriver WWTP, Baltimore MD	79,205t/DS/y			
	Ville d'Aix, France	3,285t/DS/y	2000		
SUPPLIERS / PATENTS	Several version of technology available from suppliers of anaerobic plant, e.g. GTI (Gas Technology Institute) 1700 S. Mount Prospect Road Des Paines, IL 60018				
TECHNOLOGY CONSIDERATIONS					
		⊖	⊖	⊖	⊖
COMMERCIALLY PROVEN	1	2	3	4	5
PLANT MAINTAINABLE	1	2	3	4	5
PLANT FOOTPRINT	1	2	3	4	5
ENVIRONMENTAL COMPLIANCE					
PROCESS EMISSIONS	1	2	3	4	5
PROCESS CONSUMABLES	1	2	3	4	5
WASTE PRODUCTS MINIMISED	1	2	3	4	5
BUSINESS DRIVERS					
EASE OF PROMOTION	1	2	3	4	5
MAXIMISE ENERGY PRODUCTION	1	2	3	4	5
MINIMISE CARBON FOOTPRINT	1	2	3	4	5

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Technology Scoring

- Workshop after report
- Of course, it's professional judgement
- Meaning
 - Generic, not site specific
 - Only related to Thames Water's drivers
 - May change over time
- No carbon data in literature

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The Scores

Generic Type	Technology	Technology Considerations						Environmental Compliance						Business Drivers						Scoring	
		Commercially Proven	Operational Complexity	Plant Maintainable	Flexibility	Plant Footprint	BAT	Process Emissions	Final Product quality	Process consumables	Net energy use	Waste Products Minimised	Waste Hierarchy	Ease of promotion	Minimise Customer Impact	Maximise Energy production	Avoid Landfill	Minimise Carbon Footprint	Minimise Environmental Impacts	Totals	Best in Class
Sludge Minimisation	Cannibal	3	3	4	3	3	2	4	2	5	2	3	4	3	4	1	3	2	3	54	1
	Ozonation –Biolysis	2	3	3	3	3	2	4	2	2	1	5	4	3	3	1	5	1	3	50	
	Enzymatic Treatment	2	3	4	3	3	2	4	2	2	2	4	4	3	3	1	4	2	3	51	
Sludge Pre-Treatment + AD	Acid phase hydrolysis	3	4	4	3	3	5	5	2	5	5	5	3	4	4	4	5	5	4	73	
	Thermal hydrolysis	3	2	2	4	4	5	5	5	4	5	5	3	4	4	5	5	5	5	75	1
	Enzymic hydrolysis	2	3	4	4	3	5	5	4	5	5	5	3	4	4	4	5	5	5	75	1
	Pre-pasteurisation	5	4	3	3	3	3	5	4	5	4	5	3	4	4	3	5	4	5	72	
	Ultrasound hydrolysis	4	3	3	3	4	3	5	4	3	3	3	3	4	4	4	4	4	4	65	
	Homogenisation	1	3	3	3	4	3	5	4	3	3	3	3	4	4	4	4	4	4	62	
	Chemical hydrolysis	1	4	4	4	4	2	4	4	1	3	4	3	4	4	4	4	4	3	61	
	High pressure hydrolysis	2	3	3	3	4	3	5	4	3	4	3	3	4	4	4	4	4	4	64	
	Electron beam	1	3	2	3	4	2	5	4	4	3	4	3	4	4	4	5	4	4	63	
	Extended solids retention	2	4	4	4	4	2	4	4	5	4	5	3	4	4	4	5	4	4	70	
Nutrient recovery	2	3	3	3	3	3	4	4	3	4	5	3	4	4	4	5	4	4	65		
Sludge Dewatering	Electro-dewatering	1	4	3	4	4	4	4	4	4	2	5	4	5	4	3	5	3	4	67	
	Vacuum dewatering/drying	1	3	4	3	4	3	3	2	2	1	5	4	5	4	2	5	2	3	56	
	Drying beds, filter belt/press, centrifuge	5	4	4	4	4	4	4	3	3	3	5	4	5	4	2	5	3	4	70	
	Screw press	4	4	4	4	4	4	4	4	4	3	5	4	5	4	2	5	3	4	71	1

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The Scores - Headlines

- **AD pre-treatment scores similar**
 - They're also generally the highest scores
- **Thermal processes score badly**
 - But they have their place

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Second Phase

- **Process Routes**
 - Needed to reflect reality
- **Connect the technologies together**
- **Developed to suit TWUL**
 - Now and in the future
 - Concentrated on AD to land and incineration

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The "current" Process Routes

1)	Process Routes					
Process Component						
Thickening	PFT + Drums	PFT + Drums	PFT + Drums	PFT + Drums	PFT + Drums	PFT + Drums
Sludge pre-treatment	Multi tank acid phase	THP		THP		THP
Digestion	MAD	MAD		MAD		MAD
Dewatering	Belt	Belt	Belt	Belt	Belt	Belt
Drying			Direct or Indirect	Direct or Indirect		
Thermal Destruction					Incineration	Incineration
Disposal Route	Land	Land	Land	Land	Landfill	Landfill

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The "future" Process Routes

	Process Routes	
Process Component		
Thickening	PFT + Drums	PFT + Drums
Sludge pretreatment	THP	
Digestion	MAD	
Dewatering	Belt+	Belt+
Drying	Direct or Indirect	Direct or Indirect
Thermal Destruction	Incineration	Gasification
Disposal Route	Landfill	Landfill

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Example Process Route - THP

Process Stage	Sludge Type	% DS	Relative Volume
Sewage Treatment and Sludge Imports	Raw	3	100
Thickening	Thickened	6	50
Thermal Hydrolysis (including dewatering)	Pre-treated	12	25
Mesophilic Anaerobic Digestion	Digested	8	25
Dewatering	Dewatered	32	6
Storage	Matured	34	5
Agriculture	Recycled	34	5

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Energy and Carbon

- **The problem**
 - Complexity of sludge
 - Lack of existing tools
- **Carbon Calculations**
 - Direct
 - Indirect
 - Societal
- **Calculate from first principles**
- **Need to look at whole route**

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Issues

- **Emission factors**
 - DEFRA energy related OK
 - Nitrous oxide needs scientific study
 - Sludge/soil biochemistry
- **Lack of Chemical Industry data**

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Results

- Quantitative
- Qualitative
- Future

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League Tables – NPV

Appropriate Currently Available Route	Appropriate Possible Future Route	Relative NPV (%)
1. Acid Phase Digestion Cake to Agriculture		100
2. Thermal Hydrolysis Cake to Agriculture		105
4. Enhanced Digested Dried to Agriculture		160
3. Raw Dried to Agriculture		200
	17. Raw Dried Gasification	210
6. Enhanced Digested Cake Incineration		365
	12. Enhanced Digested Dried Incineration	380
5. Raw Cake Incineration		400

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League Tables – Energy

Appropriate Currently Available Route	Appropriate Possible Future Route	Net Energy Consumption (kWhpa)
2. Thermal Hydrolysis Cake to Agriculture		-20,000,000
4. Enhanced Digested Dried to Agriculture		-18,924,000
	12. Enhanced Digested Dried Incineration	-17,479,000
6. Enhanced Digested Cake Incineration		-16,990,000
1. Acid Phase Digestion Cake to Agriculture		-15,243,000
	17. Raw Dried Gasification	1,703,000
5. Raw Cake Incineration		8,216,000
3. Raw Dried to Agriculture		35,918,000

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League Tables – Carbon Footprint

Appropriate Currently Available Route	Appropriate Possible Future Route	Total GHG emissions (tCO ₂ epa)
2. Thermal Hydrolysis Cake to Agriculture		730
4. Enhanced Digested Dried to Agriculture		1,010
1. Acid Phase Digestion Cake to Agriculture		1,210
6. Enhanced Digested Cake Incineration		1,230
	12. Enhanced Digested Dried Incineration	1,230
	17. Raw Dried Gasification	1,570
5. Raw Cake Incineration		5,230
3. Raw Dried to Agriculture		9,800

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Quantitative Results - Discussion

- **Carbon footprint is similar to net energy**
 - Differences arise from direct emissions
 - Societal/Supply Chain emissions comparatively small
- **Thermal Hydrolysis looks good**
 - VSD benefit
 - Cake dewaterability transport benefit
 - Reduced Cake N benefit needs site by site consideration
- **Incineration and Drying look bad**
 - High energy demand (reality vs design?)

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Qualitative Results

- **Thermal Hydrolysis only if agricultural route is open**
 - Issues with how to use the power can also have a high impact
- **Incineration is the pragmatic solution for conurbations**
 - Needs to be pre-treated to give the energy balance
- **Sludge Imports can have a big impact**
 - i.e. how much sludge to treat at each site
 - use of produced power, product quality, landbank distance
 - Needs regional model

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The Future?

- **Gasification**
 - Thermal Hydrolysis, Digestion, Drying and Gasification
 - Based on projections, of course

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Conclusions

- **"Not easy being green"**
 - Complex calculations and where's the money?
- **Need to model**
- **Energy balance dominates the carbon footprint**
- **Thermal Hydrolysis looks good**

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Close

- **Explained how we worked out carbon footprints**
 - Workshop to produce Process Routes from 'best in class'
 - Modelled from first principles
- **Results are in depth, lots of answers not shown**
- **More? Just ask**
- **Thank you very much**

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STRATEGIC CARBON TECHNOLOGY – HOW TO USE SLUDGE TO YOUR ADVANTAGE

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ABSTRACT

The often conflicting demands of regulation and the need to reduce costs can be turned into a win:win situation by investing in the right mix of technologies for sludge treatment. This paper will discuss the work completed by Entec UK Ltd in conjunction with Thames Water Utilities Ltd in developing their sludge strategy and, in particular, a review of the most appropriate technologies to meet their business drivers. Amongst the main drivers were to maximise renewable energy production and deliver sustainable solutions, so technology had to be the key to achieving both objectives. The short-listed or leading technology would need to be commercially proven, technically robust and in line with Thames Water Utilities Ltd's Strategic Direction Statement.

Of particular interest was the carbon footprint of the technologies. However this would be fairly meaningless in isolation and would therefore need to be investigated as part of a complete process route from production to the final recycling/disposal outlet. The approach taken therefore took two stages; the first to identify suitable technologies, the second to identify the best use of these technologies in combinations defined by the process routes.

The first stage looked at 34 established and emerging technologies and was able to rank them against Thames Water Utilities Ltd's drivers. The leading technologies for each process stage were then chosen to create the process routes for review in the second stage. The second stage reviewed and compared these process routes for; general advantages and disadvantages, location and size considerations, energy balance, carbon footprint and financial impact. The routes were divided into outlets for recycling to agriculture and thermal destruction that suited the diversity of sludge production in the Thames Water Utilities Ltd operational area that varied between high density-conurbation and constrained-rural. The results of this analysis implied that using a process route of; thermal hydrolysis, anaerobic digestion, dewatered cake to agriculture presented the best fit to Thames Water Utilities Ltd's requirements for its existing sludge to land operations.

KEY WORDS

Sludge, Carbon, Treatment, Technologies, Investment

INTRODUCTION

Thames Water Utilities Ltd approached Entec UK Ltd in November 2007 to investigate what sludge treatment process technologies are available now or could be available in the medium and long term. This approach was part of Thames Water Utilities Ltd's initiative to review their sludge strategy in the light of external business pressures and internal strategic direction. Indeed, the sludge related parts of their published Strategic Direction Statement could be summarised as;

- Recycling to Land - Improve product quality and minimise solids through enhanced digestion. Extend and secure sludge recycling capacity.
- Energy Recovery - Promote energy recovery where appropriate. Increase the use of renewable energy generation from sludge digestion and Combined Heat & Power (CHP).
- General – Seek sustainable long term solutions

As such, this approach was broadly in line with most other UK water companies and served to illustrate the general recognition that sludge to land is the preferred (on environmental and

economic grounds) route for sludge in most circumstances and that sludge has valuable potential as a source of renewable energy.

Coupled with these published direction statements were Thames Water Utilities Ltd's internal goals and targets which, put numbers against these statements to form actual targets. One of these targets was to reduce the carbon footprint of Thames Water Utilities Ltd's activities by a certain amount by a certain date. This combination of strategic direction and internal targets provided the goals that are the driving force behind the shape of Thames Water Utilities Ltd's revision to its sludge strategy.

In order to ensure these goals were realisable, a review of technologies was required that would provide information on the wider aspects of environmental impact, particularly carbon footprint, not just capex and opex. Entec UK Ltd were able to provide all this information and broke the project down into two phases – an initial review of all relevant process technologies and then a more detailed assessment of the preferred technologies when operating in appropriate process routes. Dividing the project in this way enabled a thorough review of technologies to be completed whilst only concentrating on those that would best fit with Thames Water Utilities Ltd's goals and aspirations. This paper has been split along similar lines for clarity and presents the results of this investigation.

PHASE ONE – TECHNOLOGY REVIEW

Purpose and Scope

In order to provide a thorough review of sludge treatment technologies, the first phase of the study looked at all the known technologies in sufficient detail to allow strategic considerations to be made. This provided; an overview of each technology, a selected list of current reference installations, consideration of operational experiences, capex and opex costs (where available from published or internal sources), an assessment of the maturity of each process and a list of suppliers.

Procedure

In order to structure such an all encompassing review, the sludge technologies were broken down into groups relating the general purpose of the technology. These groups and the technologies studied are listed below.

- 1) SLUDGE MINIMISATION**
 - a. Cannibal
 - b. Ozonation –Biolysis
 - c. Enzymatic Conditioning

- 2) SLUDGE PRE-TREATMENT (+ ANAEROBIC DIGESTION)**
 - a. Acid phase hydrolysis
 - b. Thermal hydrolysis
 - c. Enzymic hydrolysis
 - d. Pre-pasteurisation
 - e. Ultrasound hydrolysis
 - f. Homogenisation (ball mills, mechanical shear, macerators)
 - g. Chemical hydrolysis (acid and/or alkali) pre-conditioning
 - h. High pressure hydrolysis (e.g. MICROSLUDGE)
 - i. Electron beam
 - j. Extended solids retention
 - k. Nutrient recovery

- 3) SLUDGE DEWATERING**
 - a. Electro-dewatering

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- b. Vacuum dewatering/drying
 - c. Drying beds, filter belt, filter press, centrifuge
 - d. Screw press
- 4) **AEROBIC DIGESTION**
- a. Aerobic
 - b. Autothermic Thermophilic Aerobic Digestion (ATAD)
 - c. Reed beds, Facultative lagoons
- 5) **ANAEROBIC DIGESTION**
- a. Mesophilic Anaerobic Digestion (MAD)
 - b. MAD in Series (Anaerobic Baffled Reactor)
 - c. Thermophilic (ThAD)
- 6) **DRYING**
- a. Direct Thermal, Indirect Thermal & Hybrid
 - b. High temperature centrifuges
 - c. Solar drying
- 7) **CHEMICAL STABILISATION**
- a. Lime only (powdered, or liquid (e.g. Kalic)) added to either liquid or sludge cake
 - b. Lime (or other admixtures) with supplementary heating system (e.g. RDP process) added to sludge cake
- 8) **COMPOSTING**
- a. Static pile (e.g. agitated bay), windrow, co-composting, in vessel composting (e.g. TEG), & vermicomposting
- 9) **THERMAL TREATMENTS**
- a. Raw and Digested Incineration
 - b. Co-combustion (as dewatered cake or dry pellets)
 - c. Wet Air Oxidation / Super Critical Wet Air Oxidation
 - d. Gasification
 - e. Pyrolysis/Oil from sludge/Carbonisation
 - f. Vitrification

In order to investigate these technologies, a number of sources were used that could be grouped as follows;

Published Literature – An extensive literature review was performed to identify new technologies being developed in Europe, and to evaluate their performance and applications. Specifically, the review focused on papers presented at the European Biosolids and Organic Resources Conferences and relevant output from the Dutch Foundation for Applied Water Research (STOWA) into commonly used as well as newly developed technologies/techniques in the field of wastewater.

“Grey” Literature – Vendor-supplied information, Internet research, and consultants’ technical reports.

US Literature – recent developments in sludge technologies from the United States were reviewed including Water Environment Federation (WEF) conference proceedings and the Environmental Protection Agency (EPA) Technical Report – ‘Emerging Technologies for Sludge Management’, September 2006 (www.epa.gov/owm).

Finally, a key element of any strategic considerations is the timeframe. In broad terms, the strategic review wanted to consider the situation now, in 10 years’ time and in 25 years’ time. This became translated in the technology review as processes that are commercially proven

(i.e. available now), developed (i.e. proven to work, but not widely applied) or embryonic (i.e. proven laboratory scale concepts or developed technologies that cannot yet be applied in the UK), respectively.

Phase One Evaluation Results

After gathering the information, the details of the 34 technologies investigated were compared against a list of 18 environmental, commercial and technical criteria that were developed from Thames Water Utilities Ltd's strategic and business drivers. In conjunction with the project stakeholders, each technology was given an indicative score against each criteria to give the results presented in the table below. This analysis was based on qualitative judgement and operational experience from a team drawn from experts across the Thames Water business and from Entec UK Ltd. Professional judgement was applied in each topic area. Some of the scores have been removed to protect Thames Water Utilities Ltd.

Table 1: Technology Scores

Generic Type	Technology	Technology Considerations						Environmental Compliance						Business Drivers						Scoring	
		Commercially Proven	Operational Complexity	Plant Maintainable	Flexibility	Plant Footprint	BAT	Process Emissions	Final Product quality	Process consumables	Net energy use	Waste Products Minimised	Waste Hierarchy	Ease of promotion	Minimise Customer Impact	Maximise Energy production	Avoid Landfill	Minimise Carbon Footprint	Minimise Environmental Impacts	Totals	Best in Class
Sludge Minimisation	Cannibal	3	3	4	3	3	2	4	2	5	2	3	4	3	4	1	3	2	3	54	1
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Sludge Pre-Treatment + AD	Acid phase hydrolysis																			73	
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	Enzymic hydrolysis	2	3	4	4	3	5	5	4	5	5	5	3	4	4	4	5	5	5	75	1
	Pre-pasteurisation																			72	
	Ultrasound hydrolysis																			65	
	Homogenisation																			62	
	Chemical hydrolysis																			61	
	High pressure hydrolysis																			64	
	Electron beam																			63	
	Extended solids retention																			70	
Nutrient recovery																			65		
Sludge Dewatering	Electro-dewatering																			67	
	Vacuum dewatering/drying																			56	
	Drying beds, filter belt/press, centrifuge																			70	
	Screw press	4	4	4	4	4	4	4	4	4	3	5	4	5	4	2	5	3	4	71	1

Table 1: Technology Scores (cont.)

Generic Type	Technology	Technology Considerations						Environmental Compliance						Business Drivers						Scoring	
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Aerobic Digestion	Aerobic																			60	
	Autothermic Thermophilic Aerobic Digestion (ATAD)																			52	
	Reed beds, Facultative Lagoons	4	5	5	4	1	4	3	4	5	5	5	3	4	4	3	5	4	4	72	1
Anaerobic Digestion	Mesophilic Anaerobic Digestion																			76	1
	MAD in Series	5	4	4	4	4	4	4	3	5	5	5	3	4	4	4	5	5	4	71	
	Thermophilic (ThAD)																			72	
Drying	Direct Thermal, Indirect Thermal & Hybrid																			58	1
	High temperature centrifuges	5	2	2	3	3	2	4	5	4	1	4	4	4	4	1	5	1	4	57	
	Solar drying																			48	
	Direct Microwave Drying																			51	
Chemical Stabilisation	Lime only stabilisation																			51	
	Lime with supplementary heating	5	4	4	4	4	4	3	2	2	2	5	3	1	1	1	5	2	3	55	1
Composting	Static pile, windrow, etc & vermiculture	4	4	4	5	1	3	2	4	3	2	4	3	3	3	1	3	2	3	54	1

Table 1: Technology Scores (cont.)

Generic Type	Technology	Technology Considerations						Environmental Compliance						Business Drivers						Scoring	
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Misc Thermal	Raw and Digested	5	1	1	2	4	3	5	5	3	3	3	1	1	5	2	2	3	4	53	1
	Co-combustion (as dewatered cake or dry pellets)	5	1	1	2	4	3	5	5	3	3	3	1	1	4	3	2	3	4	53	1
	Wet Air Oxidation/Super Critical Wet Air Oxidation																			52	
	Gasification	1	1	1	3	4	1	5	4	4	4	3	1	1	5	4	3	4	4	53	1
	Pyrolysis/Oil from sludge/Carbonisation																			51	
	Vitrification																			50	

The evaluation scoring has been carried out on a scale of 1 to 5, with 1 being the lowest and 5 the highest. Since the basis for scoring each criteria may be different, a symbol legend was also used (not shown in this table) to show the degree of acceptability or preference. So for example under Operating Complexity, this would range from very complex (requiring skilled and experienced operators) at one end of the spectrum to very simple and basic at the other. This would give a score of 1 (i.e. very complex and perhaps more difficult to operate), or a medium score of 3 (i.e. average complexity compared to established technologies) or a score of 5 (i.e. very simple and basic to operate).

Although a ranking is provided this is only for comparative purposes as any actual ranking would be dependent on factors that are site specific and may change over time. Nor is any recommendation implied of one technology over another. The benefit of this ranking, though, is to pick out the 'best in class' for Thames Water Utilities Ltd's requirements and to provide an indication of the relative scores of the technologies. For example, under the anaerobic digestion pre-treatment grouping, although thermal hydrolysis and enzymic hydrolysis are joint best in class, they are only just ahead of acid phase digestion and pre-pasteurisation.

The inference here is that any of these four technologies could be appropriate – the choice will depend upon the site-specific weighting of the various criteria. Of interest are the generally low scores of thermal processes in the modern energy conscious environment. It became clear during this study that there was very little published data regarding the carbon impact of these processes. Therefore this became a key consideration of the next phase of the project.

PHASE TWO – PROCESS EVALUATION

Purpose and Scope

The second phase of this work was carried out to provide a greater level of detail for how those technologies reviewed in Phase 1 would be used together to create process routes. As such, it was designed to be used to inform the development of Thames Water Utilities Ltd's Sludge Strategy.

The benefit of considering these technologies as part of process routes rather than as isolated stand-alone technologies is that the effects of each technology on the upstream and downstream technologies with which it will actually be applied in reality can be taken into account. This will give a much more accurate assessment of each technology's impact and enable the fairest possible comparisons to be made.

Thames Water Utilities Ltd were among the first water companies to recognise their impact on the environment through their carbon footprint and began including it as part of their sustainability reporting in 1993. The importance and awareness of climate change has increased manifold in the intervening years and it is now part of the UK water companies' annual reporting requirements to the regulator, OFWAT. It is now generally considered that carbon footprint is a key environmental and economic consideration in capital schemes and hence the periodic review determinations. It was therefore important to Thames Water Utilities Ltd that the carbon footprint of each of the process routes was calculated in an auditable and standardised manner that would stand the test of time. To maximise the auditability, the calculations of carbon footprint would need to be as closely aligned as possible to the national reporting requirements as encapsulated in the UKWIR GHG Reporting Tool. However, this tool is aimed at reporting carbon footprint at company level and is not appropriate for use at process level. Entec UK Ltd had previously created and developed a sludge carbon modelling tool that gives auditable results compared to the UKWIR Tool by dint of using the same principles and emission factors (from DEFRA) in the calculations.

Procedure

Using the best in class technologies that were found from Phase 1, process routes were then populated to manage sludge from raw sludge storage to final outlet. This was carried out at a workshop of key stakeholders for; the current situation, the situation predicted in 10 years time and possible situation in 25 years time. Each stage in the process route was created (shown in the left-most column in the tables below) to provide the key functions of;

- reducing volume (thickening, dewatering and drying),
- providing a treated product (digestion (and pre-treatment), composting),
- defining an outlet (thermal destruction or agriculture).

Other variants on these key functions were discussed but were not considered to be likely to be viable in the timeframes being considered (wet air oxidation, for example).

Table 2 shows process routes that are either currently in use in Thames Water Utilities Ltd or are commercially available and could therefore be applied now.

Table 2: Appropriate Currently Available Process Routes

	Process Routes					
Process Component						
Thickening	PFT + Drums	PFT + Drums	PFT + Drums	PFT + Drums	PFT + Drums	PFT + Drums
Sludge pre-treatment	Multi tank acid phase	THP		THP		THP
Digestion	MAD	MAD		MAD		MAD
Dewatering	Belt	Belt	Belt	Belt	Belt	Belt
Drying			Direct or Indirect	Direct or Indirect		
Thermal Destruction					Incineration	Incineration
Disposal Route	Land	Land	Land	Land	Landfill	Landfill

In addition to the process routes outlined in Table 2 above, two further process routes were identified at the workshop. These routes, shown in Table 3 below, may become available or more appropriate to the needs of Thames Water Utilities Ltd at some point in the future and would be applied in the sludge strategy in addition to the routes in Table 2.

Table 3: Appropriate Possible Future Additional Process Routes

	Process Routes	
Process Component		
Thickening	PFT + Drums	PFT + Drums
Sludge pretreatment	THP	
Digestion	MAD	
Dewatering	Belt+	Belt+
Drying	Direct or Indirect	Direct or Indirect
Thermal Destruction	Incineration	Gasification
Disposal Route	Landfill	Landfill

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Of note is the fact that none of the sludge minimisation technologies (i.e. processes that reduce the production of sludge as opposed to its mass or volume) were included in the process routes. They were considered to be too unlikely to become commercially proven in the 25 year timeframe of the Thames Water Utilities Ltd sludge strategy.

The study then considered each of these process routes by first defining the process boundaries and purpose of the routes (to facilitate and legitimise the later comparisons). An example of a process route boundary diagram is shown below. This shows the boundaries of what was included in the considerations pertaining to this route, together with some process information.

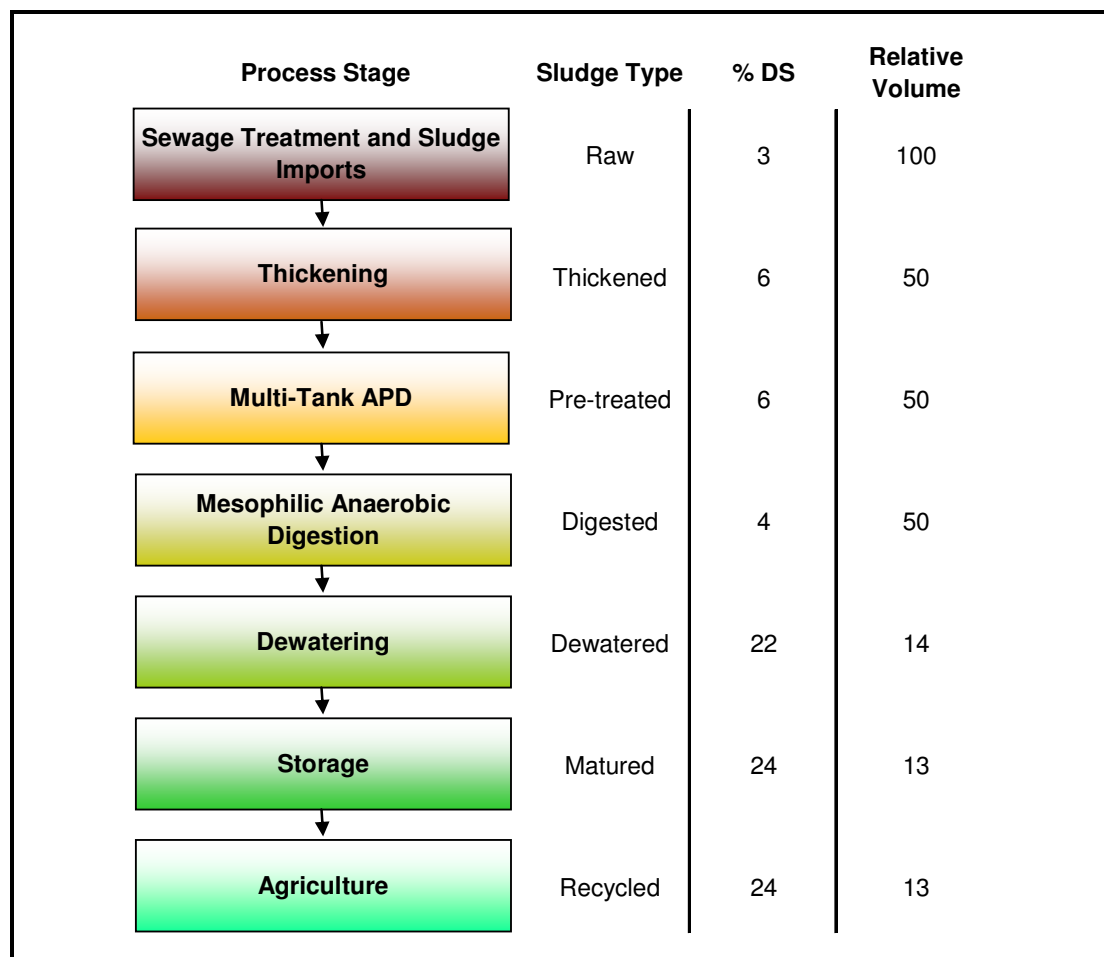


Figure 1: Acid Phase Digestion to Agriculture Process Route

The environmental impacts were considered in terms of the quantifiable impacts of; carbon footprint (see below), product outlets (traffic, odour and nutrients) and site footprint (area required for the process and product storage). The qualitative impacts were considered as part of a 'Pros and Cons' assessment.

The financial assessment used up to date cost curves from Entec UK Ltd and Thames Water Utilities Ltd. Clearly the use of cost curves will not give actual costs, but does provide a reliable and quantifiable base for comparing prices as well as a reasonable indication of cost for budgeting purposes.

Energy and Carbon Calculations

The process route was set up for a standardised 10,000tDSpa plant using Entec's sludge carbon modelling tool. This tool was created in conjunction with a major UK water company

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and has been thoroughly tested and validated (where possible) against known results. The data used here was adapted to UK water industry standards in order to protect client confidentiality. The model considers all the inputs (mass and energy) and outputs (mass, emissions, offsets) for each technology in combination with its upstream and downstream technologies or outlets.

The energy balance uses first principles to derive the energy consumed and produced from each stage of the process route. These have been normalised to kWh/year to allow comparisons to be made. The energy productions are net of parasitic heat loads.

The carbon footprint calculations use the same published (primarily collated and endorsed by DEFRA) emission factors as the 2006 UKWIR GHG Workbook, but Entec have applied them more appropriately than the approach born of reporting expediency used in the UKWIR Workbook. In Entec's view (supported by the Carbon Trust) this gives a more accurate picture of the true impact of these operations and therefore allows a realistic comparison of the processes to be carried out. The Entec model is able to calculate the carbon footprint for processes in common use that cannot be calculated by the UKWIR Workbook because the Entec model includes sufficient detail. It is simply not possible to use the UKWIR Workbook to provide the information delivered in this study.

The specific electricity emission factor used in this study was 0.43kgCO₂e/kWh, as required by DEFRA for strategic planning studies such as this.

The carbon results were calculated and presented as;

- Direct emissions – i.e. those from sources that are owned or controlled by the water company (e.g. fuels used on sites, process emissions and transport).
- Indirect emissions – i.e. those arising from a company's activities but occur from sources that are not owned or controlled by the company (e.g. electricity, agricultural activities related to sludge spreading).
- Societal emissions – i.e. those associated with the manufacture and transport of consumables used by the water industry (e.g. polyelectrolyte production). These are also known as supply chain emissions.

Embedded carbon (i.e. those associated with the manufacture and distribution of materials, especially those for materials of construction, such as concrete and steel, rather than for consumables) is not included as it was not fully developed at that time.

The direct emissions from the transport of sludge are from the diesel fuel used, but also include a factor for the methane liberated during the loading operation. This is based on the presumption of vacuum loading pumps and old sludge, which may not be appropriate to all operations.

The carbon footprint of the digestion pre-treatment plant is included in the digestion plant's figure as the one is basically part of the other. The direct emissions from the digestion plant are those associated with fugitive emissions and incomplete combustion of methane. The factors Entec has used took account of the real situation regarding secondary digestion (i.e. not always required and sometimes in covered tanks) and the likelihood of leakage and therefore are less than those expressed in the 2006 UKWIR GHG Workbook, but were similar to the latest (Summer 2008) version of the Workbook.

The indirect emissions from digestion arise because of the displacement of electricity production and therefore appear in the results as a negative. Similarly the indirect emissions from the disposal route are caused by the displacement of the need to use chemical fertilisers in the sludge to land route.

RESULTS

Quantitative Results

The detailed results from each of the process route sections have been summarised and gathered together in this section to enable the reader to judge the relative merits of each route. The results are presented in descending order of merit to facilitate this judgement.

In considering these tables it is important to keep in mind that the figures presented, whilst based on the best data available, have been calculated from a large number of variables and are therefore subject to considerable variability in their actual values. Taking table 4 as an example, this should be interpreted to say that route 5 is about 4 times more expensive than route 2. In the same vein, route 1 is similar in cost to route 2, and so on.

Table 4: NPV League Table

Appropriate Currently Available Route	Appropriate Possible Future Route	NPV (£M)
1. Acid Phase Digestion Cake to Agriculture		22
2. Thermal Hydrolysis Cake to Agriculture		23
4. Enhanced Digested Dried to Agriculture		35
3. Raw Dried to Agriculture		43
	17. Raw Dried Gasification	45
6. Enhanced Digested Cake Incineration		79
	12. Enhanced Digested Dried Incineration	82
5. Raw Cake Incineration		85

Table 5: Net Energy Consumption League Table

Appropriate Currently Available Route	Appropriate Possible Future Route	Net Energy Consumption (kWhpa)
2. Thermal Hydrolysis Cake to Agriculture		-20,000,000
4. Enhanced Digested Dried to Agriculture		-18,924,000
	12. Enhanced Digested Dried Incineration	-17,479,000
6. Enhanced Digested Cake Incineration		-16,990,000
1. Acid Phase Digestion Cake to Agriculture		-15,243,000
	17. Raw Dried Gasification	1,703,000
5. Raw Cake Incineration		8,216,000

3. Raw Dried to Agriculture		35,918,000

Table 6: Total GHG Emissions League Table

Appropriate Currently Available Route	Appropriate Possible Future Route	Total GHG emissions (tCO ₂ epa)
2. Thermal Hydrolysis Cake to Agriculture		730
4. Enhanced Digested Dried to Agriculture		1,010
1. Acid Phase Digestion Cake to Agriculture		1,210
6. Enhanced Digested Cake Incineration		1,230
	12. Enhanced Digested Dried Incineration	1,230
	17. Raw Dried Gasification	1,570
5. Raw Cake Incineration		5,230
3. Raw Dried to Agriculture		9,800

Consistently at or near the top of each league table is process route 2 – Thermal Hydrolysis Cake to Agriculture.

Routes 4 and 1 share second place, with route 1 (Acid Phase Digestion Cake to Agriculture) having better cost results and route 4 (Thermal Hydrolysis Dried to Agriculture) having better energy and carbon footprints.

The lack or minimal quantity of energy production from (respectively) routes 3 (Raw Dried to Agriculture) and 5 (Raw Cake Incineration) are placing these routes at the bottom of the league, with the cost of incineration making route 5 the bottom of the league for costs.

The high cost and relatively poor energy recovery from raw sludge incineration is generally placing those routes that include incineration towards the bottom of the league tables – although it must be noted that this is based on a 10,000tDSpa plant that would be unusually small for an incineration plant. On the other hand, Thermal Hydrolysis can be seen to be particularly beneficial.

Of the thermal destruction process routes, it may be seen that route 6 (Enhanced Digested Cake Incineration) is a good performer as is route 17 (Raw Dried Gasification [Future route]). It is interesting to note that Raw Dried Gasification is, in all cases, better than the current Raw Cake Incineration route, although clearly, gasification is not yet a proven process and this comparison is made using projected performance figures that may be optimistic.

Qualitative Results

General

Thickening is a feature that is common to all process routes considered in this study and confers the well understood advantage of reducing the size and hence cost, footprint and environmental impact of all the plant downstream of the thickening stage. The thickening process chosen for energy, carbon and cost analysis is drum thickening. A picket fence thickener (p.f.t) would use considerably less power in itself, but the high solids supernatant normally produced by a p.f.t causes the liquor treatment power consumption to be higher, resulting in only a slightly lower overall power consumption than for the drum thickener. The use of polyelectrolyte gives rise to a small supply chain/societal carbon emission for the drum thickener that does not arise from the p.f.t but this difference may be insignificant if the p.f.t emits more methane than a drum thickener. On balance it is a reasonable assumption that both the drum thickener and the p.f.t have the same carbon footprint.

Instigating routes that produce power at sites where there is inadequate Regional Electricity Company electrical infrastructure will result in high charges for this infrastructure to be installed. This issue requires the sizing of the CHP plant and hence the quantity of sludge treated by the process route to be carefully considered. This consideration needs to include the relative benefits of changing the sludge importation regime in an operational area – which will consequently have impacts on the recycling costs. This is a complex area of interactions that is best studied using computer modelling.

Agricultural Outlet

Having identified the relative merits of each process route from their position in the league tables it is clear that Thermal Hydrolysis Cake to Agriculture is the process route that most meets Thames Water Utilities Ltd's business needs. However, the limitation of this process to sites where an existing agricultural route is open and the upper capacity limit of around 40,000tDSpa mean that this route may not be suitable for the large works in the major conurbations.

The main reason that Thermal Hydrolysis (THP) appears particularly attractive in this study is because it is able to induce the highest Volatile Solids Destruction (VSD) of all proven advanced digestion processes, thus liberating the most energy from the sludge. Another advantage of THP over other advanced digestion pre-treatment is the improved dewaterability of the digested cake. This enables a lower volume 'soil-like' product to be produced that is attractive to farmers and should assist in keeping the agricultural route open to Thames Water Utilities Ltd. A further advantage of THP is that the process causes more nitrogenous material to be removed from the sludge (at the post digestion dewatering stage) than other processes do. This enables a higher sludge application rate to be attained in areas where the rate is limited by the nitrogen application rate, thus reducing the cost (financial and carbon) of the route. Of course, there is a penalty in the extra energy needed for treatment of these liquors, but in the particular case of Thames Water Utilities Ltd, this is less of an issue than it may be for other companies.

The other advanced digestion technique considered here, multi-tank acid phase digestion (APD) has the advantage over THP of relative simplicity that may be expected to confer a lower whole life cost. However, the most up to date data used in this study (from Thames Water Utilities Ltd, in part) actually shows THP to have a lower capex, opex and hence Net Present Value (NPV) than APD, although the figures are close.

THP also has the advantage that the combination of augmented gas production and dewaterability renders the sludge able to be thermally dried without the need of fossil fuel (and while still maintaining electricity production in a CHP). Hence, if at some point in the future the agricultural route becomes un-manageably restricted, then the dried product could still be recycled, by being sent to outlets as a fuel.

Thermal Destruction Outlet - Current

From this analysis, the large works in the major conurbations may be best served by a thermal destruction process in order to deal with the large quantities of sludge produced. The

classic incineration of raw sludge cake as widely practiced in the UK can be seen to give poor results in the context of the parameters analysed. Fundamentally, this is because of the large amount of water in the cake feedstock that is being incinerated. This water has no calorific value and produces a large volume of combustion products to be treated in gas clean-up equipment downstream of the incinerator's combustion chamber. In turn, this results in an occasional requirement for support fuel to be burnt to maintain the incineration and also much larger and therefore more costly plant and equipment. Removing this water will clearly have benefits and all the other thermal destruction routes considered here include for removal of more of this water first.

Thermal Destruction Outlet - Future

The league tables show Enhanced Digested Cake Incineration to have the best energy and GHG figures of the thermal destruction routes. This arises primarily because the digester gas produced by the process can be converted to electricity and heat (both of which may be used on site) and because the improved dewaterability of a thermally hydrolysed digestate reduces the cake's water content. The extra plant required for this route renders it rather more expensive than the next most attractive option - Raw Dried Gasification.

However, Gasification of sewage sludge is not a developed process and has only been considered here as the 25 year option. In developing the gasification process, its costs may increase considerably over the current projected costs used here. In the context of Thames Water Utilities Ltd's business driver to maximise energy recovery from sludge, it may be of interest to know that the combination of thermal hydrolysis, digestion, drying and gasification recovers more energy than any other investigated route. It is therefore suggested that gasification should be investigated as the preferred thermal destruction outlet in the long term and that the incineration of thermally hydrolysed cake should be further investigated as the future preferred route for the large works in the major conurbations.

CONCLUSIONS

1. The first phase of this study investigated thirty four technologies and found that for Thames Water Utilities Ltd's drivers, the highest scoring technologies were those associated with anaerobic digestion.
2. The best-in-class technologies were combined into eight process routes to enable the most appropriate technologies for Thames Water Utilities Ltd to be fairly and comprehensively compared. These routes have been analysed for their advantages and disadvantages along with their impact on the business drivers of cost, energy and carbon footprint.
3. This analysis has required a great deal of data and assumptions to be used as inputs to a fully validated sludge treatment process model. These inputs have been from a variety of sources known to Entec, including; published papers, 'industry standard' figures, Thames Water Utilities Ltd capex figures and recent costings from other Entec clients. It may be concluded that the information is the best available without asking for actual suppliers' quotes, process guarantees, etc. The sheer number of inputs brings with it a certain statistical error that means the numbers quoted from the outputs of the model should only be used to compare one route to another and to give an idea of the likely scale of the actual figures achievable in practice.
4. The most reliable method for calculating the carbon footprint is to start from first principles and work out all the inputs (mass and energy) and outputs (mass, emissions and offsets) for each technology when applied in combination with its upstream and downstream technologies (and outlets).
5. Clearly, for areas outside the major conurbations, advanced digestion in conjunction with dewatering and taking the cake to agriculture offers the most appropriate process route for Thames Water Utilities Ltd. Of the two advanced digestion techniques that have been commercially proven (Thermal Hydrolysis and Acid Phase Digestion), Thermal Hydrolysis offers lower cost, more energy and fewer GHG emissions across the whole process route. Furthermore, Thermal Hydrolysis produces a much superior cake product that

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should help to maintain the agricultural route (still the Best Practicable Environmental Option in most circumstances) open.

6. The large quantity of sludge produced at the works in major conurbations and the logistical difficulties of moving a sludge product from those works to an un-developed agricultural outlet mean that some form of thermal destruction may be preferred for those sites. The comparatively poor energy balance and high cost of the conventional raw cake incinerator is clear from this analysis when it is compared to the incineration of a sludge containing less water (i.e. after thermal hydrolysis or a thermal drying technology).
7. The benefits of installing a thermal hydrolysis advanced digestion plant prior to a (smaller) conventional incinerator are clearly shown. For the long term, there should be benefits from replacing incineration with gasification once the gasification technology has been developed.
8. By thoroughly assessing sludge technologies along their entire process route from source to final outlet, it is possible to assess the technologies that give the mix of cost, energy balance and carbon footprint that most suits the business requirements of the water company.

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REFERENCES

A large number of documents were consulted in the course of completing this study, the majority of which were published data from manufacturers. Most of the remaining documents were consultants' documents (mainly from Entec UK Ltd). The remaining references were from the annual Biosolids conferences, but are not quoted directly in this paper.