**BPEO AND BAT COMPARISON OF ENZYMIC HYDROLYSIS WITH OTHER SLUDGE TREATMENT PROCESSES FOR BLACKBURN WWTW**

*A report prepared for United Utilities Water PLC by WRc plc*

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# SUMMARY


## I BACKGROUND

United Utilities installed the Enhanced Enzymic Hydrolysis (EEH) process at Blackburn WwTW to produce enhanced treated sludge for agricultural recycling with financial support from EU LIFE. This study was carried out in order to demonstrate a proper Environmental Impact Assessment. This was done by a determination of whether it was the best available technology (BAT) and best practical environmental option (BPEO).

Enzymic hydrolysis involves heating the sludge to 42$^{o}$C for 24 hours followed by a period at 55$^{o}$C. The resultant sludge is then fed into a mesophilic anaerobic digester without secondary digestion. The digested sludge is dewatered and the cake recycled to agricultural land. The process has been designed to reduce pathogens numbers by 6 logs and, hence, produce an enhanced treated sludge.

## II METHODOLOGY

WRc used the MASTAR computer programme to estimate and compare the costs and environmental impact of the following 7 processes:

1. Digestion (enhance enzymic hydrolysis and primary), dewatering and recycle to agricultural land
2. Digestion (primary and secondary), dewatering and recycle to agricultural land
3. Raw dewatering, lime treatment and recycle to agricultural
4. Raw dewatering, incineration and disposal of ash to landfill
5. Digestion (primary and secondary), dewatering, incineration and disposal of ash to landfill
6. Fermented cake (fermentation and dewatering) and recycle to agriculture
7. Cambi process, dewatering and recycle to agriculture

WRc also made an assessment of which of the seven processes would result in an enhanced treated sludge.

Data and performance assumptions used in the analysis were those agreed with United Utilities and from published sources.

## III CONCLUSIONS

The sludge processes that could result in a log 6 kill of pathogens and, hence, produce an enhanced treated sludge that could be recycled to agriculture are:

- Enhanced hydrolysis followed by digestion,
- Lime treatment of raw sludge cake

- Cambi followed by digestion

The Enzymic hydrolysis/digestion option is most favourable in terms of combined cost and environmental impact for existing facilities if energy recovery from the sludge after the EH process replaces air cooling.

The Enzymic hydrolysis/digestion option, with energy recovery, and the Cambi digestion option are equally favourable in terms of combined cost and environmental impact for new facilities.

The use of air cooling for the Enzymic hydrolysis/digestion options puts it at a disadvantage when compared to Cambi/digestion in terms of combined cost and environmental impact but it remains equal to digestion alone and better than the other options assessed.

There is too much uncertainty to determine if the fermented cake process would achieve the required pathogen reduction. The process does produce volatile fatty acids (VFAs) that would provide biological phosphorus removal in a suitably designed activated sludge plant, but the value of this was not considered in this study.

The results of the study are based on assumptions agreed with United Utilities, including gas production and solids destruction through the Enzymic Hydrolysis process and published performance data from a Cambi system at Dublin Bay, Ireland (Pickworth B et al 2006).

# 1. INTRODUCTION

United Utilities installed the Enhanced Enzymic Hydrolysis (EEH) process as a preferred bolt-on upgrade for the Blackburn Digestion facility to guarantee enhanced treated sludge for agricultural recycling. This project was financially supported by EU LIFE in order to demonstrate best practice in sludge treatment in Europe. The process was selected for its combined advantage of simple yet robust operation and optimum enzyme activity at 55°C. The low pasteurizing temperature allows the plant to guarantee the minimum 6-log E. coli reduction using only low-grade heat. This is important, as it would enable any standard CHP scheme to use a greater proportion of the biogas for electricity production.

In order to demonstrate a proper Environmental Impact Assessment, WRc was commissioned to carry out a comparison of the EEH process with other sludge treatment processes to determine whether it was the best available technology (BAT) and best practical environmental option (BPEO) for the enhanced treatment of sludge at Blackburn WwTW.

WRc used the MASTAR computer program to estimate and compare the costs and environmental impact of the following 7 processes:

1. Digestion (primary and secondary), dewatering and recycle to agricultural land
2. Digestion (enhance enzymic hydrolysis and primary), dewatering and recycle to agricultural land
3. Raw dewatering, lime treatment and recycle to agricultural land
4. Raw dewatering, incineration and disposal of ash to landfill
5. Digestion (primary and secondary), dewatering, incineration and disposal of ash to landfill
6. Fermented cake (fermentation and dewatering) and recycle to agriculture
7. Cambi process, dewatering and recycle to agriculture

WRc also made an assessment of which of the seven processes would result in an enhanced treated sludge. Assumptions required for performances were agreed/modified by United Utilities.

This report contains the results of the BAT/BPEO assessment.

# 2. METHODOLOGY AND ASSUMPTIONS

## 2.1 Methodology

The MASTAR computer program, outlined in Appendix A, was used to calculate and compare the environmental impact and costs of the sludge treatment processes assessed. The results from MASTAR were used to determine the BPEO.

The processes were assessed in terms of whether they would produce an enhanced treated sludge by considering the operating conditions of each sludge treatment process and referring to Section 2 of the WaterUK report "The Application of HACCP Procedures in the Water Industry: Biosolids Treatment and Use on Agricultural Land" (WaterUK, 2004, http://www.water.org.uk/static/files_archive/0WUK_Haccp_guide_FINAL_19_Mar_04.pdf ).

## 2.2 Assumptions

The key assumptions regarding the initial sludge used for the assessment are contained in Table 2.1.

**Table 2.1 Key assumptions regarding the initial sludge**

| Parameter | Assumed value |
|---|---|
| Sludge dry solids (tDS/d) | 36.7 |
| Sludge volume (m3/d) | 540 |
| Sludge solids conc (% wt/wt) | 6.8 |
| Sludge loss on ignition (LOI) (%) | 70 |
| Sludge type | Mixture of primary and waste activated sludge |
| Winter mean sludge temp ($^oC$) | 6 |
| Spring mean sludge temp ($^oC$) | 10 |
| Summer mean sludge temp ($^oC$) | 18 |
| Autumn mean sludge temp ($^oC$) | 10 |
| Nitrogen conc. (kg/tDS) | 45 |
| Proportion of nitrogen that is soluble (%) | 3 |
| Phosphorus conc (kg/tDS) | 52 as $P_2O_5$ |
| Proportion of phosphorus that is soluble (%) | 40% available year 1 |

Information on the energy balance for the Enzymic Hydrolysis process was determined from a document produced by United Utilities called "The Blackburn Energy Balance – Issues and

Potential" (Le, 2007). Information on the energy balance for the Cambi process was determined from published performance data for the Cambi process at Dublin Bay, Ireland, in September 2004 (Pickworth et al, 2006).

A detailed list of the assumptions used for the treatment processes, resources costs etc are in Appendix B.

These assumptions were all agreed or provided for this study by United Utilities.

# 3. BPEO/BAT RESULTS AND COMPARISON OF PROCESSES

## 3.1 Assessment of enhanced sludge treatment

An assessment of whether enhanced sludge treatment can be achieved by the processes assessed is contained in Table 3.1.

**Table 3.1 Assessment of whether processes would result in an enhanced treated sludge recycled to agriculture**

| No. | Process | Sludge recycled to agriculture? | Enhanced treated sludge is produced? |
|---|---|---|---|
| 2 | Enhanced hydrolysis / Digestion / Dewater / Agriculture | Yes | Yes, provided the operating temperature of 55°C is maintained for 4 hours |
| 1 | Digestion / Dewater / Agriculture | Yes | No |
| 3 | Dewater / Lime / Agriculture | Yes | Yes, providing the pH value of sludge is raised to at least pH12 |
| 4 | Dewater / Incineration / Landfill | No | Not applicable |
| 5 | Digestion / Dewater / Incineration / Landfill | No | Not applicable |
| 6 | Fermented Cake / Dewater / Agriculture | Yes | Uncertain(1) |
| 7 | Cambi / Digestion / Dewater / Agriculture | Yes | Yes, because sludge is heated to 170°C |

Note(1) WRc is uncertain whether the operating conditions for the fermented cake process, of 42°C for 6 days and the presence of high concentrations of volatile fatty acids, would produce pathogen reduction equivalent to other enhanced processes.

## 3.2 Environmental impact and costs for process using new or existing facilities

Tables 3.2 and 3.3 contain summaries of the environmental impact and costs determined from MASTAR for processes using new or existing facilities, respectively. The values are presented per tonne of raw sludge dry solids treated. For processes involving digestion the use of existing facilities includes the refurbishment of the digesters at Blackburn. More detailed results are provided in Appendix C.

**Table 3.2 Environmental impact and costs of processes using new facilities**

| PARAMETER | Scheme 2A | Scheme 2C | Scheme 1A | Scheme 3A | Scheme 4A | Scheme 5A | Scheme 6A | Scheme 7A |
|---|---|---|---|---|---|---|---|---|
| | Enhanced hydrolysis Air cooling Digest Dewater Agricult. | Enhanced hydrolysis Energy recovery Digest Dewater Agricult. | Digest Dewater Agricult. | Dewater Lime Agricult. | Dewater Incin. Landfill | Digest Dewater Incin. Landfill | Ferment. Cake Dewater Agricult. | Cambi Digest Dewater Agricult. |
| Raw sludge daily dry mass (tDS/d) | 36.7 | 36.7 | 36.7 | 36.7 | 36.7 | 36.7 | 36.7 | 36.7 |
| Net Primary Energy (GJ/tRwDS)(1) | -3.8 | -6.4 | -6.3 | 2.2 | -0.9 | -1.1 | 1.1 | -4.4 |
| Greenhouse Equiv. (kgCO2/tRwDS) | 1150 | 1060 | 1396 | 1597 | 1349 | 1795 | 1366 | 1035 |
| Acid Gas Equivalent (kgH+/tRwDS) | 0.04 | 0.02 | 0.03 | 0.08 | 0.07 | 0.11 | 0.08 | 0.03 |
| Mean Daily Distance (km/tRwDS) | 10.1 | 10.1 | 9.9 | 19.9 | 18.6 | 14.0 | 11.5 | 9.3 |
| Capital Cost (Q4 2005) (£/tRwDS) | 78 | 78 | 78 | 6 | 129 | 164 | 25 | 78 |
| Operating Cost (£/tRwDS) | -14 | -34 | -28 | 61 | 65 | 56 | 31 | -17 |
| Net Present Cost over 20 years @ 6% discount rate (£/tDS) | 70 | 58 | 62 | 40 | 166 | 196 | 42 | 68 |

Note: (1) Negative Net Primary Energy value denotes net export of energy due to export of electricity from CHP or the fertiliser value from the recycling of sludge to agricultural land.

**Table 3.3 Environmental impact and costs of processes using existing facilities**

| PARAMETER | Scheme 2B | Scheme 2D | Scheme 1B | Scheme 3B | Scheme 4B | Scheme 5B | Scheme 6B | Scheme 7B |
|---|---|---|---|---|---|---|---|---|
| | Enhanced hydrolysis Air cooling Digest Dewater Agricult. | Enhanced hydrolysis Energy recovery Digest Dewater Agricult. | Digest Dewater Agricult. | Dewater Lime Agricult. | Dewater Incin. Landfill | Digest Dewater Incin. Landfill | Ferment. Cake Dewater Agricult. | Cambi Digest Dewater Agricult. |
| Raw sludge daily dry mass (tDS/d) | 36.7 | 36.7 | 36.7 | 36.7 | 36.7 | 36.7 | 36.7 | 36.7 |
| Net Primary Energy (1) (GJ/tRwDS) | -4.0 | -6.6 | -5.3 | 2.2 | -0.9 | -1.2 | 1.0 | -4.6 |
| Greenhouse Equiv. (kgCO2/tRwDS) | 1135 | 1045 | 1404 | 1595 | 1347 | 1783 | 1365 | 1023 |
| Acid Gas Equivalent (kgH+/tRwDS) | 0.04 | 0.01 | 0.03 | 0.08 | 0.07 | 0.11 | 0.08 | 0.0 |
| Mean Daily Distance (km/tRwDS) | 10.1 | 10.1 | 11.0 | 19.9 | 18.6 | 14.0 | 11.5 | 9.3 |
| Capital Cost (Q4 2005) (£/tRwDS) | 33 | 33 | 33 | 2 | 125 | 119 | 22 | 42 |
| Operating Cost (£/tRwDS) | -14 | -34 | -19 | 61 | 65 | 56 | 31 | -17 |
| Net Present Cost over 20 years @ 6% discount rate (£/tDS) | 25 | 13 | 22 | 36 | 162 | 148 | 40 | 33 |

Note: (1) Negative Net Primary Energy value denotes net export of energy due to export of electricity from CHP or the fertiliser value from the recycling of sludge to agricultural land.

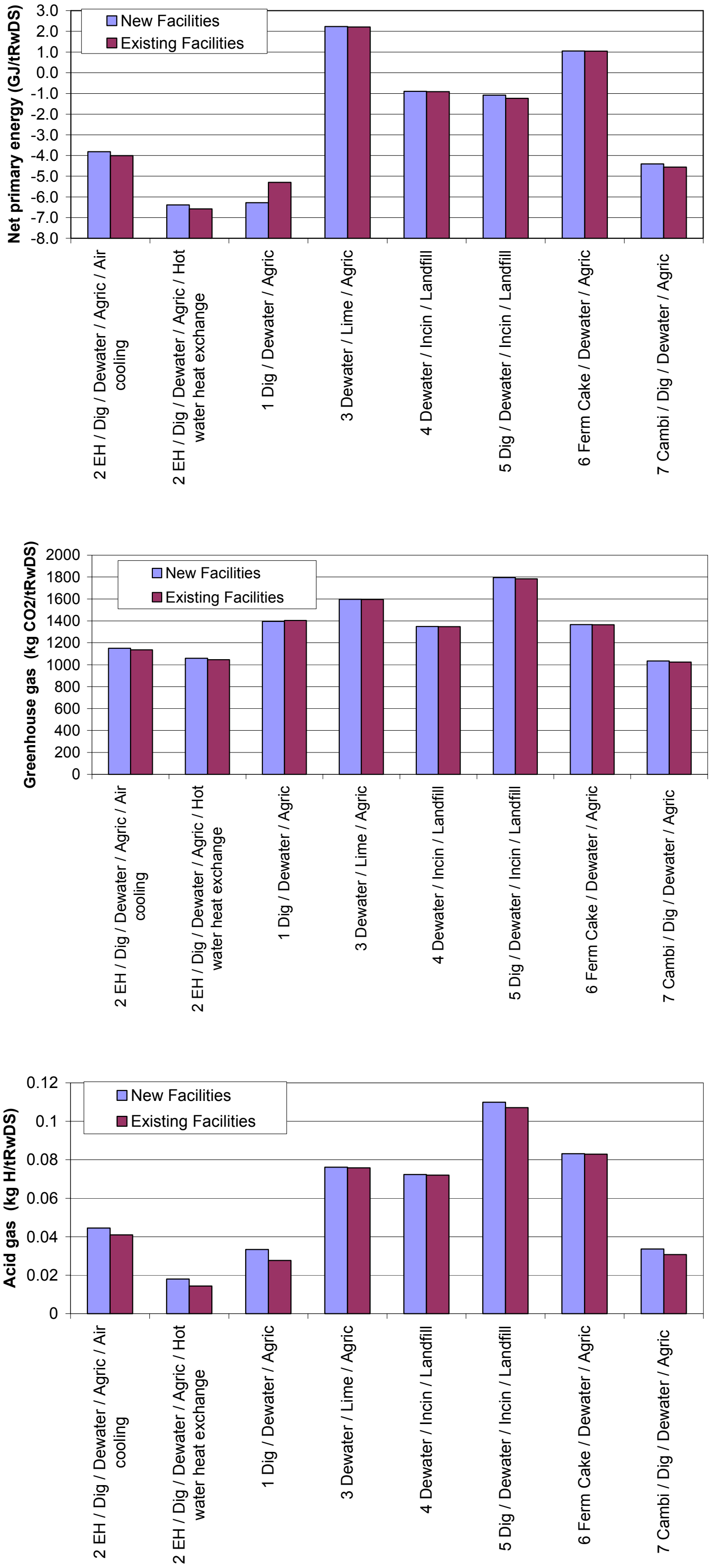


**Figure 3.1 Comparison of sludge processes using new or existing facilities for net primary energy (top), greenhouse gas and acid gas emissions**

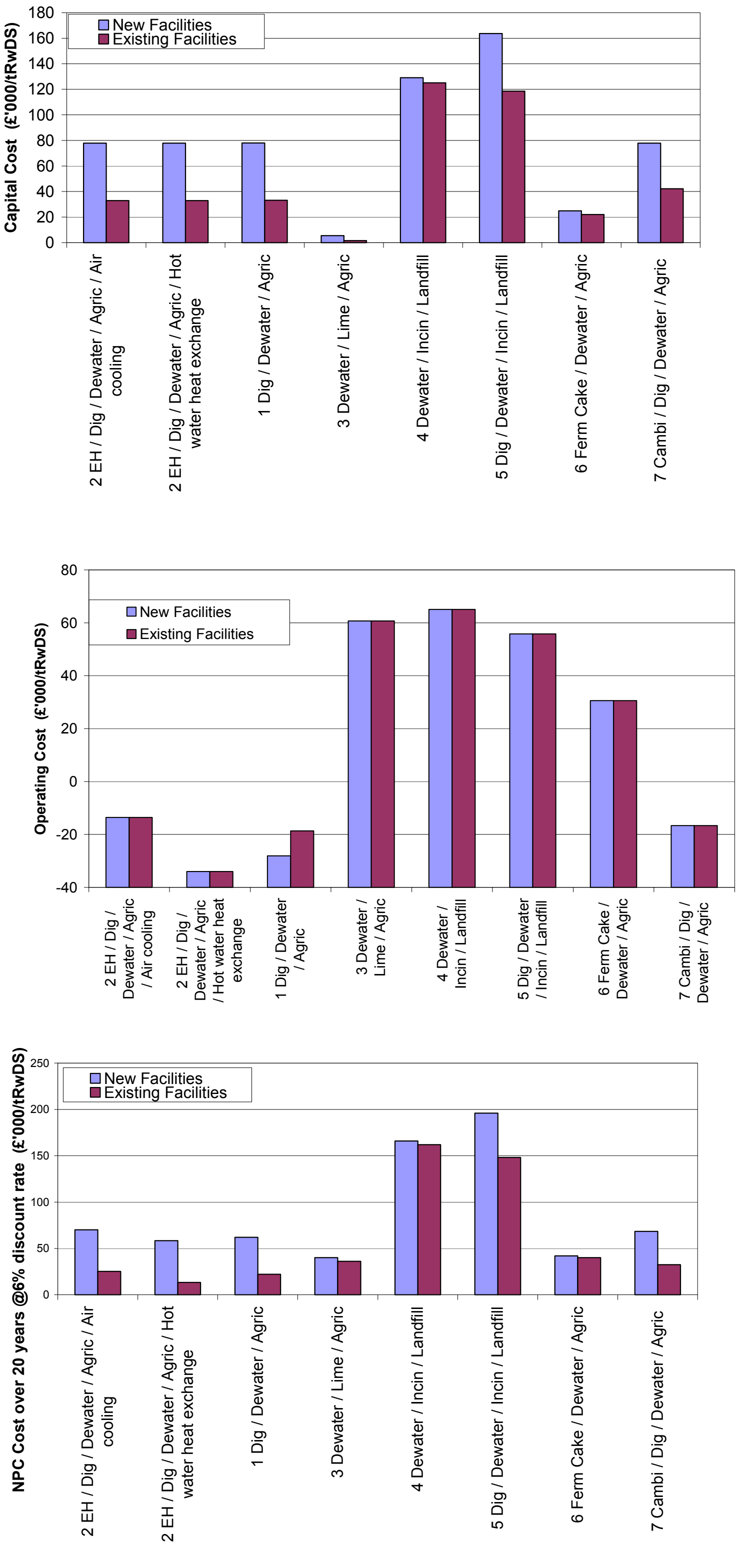


**Figure 3.2 Comparison of sludge processes using new and existing facilities for capital cost (top), operating cost and net present cost (NPC) over 20 years at 6% discount rate**

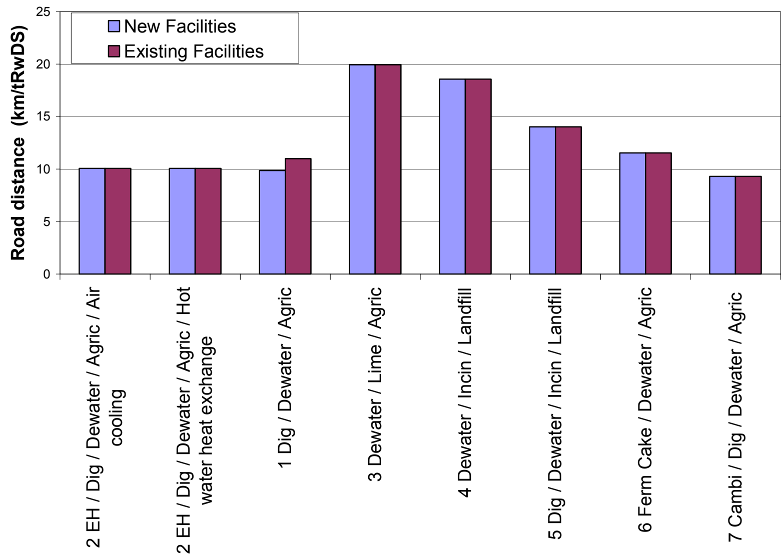


**Figure 3.3 Comparison of sludge processes using new and existing facilities for transport distance**

Table 3.4 shows the rankings of the processes in ascending order for each environmental impact category and net present cost for using new facilities. The same information is shown in Table 3.5 for the use of existing facilities.

If new facilities are used and the mean ranked position for all categories is considered, enhanced hydrolysis/digestion, with air cooling of the sludge prior to digestion, would be less favourable than Cambi/digestion but more favourable than the other processes assessed. The replacement of air cooling with energy recovery, however, could make it joint top with Cambi/digestion or digestion alone.

If existing facilities are used and the mean ranked position for all categories is considered, enhanced hydrolysis/digestion, with air cooling of the sludge prior to digestion, would also be less favourable than Cambi/digestion or digestion alone but more favourable than the other processes assessed. The replacement of air cooling with energy recovery, however, would make it the top process.

### Table 3.4 Ranking of schemes using new facilities for their environmental impact and net present cost

| | 2A | 2C | 1A | 3A | 4A | 5A | 6A | 7A |
|---|---|---|---|---|---|---|---|---|
| | **Enhanced hydrolysis Air cooling Digest Dewater Agricult.** | **Enhanced hydrolysis Energy recovery Digest Dewater Agricult.** | **Digest Dewater Agricult.** | **Dewater Lime Agricult.** | **Dewater Incin. Landfill** | **Digest Dewater Incin. Landfill** | **Ferment. Cake Dewater Agricult.** | **Cambi Digest Dewater Agricult.** |
| **Can process result in an enhanced treated sludge recycled to agriculture?** | Yes | Yes | No | Yes | No | No | Uncertain (1) | Yes |
| **Ranked position in descending order:** | | | | | | | | |
| Net primary energy | 4 | 1 | 2 | 8 | 6 | 5 | 7 | 3 |
| Greenhouse gases | 3 | 2 | 6 | 7 | 4 | 8 | 5 | 1 |
| Acid gases | 4 | 1 | 2 | 6 | 5 | 8 | 7 | 3 |
| Road transport | 3 | 3 | 2 | 8 | 7 | 6 | 5 | 1 |
| NPC cost | 4 | 4 | 6 | 1 | 7 | 8 | 2 | 3 |
| **Mean ranked position for all categories** | 3.6 | 2.2 | 3.6 | 6.0 | 5.8 | 7.0 | 5.2 | 2.2 |

Note:(1) WRc is uncertain whether the operating conditions for the fermented cake process, of 42$^{o}$C for 6 days an the presence of high concentrations of volatile fatty acids, produce pathogen reduction equivalent to other enhanced processes.

### Table 3.5 Ranking of schemes using existing facilities for their environmental impact and net present cost

| | 2B | 2D | 1B | 3B | 4B | 5B | 6B | 7B |
|---|---|---|---|---|---|---|---|---|
| | **Enhanced hydrolysis Air cooling Digest Dewater Agricult.** | **Enhanced hydrolysis Energy recovery Digest Dewater Agricult.** | **Digest Dewater Agricult.** | **Dewater Lime Agricult.** | **Dewater Incin. Landfill** | **Digest Dewater Incin. Landfill** | **Ferment. Cake Dewater Agricult.** | **Cambi Digest Dewater Agricult.** |
| **Can process result in an enhanced treated sludge recycled to agriculture?** | Yes | Yes | No | Yes | No | No | Uncertain (1) | Yes |
| **Ranked position in descending order:** | | | | | | | | |
| Net primary energy | 4 | 1 | 2 | 8 | 6 | 5 | 7 | 3 |
| Greenhouse gases | 3 | 2 | 6 | 7 | 4 | 8 | 5 | 1 |
| Acid gases | 4 | 1 | 2 | 6 | 5 | 8 | 7 | 3 |
| Road transport | 2 | 2 | 4 | 8 | 7 | 6 | 5 | 1 |
| NPC cost | 3 | 3 | 5 | 1 | 8 | 7 | 2 | 6 |
| **Mean ranked position for all categories** | 3.2 | 1.8 | 3.8 | 6 | 6.0 | 6.8 | 5.2 | 2.8 |

# 4. CONCLUSIONS

Out of the seven sludge processes assessed, the following three processes could result in a log 6 kill of pathogens and, hence, produce an enhanced treated sludge that could be recycled to agriculture are:

- Enhanced hydrolysis followed by digestion,
- Lime treatment of raw sludge cake
- Cambi followed by digestion

The Enzymic hydrolysis/digestion option is most favourable in terms of combined cost and environmental impact for existing facilities if energy recovery from the sludge, after the EH process, replaces air cooling.

The Enzymic hydrolysis/digestion option, with energy recovery, and the Cambi digestion option are equally favourable in terms of combined cost and environmental impact for new facilities.

The use of air cooling for the Enzymic hydrolysis/digestion options puts it at a disadvantage when compared to Cambi/digestion in terms of combined cost and environmental impact but it remains equal to digestion alone and better than the other options assessed.

There is too much uncertainty to determine if the fermented cake process would achieve the required pathogen reduction. The process does produce volatile fatty acids (VFAs) that would provide biological phosphorus removal in a suitably designed activated sludge plant, but the value of this was not considered in this study.

The results of the study are based on assumptions agreed with United Utilities, including gas production and solids destruction through the Enzymic Hydrolysis process and published performance data from a Cambi system at Dublin Bay, Ireland (Pickworth B et al 2006).

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Le, S (2007). "The Blackburn Energy Balance – Issues and Potential", United Utilities, April 2007.

Pickworth B, Adams J, Panter K and Solheim O (2006). "Maximising biogas in anaerobic digestion by using engine waste heat for thermal hydrolysis pre-treatment of sludge." Water Science and Technology. Volume 54 No 5 pp 101-108

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# APPENDIX A GENERAL DESCRIPTION OF MASTAR

## A1 INTRODUCTION

MASTAR provides a methodical approach for estimating the environmental impact and costs of sewage sludge treatment and recycle/disposal options. This can be used to determine the Best Practical Environmental Option (BPEO) for the treatment and recycle/disposal of sewage sludge.

The program should significantly reduce the time and expense required to carry out this type of evaluation. It should also act as a valuable audit trail. To aid this, the program contains a “notes” facility which should be used extensively to record changes to parameters and variables.

For a particular sludge treatment and disposal network the computer program will estimate:

Environmental impact in terms of:

- Net primary energy
- Greenhouse gases
- Acid gases
- Transport related accidents

Costs in terms of:

- Capital costs
- Operating costs

Resource usage, such as

- Imported fuel
- Net electricity import or export
- Consumables, such as polyelectrolyte for mechanical dewatering and lime for lime treatment
- Derv usage for transport
- Man power
- Land area

The computer program can be used in two different ways:

1. A series of networks of generic sewage sludge treatment processes can be created and used to find the BPEO for a sewage treatment works or area of a wastewater company.

2. Existing process networks or detailed designs for the treatment of sewage sludge can be evaluated to determine their environmental impacts.

A network can also be set up with two or more sludge treatment works that are either completely separate to each other or have sludge transported between them.

For every situation the user sets up a treatment and disposal sewage sludge network in the computer program, runs the computer to calculate the environmental impact and cost estimate and then exports the results to an Excel spreadsheet for viewing and additional processing.

The default values of all parameters for each process module can be changed by the user. Some values that are calculated by the computer can be over-ridden by the user by entering a user-set value.

## A2 Available Sludge Unit Processes

Sludge networks can be set up to contain the following processes:

- ✓ Gravity thickening
- ✓ Mechanical thickening
- ✓ Mechanical dewatering
- ✓ Pasteurisation
- ✓ Mesophilic anaerobic digestion (ManD)
- ✓ Thermal drying
- ✓ Incineration
- ✓ Addition of lime
- ✓ Cambi process
- ✓ Biotherm process
- ✓ Recycle to agriculture
- ✓ Disposal to landfill
- ✓ Transport
- ✓ Treatment of sludge liquors
- ✓ Buffer storage capacity
- ✓ Secondary sludge pretreatment
- ✓ Composting
- ✓ Gasification
- ✓ Inter-process pumping
- ✓ Brick and cement manufacture
- ✓ Co-combustion in a coal-fired power station

## A3 Equipment used to operate MASTAR

To operate MASTAR the following are required:

a) Computer

b) MASTAR software – installed from the CD

c) MASTAR security dongle – inserted into the back of the computer

d) Excel – used to view the results

e) Excel “Results Comparison” Spreadsheet – used to compare the results for different networks(a blank copy of the spreadsheet is installed into the directory containing the MASTAR Program Files)

f) Operating Manual – provides instructions and reference material – this will be used during the training course.

## A4 Using MASTAR

### A4.1 General operation of the program

The MASTAR Computer Program is operated using the following steps to calculate the Environmental Assessment and Cost Estimation of a sludge treatment and recycle or disposal network:

a) Create a network of sludge sources, treatment processes and recycle or disposal routes or open an existing network

b) Check and change for the particular application, where necessary, the values for the operating parameters of the sludge sources, treatment processes and recycle/disposal routes.

c) Save the new network and make notes of any changes or other information.

d) Set up the calculation run.

e) Check, and if necessary, change the global constants that affect all unit processes (e.g. unit costs of consumables and temperatures of incoming sludge and ambient air).

f) Start the calculation run.

g) Export the results to an Excel spreadsheet and, if desired, view the results immediately.

h) If desired, a copy of the results summary for each network can be copied into a “Results comparison” spreadsheet to enable a number of networks to be compared.

### A4.2 Description of the MASTAR program screens

The MASTAR program screen is split into three parts:

a) A task bar at the top of the screen – for choosing the three function windows (Admin, Toolbox and Run Setup), Help and to Exit the program.

b) The Function Screen in the bottom left section of the screen – displays function keys dependent on the function window selected.

c) The network design sheet in the bottom right section of the screen – displays the sludge treatment network.

The three Function Windows are used for the following tasks:

- Admin: This administration window is used to create and save projects and networks, print information and edit network notes (see Figure A1).

- Toolbox: This window provides the sludge treatment unit processes that are used to create the networks (see Figure A2).

- Run Setup: The selection of "Run Setup" provides "The MASTAR Simulation Processor" screen (see Figure A3). This window is used to View or Edit the global constants that affect all unit processes, start the calculation of environmental assessment and cost estimates and Export the results to an Excel spreadsheet and, if desired, view the results immediately.

The position of the Function Window can be swapped from the right to the left part of the screen in the Admin Function Window by selecting "Customise" followed by "Swap panes".

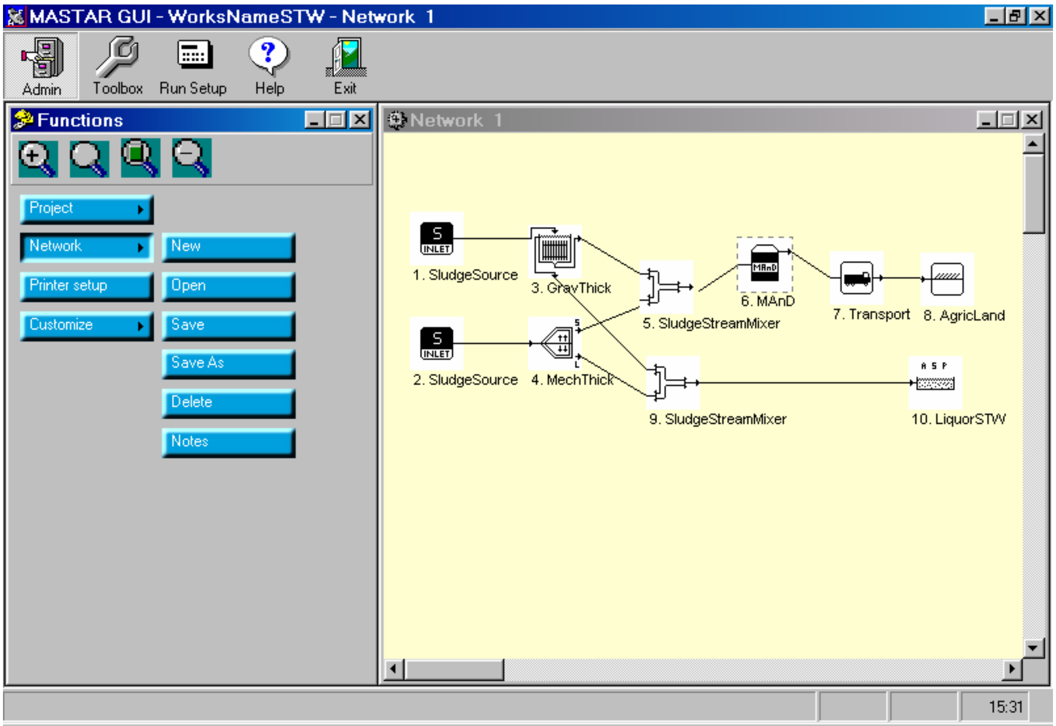


**Figure A1 Appearance of Admin Window**

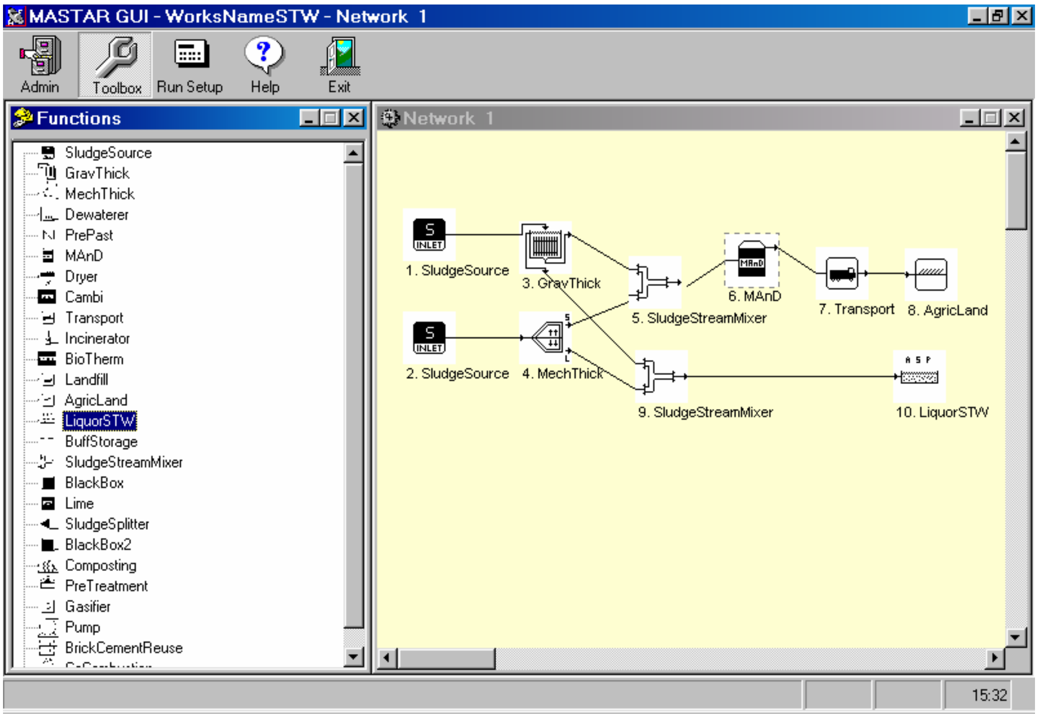


**Figure A2 Appearance of Toolbox Window**

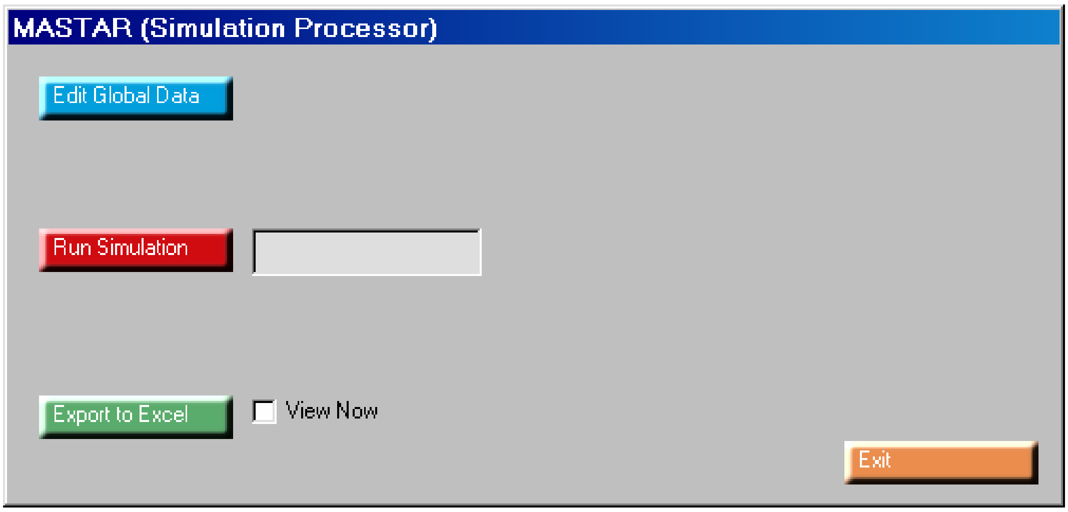


**Figure A3 Appearance of Run Setup Window**

## A3 Information provided in the MASTAR results

The spreadsheet produced for each run contains the following information in a number of worksheets:

a) **MASTAR Results Summary**: A results summary sheet (see Figure A4), which provides the sludge throughput for the sludge treatment and recycle/disposal network, and the quantitative environmental impact and costs (capital, operation and net present cost) of the sludge network expressed in terms of tonne of raw sludge treated.

   A list of qualitative parameters (see Figure A5) can also be provided. These are not automatically estimated. The user can decide whether or not to enter a score. The scoring of qualitative issues is quite difficult and there are other methods in the water industry for considering them. The comparison of relative scores for qualitative parameters for two or more networks will most likely be more helpful than the absolute values for each network.

b) **Assumptions:** Assumptions of the interest rates etc. used to estimate the net present cost.

c) **Run Data:** Detailed information of the environmental impact, resource requirements and estimated costs (capital and operating) for each unit process and the total for the network.

   The outlet parameters, such as sludge dry mass, thickness, volume, volatile solids content, ammoniacal nitrogen etc, for each unit process.

   The process parameter values assumed for each unit process. A complete list of process parameters are provided in the Operating Manual.

d) **Global Parameters:** The values for the global parameters are listed. A complete list of global variables are provided in the Operating Manual.

The “Results Comparison” Excel spreadsheet (see Figure A6) can be used to compare the MASTAR results summaries for different runs or networks.

# APPENDIX B DETAILED ASSUMPTIONS

**Initial Sludge**

| Parameter | Preliminary Assumption | Data reference | Action for UU (Check & confirm or provide data) | UU Response |
|---|---|---|---|---|
| Sludge dry solids (tDS/d) | 36.7 | UU data | Check & confirm/update | confirm |
| Sludge volume (m3/d) | 540 | UU data | Check & confirm/update | confirm |
| Sludge solids conc (% wt/wt) | 6.8 | Calculated from above information | Check & confirm/update | confirm |
| Sludge loss on ignition (LOI) (%) | 70 | UU data | Check & confirm/update | confirm |
| Sludge type | Mixture of primary and waste activated sludge | UU data | Check & confirm/update | Assume 50:50 |
| Winter mean sludge temp (oC) | 6 | UU data | Check & confirm/update | confirm |
| Spring mean sludge temp (oC) | 10 | UU data | Check & confirm/update | confirm |
| Summer mean sludge temp (oC) | 18 | UU data | Check & confirm/update | confirm |
| Autumn mean sludge temp (oC) | 10 | UU data | Check & confirm/update | confirm |
| Nitrogen conc. (kg/tDS) | 27 | WRc estimate based on typical values | Check & confirm/update | 45 |
| Proportion of nitrogen that is soluble (%) | 3 | WRc estimate based on typical values | Check & confirm/update | confirm |
| Phosphorus conc (kg/tDS) | 12 | WRc estimate based on typical values | Check & confirm/update | 52 as P2O5 |
| Proportion of phosphorus that is soluble (%) | 30 | WRc estimate based on typical values | Check & confirm/update | 40% available year 1 |

**Ambient Air Temperature**

| Parameter | Preliminary Assumption | Data reference | Action for UU (Check & confirm or provide data) | UU Response |
|---|---|---|---|---|
| Winter mean air temp (oC) | -2 | UU data | Check & confirm/update | confirm |
| Spring mean air temp (oC) | 11.5 | Calculated as mean of winter and autumn temperatures | Check & confirm/update | confirm |
| Summer mean air temp (oC) | 25 | UU data | Check & confirm/update | confirm |
| Autumn mean air temp (oC) | 11.5 | Calculated as mean of winter and autumn temperatures | Check & confirm/update | confirm |

**Resource Unit Costs/Revenue**

| Parameter | Preliminary Assumption | Data reference | Action for UU (Check & confirm or provide data) | UU Response |
|---|---|---|---|---|
| Electricity exported to the National Grid (Revenue) (£/kWh) | 0.10 | UU data | Check & confirm/update | confirm |
| Electricity imported from National Grid (Cost) (£/kWh) | 0.05 | UU data | Check & confirm/update | confirm |
| Unit cost of Polyelectrolyte (£/t) | 3000 | WRc estimate | Check & confirm/update | confirm |
| Unit cost of Derv (£/litre) | 0.9 | WRc estimate | Check & confirm/update | confirm |
| Unit cost of labour (£'000/y) | 25 | WRc estimate | Check & confirm/update | 50 |
| Unit cost of lime (£/tonne) | 75 | UU data | Check & confirm/update | 80 |
| Unit cost of Natural Gas (if required) (£/kWh) | 0.019 | DTI average value for 2006 Q2 | Provide data on cost paid by UU | confirm |
| | | | | |
| Cost basis | 2005 Q4 | | | |
| COPI index | 149 | http://www.statistics.gov.uk/statbase/TSDtimezone.asp | (Used in cost functions used by WRc to make estimates) | |
| M&E Index | 128 | http://www.statistics.gov.uk/statbase/TSDtimezone.asp | (Used in cost functions used by WRc to make estimates) | |

**Scheme 1: Digestion(primary& secondary)/Dewater/Agric**

| Parameter | Preliminary Assumption | Data reference | Action for UU (Check & confirm or provide data) | UU Response |
|---|---|---|---|---|
| **Digester** | | | | |
| VSD (%) | 40 | WRc estimate based on typical values | Check & confirm/update | 45 |
| Mean residence time (days) | 15 | WRc estimate based on typical values | Check & confirm/update | 12 |
| Number of digesters | | | Provide data | 4 |
| Have digesters fixed or floating roofs | | | Provide data | F |
| Height of digesters (m) (if floating roof, height to liquid level) | | | Provide data | 18 |
| Diameter of digester (m) | | | Provide data | 12.5 |
| Digester wall heat trans coeff (kW/m2/oC) | 0.002 | WRc estimate based on typical values | Check & confirm/update | confirm |
| Operating temp (oC) | 35 | WRc estimate based on typical values | Check & confirm/update | confirm |
| Volatile solids solubilsed (%) | 20 | WRc estimate based on typical values | Check & confirm/update | confirm |
| Soluble volatile solids to soluble N ratio | 1 | WRc estimate based on typical values | Check & confirm/update | confirm |
| Soluble volatile solids to soluble P ratio | 0 | WRc estimate based on typical values | Check & confirm/update | confirm |
| Biogas leakage (%) | 1 | WRc estimate based on typical values | Check & confirm/update | confirm |
| Biogas methane content (% v/v) | 65 | WRc estimate based on typical values | Check & confirm/update | confirm |
| Biogas CV (MJ/m3) | 22 | WRc estimate based on typical values | Check & confirm/update | confirm |
| Biogas yield (m3/kgVSD) | 1 | WRc estimate based on typical values | Check & confirm/update | 0.85 |
| Heating method | Hot water from CHP | UU data | Check & confirm/update | confirm |
| Imported fuel type | Not required | WRc assumption | Check & confirm/update | confirm |
| CHP combustion effy % | 99 | WRc estimate based on typical values | Check & confirm/update | confirm |

| Parameter | Preliminary Assumption | Data reference | Action for UU (Check & confirm or provide data) | UU Response |
|---|---|---|---|---|
| CHP biogas to hot water energy conversion (%) | 50 | WRc estimate based on typical values | Check & confirm/update | 38 |
| CHP biogas to electrical energy conversion (%) | 30 | WRc estimate based on typical values | Check & confirm/update | 33 |
| CHP electricity exported to National Grid | Yes | UU data | Check & confirm/update | confirm |
| Digester specific elec power for mixing (kW/m3) | 0.0041 | Data from WRc and CIRIA 1981 | Check & confirm/update | confirm |
| Secondary digester res time (d) | 14 | WRc estimate based on typical values | Check & confirm/update | confirm |
| **<u>Dewatering</u>** | | | | |
| Process type | Centrifuge | UU data | Check & confirm/update | confirm |
| Sludge cake solids concentration (% wt/wt) | 25 | WRc estimate based on typical values | Check & confirm/update | confirm |
| Polyelectrolyte dose (kg/tDS) | 6.5 | UU data | Check & confirm/update | confirm |
| Electricity usage (GJ/tTS) | 0.2 | WRc estimate based on information from Coombs 1988 | Check & confirm/update | confirm |
| No. of centrifuges | | | Provide data | |
| Liquor treated in an ASP plant? | Yes | WRc assumption | Check & confirm/update | confirm |
| **<u>Agricultural Recycle</u>** | | | | |
| Mean distance sludge travels (km) | 40 | UU data | Check & confirm/update | 25 miles |
| Lorry capacity (m3) | 20 | WRc estimate | Check & confirm/update | confirm |
| Vehicle availability (d/y) | 255 | WRc estimate | Check & confirm/update | confirm |
| Trips per vehicle per day | 4 | WRc estimate | Check & confirm/update | confirm |
| Lorry life span (years) | 5 | WRc estimate | Check & confirm/update | confirm |
| Steel mass per vehicle (tonne) | 18 | WRc estimate | Check & confirm/update | confirm |
| Lorry fuel consumption (l/km) | 0.45 | WRc estimate | Check & confirm/update | confirm |
| Lorry cost for 20m3 capacity (£'000) | 50 | WRc estimate | Check & confirm/update | 75 |

| Parameter | Preliminary Assumption | Data reference | Action for UU (Check & confirm or provide data) | UU Response |
|---|---|---|---|---|
| Additional vehicle operating costs in addition to fuel and labour (£'000/y) | 5 | WRc estimate | Check & confirm/update | 0 |
| Soluble nitrogen utilisation by crops (%) | 100 | WRc estimate | Check & confirm/update | confirm |
| Soluble Phosphorus utilisation by crops(%) | 100 | WRc estimate | Check & confirm/update | confirm |
| Insoluble N utilisation by crops % | 20 | WRc estimate | Check & confirm/update | yes, per year |
| Insoluble P utilisation by crops % | 50 | WRc estimate | Check & confirm/update | yes, per year |
| Nitrogen fertiliser energy unit value (GJ/t) | 80 | Data estimate for the production and packaging of artificial fertilisers | Check & confirm/update | confirm |
| Phosphorus fertiliser energy unit value (GJ/t) | 28 | Data estimate for the production and packaging of artificial fertilisers | Check & confirm/update | confirm |
| Ultimate VSD after agric (including preceding treatment processes) (%) | 65 | WRc estimate | Check & confirm/update | 85 |
| Proportion of VSD in agricultural recycle that is anaerobic (%) | 10 | WRc estimate | Check & confirm/update | 5 |
| **Capital cost of scheme** | | | | |
| 1A: New Digesters & New Dewatering (£'000) | | | Provide data | 16,719 |
| 1B: Refurbish Digesters & Use Existing Centrifuge (£'000) | | | Provide data | 7,000 |
| **Labour** | | | | |
| Total labour requirement (no. of staff) | 1 | UU data | Check & confirm/update | 1.5 |

**Scheme 2: Enzymic Hydrolysis/Digestion/Dewater/Agricultural Recycle**

| Parameter | Preliminary Assumption | Data reference | Action for UU (Check & confirm or provide data) | UU Response |
|---|---|---|---|---|
| **Enzymic Hydrolysis** | | | | |
| Operating temp (oC) | 24 hs: 42oC | UU data | Check & confirm/update | Confirm |
| | Then: 55oC | UU data | Check & confirm/update | Confirm |
| Heating method | Biogas/hot water from digestion/CHP | UU data | Check & confirm/update | Confirm |
| Outlet temp (oC) | 39 | UU data | Check & confirm/update | Confirm |
| Cooling method: | | | | |
| Scheme 2A | Air cooled | UU data | Check & confirm/update | Confirm |
| Scheme 2B | Heat exchanger returns heat to feed sludge | UU data | Check & confirm/update | in future |
| Electrical power of process (kW) | | | Provide data | 10 |
| Solubilisation of volatile solids % | | | Provide data | 20 |
| **Digester** | | | | |
| VSD (%) | 53.5 | UU data | Check & confirm/update | Confirm |
| Mean residence time (days) | 15 | WRc assumption | Check & confirm/update | 12 |
| Number of digesters | | | Provide data | 4 |
| Have digesters fixed or floating roofs | | | Provide data | F |
| Height of digesters (m) (if floating roof, height to liquid level) | | | Provide data | 18 |
| Diameter of digester (m) | | | Provide data | 12.5 |
| Digester wall heat trans coeff (kW/m2/oC) | 0.002 | WRc assumption | Check & confirm/update | Confirm |
| Operating temp (oC) | 35 | WRc assumption | Check & confirm/update | Confirm |
| Volatile solids solubilised (%) | 20 | WRc assumption | Check & confirm/update | Confirm |
| Soluble volatile solids to soluble N ratio | 1 | WRc assumption | Check & confirm/update | Confirm |
| Soluble volatile solids to soluble P ratio | 0 | WRc assumption | Check & confirm/update | Confirm |
| Biogas leakage (%) | 5 | WRc assumption | Check & confirm/update | 1 |
| Biogas methane content (% v/v) | 65 | UU data | Check & confirm/update | Confirm |
| Biogas CV (MJ/m3) | 22 | UU data | Check & confirm/update | Confirm |

| **Parameter** | **Preliminary Assumption** | **Data reference** | **Action for UU (Check & confirm or provide data)** | **UU Response** |
|---|---|---|---|---|
| Biogas yield (m3/kgVSD) | 0.85 | WRc assumption | Check & confirm/update | 0.85 |
| Heating method | Heat of sludge from EH process | UU data | Check & confirm/update | Confirm |
| Imported fuel type | Not required | UU data | Check & confirm/update | Confirm |
| CHP combustion effy % | 99 | WRc assumption | Check & confirm/update | Confirm |
| CHP biogas to hot water energy conversion (%) | 50 | WRc assumption | Check & confirm/update | 38 |
| CHP biogas to electrical energy conversion (%) | 30 | WRc assumption | Check & confirm/update | 33 |
| CHP electricity exported to National Grid | Yes | UU data | Check & confirm/update | Confirm |
| CHP hot water heat trans effy % | 100 | WRc assumption | Check & confirm/update | Confirm |
| Digester specific elec power for mixing (kW/m3) | 0.0041 | WRc assumption | Check & confirm/update | Confirm |
| Secondary digester res time (d) | 0 | WRc assumption | Check & confirm/update | Confirm |

**Scheme 2 (Enhanced Hydrolysis): Energy Balance**

| | No heat recovery | Heat recovery |
|---|---|---|
| Sludge dry solids (tDS/d) | 36.7 | 36.7 |
| Raw sludge feed per day (m3/d) | 540 | 540 |
| Feed sludge solids conc (%) | 6.8 | 6.8 |
| VS (%) | 70 | 70 |
| VSD (%) | 53.5 | 53.5 |
| Biogas production (m3/d) determined from Figure 1 in Le (2007) | 11500 | 11500 |
| CHP electrical output (kWh/d) | 16250 | 23750 |
| Reference for CHP electrical output | Figure 5 in Le (2007) | Figure 6 in Le (2007) |
| Methane content (%) | 65 | 65 |
| Biogas CV content (MJ/m3) | 22 | 22 |
| **Biogas energy content (kW)** | **2928** | **2928** |
| CHP electrical output (kW) | 677 | 990 |
| Mixing power (kW/m3) | 0.0041 | 0.0041 |
| No of digesters | 4 | 4 |
| Digester height (m) | 18 | 18 |
| Digester diameter (m) | 12.5 | 12.5 |
| Volume of digestions (m3) | 8836 | 8836 |
| Electrical power for EH process (kW) | 10 | 10 |
| Electrical energy for mixing (kW) | 36 | 36 |
| **CHP electricity energy exported (kW)** | **631** | **943** |
| Biogas combustion - specific CO2 emission (kg/1000m3) | 1957 | 1957 |
| Biogas fugitive leaks - CH4 emission (kg/tDS) based on 45% VSD | 1.4 | 1.4 |
| Biogas fugitive leaks - CH4 emission (kg/tDS) based on 53.5% VSD | 1.7 | 1.7 |
| Biogas combustion effiency (%) | 99 | 99 |
| Electricity production - specific CO2 emission (kg/GJ) | 122 | 122 |
| Biogas generation (m3/s) | 0.133 | 0.133 |
| CO2 emission - biogas combustion (kg/s) | 0.260 | 0.260 |
| CO2 emission - electricity generation savings (kg/s) | -0.077 | -0.115 |
| CO2 emission - total (kg/s) | 0.184 | 0.145 |
| CH4 content of biogas (%) | 65.000 | 65.000 |
| CH4 molecular mass (g/mol = kg/kmol) | 16.000 | 16.000 |
| Molecular gas volume (m3/kmol) | 22.400 | 22.400 |
| CH4 fugitive emission volume - incomplete combustion (m3/s) | 0.00087 | 0.00087 |
| CH4 fugitive emission - incomplete combustion losses (kg/s) | 0.00062 | 0.00062 |
| CH4 emission - fugitive leaks (kg/s) | 0.0007 | 0.0007 |
| CH4 emission - fugitive total (kg/s) | 0.0013 | 0.0013 |
| Labour requirement (No. of staff) | 1.5 | 1.5 |
| Labour unit cost (£'000/y) | 25.0 | 25.0 |
| Labour cost (£'000/y) | 37.5 | 37.5 |
| Elec unit value for export to Nat Grid (£/kWh) | -0.1 | -0.1 |
| Elec revenue (£'000/y) | -552.6 | -826.4 |
| **Net operating cost (£'000/y)** | **-515.1** | **-788.9** |

| Parameter | Preliminary Assumption | Data reference | Action for UU (Check & confirm or provide data) | UU Response |
|---|---|---|---|---|
| **Dewatering** | | | | |
| Same as for Scheme 1 | | | | |
| **Agricultural Recycle** | | | | |
| Same as for Scheme 1 | | | | |
| **Capital cost of scheme** | | | | |
| Scheme 2C: New EH process, New Digesters & New Dewatering (£'000) | | | Provide data | 16,719 |
| Scheme 2D: New EH process, Refurbish Digesters & Use Existing Dewatering Process (£'000) | | | Provide data | 7,000 |
| **Labour** | | | | |
| Total labour requirement (no. of staff) | 1.5 | UU data | Check & confirm/update | Confirm |

**Scheme 3: Dewater/Lime/Agricultural Recycle**

| Parameter | Preliminary Assumption | Data reference | Action for UU (Check & confirm or provide data) | UU Response |
|---|---|---|---|---|
| **Dewater** | | | | |
| Process type | Centrifuge | UU data | Check & confirm/update | Confirm |
| Sludge cake solids concentration (% wt/wt) | 25 | WRc estimate based on typical values | Check & confirm/update | confirm |
| Polyelectrolyte dose (kg/tDS) | 6.5 | UU data | Check & confirm/update | confirm |
| Electricity usage (GJ/tTS) | 0.2 | WRc estimate based on information from Coombs 1988 | Check & confirm/update | confirm |
| No. of centrifuges | | | Provide data | 3 |
| Liqueur treated in an ASP plant? | Yes | WRc assumption | Check & confirm/update | confirm |
| **Lime treatment** | | | | |
| Lime dose (kg/wet tonne) | 50 | UU data | Check & confirm/update | confirm |
| Lime dose (kg/dry tonne) & 25% solids conc | 200 | Calculated from lime dose and estimate cake solids conc. | Check & confirm/update | confirm |
| Silo supply capacity (d) | 30 | WRc assumption | Check & confirm/update | confirm |
| **Agricultural recycle** | | | | |
| Same as Scheme 1 | | | | |
| **Capital Cost** | | | | |
| Scheme 3A: New Dewatering process and New Lime Treatment Process | WRc will estimate | | Confirm that this is to be determined | confirm |
| Scheme 3B: Existing Dewatering process but New Lime Process | WRc will estimate | | Confirm that this is to be determined | confirm |
| **Labour** | | | | |
| Total labour requirement (no. of staff) | 1 | UU data | Check & confirm/update | 2 |

**Scheme 4: Dewater/Incin/Landfill**

| Parameter | Preliminary Assumption | Data reference | Action for UU (Check & confirm or provide data) | UU Response |
|---|---|---|---|---|
| **Dewater** | | | | |
| Same as Scheme (3) | | | | |
| **Incineration** | | | | |
| Distance to transport material to Incinerator (km) | 40 | UU data | Check & confirm/update | confirm |
| Distance to transport ash from Incinerator to landfill (km) | 80 | UU data | Check & confirm/update | confirm |
| Lorry capacity (m3) | 20 | WRc estimate | Check & confirm/update | confirm |
| Vehicle availability (d/y) | 255 | WRc estimate | Check & confirm/update | confirm |
| Trips per vehicle per day | 4 | WRc estimate | Check & confirm/update | confirm |
| Lorry life span (years) | 5 | WRc estimate | Check & confirm/update | confirm |
| Steel mass per vehicle (tonne) | 18 | WRc estimate | Check & confirm/update | confirm |
| Lorry fuel consumption (l/km) | 0.45 | WRc estimate | Check & confirm/update | confirm |
| Lorry cost for 20m3 capacity (£'000) | 50 | WRc estimate | Check & confirm/update | 75 |
| Additional vehicle operating costs in addition to fuel and labour (£'000/y) | 5 | WRc estimate | Check & confirm/update | 0 |
| Landfill charge for ash disposal (gate fee plus landfill tax)(£/tonne) | 45 | WRc estimate | Check & confirm/update | 50 |
| Capital cost (£'000) of incinerator receiving sludge from Blackburn and other sites and having a throughput of 40,000 tDS/year | | | Provide data | 80,000 |
| Blackburn WwTW sludge output (tDS/y) | 13396 | Calculated | | |
| Proportion of capital cost attributed to Blackburn sludge (%) | 33 | Calculated | | |
| Capital cost (£'000) of incinerator attributed to | 26791 | Calculated | | |

| Parameter | Preliminary Assumption | Data reference | Action for UU (Check & confirm or provide data) | UU Response |
|---|---|---|---|---|
| sludge from Blackburn | | | | |
| Electricity generation from raw sludge (GJ/tonne) | 1.15 | Determined in WRc report by Frost and Bull, 1988 | Check & confirm/update | confirm. This is gross figure |
| Capital costs determined for: | | | | |
| Scheme 4A: New dewatering process and New Incineration Contribution | | | Confirm that this is to be determined | Confirm |
| Scheme 4B: Existing dewatering process and New Incineration Contribution | | | Confirm that this is to be determined | Confirm |
| **Labour** | | | | |
| Total labour requirement (no. of staff) | 0.5 | UU data | Check & confirm | 10<br>The incinerator will employ a total of 30 staff plus one at Blackburn |

**Scheme 5: Digest/Dewater/Incin/Landfill**

| Parameter | Preliminary Assumption | Data reference | Action for UU (Check & confirm or provide data) | UU Response |
|---|---|---|---|---|
| **Digestion** | | | | |
| Same as Scheme (1) | | | | |
| **Dewater** | | | | |
| Same as Scheme (1) | | | | |
| **Incineration** | | | | |
| Distance to transport material to Incinerator (km) | 40 | UU data | Check & confirm/update | confirm |
| Distance to transport ash from Incinerator to landfill (km) | 80 | UU data | Check & confirm/update | confirm |
| Lorry capacity (m3) | 20 | WRc estimate | Check & confirm/update | confirm |
| Vehicle availability (d/y) | 255 | WRc estimate | Check & confirm/update | confirm |
| Trips per vehicle per day | 4 | WRc estimate | Check & confirm/update | confirm |
| Lorry life span (years) | 5 | WRc estimate | Check & confirm/update | confirm |
| Steel mass per vehicle (tonne) | 18 | WRc estimate | Check & confirm/update | confirm |
| Lorry fuel consumption (l/km) | 0.45 | WRc estimate | Check & confirm/update | confirm |
| Lorry cost for 20m3 capacity (£'000) | 50 | WRc estimate | Check & confirm/update | 75 |
| Additional vehicle operating costs in addition to fuel and labour (£'000/y) | 5 | WRc estimate | Check & confirm/update | 0 |
| Capital cost (£'000) of incinerator receiving sludge from Blackburn and other sites and having a throughput of 40,000 tDS/year | | | Provide data | 80,000 |
| Blackburn WwTW sludge output (tDS/y) | 9176 | Calculated | | |
| Proportion of capital cost attributed to Blackburn sludge (%) | 23 | Calculated | | |

| Parameter | Preliminary Assumption | Data reference | Action for UU (Check & confirm or provide data) | UU Response |
|---|---|---|---|---|
| Capital cost (£'000) of incinerator attributed to sludge from Blackburn | 18352 | Calculated | | |
| Electricity generation from raw sludge (GJ/tonne) | 0 | Determined in WRc report by Frost and Bull, 1988 | Check & confirm/update | confirm |
| Capital costs determined for: | | | | |
| Scheme 5A: New dewatering process, New digesters and New Incineration Contribution | | | Confirm that this is to be determined | confirm |
| Scheme 5B: Existing dewatering process, Refurbish digesters and New Incineration Contribution | | | Confirm that this is to be determined | confirm |
| **Labour** | | | | |
| Total labour requirement (no. of staff) | 0.5 | UU data | Check & confirm | 10 The incinerator will employ a total of 30 staff plus one at blackburn |

**Scheme 6: FermentedCake/Dewater/Agric**

| Parameter | Preliminary Assumption | Data reference | Action for UU (Check & confirm or provide data) | UU Response |
|---|---|---|---|---|
| Operating temperature (oC) | 42 | UU data | Check & confirm/update | confirm |
| Heating method | Biogas provides sufficient energy | UU data | Check & confirm/update | confirm |
| VSD (%) | 12.5 | UU data | Check & confirm/update | 40 |
| Electrical power of process (kW) | | | Provide data | 10 |
| Solubilisation of volatile solids % | | | Provide data | 40 |
| **Dewater** | | | | |
| Same as Scheme 1 | | | | |
| **Agricultural Recycle** | | | | |
| Same as Scheme | | | | |
| **Capital cost of scheme** | | | | |
| Scheme 6A: New Fermented Cake Process & New Dewatering (£'000) | | | Provide data | 5,275 |
| Scheme 6B: New Fermented Cake Process & Use Existing Dewatering Process (£'000) | | | Provide data | 4,641 |
| **Labour** | | | | |
| Total labour requirement (no. of staff) | 1 | UU data | Check & confirm/update | 1.5 |

**Scheme 7: Cambi/Digestion/Dewater/Agricultural Recycle**

**Interpretation of data from Cambi process at Dublin (Pickworth, 2006) and application of the data for Blackburn:**

| | Dublin Bay | Blackburn |
|---|---|---|
| Sludge dry solids (tDS/d) | 83.5 | 36.7 |
| Raw sludge feed per day (m3/d) | 700 | 308 |
| Feed sludge solids conc (%) | 11.93 | 11.9 |
| VS (%) | 81 | 70 |
| Biogas production (m3/d) | 30,000 | 11395 |
| Methane content (%) | 65 | 65 |
| Biogas CV content (MJ/m3) | 22 | 22 |
| **Biogas energy content (kW)** | **7639** | **2902** |
| Biogas flow to main steam boiler (m3/d) | 4000 | 2150 |
| Steam production from main steam boiler (t/h) | 1.3 | 0.7 |
| Steam production from main steam boiler per biogas flow (t/m3) | 0.0078 | 0.0078 |
| Biogas flow to thermal oxidisers (foul gas removal) (m3/d) | 1500 | 570 |
| Biogas flow to Jenbacher engines (m3/d) | 23000 | 8105 |
| Steam production from Jenbacher engines (t/h) | 1.5 | 0.53 |
| Biogas energy to Jenbacher engines (kW) | 5856 | 2064 |
| Natural gas imported (m3/d) | 1250 | 475 |
| Natural gas CV (MJ/m3) | 37 | 37 |
| **Natural gas energy imported to JenBacher engines (kW)** | **535** | **203** |
| Biogas and natural gas to JenBacher engines (kW) | 6392 | 2267 |
| Biogas and natural gas to JenBacher engines (kWh/h) | 6392 | 2267 |
| Steam production from Jenbacher engines per biogas flow (t/kWh gas energy) | 0.0002 | 0.0002 |
| Biogas flow to flare stack (m3/d) | 1500 | 570 |
| Steam available for Cambi (KW) | 2.8 | 1.23 |
| Steam requirement for Cambi (t/h) | 2.8 | 1.23 |
| Steam energy balance check (kW) (difference between available and requirement) | 0.00 | 0.00 |
| Total biogas check (m3/d) | 30000 | 11395 |
| **Electricity generated (kW)** | **2500** | **881** |
| Biogas to electrical energy conversion (%) | 43 | 43 |
| **Total biogas and nat gas (kW)** | **8174** | **3105** |

**Data used for Blackburn estimate:**

**Cambi/Digestion**

| | |
|---|---|
| Volatile solids in feed (tVS/d) | 25.69 |
| VSD (%) | 60.0 |
| Volatile solids destroyed (tVS/d) | 15.4 |
| Biogas energy (kW) | 2902 |
| Nat Gas energy to Boiler(kW) | 203 |
| CHP electricity energy generated (kW) | 881 |
| Mixing power (kW/m3) | 0.0041 |
| No of digesters | 4 |
| Digester height (m) | 18 |
| Digester diameter (m) | 12.5 |
| Volume of digestions (m3) | 8836 |
| Electrical energy for mixing (kW) | 36 |
| Electrical power for Cambi (kW) | 75 |
| **CHP electricity energy exported (kW)** | **769** |
| Biogas combustion - specific CO2 emission (kg/1000m3) | 1957 |
| Biogas fugitive leaks - CH4 emission (kg/tDS) based on 45% VSD | 1.4 |
| Biogas fugitive leaks - CH4 emission (kg/tDS) based on 60% VSD | 1.9 |
| Biogas combustion effiency (%) | 99 |
| Electricity production - specific CO2 emission (kg/GJ) | 122 |
| Biogas generation (m3/s) | 0.152 |
| CO2 emission - biogas combustion (kg/s) | 0.297 |
| CO2 emission - electricity generation savings (kg/s) | -0.094 |
| CO2 emission - total (kg/s) | 0.203 |
| CH4 content of biogas (%) | 65.000 |
| CH4 molecular mass (g/mol = kg/kmol) | 16.000 |
| Molecular gas volume (m3/kmol) | 22.400 |
| CH4 fugitive emission volume - incomplete combustion (m3/s) | 0.00099 |
| CH4 fugitive emission - incomplete combustion losses (kg/s) | 0.00070 |
| CH4 emission - fugitive leaks (kg/s) | 0.0013 |
| CH4 emission - fugitive total (kg/s) | 0.0020 |
| Labour requirement (No. of staff) | 4.0 |
| Labour unit cost (£'000/y) | 25.0 |
| Labour cost (£'000/y) | 100.0 |
| Nat Gas Unit Cost (£/kWh) | 0.019 |
| Nat Gas Units (kWh/y) | 1781910 |
| Nat Gas Cost (£;000/y) | 33.9 |
| Electricity unit revenue value for export to Nat Grid (£/kWh) | -0.1 |
| Electricity revenue (£'000/y) | -674.0 |
| **Net operating cost (£'000/y)** | **-540.2** |

| Parameter | Preliminary Assumption | Data reference | Action for UU (Check & confirm or provide data) | UU Response |
|---|---|---|---|---|
| **<u>Dewatering</u>** | | | | |
| Same as for Scheme 1 | | | | |
| **<u>Agricultural Recycle</u>** | | | | |
| Same as for Scheme 1 | | | | |
| **Capital cost of scheme** | | | | |
| Scheme 7A: New Cambi process, New Digesters & New Dewatering (£'000) | | | Provide data | 16,719 |
| Scheme 7B: New Cambi, Refurbish Digesters & Use Existing Dewatering Process (£'000) | | | Provide data | 9,000 |
| **Labour** | | | | |
| Total labour requirement (no. of staff) | 1.5 | UU data | Check & confirm | 4 |

**Parameters for Calculating the Environmental Impact**

| Parameter | Units | Value |
|---|---|---|
| NPE conversion: Imported fuel: Natural gas | GJ/GJ | 1.06 |
| NPE conversion: Imported fuel: Fuel oil | GJ/GJ | 1.1 |
| NPE conversion: Imported fuel Derv | GJ/GJ | 1.1 |
| NPE conversion: Imported fuel: Biogas | GJ/GJ | 1.06 |
| NPE conversion: Electricity | GJ/GJ | 3.5 |
| NPE conversion: Manufacture of consumables using fuel oil | GJ/GJ | 1.1 |
| NPE conv: Manufacture of cap. assets using fuel oil & coal | GJ/GJ | 1.07 |
| NPE conversion: Waste heat recovery as: natural gas saved | GJ/GJ | 1.07 |
| NPE conversion: Waste heat recovery as: fuel oil saved | GJ/GJ | 1.1 |
| NPE conversion: Transport fuel: Derv | GJ/GJ | 1.1 |
| NPE conv: Manufacture of transport assets using fuel oil | GJ/GJ | 1.07 |
| NPE conv: Savings in fuel oil use in fertiliser manufacture | GJ/GJ | 1.1 |
| BOD to soluble volatile solids ratio | kg/kg | 1.6 |
| Heat capacity of water | KJ/kg/°C | 4.2 |
| Gas molecular volume | $m^3$/kmol | 22.4 |
| Relative molecular mass of methane | g | 16 |
| Relative molecular mass of carbon dioxide | g | 44 |
| Calorific value of natural gas | MJ/$m^3$ | 37 |
| Methane content of natural gas | % | 100 |
| Calorific value of Derv | GJ/l | 0.036 |
| Unit cost of fuel oil | £/l | 0.75 |
| Proportion of mech. & electrical capital costs due to steel | | 0.2 |
| Unit cost of steel | £/t | 669 |
| Energy value of steel | GJ/t | 21.4 |
| Life span of mechanical and electrical equipment | Y | 20 |
| Proportion of civil capital costs due to cement | | 0.2 |
| Proportion of cement costs due to cement raw materials | | 0.35 |
| Unit cost of cement | £/t | 75 |
| Energy value of cement | GJ/t | 4.3 |
| Life span of civil capital equipment | Y | 40 |
| Energy value of polyelectrolyte | GJ/t | 164 |
| Energy value of sodium hydroxide | GJ/t | 11.3 |
| Energy value of lime | GJ/t | 4.3 |
| Density of lime | t/$m^3$ | 0.48 |
| Mechanical dewatering: direct methane emission | kg/tDS | 1 |
| Mechanical dewatering: direct carbon dioxide emission | kg/tDS | 0 |
| Mesophilic anaerobic digestion: methane emission (primary with fixed roof and secondary, assuming 45% VSD) | kg/tDS | 9.4 |
| Mesophilic anaerobic digestion: methane emission (primary with fixed roof but no secondary, assuming 45% VSD) | kg/tDS | 1.4 |
| Combustion of biogas: carbon dioxide emission | Kg/1000$m^3$ | 1957 |
| Combustion of biogas: NOx emission | Kg/1000$m^3$ | 4.6 |
| Combustion of biogas: SOx emission | Kg/1000$m^3$ | 2.3 |
| Combustion of natural gas: carbon dioxide emission | Kg/GJ | 55.6 |
| Combustion of natural gas: NOx emission | Kg/GJ | 0.25 |
| Combustion of natural gas: SOx emission | Kg/GJ | 0.007 |
| Combustion of derv: carbon dioxide emission | Kg/l | 3 |

| Parameter | Units | Value |
|---|---|---|
| Combustion of derv: carbon monoxide emission | Kg/l | 0.022 |
| Combustion of derv: NOx emission | Kg/l | 0.15 |
| Combustion of derv: SOx emission | Kg/l | 0.0042 |
| Combustion of fuel oil: carbon dioxide emission | Kg/l | 2.66 |
| Combustion of fuel oil: NOx emission | Kg/l | 0.0038 |
| Combustion of fuel oil: SOx emission | Kg/l | 0.0042 |
| Road traffic accident rate | No/km | 7.57E-07 |
| Incineration of raw & digested sludge volatile solids: CO2 | Kg/tVs | 1800 |
| Incineration of raw & digested sludge volatile solids: N0x | Kg/tVs | 1.92 |
| Incineration of raw & digested sludge volatile solids: S0x | Kg/tVs | 0.48 |
| Electricity generation: carbon dioxide emission | Kg/GJ | 122 |
| Electricity generation: NOx emission | Kg/GJ | 0.31 |
| Electricity generation: SOx emission | Kg/GJ | 0.94 |
| Consumables and capital assets creation: CO2 emission | Kg/GJ | 76 |
| Consumables and capital assets creation: NOx emission | Kg/GJ | 0.13 |
| Consumables and capital assets creation: SOx emission | Kg/GJ | 0.51 |
| Agric & Landfill: anaerobic volatile solids destruction: CH4 | Kg/tVS | 403 |
| Agric & Landfill: anaerobic volatile solids destruction:CO2 | Kg/tVS | 597 |
| Agric & Landfill: aerobic volatile solids destruction: CH4 | Kg/tVS | 0 |
| Agric & Landfill: aerobic volatile solids destruction: CO2 | Kg/tVS | 1800 |
| Conversion of methane to greenhouse gas equivalent | kgCO2equi/kgCH4 | 21 |
| Conversion of carbon dioxide to greenhouse gas equivalent | kgCO2equi/kgCO2 | 1 |
| Conversion of SOx to greenhouse gas equivalent | kgCO2equi/kgSOx | 0.28 |
| Conversion of SOx to acid gas equivalent | kgH+equi/kgSOx | 0.0313 |
| Conversion of NOx to acid gas equivalent | kgH+equi/kgNOx | 0.0217 |
| Conversion of nitrous oxide to greenhouse gas equivalent | kgCO2equi/kgN2O | 310 |
| NPE conversion: Imported fuel: Coal | GJ/GJ | 1.03 |
| Fuel oil calorific value | GJ/l | 0.0385 |
| Coal calorific value | GJ/t | 29.4 |
| Combustion of coal: carbon dioxide emission | kg/GJ | 82.8 |
| Combustion of coal: NOx emission | kg/GJ | 0.164 |
| Combustion of coal: SOx emission | kg/GJ | 0.91 |
| Combustion of sludge: carbon dioxide emission | kg/tVS | 1800 |
| Combustion of sludge: NOx emission | kg/tVS | 1.92 |
| Combustion of sludge: SOx emission | kg/tVS | 0.48 |
| Agriculture: direct nitrous oxide emission as nitrogen | % TKN | 0.7 |
| Liquor treatment: direct carbon dioxide emission | kg/kgBOD | 0.7 |
| Composting: direct carbon dioxide emission | kg/tVS | 1800 |
| Composting: direct nitrous oxide emissions as nitrogen | % TKN | 0.7 |

# APPENDIX C DETAILED RESULTS

This appendix contains the detailed results from MASTAR for the sludge processes using new (Table C1) or existing facilities (Table C2).

### Table C1 Detailed results from MASTAR for processes using new facilities

| PARAMETER | Scheme 2A | Scheme 2C | Scheme 1A | Scheme 3A | Scheme 4A | Scheme 5A | Scheme 6A | Scheme 7A |
|---|---|---|---|---|---|---|---|---|
| | EH Air cooling Digest Dewater Agric | EH Recover Energy Digest Dewater Agric | Digest Dewater Agric | Dewater Lime Agric | Dewater Incin Landfill | Digest Dewater Incin Landfill | Ferment Cake Dewater Agric | Cambi Digest Dewater Agric |
| **SUMMARY OF VALUES** | | | | | | | | |
| **Raw sludge daily dry mass (tDS/d)** | **36.7** | **36.7** | **36.7** | **36.7** | **36.7** | **36.7** | **36.7** | **36.7** |
| **Net Primary Energy Total (GJ/tRwDS)** | **-3.8** | **-6.4** | **-6.3** | **2.2** | **-0.9** | **-1.1** | **1.1** | **-4.4** |
| **Total Greenhouse Equivalent (kgCO2/tRwDS)** | **1150** | **1060** | **1396** | **1597** | **1349** | **1795** | **1366** | **1035** |
| **Total Acid Gas Equivalent (kgH+/tRwDS)** | **0.04** | **0.02** | **0.03** | **0.08** | **0.07** | **0.11** | **0.08** | **0.03** |
| **Total Mean Daily Distance (km/tRwDS)** | **10.1** | **10.1** | **9.9** | **19.9** | **18.6** | **14.0** | **11.5** | **9.3** |
| **Net Capital Cost (£/tRwDS)** | **78** | **78** | **78** | **6** | **129** | **164** | **25** | **78** |
| **Net Operating Cost (£/tRwDS)** | **-14** | **-34** | **-28** | **61** | **65** | **56** | **31** | **-17** |
| **Net Present Cost (£/tDS)** | **70** | **58** | **62** | **40** | **166** | **196** | **42** | **68** |
| **BREAKDOWN OF VALUES** | | | | | | | | |
| **NET PRIMARY ENERGY** | | | | | | | | |
| Npe imported fuel - E1 (GJ/tRwDS) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.51 |
| Npe net electricity - E2 (GJ/tRwDS) | -4.06 | -6.63 | -6.45 | 0.82 | -3.25 | -3.02 | 0.95 | -5.13 |
| Npe consumables - E3 (GJ/tRwDS) | 0.73 | 0.73 | 0.72 | 2.12 | 1.48 | 1.07 | 0.84 | 0.68 |
| Npe capital - E4 (GJ/tRwDS) | 0.33 | 0.33 | 0.26 | 0.02 | 0.53 | 0.61 | 0.10 | 0.33 |
| Npe waste heat recovery - E5 (GJ/tRwDS) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Npe transport fuel - E6 (GJ/tRwDS) | 0.18 | 0.18 | 0.18 | 0.36 | 0.33 | 0.25 | 0.21 | 0.17 |
| Npe transport capital - E7 (GJ/tRwDS) | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Npe disposal byproducts - E8 (GJ/tRwDS) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Npe Consumables saved - E9 (GJ/tRwDS) | -1.01 | -1.01 | -1.00 | -1.09 | 0.00 | 0.00 | -1.05 | -0.97 |
| **Npe total (GJ/tRwDS)** | **-3.81** | **-6.39** | **-6.28** | **2.23** | **-0.90** | **-1.08** | **1.06** | **-4.41** |
| **GAS EMISSIONS** | | | | | | | | |
| CH4 gas emissions (kg/tRwDS) | 8.14 | 8.14 | 16.11 | 12.99 | 1.00 | 11.85 | 9.27 | 7.64 |
| CO2 gas emissions (kg/tRwDS) | 877 | 787 | 957 | 1,173 | 1,328 | 1,546 | 1,056 | 779 |
| SOX gas emissions (kg/tRwDS) | -0.32 | -1.01 | -0.79 | 0.80 | 0.53 | 1.14 | 0.77 | -0.62 |
| N2O gas emissions (kg/tRwDS) | 0.33 | 0.33 | 0.32 | 0.48 | 0.00 | 0.00 | 0.37 | 0.31 |
| NOX gas emissions (kg/tRwDS) | 1.77 | 1.54 | 1.94 | 1.55 | 2.57 | 3.42 | 1.94 | 1.73 |
| **GREENHOUSE EQUIVALENT** | | | | | | | | |
| CH4 greenhouse equivalent (kgCO2/tRwDS) | 170.85 | 170.85 | 338.39 | 272.77 | 21.00 | 248.95 | 194.67 | 160.48 |
| CO2 greenhouse equivalent (kgCO2/tRwDS) | 876.91 | 787.29 | 956.98 | 1,173.47 | 1,327.65 | 1,545.75 | 1,055.83 | 779.20 |
| SOX greenhouse equivalent (kgCO2/tRwDS) | -0.09 | -0.28 | -0.22 | 0.22 | 0.15 | 0.32 | 0.22 | -0.17 |
| N2O greenhouse equivalent (kgCO2/tRwDS) | 102.13 | 102.13 | 100.42 | 150.10 | 0.00 | 0.00 | 115.10 | 95.17 |
| **Total greenhouse equivalent (kgCO2/tRwDS)** | **1,150** | **1,060** | **1,396** | **1,597** | **1,349** | **1,795** | **1,366** | **1,035** |
| **ACID GAS EQUIVALENT** | | | | | | | | |
| SOX acid gas equivalent (kgH+/tRwDS) | 0.01 | -0.02 | -0.01 | 0.04 | 0.02 | 0.04 | 0.04 | 0.00 |
| NOX acid gas equivalent (kgH+/tRwDS) | 0.04 | 0.03 | 0.04 | 0.03 | 0.06 | 0.07 | 0.04 | 0.04 |
| **Total acid gas equivalent (kgH+/tRwDS)** | **0.04** | **0.02** | **0.03** | **0.08** | **0.07** | **0.11** | **0.08** | **0.03** |
| **TRANSPORT** | | | | | | | | |
| Total mean daily distance (km/tRwDS) | 10.1 | 10.1 | 9.9 | 19.9 | 18.6 | 14.0 | 11.5 | 9.3 |
| **COSTS** | | | | | | | | |
| Net capital cost £'000 (Total Cost) | 20,860 | 20,860 | 20,909 | 1,484 | 34,586 | 43,842 | 6,680 | 20,853 |
| Net operating cost (£'000/y) | -181 | -455 | -376 | 814 | 872 | 748 | 410 | -223 |
| Net capital cost (£/tRwDS) [20 years] | 78 | 78 | 78 | 6 | 129 | 164 | 25 | 78 |
| Net operating cost (£/tRwDS) | -14 | -34 | -28 | 61 | 65 | 56 | 31 | -17 |
| Net present cost (£'000) [20 years] | 18,780 | 15,637 | 16,928 | 10,102 | 43,819 | 51,764 | 11,025 | 18,301 |
| Net present cost (£/tRwDS) [20 years] | 70 | 58 | 62 | 40 | 166 | 196 | 42 | 68 |

## Table C2 Detailed results from MASTAR for processes using existing facilities

| PARAMETER | Scheme 2B | Scheme 2D | Scheme 1B | Scheme 3B | Scheme 4B | Scheme 5B | Scheme 6B | Scheme 7B |
|---|---|---|---|---|---|---|---|---|
| | EH Air cooling Digest Dewater Agric | EH Recover energy Digest Dewater Agric | Digest Dewater Agric | Dewater Lime Agric | Dewater Incin Landfill | Digest Dewater Incin Landfill | Ferment Cake Dewater Agric | Cambi Digest Dewater Agric |
| **SUMMARY OF VALUES** | | | | | | | | |
| **Raw sludge daily dry mass (tDS/d)** | **36.7** | **36.7** | **36.7** | **36.7** | **36.7** | **36.7** | **36.7** | **36.7** |
| **Net Primary Energy Total (GJ/tRwDS)** | **-4.0** | **-6.6** | **-5.3** | **2.2** | **-0.9** | **-1.2** | **1.0** | **-4.6** |
| **Total Greenhouse Equivalent (kgCO2/tRwDS)** | **1135** | **1045** | **1404** | **1595** | **1347** | **1783** | **1365** | **1023** |
| **Total Acid Gas Equivalent (kgH+/tRwDS)** | **0.04** | **0.01** | **0.03** | **0.08** | **0.07** | **0.11** | **0.08** | **0.0** |
| **Total Mean Daily Distance (km/tRwDS)** | **10.1** | **10.1** | **11.0** | **19.9** | **18.6** | **14.0** | **11.5** | **9.3** |
| **Net Capital Cost (£/tRwDS)** | **33** | **33** | **33** | **2** | **125** | **119** | **22** | **42** |
| **Net Operating Cost (£/tRwDS)** | **-14** | **-34** | **-19** | **61** | **65** | **56** | **31** | **-17** |
| **Net Present Cost (£/tDS)** | **25** | **13** | **22** | **36** | **162** | **148** | **40** | **33** |
| **BREAKDOWN OF VALUES** | | | | | | | | |
| **NET PRIMARY ENERGY** | | | | | | | | |
| Npe imported fuel - E1 (GJ/tRwDS) | 0.00 | 0.00 | 0.24 | 0.00 | 0.00 | 0.00 | 0.00 | 0.51 |
| Npe net electricity - E2 (GJ/tRwDS) | -4.06 | -6.63 | -5.62 | 0.82 | -3.25 | -3.02 | 0.95 | -5.13 |
| Npe consumables - E3 (GJ/tRwDS) | 0.73 | 0.73 | 0.80 | 2.12 | 1.48 | 1.07 | 0.84 | 0.68 |
| Npe capital - E4 (GJ/tRwDS) | 0.14 | 0.14 | 0.11 | 0.00 | 0.51 | 0.46 | 0.09 | 0.18 |
| Npe waste heat recovery - E5 (GJ/tRwDS) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Npe transport fuel - E6 (GJ/tRwDS) | 0.18 | 0.18 | 0.20 | 0.36 | 0.33 | 0.25 | 0.21 | 0.17 |
| Npe transport capital - E7 (GJ/tRwDS) | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Npe disposal byproducts - E8 (GJ/tRwDS) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Npe Consumables saved - E9 (GJ/tRwDS) | -1.01 | -1.01 | -1.04 | -1.09 | 0.00 | 0.00 | -1.05 | -0.97 |
| **Npe total (GJ/tRwDS)** | **-4.01** | **-6.58** | **-5.29** | **2.22** | **-0.92** | **-1.23** | **1.04** | **-4.56** |
| **GAS EMISSIONS** | | | | | | | | |
| CH4 gas emissions (kg/tRwDS) | 8.14 | 8.14 | 17.21 | 12.99 | 1.00 | 11.85 | 9.27 | 7.64 |
| CO2 gas emissions (kg/tRwDS) | 862 | 773 | 932 | 1,172 | 1,326 | 1,534 | 1,055 | 768 |
| SOX gas emissions (kg/tRwDS) | -0.41 | -1.11 | -0.83 | 0.79 | 0.52 | 1.06 | 0.77 | -0.70 |
| N2O gas emissions (kg/tRwDS) | 0.33 | 0.33 | 0.36 | 0.48 | 0.00 | 0.00 | 0.37 | 0.31 |
| NOX gas emissions (kg/tRwDS) | 1.74 | 1.51 | 1.71 | 1.55 | 2.57 | 3.40 | 1.94 | 1.71 |
| **GREENHOUSE EQUIVALENT** | | | | | | | | |
| CH4 greenhouse equivalent (kgCO2/tRwDS) | 170.85 | 170.85 | 361.37 | 272.77 | 21.00 | 248.95 | 194.67 | 160.48 |
| CO2 greenhouse equivalent (kgCO2/tRwDS) | 862.32 | 772.71 | 932.46 | 1,172.17 | 1,326.35 | 1,534.19 | 1,054.87 | 767.63 |
| SOX greenhouse equivalent (kgCO2/tRwDS) | -0.12 | -0.31 | -0.23 | 0.22 | 0.15 | 0.30 | 0.21 | -0.19 |
| N2O greenhouse equivalent (kgCO2/tRwDS) | 102.13 | 102.13 | 110.37 | 150.10 | 0.00 | 0.00 | 115.10 | 95.17 |
| **Total greenhouse equivalent (kgCO2/tRwDS)** | **1,135** | **1,045** | **1,404** | **1,595** | **1,347** | **1,783** | **1,365** | **1,023** |
| **ACID GAS EQUIVALENT** | | | | | | | | |
| SOX acid gas equivalent (kgH+/tRwDS) | 0.00 | -0.02 | -0.01 | 0.04 | 0.02 | 0.03 | 0.04 | -0.01 |
| NOX acid gas equivalent (kgH+/tRwDS) | 0.04 | 0.03 | 0.04 | 0.03 | 0.06 | 0.07 | 0.04 | 0.04 |
| **Total acid gas equivalent (kgH+/tRwDS)** | **0.04** | **0.01** | **0.03** | **0.08** | **0.07** | **0.11** | **0.08** | **0.03** |
| **TRANSPORT** | | | | | | | | |
| Total mean daily distance (km/tRwDS) | 10.1 | 10.1 | 11.0 | 19.9 | 18.6 | 14.0 | 11.5 | 9.3 |
| **COSTS** | | | | | | | | |
| Net capital cost £'000 (Total Cost) | 8,803 | 8,803 | 8,869 | 411 | 33,512 | 31,785 | 5,886 | 11,282 |
| Net operating cost (£'000/y) | -181 | -455 | -249 | 814 | 872 | 748 | 410 | -223 |
| Net capital cost (£/tRwDS) [20 years] | 33 | 33 | 33 | 2 | 125 | 119 | 22 | 42 |
| Net operating cost (£/tRwDS) | -14 | -34 | -19 | 61 | 65 | 56 | 31 | -17 |
| Net present cost (£'000) [20 years] | 6,723 | 3,580 | 6,229 | 9,029 | 42,746 | 39,707 | 10,231 | 8,730 |
| Net present cost (£/tRwDS) [20 years] | 25 | 13 | 22 | 36 | 162 | 148 | 40 | 33 |