



**CO-FIRING SEWAGE SLUDGE AND  
BIOMASS**

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***CO-FIRING SEWAGE SLUDGE AND BIOMASS***

***Final Report***

**DTI New and Renewable Energy Programme**

**Contract No. B/T1/00771/00/00**

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# **CO-FIRING SEWAGE SLUDGE AND BIOMASS: FINAL REPORT**

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## **SUMMARY**

There is increasing pressure within the UK and Europe to develop and implement ways of using renewable energy sources to produce power in order to reduce carbon dioxide emissions (as renewable energy sources are regarded as CO<sub>2</sub> neutral). Interest in the development of biomass energy technologies has been encouraged by the introduction of legislative measures in Europe to reduce CO<sub>2</sub> emissions from power generation in response to the potential threat of global warming. Biomass combustion and gasification are seen as high priority approaches because of the modest risk involved, the availability of waste biomass in many countries and the socio-economic benefits farming biomass as a fuel could bring to the European agricultural sector.

Sewage sludge is a potential fuel that is available for co-firing with biomass. The use of sewage sludge as a supplementary fuel in a biomass co-fired system, rather than as a main fuel, offers the potential to recover its inherent energy more efficiently, as the drying of both fuels can be effectively integrated into the plant. The potential utilisation of sewage sludge as an energy source in advanced gasification or combustion processes is currently an attractive option for water utility companies, as increasing legislative pressures and public perception, could prevent the future utilisation of sludge in agriculture; the main utilisation route currently. The economic viability of biomass/sewage sludge co-fired systems is highly dependant on the regulatory framework at plant locations (e.g. in terms of renewable energy generation – i.e. price of biomass and resulting heat/power/chilled water - and sludge disposal – i.e. gate fee of sludge), as well as the inherent costs associated with the plant (e.g. capital and operating costs). The availability of both biomass and sewage sludge, at any particular location, are limited by both geographic factors (e.g. population distributions, agricultural production) and by transport costs. Typical proposed biomass power systems are in the range 1-30 MW<sub>e</sub>.

The overall aim of the project was to assess the viability of using advanced solid fuel gasification and combustion technologies to co-fire sewage sludge and biomass (e.g. wood) as a route for sewage sludge utilisation combined with the production of heat and/or power generation with minimal environmental emissions, in terms of both system economics and process efficiency.

A preliminary process analysis of potentially viable biomass/sludge co-firing options was carried out. The analysis assessed potential process routes and included details of the availability and compositions of both biomass and sewage sludge feed-stocks. The current legislation that would affect co-firing of sewage/biomass was reviewed. It was clear that many possible options for co-

firing sewage sludge and biomass exist so distinct scenarios were identified for which technology and feedstock options can be defined.

Modifications were made to both combustion and gasification test facilities at Cranfield University in order to co-fire the range of sewage sludge and biomass mixtures required during the course of the project. The modifications included the introduction of appropriate sludge and biomass handling, storage and feed systems and alterations to the rig control systems to ensure their safe operation. A co-firing test programme has been carried out in the combustion and gasification facilities using a range of sewage/biomass mixtures. Fuel feeding problems were a major problem during the testing particularly with the gasifier trials. It is not expected that this would be a major problem with a larger scale power plant. The test programme identified a limiting fuel CV required for co-firing to be viable operation. This limit identified is specific to the Cranfield combustor and it would be expected that a larger scale plant could use a lower CV fuel due to the lower heat losses associated with larger scale operations. Gas emissions and ash/char residue compositions were obtained for the test fuel mixes. Operating constraints such as fuel moisture content have been identified and, where required, gas cleaning and disposal requirements highlighted.

A mass/energy flow and life cycle analysis has been carried out for both the combustion and gasification processes. In the combustion case the major potential emissions issue is mercury. It is likely that a mercury capture system would be required to clean the flue gas. The output from the gasifier model has demonstrated that the co-firing of sewage sludge results in an increased requirement for gas cleaning over firing with wood alone, although this probably does not result in extra cleaning modules being required but a higher load than that required for wood alone.

A techno-economic model has been developed that can give predictions of the financial impact of building and running both combustion and gasification facilities that co-fire biomass and sewage sludge. To identify potential scales of operation, under which co-firing of biomass and sewage sludge may be economically viable an assessment was made of nine co-firing scenarios. The scenarios included both gasification and combustion at a rural and urban scale with two sewage sludges. Overall, combustion on the larger scale as modelled for the urban scenario gave the lowest disposal cost for sewage sludge. The variability in the price of electricity and the potential for biomass prices to rise make even the best option from the modelling an unlikely option as cheaper disposal routes exist which do not entail the capital outlay required for these options. Further legislation could remove these cheaper disposal routes and make combustion a more attractive option.

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# **CO-FIRING SEWAGE SLUDGE AND BIOMASS: FINAL REPORT**

## **1. INTRODUCTION**

There is increasing pressure within the UK and Europe to develop and implement ways of using renewable energy sources to produce power in order to reduce carbon dioxide emissions (as renewable energy sources are regarded as CO<sub>2</sub> neutral). In the UK legislation has been introduced to compel the power utilities to provide 15.4% of their generated power from renewable sources by 2015. Biomass represents one route to providing this power.

Sewage sludge is a potential fuel that could be used to co-fire with predominantly biomass (e.g. wood, straw) fired systems. The use of sewage sludge as the minor fuel in a biomass co-fired system, rather than as a pure fuel, offers the potential to recover its inherent energy more efficiently, as the drying of both fuels can be effectively integrated into the plant. The UK produces ~1.4 Mtonnes dried sludge per annum. In addition, the use of advanced gasification or combustion processes, developed over the last 20 years for coal fired power systems with the aim of producing heat and/or power at much higher efficiencies and lower environmental emissions than conventional solid fuel burning technologies, offer potential benefits for the co-firing of sewage sludge and biomass. For example, the introduction of sewage sludge into a biomass combustion plant would allow improved efficiencies to be achieved as the introduction of a higher sulphur containing fuel would generate less corrosive deposits which would permit higher superheater temperatures (and hence improved steam conditions).

The potential future utilisation of sewage sludge as an energy source in such advanced gasification or combustion processes is currently an attractive option for sludge producers, as increasing legislative pressures and public perception, could prevent the future utilisation of sludge in agriculture; the main utilisation route currently. Gasification is generally considered to be "greener" and more economically viable at smaller scales, making it attractive to some local authorities. Incineration is a more established technology but tends to be viable only at larger scales (>15,000 tonnes ds/a), and invokes strong public aversion. Whilst the gasification of sewage sludge is more established in countries such as Germany, where gate fees are substantially higher (>£100/tonne) than those in the UK, there remains a credibility gap with the process in the UK. This has been exacerbated by problems associated with the use of pure sewage sludge encountered recently with projects at two water utility sites. The economic viability of biomass/sewage sludge co-fired systems is highly dependant on the regulatory framework at plant locations (e.g. in terms of renewable energy generation – i.e. price of biomass and resulting heat/power/chilled water - and sludge disposal – i.e. gate fee of sludge), as well as the inherent costs associated with the plant (e.g. capital and operating costs).

Both advanced gasification and combustion technologies can be considered as potential routes for co-firing of biomass and sewage sludge, with the industrial collaborators and private sector funders of this proposed project keen to assess the potential viability of both classes of technologies. Within each basic class of technology there are numerous potential options. For example, fuel gases produced from gasification plants have several potential routes to produce power: e.g., driving gas turbines or diesel engines, steam generation, chilled water production, co-firing in existing pulverised coal plants (if gasifier sited locally) and, in the longer term, fuel cells. In addition, such plants produce substantial amounts of waste heat that could be used locally (if the gasifier is sited near potential users, e.g. industrial estates), and/or could be integrated with sewage sludge processing requirements.

The availability of both biomass and sewage sludge are limited by both geographic factors (e.g. population distributions, agricultural production) and by transport costs. Typical operating and proposed biomass power systems are in the range 1-30 MWe. The scale for sewage sludge production (at ~300-15,000 tonnes dried sludge per annum per site in the UK) would make this the secondary fuel in such systems. This will limit the size of potential heat/power plant using these fuels and it is expected that optimum size ranges for candidate integrated systems will be identified within this project. It is anticipated that the scale of viable heat/power plants that will be found will be suitable for use in future distributed power systems. There is a drive towards using distributed generation within the UK and EU, especially using CO<sub>2</sub> neutral technologies such as biomass fired energy systems. The potential co-firing of sewage sludge (with the benefit of its anticipated gate fees) in some of these systems will enhance their economic viability, if the correct technologies are applied in the right locations.

## **2. AIMS AND OBJECTIVES OF THE PROJECT**

The overall aim of the project was to assess the viability of using advanced solid fuel gasification and combustion technologies to co-fire sewage sludge and biomass (e.g. wood) as a route for sewage sludge utilisation combined with the production of heat and/or power generation with minimal environmental emissions, in terms of both system economics and process efficiency. The project has investigated the effects of the different fuel compositions and mixes on the performance of the processes in terms of their gaseous and solid products.

The specific objectives to meet this aim were:

- To assess potential process configurations, scale, system integration issues and fuels (including sewage sludge and biomass, e.g. wood) to give power, heat and chilled water production
- To establish pilot scale test facilities for the co-gasification and co-combustion of sewage sludge and biomass (e.g. wood)

- To determine emissions and ash/char residue compositions for the most promising fuel mixes and define operating constraints, control measures and disposal requirements
- To carry out an analysis of the inter-relationships between the key parameters in gasification/combustion of sewage sludge/biomass mixtures and sewage sludge production parameters and their impact on overall technical viability and cost (including an energy flow characterisation/life cycle analysis)
- To identify the energy usage scenarios, including potential scales of operation, under which co-firing of biomass and sewage sludge may be economically viable

### **3. ACTIVITY A – PRELIMINARY PROCESS ANALYSIS**

#### **3.1. Introduction**

In order to provide a clear focus for the overall programme, a number of key decisions were taken. Firstly, co-firing operation using around 5000 – 15000 tonnes of dried solids (tds) sludge per year was agreed as realistic; on its own this was estimated to produce less than 1 MW<sub>e</sub>.

Secondly, there are many types of sewage sludge from the different sewage treatment schemes used around the UK that could have been included in the project. In addition, it was important to define the likely availability of each type, in order to avoid an unrealistic transport requirement.

The following sewage sludge types were initially selected as representative of the breadth of options as well as presenting all the various challenges that need to be addressed:

- Dewatered raw sludge (laboratory dried before use in pilot plants)
- Biologically dried sludge (composted with wood chip)
- Sludge screenings
- Digested sludge cake

(Note that another fuel, raw dried sludge pellets became available during the course of the project and so was added to the co-firing test programme. A full description of the fuels used in the co-firing test programme is given in section 5.2.)

Thirdly, the types of biomass for co-firing needed careful consideration. Those chosen for investigation in the project needed to cover both those that could be used in a near-term commercial scheme (such as wood chip) as well as those opportunity biomass fuels that might only be available in specific locations but where the commercial prospects were encouraging (such as poultry litter). The following were selected for use in the desktop activities at this stage:

- Wood chips (both from waste and short rotation coppice)
- Green waste from municipal waste collection
- Poultry litter
- Straw

Municipal solid waste (MSW), refuse derived fuel (RDF), tyre waste and paper sludge were also included for preliminary studies as these were felt to be of commercial relevance while being outside the scope of the project. For the co-firing programme, the priority was to determine the issues surrounding the use of the various types of sewage sludge, rather than to explore an extensive range of biomass types so it was agreed that this part of the work would use wood chips. The appropriate ratio of wood chips to sewage sludge in each case was assessed on the basis of calorific value (CV – see appendix 1) rather than moisture content.

Finally, it was also necessary to narrow down the scope of the programme in terms of likely location and scale before being able to plan the experimental testing activities. It was agreed that two distinct options should form the focus for the testing work. These were as follows:

- A rural, small-to-medium scale scheme where the priority was the disposal of available sewage sludge with the biomass content being limited by that which was readily available from the surrounding area; the energy produced would most likely be exported to the grid.
- An urban, medium-to-large scale scheme where the opportunity to optimise power/heat/chilled water sales would exist offsetting the issue of transporting biomass and including imported biomass.

Both co-combustion and co-gasification options would be considered for both scenarios.

## **3.2. Overview of sewage sludge production, types and distribution**

### **3.2.1. Background**

The production of sewage sludge in the EU is anticipated to increase, in part, due to higher wastewater effluent treatment standards resulting in greater numbers of sewage treatment works and processes and subsequent increases in sludge production. Currently, the key utilisation or disposal options in the UK for sewage sludge comprise application to agricultural land (51%), incineration (5%) and landfill (16%) (1990 % data [1]). Continuing pressure arising from environmental legislation, public perception and supermarket consumer groups is potentially limiting the expansion of agricultural utilisation. Whilst the shortage of landfill capacity, and increasing taxation also limits increased use of landfills as a sludge disposal option. In addition incineration can meet with widespread public aversion in relation to new planning applications and there are concerns regarding low energy efficiencies and atmospheric emissions. Therefore, a longer-term sustainable option needs to be investigated, with co-firing options for sludge utilisation resulting in a number of potential benefits,

including energy recovery and potentially lower atmospheric emissions together with pathogen destruction and waste volume reduction.

At the last UK Sludge Survey (1996/7) approximately  $1.12 \times 10^6$  tds of sludge was produced in the UK with over half of that sludge treated by mesophilic anaerobic digestion (MAD) [2]. There were 1679 sludge treatment centres at that time, the number of which will be higher today due to the trend towards the creation of regional sludge centres. Approximately 930 works produce less than 300 tds of sludge per year, while those which produce more than 4500 tds of sludge per year number about 126 [2]. This study has examined the potential for energy production from these larger works producing 5000 to 15000 tds of sludge per year which equated to a population equivalent (pe) of about 0.167 to 0.5 million. If oven dry sludge has a CV of around 16MJ/kg then 5000 tds of sludge is equivalent to 80TJ or approximately 22GWh. Operating at this scale gives a reasonable repeatability to the project outcomes, i.e. there is the potential to apply the project findings to over 100 treatment centres.

In 2000, sewage sludge digestion produced 5.03PJ of electricity and 1.7PJ of heat, excluding that used to heat the digesters themselves. This equates to 7% of the total electricity production from all biofuels and 5% of the heat production from biofuels. Landfill gas and MSW combustion produced 42% and 33% of electricity respectively. Wood is the largest biofuel contributor to heat production, domestic and industrial use accounting for 67 % of the total [3]. However, renewables as a whole produced only 1% of the UK's total primary energy production in 2002.

Properties of raw sludge vary according to location and also with sludge source within a specific wastewater treatment train. Sludge from primary settlement has different characteristics from that produced during an activated sludge process. Both physical and chemical parameters vary as does the CV of the sludge (Table 1). In most treatment plants the sludge collected from the different process stages will be combined prior to further treatment, such that the characteristics specific to the unit operation from which the sludge is generated will be lost. It is also the case that, since sludge is generally viewed as a waste material, treatment processes are operated so as to minimise sludge production, despite its prospective end use as a fuel.

### **3.2.2. Sludge production**

There are many methods for treating sewage sludge to reduce the overall volume, but nearly all are designed to either reduce the carbon content or the water content (or possibly both). Processes ostensibly reducing carbon content proceed either through biological (aerobic or anaerobic digestion), or (thermo) chemical (e.g. wet air oxidation) treatment. Processes that remove water (thickening, dewatering or drying) range from simple sedimentation, which can increase the solids content to around 5% by volume, to thermal drying, which can increase the solids content to 95%. Conventionally, chemical conditioning of the sludge – pre-dosing with chemical precipitants, coagulants and flocculants, is carried out to increase its dewaterability. Thus, a complete

treatment train, designed according to the source and the end utilisation or disposal route, may contain a number of unit operations which then have a profound effect on the quality of the sludge product. Treatment processes operated by both Thames and Severn Trent Water are outlined in Table 2 along with sludge quality information.

Anaerobic digestion may reduce the CV of the sludge by up to 40%. The total volume of the sludge is also reduced and the dewaterability increased. Methane (65%) and carbon dioxide (35%) are produced and the methane can be used as an energy source. The heating value of the digester gas is approximately  $22.4\text{MJ/m}^3$  and this can be used to fire boilers, diesel engines and gas turbines to produce electricity and/or heat. Digester gas will, however, contain contaminants such as hydrogen sulphide, particulates and water vapour and so requires some cleaning prior to use as an energy source. Aerobic digestion provides similar volatile solids reduction compared to anaerobic digestion but there are additional operating costs due to aeration and no useful combustible by-product, such as methane, is generated.

Chemical treatment is used either to create an environment in the sludge that is not conducive to the survival of micro-organisms (although heat treatment is more usually employed) or to improve the dewatering characteristics of the sludge, i.e. to condition it. The process can increase the final product solids content by more than an order of magnitude in some cases, and chemicals used include ferric chloride, alum, organic polymers and lime. Organic polymers have been shown to promote the pyrolysis rate in dried sludge solids [4] but dosing with inorganic chemical coagulants or precipitants is likely to reduce the CV of the sludge.

Physical treatment, employed downstream of a conditioning operation, increases the solids concentration of the sludge. Thickening methods are used to produce sludge with up to 10% solids whilst dewatering processes, most typically belt or filter pressing, following conditioning can produce a solids content of up to 35%. The nature of the processes implies that the total organic carbon content is unchanged and the CV of the sludge is increased by processing in accordance with the amount of water removed.

Heat treatment is most commonly used as a pasteurisation process but can also be used for conditioning. However, the high capital costs mean this method is most applicable to otherwise difficult-to-treat sludge on a large scale. The combustibility of the treated sludge is high at approximately  $28\text{--}30\text{MJ/kg}$  and the final solids content range from 30–50%. Thermal drying is a minimisation process that provides a product suitable for various re-use options, including agricultural recycling or as a fuel. The processing of sludge by thermal drying increases the dry solids content to around 95%. The CV of thermally dried products, based on bomb calorimetry, can be in the region  $20\text{MJ/kg}$ . However, this can be reduced (to  $15\text{MJ/kg}$ ) if the source sludge material is digested and organic matter is lost in the digestion process. One of the noted problems in drying sewage sludge, however, is the formation of a very “sticky” and difficult-

to-handle matrix at around 50-60% solids concentration [5]. Lower cost processes such as air-drying using thin drying beds require a large land area but can produce solids concentrations up to 70%.

Sludge composting, similar to that practised at Thames Water, uses aerobic, microbially mediated processes to stabilise organic matter. These processes generate heat and composting temperatures are typically in the 55–65°C range but can reach up to 75–80°C. Sludge can be composted with a variety of bulking materials, e.g. straw or woodchip. Treated and untreated sludge may be composted successfully. The addition of a bulking agent has two main functions. As the sludge cake does not have an open porous structure for air to pass freely, the bulking agent allows for a more open matrix and in addition can help to adjust the C:N ratio. The optimum amount to add is often found through experience, e.g. Thames Water use a mix of 2 parts woodchip to 1 part sludge cake by volume. As a percentage of the bulking agent can be recovered by the final screening of the finished compost, recycling is a viable option and is often determined by scarcity and cost of the bulking agent. The bulking agent use is an important cost consideration and overuse can add substantially to costs.

Composting of sludge will produce a reduction in volatile solids and will yield a product with a moisture content of 55–60%. The reduction in volume, stabilisation, disinfection and reduced moisture contents are some of the benefits of composting. However, concentrations of metals and toxic organics in the final sludge will be increased and this can restrict its final application to land. Nevertheless, it could be a successful sludge material for co-firing due to its lower moisture content, compared to untreated or digested sludge, and the presence of combustible biomass material.

### **3.2.3. Sludge properties**

The final properties of treated sludge vary enormously and, when considering thermolytic destruction methods as a final process stage, the sludge solids content, CV, water content, handleability, carbon content, ash content etc. are of key importance. Some limited summary data are presented in Tables 1 and 3 with more data available in the biomass types, availability and characteristics database outlined in Section 3.3. The emission of polluting gases and the handling of solid by-products are also key factors in determining the feasibility. In comparison to alternative biofuels the combustion of sewage sludge may produce higher  $\text{N}_2\text{O}$ ,  $\text{NO}_x$  and  $\text{SO}_2$  emissions [6] and the ash produced may contain a higher concentration of heavy metals.

In addition to the characteristics of the sludge required for different utilisation or disposal routes and the overall balance of energy, carbon and pollutants in the process should be considered. For example, for low solids concentration applications, less energy is required for processing the sludge but transportation costs will be higher if the location of the application site is distant from the production site. Some techniques will produce useful by-products, in some cases fuels with a substantial CV. However, contamination of by-product streams by unwanted pollutants may increase treatment costs or

limit the application as a useful resource. Changes in wastewater treatment works (WwTW) operation and sludge processing plus monitoring of feed streams to the WwTW could be considered as viable alternatives to post treatment options. For example, mechanically dewatered sludge has higher nitrogen content than pre-dried sludge and thus NO<sub>x</sub> and N<sub>2</sub>O emissions may be reduced during combustion by using the latter.

#### **3.2.4. Sludge distribution**

Following processing, sludge is transported for final utilisation or disposal either directly or through a centralised facility. The cost of transportation is often a large proportion of processing costs and the location of the WwTW in respect to the final disposal facility should be considered when selecting the optimum utilisation or disposal route. The rheological properties of the sludge are also important in selecting the best equipment to be used for transport.

Sludge can be transported by pipeline, barge, rail or truck, and despite contributing the highest environmental pollution load, the latter option is often used due to the flexibility of operation. For pumping sludge over long distances solids concentration must be below 6-10%; it is otherwise necessary to use higher specification pumping operations. For the other modes of transport there are no limitations on sludge solids concentrations.

### **3.3. Overview of biomass types, availability and characteristics**

#### **3.3.1. General**

The ranges of biomass materials that potentially may be co-fired with sewage sludge for energy generation have been reviewed. The quantity and quality of potential co-firing materials has been considered to assess their suitability for the purpose. A database has been developed concerning the quality of these materials as fuels, which was used during the Activity E modelling phase (section 7).

The suitability of biomass for co-firing depends on availability, fuel density, physical and chemical quality and the regulator controls governing their use as fuels. Factors included in availability include geographical distribution, cost, quantities and competing uses.

Biomass fuels are generally regarded as being renewable and therefore qualify for such incentive schemes and fiscal benefits that may exist. This means that any consideration of co-firing sludge and biomass needs to be undertaken within the context of renewable energy. An accurate and detailed assessment of the currently available and potential future biomass fuel resource is difficult to achieve. Many studies have been done each of which have had to make a series of major assumptions to be able to provide quantitative assessments. The most recent of these are the regional renewable energy assessments commissioned by the Regional Assemblies.



Renewable energy project developers have had limited success in obtaining planning permission for projects. In recognition of these difficulties, the DTI and DTLR requested that the Regional Assemblies undertake an assessment of renewable energy potential with a view to adopting regional targets and approaches within Regional Planning Guidance and within Regional Sustainable Development Framework [7]. Such reviews help central government assess the likelihood of their target of 15.4% electricity consumption from renewables by 2015 being achieved. Further, the introduction of the Renewables Obligation, placed a statutory requirement on electricity suppliers to supply electricity from renewable sources and increased the need for more detailed information about the regional renewable energy potential.

The Regional Assemblies have reviewed existing renewable generating capacity (Figure 1), assessed the available resource and made a judgement on the achievable generating capacity that those resources could support (Tables 4 and 5). These assessments may be used to give an indication of the potential of a particular biomass source, but actual project planning would require more local investigation. Similarly the Municipal Waste Surveys conducted by the Environment Agency can provide indicative figures of the availability of waste biomass.

A primary factor in the provision of energy from biomass is fuel supply. All biomass sources are widely dispersed, whether they are virgin fuels such as forest thinnings or waste materials. However, waste materials are already collected and it need not be a major change in activity to collect and treat for use as a fuel, compared with landfilling. A fuel may be unattractive, either because of its chemical make up or public acceptability, but if it is readily available it may be more attractive/viable for co-firing with sludge than one which is homogeneous, but difficult to supply.

Materials produced for the purpose of energy production will tend to have a higher degree of supply reliability than will those which are by-products or wastes, since the supply of the latter is dependant on activities not connected with energy supply.

Relatively few biomass fuels are produced solely as a fuel. The majority are the by-product of another activity. Many have alternative uses other than for energy production and hence there may be competition for their availability, which could increase fuel price. The use of anaerobic digestion (AD) as a pre-treatment of putrescible waste prior to landfilling, is receiving increasing attention from the waste management industry. The rise in AD could create a competitive market for some wastes that could also be used for co-firing with sludge.

The selection of a fuel for co-firing with sewage sludge depends on technical, planning, fuel supply and cost issues. Choices will differ where economic sludge management is the primary activity/target, compared with a situation

where the key objective is optimisation of energy production. These objectives need not be exclusive, but in every situation it must be clear whether one is primary in order to avoid project failure. Sludge management is a core activity for the water companies; hence cost reduction and the sustainability of a management strategy will be key to the choices made. Power generation is potentially an income generator, but is not a core activity and may not be viewed favourably when investment decisions are being made if it is regarded as vulnerable to external influences. That said, where the returns are potentially high, greater risks may be considered viable than would be acceptable for a core activity. Whether biomass is a support fuel or a primary fuel with sewage sludge in support, the reliability of fuel supply is key. In a situation where sludge management is the primary objective, control of the biomass fuel supply may be regarded as of greater importance than where power generation is main aim. The importance of fuel supply reliability is also dependant on the size of a scheme. Larger fuel conversion units are likely to be able to tolerate greater variability in the fuel type than small-scale units. Hence, it may be necessary to have greater control over fuel supply in smaller schemes, which will itself dictate to some degree the type of fuel used.

### **3.3.2. Energy generation from sludge**

It is worth considering the co-firing of sewage sludge in the wider context of energy derived from biomass, derived from renewable sources and the overall energy use in the UK. In 2000, anaerobic digestion of sewage sludge produced 5.03PJ electricity and 1.7PJ heat, excluding that used to heat digesters themselves. This equates to 7% of total electricity production from all biofuels and 5% of heat production from biofuels. However, all renewables produced only 1% of the UK's total primary energy production in 2002. Landfill gas and MSW combustion produced 42% and 33% of electricity respectively. Wood is the largest biofuel contributor to heat production, domestic and industrial use accounting for 67% of the total [3].

Power generation using sewage sludge does not qualify for support through NFFO since it is now regarded as a mature technology. Green power brokers are not keen on energy sources that have a waste source and electricity generated from sludge digestion is unlikely to attract the premium prices often given to other renewable sources, though this does vary with the purchasing company. For example, some companies sell power generated from landfill gas as green electricity. Given the dubious status of sewage sludge derived electricity and the potential for its status to change, there is merit in water companies using that electricity within their own operations and taking the carbon credits. Alternatively, the electricity could be sold directly to a user wanting to buy from renewable sources. In particular, local authorities are increasingly trying to source power from CO<sub>2</sub> neutral sources for public buildings and schools.

As described in section 3.2.1 the current study has determined it is these larger works producing 5000 to 15,000 tds of sludge per year that are most suitable for co-firing with biomass (5000 tds is equivalent to 22 GWh). By way of

comparison, 1 MW capacity is fuelled by 4,500 oven-dry tonnes per annum (odt/yr) of forestry residues, 4,600 odt/yr of short rotation coppice, 4,300 odt/yr of straw, 14,000 odt/yr of poultry litter, and 14,000 odt/yr of farm slurry.

### 3.3.3. Biomass characteristics

Biomass may be broadly divided into three categories:

- **Wastes** – MSW, RDF, tyres, poultry litter and MSW compost
- **By-products** – forest residues and thinnings, bark, straw and wood processing waste
- **Energy crops** – coppice timber, miscanthus, phalaris and other grasses, rape and other oil crops and triticale (wheat – rye cross)

Each category has benefits and drawbacks with regard to co-firing with sludge (Table 6). A broad summary of the principle characteristics of key biofuels is provided in Table 7, these biofuels are discussed in more detail in the next sections.

#### 3.3.3.1. Wood

Wood is the first material that most people think of when discussing biomass fuels. It is available as a by-product of forestry activity, including thinning, brashing and harvesting, as a waste from wood processing and as a component of demolition and construction waste. It can also be grown specifically for use as a fuel, in the form of short rotation coppice (SRC). Coppice is usually willow (but may be poplar) densely planted at 12-15,000 trees per hectare and harvested every three to four years.

Wood quality is variable, depending on species and source. Timber construction waste will tend to have been treated with preservative and will be poorer quality chemically. Forest residues can be fairly high in soil and stones due to the manner in which they are collected.

Estimates are available for the availability of wood from forest residues as shown in Table 8. The analysis of the availability of SRC is based on soil type, farming activities and potential market conditions. These figures are highly speculative since there is only around 1000 ha of SRC planted throughout the UK. If wood from SRC was to be co-fired with sewage sludge, the water company would need to collaborate with landowners to ensure that sufficient SRC was planted. The lack of a contracted market for the wood is a significant barrier to the planting of SRC, and it is unlikely that farmers will plant significant areas speculatively. Planting grants of £600 and £400 per hectare for non-set aside and set aside land respectively are available for sites within a 50 mile radius of an energy market. The minimum economic scale of a coppice powered facility is regarded as between 5 and 15 MW and more than 15 MW for forestry residues. The production of SRC for co-firing can be combined with a sludge to land operation whereby the SRC is grown using sludge as the fertiliser input and then burned in combination with further quantities of sludge.

### **3.3.3.2. Straw**

Straw is obtained from cereal and other combinable crops such as rape and linseed. High density bales of about 0.5t can be used to transport it to straw burning power stations. Competing uses are as animal bedding and as a bulking material/carbon source for composting. On-farm whole-bale burners up to 400 kW<sub>th</sub> are relatively common in the UK and large-scale straw use in power stations is widespread in Denmark. A 36 MW<sub>e</sub> straw fired power station at Ely was licensed under NFFO-3 and commenced operations in 2001. It burns about 200,000t of straw annually which represents approximately 2% of the UK's surplus straw.

Straw has a high alkali content and boiler slagging and fouling can be a problem. However, it is a relatively homogeneous fuel, and in arable farming areas, is plentiful at appropriate times during the year (Table 9).

### **3.3.3.3. Green Waste**

Green waste is derived from parks and gardens. It is heterogeneous, and traditionally has been landfilled. The Landfill Directive is forcing local authorities to instigate home or centralised composting activities to manage these materials. Composting these materials will contribute to the local authority recycling targets. However, combustion for energy production does not. Consequently, local authorities are not actively considering green waste as a biofuel. The quality of the compost achieved is often highly variable and screening is required to remove coarse material, which may then need to be landfilled as a treated/stabilised waste as permitted under the Landfill Directive. There may be opportunities to use poorer quality composted green waste as a co-firing fuel to be used with sewage sludge. Indeed, targets for the combustion of green waste have been identified within the Southeast Regional Renewables Assessment (Table 10) [8]).

### **3.3.4. Fuel quality database**

A fuel quality database was constructed using Microsoft Excel, for use in the fate and behaviour modelling at a later stage of the project. The materials for which data were collected are listed in Table 11 and the fuel characteristics recorded in the database are presented in Table 12.

The principal sources of data for the database have been:

- a dataset compiled from literature and fuel testing activities by the Power Generation Technology Centre at Cranfield University;
- the Phyllis database compiled and updated by the Netherlands Energy Research Foundation (ECN) funded by the Dutch Energy Agency.
- a new literature review.

Data on biomass fuel quality are scattered throughout the biomass industry and research groups and is not necessarily placed in the public domain. The same type of data may be expressed using different units, and it may not be appropriate to convert between types of unit, if strict accuracy is to be maintained. Consequently, the database records similar data in a number of

different ways (Table 12), which itself can make comparison and summarising of data problematic. However, for the purposes of material flow modelling, it is more accurate to test a number of different examples of a fuel type than it is to test an average of several fuels, which may have widely differing chemical and physical qualities.

The analysis conducted by a study will depend on the purpose of that study, hence, only a portion of the potential constituents/parameters will be analysed and reported. The number of studies that have considered a particular fuel is highly variable. Consequently, there are a large number of data for certain fuel types and constituents/parameters, while for others there may be relatively few. This is illustrated by the data presented in Tables 13 to 16. These data are summarised from the Phyllis database. The number of data points for RDF contributing to the summary of fuel quality is relatively few compared with the data available on bark. The amount of data available for willow is similar to that for RDF, but about half that available for wheat. This variability in the size of the data pool needs to be borne in mind when considering the behaviour of a fuel type in different combustion conditions.

### **3.4. Review of combustion and gasification plant technologies**

#### **3.4.1. General**

There are a variety of possible conversion technologies available to produce heat or electricity from biomass fuels. These technologies are at differing stages of development and vary in their suitability with scale. These may be integrated with gas clean up plant to comply with the limits set down by environmental legislation.

#### **3.4.2. Primary conversion**

There are three basic primary conversion processes that may be applicable.

##### **3.4.2.1. Combustion**

This is the complete oxidation of the fuel in an excess oxygen atmosphere. The heat released is recovered in the form of hot water or steam in a boiler, by means of heat exchange. There are various designs of combustor, falling broadly into the categories of mechanical grates, rotary drums, fluidised beds, and pulverised fuel / cyclone burners.

##### Mechanical grates

Mechanical grates are suited only to small and medium sized systems (typically <15kg s<sup>-1</sup> steam production) rather than large utility scale due to their relatively low burning rate that demands a large furnace width per unit fuel. The simplest mechanical grates have a fixed grate on which the fuel burns. The underfeed stoker design is simple and well suited to smaller scales. The fuel is fed upwards from a feed system into the middle of the grate where it burns in a heap and the ash falls through the grate from where it is removed. Vibrating grates have fuel introduced at the upper end of a sloped grate and it burns as it

is shaken to the other end where the ash falls off the end and is removed. The largest mechanical grates are travelling grate designs (also known as chain grates). These have links joined in a continuous belt that are driven by a sprocket at one end. The fuel is fed onto one end of the grate and burns as it is slowly transported across the furnace on the moving grate. The ash drops off the far end of the grate and is removed.

### Rotary Drums

In a rotary drum the fuel is fed into one end of a large drum that slowly rotates tumbling the fuel. The fuel is slowly transported down the drum, and ash is discharged at the other end. This design is often adopted for large and non-uniform feed stocks, and with the addition of supplementary gas burners for wet feed stocks e.g. for waste incineration.

### Fluidised Beds

In a fluidised bed design the fuel is burnt in an inert medium, usually sand, with air blown in from below so that the particles separate and are supported by the air flow itself. At high temperatures the sand behaves in a manner similar to a fluid. At lower air velocities the design is known as a bubbling bed. As the air velocity is increased, the bed becomes more turbulent and particles are fully entrained - it is then termed a fluidised bed (FB). A development of this is the circulating fluidised bed in which the bed material is allowed to carry over with the flue gas from the top of the furnace and is separated from the gas in a cyclone and returned through a downcomer into the base of the bed. Ash is periodically drained from the base of the bed. Fluidised beds have a number of advantages:-

- High combustion efficiency but with a relatively low combustion temperature, which reduces thermal  $\text{NO}_x$  generation and the risk of slagging problems;
- Potential for addition of materials for in-bed pollution control e.g. calcium carbonate for  $\text{SO}_x$  control;
- Relatively tolerant to variation in particle size;
- In bed heat exchange tubes which have higher heat transfer rates than a conventional boiler design leading to a compact system

### Pulverised Fuel (PF) / Cyclone Burners

In these systems the fuel is crushed to a fine particle size (larger particles for cyclone burners than PF burners). In PF burners the pulverised fuel is blown into the burner where it mixes with the main combustion air and ignites. The flame extends into the main volume of the furnace. A cyclone burner is cylindrical in shape. The fuel is introduced with high velocity combustion air tangentially to the refractory lined cylinder. The combustion temperature is very high and the ash melts and is deposited on the surface of the cylinder. It drains to the bottom and is removed. The removal of slag from the burners is one of the major advantages for the design when used for low grade coals that would

otherwise cause tube fouling. The fuel is completely burnt within the confines of the burner.

#### 3.4.2.2. Pyrolysis

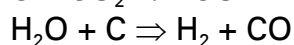
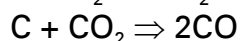
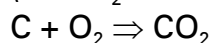
Pyrolysis is the thermal decomposition of the fuel in the absence of oxygen. It produces a mixture of 'producer' gas, pyrolysis oil and carbon char. Pyrolysis occurs as a first step in gasification and combustion processes, but in the former two, oxygen is then introduced so that some oxidation then occurs. The relative yield of the different products depends on the process conditions. High heating rates, moderate temperatures (~500°C) and rapid quenching of vapours ('fast pyrolysis') favour the formation of pyrolysis oil (~75% oil, balance char and gas in about equal proportions). Lower temperatures and longer vapour residence times yield lower fractions of oil (~30% oil, balance char and gas in about equal proportions).

There are a variety of designs for pyrolysis reactors. All designs incorporate a means of rapidly transferring heat from an external source to the biomass and of separating the three reaction products. In most designs the gas and char are burnt to provide the heat for the reactor. Reactor / process designs include:-

- Bubbling bed
- CFB
- Entrained flow
- Rotating cone
- Ablative
- Vacuum

#### 3.4.2.3. Gasification

Gasification is a high temperature (typically 800 - 1000°C for biomass feedstocks) process of partial oxidation of the fuel by reaction with steam / oxygen to yield a combustible product gas which consists mainly of CO and H<sub>2</sub> (and N<sub>2</sub> in air blown designs). The main reactions involved are:-



A variety of other hydrocarbons, such as CH<sub>4</sub>, C<sub>2</sub>H<sub>4</sub>, C<sub>2</sub>H<sub>6</sub> and larger aromatic compounds ('tars') are also formed. The release of heat by partial oxidation is sufficient to maintain the required reaction temperature.

Again a variety of process designs exist. In an up-draught gasifier air is introduced into a reaction zone at the base of a fixed bed of biomass and the hot product gas flows up through the biomass. In the down-draught gasifier the air is injected into a throat at the base of a fixed bed of biomass and the product gas is drawn off downwards from the throat. Both designs are simple, demonstrated and suited to the small scale. The down-draught design tends to produce a gas with a lower tar content.

At the larger scale, designs include:-

- Bubbling and circulating fluidised beds (atmospheric or pressurised)

- Entrained flow
- Twin fluid bed ('Batelle' process)
- Rotary kiln

Of these, the CFB designs are probably most popular and best proven for biomass.

### **3.4.3. Secondary conversion and applications**

#### **3.4.3.1. Steam**

The steam output from a boiler can be put to a number of uses.

It can be directly used for heating and cooling: Steam can be used directly for heating (e.g. district heating) or process applications. The distance over which the steam can be transported without excessive heat loss is limited, so the heat load needs to be close by. The demand for heating is usually seasonal, and in the winter heat demand may be high whilst in the summer there may be no demand for heat at all. Adsorption coolers are driven by a heat source so that cooling can also be provided from the steam. Steam can be used directly for many other applications e.g. drying, steam cleaning and chemical processes. Ideally on-site heating, cooling or process steam needs would be met.

Steam can be used for mechanical power generation due to the steam being expanded in a steam turbine to provide mechanical shaft power, but this is less common.

Secondary conversion of steam to electricity with a steam turbine coupled with a generator to produce electricity. The highest electrical efficiency is achieved if the turbine outlet is to a water cooled condenser which will give a good backend vacuum, maximising the pressure drop across the turbine. However the turbine may be run in back pressure mode or steam may be bled from the turbine to provide low pressure steam for heating (combined heat and power) or other applications. The retail price of electricity is higher than the wholesale price, so normally it would make sense to supply on site electricity demand and displace electricity bought in at the retail price, rather than selling it through the grid at a wholesale price. However biomass and sewage sludge are considered to be renewable fuels so electricity generated from them attracts 'renewable obligation certificates' (ROCs) which considerably enhance the sale value of the power. At present the wholesale price of electricity is around £15/MWh whilst the ROCs are worth around £40-50/MWh.

#### **3.4.3.2. Pyrolysis product use**

Pyrolysis oil may be fired in a gas turbine or a static reciprocating engine, which can again be used to provide shaft power (less common) or coupled with a generator to provide electricity. Heat can be recovered from the hot exhaust of the engine to provide hot water or steam. Alternatively, pyrolysis oil can be used as a feedstock for chemical production or upgraded to 'biodiesel' for transport applications. The oil could also be co-fired in an existing boiler. If co-



fired in an existing utility boiler, the system will benefit from the higher efficiency brought about by the large scale of utility plant. The investment requirement for co-firing in an existing plant is also likely to be lower than for a stand-alone power plant. ROCs can be claimed on the basis of the proportion of bio-oil fuel used.

#### **3.4.3.3. Gasification product use**

Product gas from gasification as above, could be co-fired in an existing utility boiler. Ideally the gasifier should be closely coupled to the existing boiler to allow the product gas to be injected into the boiler at high temperature ( $>300^{\circ}\text{C}$ ) so that tar condensation / clean-up can be avoided. It can also be fired in a stand-alone boiler or again may be fired in a gas turbine or static reciprocating engine with the potential for exhaust heat recovery. If it is to be used in an engine of some sort, it will need to be cleaned first. Tars need to be taken out if the gas is to be injected cold into an engine to prevent them from condensing and fouling the engine. Particulates also need to be filtered out and depending on the gas composition, it may be preferable to at least partially dry the gas by condensing out some of the water vapour. The gas may also be upgraded for use in other applications e.g. as a liquid transport fuel. The ratio of CO to  $\text{H}_2$  can be adjusted by shift reactions and CO and  $\text{H}_2$  can then be combined by processes that are commercially available (e.g. Lurgi, ICI) to produce methanol. Methanol can be used as a fuel itself or as a feedstock for other processes. The gasification product gas can also form the basis for manufacture of a variety of heavier hydrocarbons by the Fischer-Tropsch process.

#### **3.4.4. Flue gas clean-up**

With increasingly stringent environmental regulations, flue gas cleaning may be a requirement. Pollutants that are typically regulated are particulates, CO,  $\text{NO}_x$ ,  $\text{SO}_x$  and heavy metals.

Particulate removal is relatively easy to achieve with either electrostatic precipitators or bag filters. The presence of CO is an indicator of incomplete combustion. In well-controlled combustion the CO level should not need additional control. However catalytic oxidation to  $\text{CO}_2$  is possible if required.  $\text{NO}_x$  may have two sources. Thermal  $\text{NO}_x$  is formed in high temperature combustion – the higher the temperature, the greater the amount of  $\text{NO}_x$  that will be formed.  $\text{NO}_x$  may also be formed from fuel bound nitrogen. Careful control of combustion conditions can minimise thermal  $\text{NO}_x$  formation as in modern low  $\text{NO}_x$  gas turbine burners. If necessary,  $\text{NO}_x$  may be removed from the flue gas by selective catalytic reduction (SCR).  $\text{SO}_x$  arises from oxidation of sulphur contained in the fuel. Biomass fuels are generally low in sulphur and biomass combustion plant does not usually require any means of  $\text{SO}_x$  control. The need for any  $\text{SO}_x$  control measures will therefore depend on the amount of sulphur in the sewage sludge.  $\text{SO}_x$  control can be accomplished by the injection of a suitable chemical absorbent such as lime. Most heavy metals will concentrate in the ash. However the more volatile metals (e.g. Hg) may appear in the flue gas. Again biomass fuels, unless grown on heavily contaminated land, tend to have very low heavy metal contents, so the requirement will

depend on heavy metal levels in the sewage sludge. Heavy metals can be removed by the injection of activated carbon upstream of the filter. The heavy metals are adsorbed on the carbon particles that are then collected by the filter.

### **3.4.5. Technology selection**

It was necessary to select a small number of conversion equipment designs to be used in the experimental programme. Resource constraints mean that no more than 4 technology options could be considered. A number of criteria were used to select the best options.

#### **3.4.5.1. Technological maturity**

The aim of this project was to arrive at a plant design that is commercially attractive to water companies as a means of sludge disposal and also as a means of renewable energy generation. In order to stand a reasonable chance of obtaining commercial funding the technology needs to have been demonstrated. All of the combustor / boiler designs mentioned above are well demonstrated and many reference plants exist. They represent the lowest technical risk. In contrast, although some prototype / pilot pyrolysis plant is under construction or operational, there is no demonstrated reference plant. Gasification technology lies somewhere between these two. Small scale fixed bed gasifiers are available commercially from a number of companies. Although the number of operational plants is relatively small, reference plants do exist and fixed bed gasification should be considered as an option. Fluidised bed gasification of biomass has only been implemented in a small number of plants worldwide. A number of fluidised bed gasifiers are also operating on various wastes. There is not enough experience of fluidised bed gasification to regard it as fully commercially mature and such a plant would have to be considered as having a relatively high degree of technical risk. However as a technology that is currently on the fringe of commercial development and receiving a lot of attention, it should be at least considered as an option.

#### **3.4.5.2. Scale**

Consideration of available sewage sludge and biomass volumes has established the likely scale of plant. As detailed above, two scenarios are to be considered, both of which are a lot smaller than the centralised utility power plant and may be considered as small and medium scale respectively. In general, the smaller the scale of operation, the simpler the technology has to be in order to compete. Increasing complexity may yield greater efficiencies but the increased capital cost cannot be justified normally for a small plant. Pilot scale pyrolysis units are only being developed at the small scale. Fixed bed gasifiers are best suited to the small scale. The design is simple with little control complexity and fuel may be fed on a batch basis. A simple water wash can provide adequate gas clean up to fire the gas in a reciprocating engine. CFB gasifiers could be used at the small scale but are more complex in design and operation, which means that they are better suited to the medium scale. The underfeed stoker is the simplest of the combustor designs and best suited to the smaller scale. While the other combustor designs could be used at the small scale, they are better suited to medium scale due to their greater complexity.

#### **3.4.5.3. Fuel flexibility**

The various designs differ in their suitability for use with different fuels. Biomass fuels show a lot of variability in physical and chemical characteristics compared to a fossil fuel. In particular, unless pre-dried, there can be a large variation in moisture content and it is hard to achieve a uniform particle shape and size. Fixed bed gasifiers are not suitable for finely divided fuels and require a consistent particle size to achieve a uniform air distribution through the throat. A consistent 'chunk' or 'chip' fuel is needed. The fluidised bed is much more tolerant. The mechanical grate combustors can be designed for a range of particle sizes but will operate most efficiently with a consistent particle size. Oversize particles may not be completely burnt out before dropping off the grate. Too fine a fuel may give rise to an uneven air distribution through the grate. A fluidised bed is tolerant of a large variation in particle size as the particles remain in the bed until completely burnt. Pulverised fuel burners require a fuel with very consistent small particle size (typically ~0.1mm and below). Cyclone burners use a larger particle size, but consistency is again important. A large amount of fuel processing would be required to provide a biomass / sewage sludge fuel that would be suitable for firing in a PF / cyclone burner. In all cases fuel-feeding systems will work best with a consistent fuel. Feed systems are vulnerable to blocking by oversize particles (such as the 'rats tails' that frequently occur in chipped wood fuels) and screening for oversize particles will almost always be justified. All systems will work more efficiently with fuels that have consistent moisture contents. For example a dry fuel used in a fluidised bed may mean that in-bed heat exchange tubes are used while with a wet fuel in bed tubes might quench the bed.

#### **3.4.5.4. Efficiency**

It is difficult to compare the efficiencies of the different technologies without knowing what the eventual output required is (steam, heat, electricity etc.). If there is a good market for the waste heat, then the electrical efficiency may not be that important. For a power only scheme, the electrical efficiency is more important. It is generally considered that at the medium scale, the so-called advanced conversion technologies (gasification, pyrolysis) offer higher electrical efficiencies than combustion.

#### **3.4.5.5. Flexibility of output**

The gasification / pyrolysis options give greater flexibility in eventual energy use as they produce a secondary fuel which may be stored, transported and upgraded. A gasifier for example could be run in a continuous steady state with the gas produced being cleaned, cooled and stored. The gas can then be used to generate electricity only at times of peak demand at which a higher price can be demanded. A pyrolysis oil can be upgraded for use as a chemical feedstock or liquid transport fuel. Combustion systems on the other hand do not offer so much flexibility – electricity must be generated at the time of firing. All technologies offer a waste heat stream and heat may be stored for short periods as hot water in lagged tanks.

#### **3.4.5.6. Ranking**

These factors have been ranked on a scale of 1-5 for each of the technologies on a consensus of opinion amongst the project partners and the overall scores used to guide selection for the next task. Table 17 presents this analysis.

The factors above suggest that at the small scale the best options to examine further are fixed bed gasification and underfeed stoker combustion. There are two options for fixed bed gasification: up-draft and down-draft. The down-draft tends to produce a cleaner gas with lower tar content, and for this reason has been chosen. At the medium scale the best technology options appear to be fluidised bed combustion and fluidised bed gasification. Again for the gasification option there are two variants – atmospheric and pressurised. The choice depends to a degree on the use to which the product gas will be put. In the integrated gasification, combined cycle (IGCC) application the product gas must be compressed before injection into the gas turbine. In the atmospheric system the gas must be cooled before compression causing tars to condense, and a satisfactory system for removal and handling of the tars has not yet been found. In the pressurised system the gas is pressurised throughout the system and may be hot filtered, so there is no need to cool below the tar dewpoint. For IGCC application, pressurised gasification might therefore be the favoured choice. If the gas is to be fired in a conventional boiler so that there is no need to cool and clean the gas, atmospheric gasification might be favoured.

### **3.5. Review of current legislation**

This section provides an introduction to some of the legislation and fiscal conditions that need to be considered when considering whether to adopt co-firing with biomass as a sewage sludge management strategy. The legislation, regulations and government incentives that impinge on the co-firing of sludge and biomass have been reviewed. Some legislation impacts in a direct technical sense on co-firing activities, such as the Waste Incineration Directive and some may influence decision making regarding scale of an operation or the choice of co-firing materials, such as the climate Change Levy.

#### **3.5.1. Power generation and the electricity market**

A sludge co-firing scheme would produce heat and/or electricity. This may be used by the water company internally, or sold on the open energy market. The market for heat in the UK is not well developed and large combined heat and power (CHP) systems, such as the SELCHP energy from waste facility in London, find it difficult to sell the heat they produce. There are many industrial users of CHP for onsite process heat and electricity. An arrangement may be developed whereby a water utility supplies supplementary fuel in the form of dewatered or dried sludge for use in a third party's plant. Alternatively, where the economics are favourable, a scheme could be established by the water utility to generate and sell electricity on the open market.

Electricity generated from the digestion of sewage sludge has not qualified for support under the Non-Fossil Fuels Obligation since the 2nd round. However, Energy from waste still qualifies and in NFFO-5 the average price agreed for

municipal waste was 2.49-2.9 p/kWh. This compares with 5.79 p/kWh for biomass, 5.2 p/kWh for biogas from farm wastes and 4.5-7.5 p/kWh for coppice under the NI Renewables Order [7].

### **3.5.2. New energy trading arrangements (NETA)**

The structure of the electricity industry changed in March 2001 with the introduction in England and Wales of the New Electricity Trading Arrangements (NETA). Prior to this, the generators and suppliers traded electricity through the Electricity Pool. This was regulated by its members and operated by the National Grid Company that owns the transmission network. Initially, supply companies and generating companies were separate entities, but in recent years there has been increased vertical integration as supply companies acquired generating businesses and vice versa.

NETA was designed to be more efficient than the Pool trading arrangement and to bring greater choice to the market. It was also designed to reduce the fluctuations in price that reinforced peaks and dips in supply availability at key times. It had the effect of reducing the wholesale price of electricity by an average of 20-25% compared with those under the Electricity Pool system [9]. Output by the smaller generators (< 100MWh per site) dropped by 44% as a result of the lower prices. Basic fuels prices also increased by around 14%, at the same time as the electricity sale price under NETA fell. The resulting lack of difference between the price that power could be sold to the open market at time of high demand, and the price at which smaller generators could buy meant that there was little or no economic benefit to selling power and on-site generated power was used internally rather than exported.

Output from CHP operators was particularly impacted, exports to the market dropping by about 61% in response to a drop in price of about 14%. The price of power from biomass and EfW facilities dropped by about 25%. However, export from these sources declined by only 8%. This illustrates some sensitivity to price, but also a lack of alternative market, at least in the short term.

NETA had the effect of reducing reserve capacity for electricity generation to its lowest recorded level since it left the issue of adequate supply to market forces, unlike the Pool which contained a specific mechanism to encourage generators to provide reserve capacity.

Co-firing with waste biomass may be less market sensitive than using fossil fuels or biomass energy crops, since the influences on waste costs are less driven by the market and more controlled by legislation. The early experiences of NETA illustrate the need for a scheme to be economically robust and flexible, where it is dependant on export to the open market for its viability.

NETA was extended in April 2005 to include Scotland and became BETTA - British Energy Transmission and Trading Arrangements. The scheme is little changed from NETA, with the same principle objectives. It involves a single GB system operator, common rules and charging arrangements for connecting to

and using the transmission system, and a common set of balancing and settlement arrangements.

BETTA and previously NETA value generation that is flexible and reliable, because of the importance to suppliers of meeting short-term contractual commitments, and the costs of making up any shortfall. However, intermittent technologies such as many of the new renewable and CHP find it difficult to obtain good prices in the absence of consolidation services under these schemes. As a result of this, and in spite of significant financial support, NETA was one factor in the slower than expected adoption of these technologies.

### **3.5.3. Renewables obligation**

The Renewables Obligation and Scottish Renewables Obligation are the main mechanism by which the UK Government plans to achieve its 10% by 2010 target for renewable electricity gross consumption, compliant with the EU Renewable Energy Directive [10]. The Obligation came into force on 1 April 2002 and will apply until March 2027. It initially compelled electricity suppliers to supply an increasing amount of their electricity from renewable sources reaching 10.4% by 2010 and remaining constant at that level until 2027. In 2003 the target was revised to 15.4% by the end of 2015.

The Obligation differs from the Directive in that it does not support mixed waste incineration. Energy from the non-fossil fuel component of mixed waste will be eligible as will energy from the non-fossil fuel element of mixed wastes using advanced technologies such as gasification or pyrolysis. The Obligation creates a favourable market for electricity generated from renewable sources. It is also encouraging the larger electricity companies to invest in renewable generation capacity. The water companies may be able to take advantage of this situation and enter into joint ventures agreements for the development of facilities capable of co-firing sludge and biomass.

### **3.5.4. Climate Change Levy (CCL) and Climate Change Agreements (CCA)**

The Climate Change Levy (CCL) was introduced in April 2001. It is a tax on the business use of gas, coal and electricity which adds approximately 15% to energy bills of UK businesses. Oil is not included as it is already subject to excise duty. Electricity produced from renewable sources is exempt from the tax, which is levied at 0.43p/kWh [11], as is fuel used by good quality combined heat and power schemes, certified via the CHP Quality Assurance Programme (CHPQA). CHP would be an appropriate way to optimise the benefits of the scheme to a sludge co-firing operation. The potential for 100% of the cost of new good quality CHP units to be set against corporation or income tax also makes this an attractive option.

Generating stations, which qualify as operations using renewable sources, are accredited by the Office of Gas and Electricity Markets (OFGEM) and issued with Levy Exemption Certificates. Electricity Suppliers who buy the output from these generators to sell to non-domestic uses do not have to pay CCL on that electricity.

The scheme assumes that 50% of the fuel used in Energy from Waste facilities is from renewable sources and hence does not charge the Levy on that portion of the electricity produced from that fuel. Where it can be shown that a facility uses a higher proportion of renewable fuel, the Levy is reduced in proportion. Sewage sludge digestion facilities also qualify as renewable generators under the scheme (Table 18). It is reasonable to expect that the co-firing of sludge and biomass would qualify for exemption and hence, be viewed favourably in the energy market.

### **3.5.5. Waste incineration directive**

The Waste Incineration Directive came into force on the 28th December 2000. It applies to new plants built after the 28th December 2002 and to existing plants from the 28th December 2005. The aim of this Directive is to prevent or reduce, as far as possible, air, water and soil pollution caused by the incineration or co-incineration of waste, as well as the resulting risk to human health. When the proposal for this Directive was introduced the Community's waste incineration system was covered by Directives 89/369/EEC [12] air pollution control from new, and 89/429/EEC [13] air pollution control from existing municipal waste incineration plants, and 94/67/EC [14] incineration of hazardous waste. The latter imposes more stringent standards for emissions than the former, and specifies numerical emission limits for a number of toxic heavy metals, dioxins and furans emitted to the air. Waste water discharges from incineration plant sites are also subject to a permit process under Directive 80/68/EEC [15] on the protection of groundwater against pollution caused by certain dangerous substances.

This Directive is intended to fill the gaps existing in that legislation. Apart from the incineration of non-toxic municipal waste its scope extends to the incineration of non-toxic non-municipal waste, such as sewage sludge, tyres and hospital waste, and toxic wastes not covered by Directive 94/67/EC [14], such as waste oils and solvents. At the same time it is intended to incorporate the technical progress made on monitoring incineration-process emissions into the existing legislation, and to ensure that the international commitments entered into by the Community are met in terms of pollution reduction, and more particularly those laying down limit values for the emissions of dioxins, mercury and dusts arising from waste incineration. The proposal is based on an integrated approach: limits for discharges into water are added to the updated limits for emissions to atmosphere.

This Directive applies not only to facilities intended for waste incineration ("dedicated incineration plants") but also to "co-incineration" plants defined as facilities whose main purpose is to produce energy or material products and which use waste as a regular or additional fuel, this waste being thermally treated for the purpose of disposal. The Directive does not cover experimental plants for improving the incineration process and which treat less than 50 tonnes of waste per year. Nor does it cover plants treating only:

- vegetable waste (agriculture and forestry), the food processing industry or paper production;
- wood waste;
- cork waste;
- radioactive waste;
- animal carcasses;
- waste, resulting from the exploitation of oil and gas, incinerated on offshore installations.

All incineration or co-incineration plants must be authorised. Permits will be issued by the competent authority and will list the categories and quantities of hazardous and non-hazardous waste that may be treated, the plant's incineration or co-incineration capacity and the sampling and measurement procedures that are to be used. A facility co-firing sludge and biomass will need to comply with the requirements of the Waste Incineration Directive.

### **3.6. Overview of modelling approach and preliminary findings**

#### **3.6.1. Background**

This section describes the results of a preliminary investigation into the modelling required for Activity E (section 7) which involved a detailed mass/energy flow and life cycle analysis of combustion and co-firing systems. Results from this analysis have been used as an input to the systematic study examining the effects of different technical, economic and environmental constraints on the viability, impact and benefits of combustion and gasification processes.

#### **3.6.2. Life cycle analysis**

##### **3.6.2.1. General**

Life cycle analysis is a technique for assessing the environmental impacts associated with a product, service or process. Life cycle analysis is particularly useful as it can be used to assess a whole system in terms of both on-site and off-site activities [16]. Potential impacts can be assessed throughout the life of a product or process from raw material acquisition through production, use and disposal.

Although a relatively new environmental management tool, life cycle analysis is widespread use and is covered by the international standards ISO14040-ISO14043 [17-20].

According to ISO14040 [17], life cycle analysis can assist in:

- identifying opportunities to improve the environmental aspects of products at various points in their life cycle;
- decision-making in industry, governmental or non-governmental organizations (e.g. strategic planning, priority setting, product or process design or redesign);



- selection of relevant indicators of environmental performance, including measurement techniques; and
- marketing (e.g. an environmental claim, eco-labelling scheme or environmental product declaration).

Because life cycle analysis is suited to both on and off-site activities, and because of its potential use for strategic planning, it is an ideal tool for the modelling of co-firing options.

### **3.6.2.2. The life cycle analysis process**

ISO14040 [17] defines a four-stage methodology for life cycle analyses, as shown in Figure 2. The stages are goal and scope definition, inventory analysis, impact assessment, and interpretation. It should be recognised that life cycle analysis is an iterative technique, and as the analysis proceeds, activities undertaken in these stages may change. In some cases, the goal of the study itself may be revised due to unforeseen limitations, constraints or as a result of additional information [18].

### **3.6.2.3. Goal and scope definition**

According to ISO14040 [17] the goal of a life cycle analysis study shall unambiguously state the intended application, the reasons for carrying out the study and the intended audience, i.e. to whom the results of the study are intended to be communicated.

Three principal elements should be described in the goal and scope definition:

1. Functional unit
2. Initial system boundaries
3. Data requirements

### **3.6.2.4. Functional unit**

The scope of a life cycle analysis should include a clear statement on the performance characteristics, or functions, of the system being studied. The functional unit defines the quantification of these functions and provides a reference to which the inputs and outputs of a system can be related. The functional unit should be clearly defined and measurable, and forms the basis for comparison of different scenarios. When the functional unit is defined, the amount of materials or energy required to fulfil the function can be determined. This determines the reference flow for comparisons.

ISO14041 [18] provides an example functional unit definition. In the function of drying hands, both a paper towel and an air-dryer system are studied. The selected functional unit may be expressed in terms of the identical number of pairs of hands dried for both systems. For each system, it is possible to determine the reference flow, e.g. the average mass of paper or the average volume of hot air required for one hand-dry, respectively. For both systems, it is possible to compile an inventory of inputs and outputs on the basis of the reference flows. At its simplest level, in the case of paper towel, this would be

related to the paper consumed. In the case of the air-dryer, this would be largely related to the energy input to the air dryer.

Some example functional unit definitions from literature life cycle analysis studies are shown in Table 19.

#### **3.6.2.5. Initial systems boundaries**

The system boundaries determine which processes should be included within the life cycle analysis, and hence also influence the inputs and outputs to the system.

It is not usually practical to model every input and output for the system, and input/output selection is an iterative process. The initial identification of inputs/outputs is typically made in light of mass, energy or environmental relevance, and the availability of data. Inputs/outputs are likely to be refined during the course of the study.

ISO14041 [18] suggests that several life cycle stages, unit processes and flows should be taken into consideration, e.g.:

- inputs and outputs in the main processing sequence;
- distribution/transportation;
- production and use of fuels, electricity and heat;
- use and maintenance of products;
- disposal of process wastes and products;
- recovery of used products (including reuse, recycling and energy recovery);
- manufacture of ancillary materials;
- manufacture, maintenance and decommissioning of capital equipment;
- additional operations, such as lighting and heating;
- other considerations related to impact assessment (if any).

Figures 3-6 shows some examples of boundary definition for various waste treatment processes. In each case, the system is encapsulated such that resource and energy inputs can be identified, and impacts and benefits in terms of processes materials, emissions or energy can be defined. These inputs and outputs are used in the subsequent inventory and impact analysis stages.

#### **3.6.2.6. Data requirements**

The data required for a life cycle analysis study may be collected from sites associated with the processes inside the system boundary, or they may be obtained or calculated from published sources. In practice, a life cycle analysis is likely to contain a mixture of measured, calculated or estimated data.

Major headings for data categories include [18]:

- energy inputs, raw material inputs, ancillary inputs, other physical inputs;
- products;

- emissions to air, emissions to water, emissions to land, other environmental aspects.

Energy inputs and outputs are treated as any other input or output to a life cycle analysis. The various types of energy inputs and outputs include inputs and outputs relevant for the production and delivery of fuels, feedstock energy and process energy used within the system being modelled.

Emissions to air, water and land often represent discharges from point or diffuse sources, after passing through emissions control devices. The category should also include, when significant, fugitive emissions.

Other data categories for which input and output data may be collected include, for example, noise and vibration, land use, radiation, odour and waste heat.

Data quality issues should also be addressed, including [18]:

- time-related coverage: the desired age of data (e.g. within the last five years) and the minimum length of time (e.g. one year) over which data should be collected;
- geographical coverage: geographical area from which data for unit processes should be collected to satisfy the goal of the study (e.g. local, regional, national, continental, global);
- technology coverage: technology mix (e.g. weighted average of the actual process mix, best available technology or worst operating unit).
- precision: measure of the variability of the data values for each data category expressed (e.g. variance);
- completeness: percentage of locations reporting primary data from the potential number in existence for each data category in a unit process;
- representativeness: qualitative assessment of degree to which the data set reflects the true population of interest (i.e. geographical coverage, time period and technology coverage);
- consistency: qualitative assessment of how uniformly the study methodology is applied to the various components of the analysis;
- reproducibility: qualitative assessment of the extent to which information about the methodology and data values allows an independent practitioner to reproduce the results reported in the study.

#### **3.6.2.7. Inventory analysis**

Inventory analysis involves data collection and calculation procedures to quantify the relevant inputs and outputs of the system, consistent with the goal and scope definition. These inputs and outputs are likely to include the use of resources and releases to air, water and land associated with the system. The data-collection and calculation exercise results in a life cycle inventory, which is used as an input to the life cycle impact assessment.

It is useful to draw up a process flow diagram for the system being studied, showing all the unit processes to be modelled and the interrelationships

between these unit processes. Life cycle inventories are based on material and energy balances about the unit processes that make up the system. The derivation of a life cycle inventory relies on being able to link unit processes within the system by simple material and energy flows. In practice it is relatively uncommon for a process to produce a single output or have a linear flow of materials or energy without loops or recycling. This leads to the problem of allocating the relevant inputs to one or more product outputs.

The problem of recycling of materials or energy is simplified in closed-loop systems, where the recycled material or energy merely reduces the input of virgin materials or energy. This is likely to be the case in a combustion/gasification system where electricity, heat or steam is recycled within the system for the purposes of sludge drying for example.

The problem of multiple outputs from a system is has been illustrated using waste incineration as an example [21]. This supposes an incineration and landfill scenario are being compared. There is an immediate difficulty in comparing these cases, as both the landfill and waste incinerator provide the function of waste disposal, but the incinerator also provides an additional function in terms of generating heat (Figure 7).

In order to make the systems comparable, the environmental interventions of the two functions 'treatment of solid waste' and 'heat' must somehow be allocated in the incineration system. The environmental interventions in the incineration system can then be compared to the environmental interventions of the landfill system. This is a difficult problem however, and there is currently no agreement on how the allocation should be made.

A possible solution to this problem is to avoid allocation by broadening the system (Figure 8). In the broadened system, an alternative way of producing an equivalent amount of energy has been added to the landfill system, or alternatively, an alternative heat source is removed from the incinerator. It is then possible to directly compare the two systems

#### **3.6.2.8. Impact analysis**

The aim of the impact assessment is to utilise the results of the life cycle inventory to evaluate the significance of potential environmental impacts. Typically, this involves allocating inventory data with specific environmental impacts and attempting to understand those impacts. The impact assessment phase may include elements such as [17]:

- assigning of inventory data to impact categories (classification);
- modelling of the inventory data within impact categories (characterization);
- possibly aggregating the results in very specific cases and only when meaningful (weighting).

There is an element of subjectivity in the life cycle impact phase, such as the choice, modelling and evaluation of impact categories. There are a number of impact models available which attempt to condense the inventory results into specific measures in a number of categories such as global warming potential, acidification, human health effects etc. These may then be weighted and condensed into a single eco-indicator value. Figure 9 shows the relationship of the life cycle inventory to the life cycle analysis, the categories used, the steps involved in determining an eco-indicator value.

### **3.6.2.9. Interpretation**

Interpretation is the phase on a life cycle analysis where the results of the inventory analysis and the impact assessment are combined, consistent with the defined goal and scope, in order to reach conclusions and recommendations.

## **4. ACTIVITY B – FACILITY DEVELOPMENT**

### **4.1. Introduction**

In this activity the existing coal-fired gasification and combustion pilot plants at Cranfield University were adapted to enable them to be co-fired simultaneously on sewage sludge and biomass (i.e. wood). The adaptations included the introduction of sludge/biomass handling, storage and feed systems together with alterations to the rig control systems. As the fuels to be used in the test programme are critical to the fuel handling modifications needed to the test rigs (both in terms of fuel handling properties, e.g. hardness, flow, density, etc, and the volumes of fuels required, i.e. energy required to operate test rigs) a fuel selection process was carried out as described in section 5.2.

### **4.2. Combustion pilot plant**

The combustion pilot plant at Cranfield University is shown schematically in Figure 10 and in photographs in Figure 11. This plant has been developed in a series of stages from an originally coal-fired fluidised bed combustor. It now consists of a solid fuel fired fluidised bed combustor (FBC, with operating temperature  $\sim 900^{\circ}\text{C}$ ) connected to a second combustion chamber into which pulverised coal can be added to increase the combusted gas temperature to  $\sim 1400^{\circ}\text{C}$ . The hot combustion gases pass through two test sections that can be used to expose heat exchanger materials and/or sample the product gas streams, before passing through a back-end heat exchanger, cyclone and fan en-route to the chimney. Both the combustion chambers have natural gas pilot lights / pre-heaters; in addition, the second combustion chamber can be fully fired on natural gas. The nominal operating conditions of this test facility on coal are given in Table 20.

For simplicity in fuel handling and to ensure a consistent fuel mix, biomass / sewage sludge fuels were pre-mixed and the combined fuel mix fed into the first combustion chamber. For fluidised bed combustion operation, the fuel mix was screw fed into the top of the combustion chamber so it would fall on to the surface of the fluidised bed through a drop tube. The fuel storage chamber for

this screw feed system had to be sealable and flushed with nitrogen during use, and so needed to be sufficiently large to give reasonable operating times between fuel re-fills. Figures 12 and 13 show this fuel storage and feed system. Trials of this feed system with a wood chip feedstock showed that it has a feed rate range of 0 - ~10 kg/hour.

### **4.3. Gasification pilot plant**

The gasification pilot plant facility at Cranfield University is shown schematically in Figure 14. This plant has been developed in a series of stages to investigate a variety of hot gas cleaning options for coal fired power systems. This plant now consists of a trace heated spouted fluidised gasifier, operating at ~900°C on coal, that produces fuel gases which can be directed through different gas paths to study the effects of fuel compositions on the resulting gas compositions, deposition phenomena or contaminant removal by different gas clean-up processes, before passing through a flare and to a chimney. The nominal operating conditions of this test facility on coal are given in Table 21.

As for the combustion system, for simplicity in fuel handling and to ensure a consistent fuel mix, pre-mixed biomass / sewage sludge fuels were fed into the gasification system. During coal operation, the finely ground fuel has traditionally been blown into the spout of the fluidised bed. However, it was believed that this was not a viable option for the proposed biomass / sewage sludge mixtures, so a screw feed system was designed (Figure 15) that allows these fuel mixes to be dropped onto the top of the gasifier's spouted fluidised bed. The fuel storage chamber for this screw feed system has to be sealable and flushed with nitrogen during use, and so needed to be sufficiently large to give reasonable operating times between fuel re-fills.

### **4.4. Fuel feeding issues**

The feed systems developed for the both the combustor and gasifier have been described above. It was anticipated that the diverse range of sewage based/wood chip fuel mixes used in this work would have varying feeding properties but it was expected that screw feeders would be suitable from previous experience of screw feeding of wood chip. Unfortunately some of the sewage/wood chip mixes were particularly difficult to feed with the main result being that the gasifier feed system had a number of modifications made to improve/allow feeding of these fuels. Problems and modifications for each system are detailed below.

#### **4.4.1. Combustor**

The end of the feeder screw/entry into top of combustor had a spyhole that allowed the feeding to be monitored and allowed minor feed problems to be dealt with as required. This area at the end of the feed screw was where most of the feed system blockages occurred. The spyhole could be opened due the system being designed to work at atmospheric pressure and therefore allowed unblocking of the system at this point without major interruption the test. The fuel hopper could be opened to allow fuel levels to be checked and also manual stirring of the fuel to avoid bridging. Whilst stopping the feeder and unblocking

etc. interrupted the fuel feeding the time involved did not affect the test significantly in most cases, for the most difficult fuels to feed e.g. mix with screenings, this effectively limited the feeding rate.

#### **4.4.2. Gasifier**

In contrast to the combustor the gasifier and feed system had to be kept sealed during operation due to the toxic gases produced at pressure within the system. The end of the screw/gasifier entry was sealed by a slider valve before the fuel hopper lid was lifted for inspection and refilling. As fuel feeding is a major part of the control of the gasifier it was found that the time taken to open and close the hopper for stirring fuels that bridged was too long. This problem was overcome by fixing a stirring rod through the lid of the hopper that remained sealed during operation. This allowed not only for stirring but gave an indication of the fuel level and reduced the number of hopper inspections required.

A blockage in the fuel feed system or at the top of the gasifier could not be cleared while the test was running so blockages resulted in the test being stopped and the system being flushed and cooled. Additionally, a blockage obviously stopped fuel reaching the gasifier bed and as fuel feeding partially controlled the bed temperature, this could result in rapid increases in bed temperature and sintering. These increases in bed temperature could be controlled by using nitrogen in place of some air to fluidise the bed, but the blockage needed to be identified quickly. The end of the screw/ gasifier entry does not have a spyhole and therefore blockages in the system could not be detected visually. As the initial feed system was a screw within a tube, minor blockages would develop into major blockages as the feed system would continue to compress fuel behind the blockage resulting in major downtime to unblock the system.

To overcome these problems two modifications were made. The feed system tube was split into two halves that could be bolted back together. This allowed for much faster unblocking of the feed system although the test still had to be halted. The second modification was to add a display of the current usage of the motor that turned the feed screw. The current increasing rapidly and going above an identified value indicated a blockage in the system and allowed appropriate measures to be taken.

Overall, feeding of fuels still remained the major hurdle in the gasifier tests but the modifications made greatly improved fuel feeding and although blockages in the gasifier feed system could not be stopped the early warning minimised the downtime that resulted.

## 5. ACTIVITY C – CO-FIRING TEST PROGRAMME

### 5.1. Introduction

### 5.2. Fuel selection and co-firing test matrix

The following sewage sludge types were selected for testing in the co-firing test programme:

- *'Raw dewatered'* – A raw dewatered sludge from Thames Water (laboratory dried before use in pilot plants)
- *'Composted sludge'* – A biologically dried sludge from Thames Water. The mixture is made of raw sludge with woodchip as the amendment material in a composting process. Woodchip is used as a bulking agent and mixed with raw cake at a 2:1 woodchip/sludge ratio by volume. Table 22 shows composition of the component materials.
- *'Screenings'* - Sewage screenings from Thames Water
- *'Digested sludge'* - Digested sludge cake (dewatered digested sludge) from Severn Trent.
- *'Raw dried sludge pellets'* – Raw dried sludge pellets from Severn Trent.

For Activity C, the priority was to determine the issues surrounding the use of the various types of sewage sludge, rather than to explore an extensive range of biomass types. As a result the experimental part of the project was carried out using wood chips. The appropriate ratio of biomass to sewage sludge in each case was assessed on the basis of CV rather than moisture content. The preliminary modelling of the combustion and gasification processes was used to determine the appropriate ratio of biomass to sewage sludge to be used in the tests. As moisture content and CV varied amongst the sludge types, the suitable mixtures for experimentation varied also for each combination of biomass/sludge. Examples of these modelling results are compiled in Figure 16 which shows possible mixtures for two different types of sludge: digested and composted. The results are shown in terms of the percentage of sludge in the mixture (X axis) versus the percentage of moisture in the sludge at the dryer exit (Y axis). The blue line represents the limit (both in terms of moisture and sludge content) to achieve a good combustion temperature. The pink line represents the limit (in terms of moisture and sludge content) to be in the suitable temperature range for the dryer inlet. A suitable mixture (in terms of moisture content) lies between the blue and pink lines as indicated. The modelling results showed that some mixtures are not feasible due to sludge drying limits, but also that some potential fuels do not need any drying even when they are used on their own without added biomass.

The initial test matrix obtained from this modelling exercise was modified during the process of carrying out the experiments due to the information gained from the practical experience of running the tests (e.g. temperatures achieved in the combustor, mixing and feeding problems). For example, some mixtures that initially seemed suitable in the modelling actually in practice gave a low combustion temperature and low gas temperature in the fluidised bed (see section 5.4.2.3). Tables 23 and 24 list the mixtures tested in the



combustion and gasification experiments together with some comments and Figure 17 gives the gross calorific value (GCV – see appendix 1) of each mixture.

### **5.3. Fuel analysis**

Proximate and ultimate analysis (as received) and ash elemental were performed on the fuels by TES Bretby (ash fusion analysis was also carried out and is described in section 6.2.2). Each primary fuel was analysed twice, once when it was received and secondly near the end of the test programme (fuel mixes were analysed once). The results of these analyses have been compiled in Table 25 and Table 26. It can be seen that the sludges have higher moisture content and higher ash contents compared with wood chips. It can also be seen that the sulphur and nitrogen contents in the sludge are higher than those in wood chips. In comparison to alternative biofuels, the combustion of sewage sludge may produce higher  $N_2O$ ,  $NO_x$  and  $SO_2$  emissions [22] and the ash produced may contain a higher concentration of heavy metals. Looking at the ash elemental analysis, it can be seen that the alkali content is higher in both (sludge and wood chips) than in coal (Maltby coal taken as an example). This will affect to the formation and composition of deposits. Both, the GCV and the net calorific values (NCV – see appendix 1) are lower in all the sludge types compare with wood chips and coal. Ash samples (fly ash and bed ash) were collected after the different experiments and sent for analysis.

### **5.4. Combustion experiments**

#### **5.4.1. Test procedure**

For simplicity in fuel handling and to ensure a consistent fuel mix, the biomass / sewage sludge fuels were pre-mixed and then fed as a combined fuel mix into the fluidised bed combustion chamber.

For fluidised bed combustion operation, the fuel mix was screw fed into the top of the combustion chamber and then allowed to fall on to the surface of the fluidised bed through a drop tube. Experimental conditions used in the tests such as fuel feeding rate and air flow are given in Table 27, together with the resulting combustion temperatures and gas compositions.

#### **5.4.2. Experimental issues**

##### **5.4.2.1. Introduction**

During the course of carrying out the matrix of combustion experiments a few issues need to be taken into account.

Properties of raw sludge vary according to location but also with sludge source within the specific wastewater treatment train. Sludge from primary settlement has different characteristics from that produced during an activated sludge process. Both physical and chemical parameters vary as does the CV of the sludge. In most treatment plants the sludge collected from the different process stages will be combined prior to further treatment, such that the characteristics specific to the unit operation from which the sludge is generated will be lost. It

is also the case that, since sludge is generally viewed as a waste material, treatment processes are operated so as to minimise sludge production, despite its prospective end use as a fuel.

The final properties of treated sludge vary enormously and, when considering thermolytic destruction methods as a final process stage, the sludge solids content, CV, water content, handleability, carbon content, ash content, etc, are of key importance. The emission of polluting gases and the handling of solid by-products are also key factors in determining the feasibility of a co-firing plant. In comparison to alternative biofuels the combustion of sewage sludge may produce higher  $N_2O$ ,  $NO_x$  and  $SO_2$  emissions [22] and the ash produced may contain a higher concentration of heavy metals.

In addition to the range of compositions of potential biomass and sludge fuels, other important properties like physical particle shape, size and density of the fuels can vary in a wide range. For example, there are considerable differences in these parameters between chopped wheat straw, coppiced willow and milled palm nuts and between sludge screenings, digested sludge and composted sludge, so that substituting one for another in a power system is far more difficult than changing coals. Such differences also give rise to significant difficulties in storing and handling biomass.

#### **5.4.2.2. Handling issues**

As has been described above, not only the thermal characteristics but also the physical characteristics of the sewage sludge vary significantly depending on its treatment. These characteristics will affect to the final fuel mixture, influencing suitability of the feeding system configuration and other issues related with mixing processes and storage.

For the mixing process in the co-firing experiments carried out at Cranfield University, a rotary mixer has been used. Fixed batches of wood chips and sludge were introduced in the mixer and the mixing time was varied depending on the characteristics of the sludge. The quality of the mixture achieved in all the cases was good, except for the digested sludge from Severn Trent. The inconsistency of the sludge made it impossible to reach a satisfactory mixture between the wood chips and this sludge. A photograph of this blend is shown in Figure 18. These problems mixing the digested sludge made it impossible to carry out a proposed experiment of 50% digested sludge and 50% wood chip (by wt), and so a replacement experiment has used a maximum sludge percentage of 30% (by wt).

The premixed fuels were introduced into a hopper and fed into the top of the combustor and then down a drop tube into the FBC. This feeding system proved to be suitable for all the fuels used in the experiments, except for screenings. The low density of this waste material (similar to paper) made it really difficult to feed the material from the top of the combustor, and moreover, due to the low calorific density (lower densities in the fuel requires

higher volume to be fed in the rig) the combustion temperature achieved was relatively low.

#### **5.4.2.3. Moisture content and calorific value (CV)**

The moisture content of the fuels used in the experiments was quite high; the values are given in Table 25 together with the CVs (GCV, NCV and dry ash free CV – see appendix 1) of these fuels. According to some authors to provide a good combustion process, the sludge should be pre-dried to a water content of about 30-40%. The NCV of the sludge with this moisture content has been reported to be about 7 KJ/kg [23]. Calculations of the CV of a blend based on 30% sludge (with a CV of 7 KJ/kg) with 70% biomass shows that the blend CV is comparative with the biomass only CV.

Figure 17 shows the GCVs for the original supplied fuels and the blends that were used in the experiments. It was important to obtain the relationship between the fuel CV and resulting combustion temperature achieved in the fluidised bed (target >850°C) in the early tests to allow initial screening of fuel mixtures. The mixture of 50% composted sludge and 50% biomass (by wt, as received) only achieved a low combustion temperature in the fluidised bed so the CV of this mixture was considered as the lower limit for the remaining mixtures in the combustion experiments. This lower limit for fuel CV is represented on Figure 17 as a dotted line.

### **5.5. Gasification Experiments**

#### **5.5.1. Test procedure**

Pre-mixed biomass / sewage sludge fuels were fed into the gasifier for the same reasoning given above for the combustor. The fuel mix was screw fed into the top of the gasifier and then allowed to fall on to the surface of the fluidised bed through a drop tube.

The successful and stable operation of the gasifier relies on maintaining the balance between combustion and gasification in the rig. Combustion in the rig is used initially to bring the rig from the starting temperature of 600°C up to the working temperature of 800-850°C. Once in this temperature range the balance is shifted more towards gasification by ideally increasing feed rates or replacing some of the fluidising air with nitrogen i.e. decreasing the air to fuel ratio. A stable gasifier bed temperature is achieved by balancing the heat produced by the limited combustion with the energy used to heat and evaporate moisture from the fuel and energy required by endothermic gasification reactions. The balance between combustion and gasification is monitored using thermocouples in the fluidised bed and by measuring CO<sub>2</sub> and CO levels in the produced gas. If the balance shifts too far towards combustion, as would be the case with a fuel feed problem, the bed temperature rises and CO<sub>2</sub> levels increase while CO levels drop. The rise in temperature can occur rapidly and can be localised to one part of the bed, if the temperature goes high enough the bed can sinter. If the balance shifts too far towards gasification, then the temperature decreases and the CO level rises as CO<sub>2</sub> levels fall. These effects

are shown schematically in Figure 19. As most of the fuels used in this work were difficult to feed there was non-uniform feeding that resulted in periods of gasification of variable duration rather than stable conditions.

Experimental conditions used in the tests, such as fuel feeding rate and air flow, are given in Table 27, together with the resulting process temperatures and gas compositions.

## **6. ACTIVITY D – ASSESSMENT OF EMISSIONS AND ASH PRODUCTS**

### **6.1. Introduction**

Analytical results have been generated from the fuel feed-stocks (described in section 5.3), ash/char collection and gas sampling carried out during the combustion and gasification tests. The compositions of the gaseous and solid products from the processing are important due to the regulations that control environmental emissions and solid waste disposal. The accurate measurement of contaminant levels in biomass gasification systems is essential as it allows the quality of the produced gas to be established and optimisation of gas cleaning. For most measurements, there are well-developed techniques, standards and equipment that allow accurate determination of contaminant levels. Unfortunately the measurement of tars has not been standardised and many different sampling and analysis methods are currently used. As the absence of a well-defined and widely accepted tar measurement method may hinder the development of biomass gasification systems, the issue is being addressed by a CEN programme to develop a standard. The tar sampling method used is described in section 6.3.3.1.

### **6.2. Combustion**

#### **6.2.1. Gas emissions**

The gases produced during the combustor tests were monitored using the sampling train shown schematically in Figure 20. Bulk gas compositions,  $\text{CO}_2$ , CO and  $\text{O}_2$ , were continuously monitored at the outlet of the fluidised bed combustor using gas analysers. Batch analysis of  $\text{SO}_2$ , HCl, NO,  $\text{N}_2\text{O}$ , was made using Draeger tubes during stable operating conditions. The results from the continuous gas monitoring and batch gas analysis are given in Table 27.

Emissions will depend on the fuels and blend composition. As has been shown in other investigations [22], co-firing of biomass with coal has a positive effect in terms of sulphur due to the lower biomass sulphur content. Due to the high volatile content of the biomass, low NO<sub>x</sub> emissions can be achieved too. When co-firing biomass with sewage sludge, emissions will depend on both the biomass and the sludge composition. For the fuels employed in these experiments, the sludges all have higher sulphur, chlorine and nitrogen contents than the wood chips.

The production of  $\text{SO}_2$  during combustion depends directly on the sulphur content of the fuels. In fluidized bed systems, it is possible to reduce the  $\text{SO}_2$  emissions through the use of sorbents such as limestone and dolomite. There are indications that an optimum size of limestone corresponds to 0.3-0.4 mm for a calcium/sulphur ratio of 2. For fuels containing calcium compounds, the required sorbent addition is generally lower; however, this depends on the activity of the calcium compounds regarding  $\text{SO}_2$  capture. Several papers on sulphur behaviour in coal and coal-biomass blends have been published [24, 25]. In the case of coals, calcium plays a dominant role in sulphur retention, while the contribution of other elements is limited. For co-combustion of coal-biomass blends, investigation reveals that  $\text{SO}_2$  may be partly retained in the ash by the alkaline-earth fraction of the biomass. Other workers have investigated the influence of sludge during coal combustion [26]. Sulphur retention in sludge blends depends on several factors, such as combustion temperature, calcium oxide ( $\text{CaO}$ ) available to combine with sulphur, 'rank' of the coal and the dispersion of  $\text{CaO}$  in the minerals. Figure 21 shows a comparison between  $\text{SO}_2$  emissions versus  $\text{SO}_2$  input (calculated assuming all fuel sulphur is converted to  $\text{SO}_2$  in flue gas) for the different blends used during the experiments. In all the cases it can be seen that  $\text{SO}_2$  emissions are lower than the sulphur input in the fuels. The ash composition in terms of calcium, magnesium and iron is very important to the sulphur reduction achieved. The proportion of active  $\text{CaO}$  available to combine with sulphur may be decreased by the presence of other oxides, such as iron oxide ( $\text{Fe}_2\text{O}_3$ ), that are capable of reacting with  $\text{CaO}$  to form clinker minerals. Figure 22 shows the effect of calcium, magnesium and iron in the ashes on the sulphur capture in the experiments.

The potential for  $\text{N}_2\text{O}$  and  $\text{NO}_x$  emissions is high during the combustion of sewage sludge due to its high nitrogen content. It has been found that dry sludge exhibits  $\text{NO}_x$  and  $\text{N}_2\text{O}$  emission characteristics similar to those of coals [27]. Unlike dry sludge, wet sludge was found to exhibit totally different  $\text{NO}_x$  and  $\text{N}_2\text{O}$  emission characteristics [28]. Very low  $\text{NO}_x$  ( $<200 \text{ mg/m}^3$ ) was measured from wet sludge, although the nitrogen content was higher than that of the dry sludge. This has been validated by the  $\text{NO}_x$  emission data collected from some large-scale incineration plants in Germany that were burning wet sludge [29]. The wet sludge contains a lot of ammonia dissolved in water that helps in reducing  $\text{NO}$  (as in the SNCR process). The result of the presence of ammonia in the sludge water is that the  $\text{NO}_x$  emission is stabilised at a very low level. It has been seen that the  $\text{NO}_x$  emission characteristics of semi-dried sludge samples are closer to those previously obtained for wet sludge samples [30]. However, whereas it is possible to meet the  $\text{NO}_x$  limits of  $200 \text{ mg/m}^3$  when burning wet sludge using single-stage combustion, this appears not to be guaranteed during the combustion of semi-dried sludge especially within the normal operating conditions (i.e. 6-11% vol. of  $\text{O}_2$ ). In the experiments carried out in this work, in all the cases the  $\text{NO}_x$  measured was lower than the emissions expected coming from the fuel but always higher than this  $200 \text{ mg/m}^3$ . This can be seen in Figure 21.

### **6.2.2. Solids**

Solid samples have been taken from the bed material and fly ash; in both cases the carbon content has been analyzed, the results are compiled in Table 29. Pictures of the bed material have been taken; examples have been compiled in Figure 23. In general the reddish colour in the bed material indicates high content in iron, mainly from the sludge. No sintering problems were observed except in the experiment with 100% composted sludge. Another characteristic that deserves to be highlighted occurred in the experiments carried out with dried and pelletised raw dewatered sludge. Due to the high ash content in the sludge, the pellet shape of the sludge remained in the bed after the carbonaceous material was burnt, this can be appreciated in the pictures in Figure 23. Fly ash samples were sent for analysis, the ash elemental results are given in Tables 30, and ash fusion results in Table 31.

## **6.3. Gasification**

### **6.3.1. Gas Composition**

The gas compositions produced during the gasification tests was monitored using the gas sampling train shown schematically in Figure 24. Bulk gas compositions,  $\text{CO}_2$ ,  $\text{CO}$  and  $\text{CH}_4$ , were continuously monitored. Batch analysis of  $\text{H}_2\text{S}$  and  $\text{HCl}$  was made using Draeger tubes during stable operating conditions. The results from the continuous gas monitoring and batch gas analysis are given in Table 28.

### **6.3.2. Solids**

Char was collected in the two cyclones shown in the schematic of the gasifier, Figure 14. Char samples were sent for analysis (proximate, ultimate and ash elemental) and the results are given in Tables 32 and 33.

### **6.3.3. Tar**

Tar is a complex mixture of condensable hydrocarbons, but a unique definition is lacking. Generally, the gas from biomass gasification contains tar, which forms a serious problem for its use in IC engines and turbines. When biomass is heated the molecular bonds of the biomass break forming small gaseous molecules and larger molecules called primary tars. Primary tars are fragments of the original material that can react to form secondary tars and tertiary tars at high temperature. The amount of individual compounds present in biomass gasification tars generally numbers a few hundred but can be several thousand for tars formed at low temperature. The amount and composition of the tar depends on:

- Biomass properties (chemical composition, moisture, size)
- Gasification conditions (pressure, temperature, residence time)
- Gasifier technology

The effect of temperature on tar yield for wood gasification is shown schematically in Figure 25. Increasing the gasification temperature causes a reduction in yield as more of the tar is thermally cracked.

Tars can cause problems in biomass gasification systems for a number of reasons. The heavier tar compounds can condense on cool surfaces or form tar aerosols as the gas temperature decreases. Tar aerosols occur as fine droplets that may be less than 1  $\mu\text{m}$  in diameter. Partial combustion of tar can lead to PAH and/or soot formation, which can give problems with wear and corrosion.

#### **6.3.3.1. Sampling Method**

It has been recognised that data on tar concentration from different biomass gasifiers cannot be properly compared due to the differences in tar definitions and tar measurement methods used. This has been the major reason to start the development of the common tar measurement protocol sponsored by the European Commission.

The draft tar measurement standard produced by this programme along with other information in the literature was consulted in the development of the tar sampling method employed in this work. The tar sampling was carried out using the sampling train shown in Figure 24. The gasifier gas is sucked by a pump along a heated line and through a series of six capture vessels each containing 100cm<sup>3</sup> of isopropyl alcohol (total of 600cm<sup>3</sup>). The first, second and fourth vessel are kept at room temperature whilst the remaining three are maintained at -20°C. The solvent from each vessel was combined and a sample sent for analysis by TES Bretby. Due to the problems encountered during the gasification test programme the total volume of solvent used was reduced from 600cm<sup>3</sup> to 400cm<sup>3</sup> to counter the effects of short sampling times on the tar capture.

#### **6.3.3.2. Results**

The full raw data obtained from the tar analysis are given in appendix 4 to allow the full range of compounds analysed to be listed. Table 35 gives a shorter results summary of the compounds that were above the detection level. Comparison between the tests is difficult as the gasification temperature and level of gasification varied during and between tests.

Table 34 gives the gas quality requirements for an IC engine and a gas turbine. The required tar levels are lower than that produced during our tests. The gasification system used was not optimised to reduce tar levels and by simply increasing the bed temperature the tar yield would be reduced. The results suggest that tar removal would be required in a full scale industrial system to meet the required limit, techniques for tar removal are briefly discussed in the next section.

#### **6.3.3.3. Tar Removal**

Tar can be removed from gasifier gas by both chemical and physical methods. The chemical methods break down the tar whereas physical methods remove the tar as a tar waste stream. The tar conversion (chemical) methods include catalytic cracking, thermal cracking and plasma reactors. The tar removal (physical) methods include cyclones, filters (baffle, fabric, ceramic, granular beds, RPS), precipitators and scrubbers. The combustion enthalpies for the tar

varies from 20 - 40 MJ/kg, which makes it a very useful fuel, therefore conversion is strongly preferred above removal.

## **7. ACTIVITY E – IDENTIFICATION OF KEY SYSTEMS VARIABLES AND THEIR INTER-RELATIONSHIPS**

### **7.1. Introduction**

The objective of this activity was to develop the data required to define the economic viability of gasification and combustion and then to optimise system performance and emission/waste requirements whilst retaining operating flexibility. A parametric analysis was carried out of the main variables and outputs of the gasification and combustion processes together with the sewage sludge production processes to identify the key variables for the whole system, their inter-relationships and the effect on technical viability and operating costs.

A life cycle model has been created to investigate the economic viability of the candidate scenarios. Two life cycle models, one each for gasification and combustion processes, have been created to allow the analysis of system performance and emission levels. A systematic study has been carried out to examine the effects of different technical, economic and environmental constraints to determine the viability, impact and benefits of the various candidate processes.

### **7.2. Mass/Energy Flow and life cycle Analysis**

#### **7.2.1. Model Development**

Mass and energy balance models have been developed for both combustion and gasification systems. These models are shown schematically in Figures 26 and 27. These models have built on the initial assessment work carried out in Activity A (section 3).

The models were developed in a modular form to allow each distinct part to be considered and developed separately. Different modules were contributed by Cranfield University, ME Engineering and project sub-contractors. This structure had the benefit of allowing each module to be updated as new information became available. It also permitted flexibility in choosing the potential fuel usage scenarios that were to be evaluated later in the project.

For the generic combustion system, the modules include ones for:

- Off-site fuel drying using natural gas driers
- Transport of fuel to combustor site
- Drying of fuel(s) using flue gases from the combustion system
- Co-combustion of both fuels
- Heat exchanger for steam generation in the combustion unit
- Electrical power generation from steam
- Heat supply from steam generated
- Electrostatic precipitator and scrubber for gas clean-up



For the generic gasification system, the modules include ones for:

- Off-site fuel drying using natural gas driers
- Transport of fuel to combustor site
- Drying of fuel(s) using steam generated in heat exchangers elsewhere in the gasification system
- Co-gasification of both fuels
- Heat exchanger for fuel gas cooling / steam generator
- Fuel gas cleaning system
- Fuel gas compressor
- Gas turbine
- Gas engine
- Heat recovery steam generator
- Electrical power generation from steam
- Heat supply from steam generated

The inputs required for each model allow a flexible choice in the drying / transport of the fuel supplied to the power system, as well as the usage of the steam / fuel gases generated. For example:

- a balance between using the steam to generate electricity or supply heat
- using fuel gases in a gas engine or gas turbine

Data generated in the pilot plant tests and associated analyses were used to test the combustion and gasification parts of these models. This process was also used to confirm that the correct parameters (in terms of fuel composition, process operating conditions and ash composition) had been identified and used in the development of the models.

The parameters used in the combustion model are given in Tables 36-38 and those for the gasification models in Tables 39-41. Tables 42-44 summarise the emission factors that have been included in these models. There are obviously a large number of parameters in these models, some of which have to be chosen to evaluate a particular scenario, whilst others can be measured or estimated. For both systems, these parameters fall into three classes:

- Fuel properties (Tables 36 and 39) – these parameters can be measured (and have been for the fuels used in this project)
- Other fuel parameters that describe how a particular fuel responds to the process, e.g. trace element partitioning (Tables 37 and 40 – these parameters can be measured / estimated from the results of the pilot plant testing)
- Process parameters that need to be set, e.g. how much fuel drying is required, transport distances for fuels, use of steam / fuel gas produced (Tables 38 and 41)

## **7.2.2. Analysis Results**

### **7.2.2.1. Combustion**

The initial combustion condition modelled was scenario 2 used in the techno-economic model shown in Table 45. The fuel input was matched at 417kg ds/hr (10 tds/day) of sewage sludge and 2010kg ds/hr of wood that gives a sludge/wood ratio of just over 0.2. For digested sludge (sludge 1) the model predicts an electricity output of 1.93MW with 3996kg/hr CO<sub>2</sub> and 212 kg/hr of ash produced. There are many more outputs from the model but the main concern is with the environmental impact of the process, specifically in relation to WID emission limits (Table 43). Figure 28 shows how much of the WID emission allowance is predicted to be used for this sludge/wood ratio for both digested sludge and raw dewatered sludge (sludge 2). All WID controlled emissions are well below the limits apart from mercury that breaks the limit of 0.05mg/m<sup>3</sup> for one of the fuels. The mercury is introduced into the fuel mix from the sewage sludge and not the wood. The levels of mercury in the sewage sludge is related to the location of the WwTW and not the process the sewage sludge has undertaken i.e. an urban WwTW would be expected to have higher mercury levels than rural WwTW. The main source of mercury in the sewage sludge is from dental amalgam.

As mercury emissions appeared to be the main problem identified by the model it was further investigated. Figure 29 shows the effect of fuel ratio on predicted mercury emission. As the major source of mercury is from the sewage sludge the effect of reducing the fuel ratio is to decrease the mercury emission levels. Using less sewage sludge in the fuel mix is a way of reducing mercury emissions but is opposed to the main aim of using this process as a disposal route. The target is to use as much sewage sludge as possible and as little biomass that has to be purchased. Also shown in the figure is the effect of including 5% screenings in one of the fuel mixes. Fuel mixing is an attractive option as it allows disposal of all waste streams potentially in the ratio that they accumulate. The addition of screenings is at such a low level that it does not impact greatly on emissions. Overall the main problem identified is mercury emission and this would need a mercury capture system installed to clean the flue gas.

### **7.2.2.2. Gasification**

The gasification model condition was based on the urban gasification scenarios listed in Table 45, which give outputs of 3MWe. The same two sewage sludges, digested sludge (sludge 1) and raw dewatered sludge (sludge 2), were modelled as in the combustion case. The fuel properties (Table 39) used in the modelling are based on fuel analysis carried out during the testing. The total fuel throughput was 3250kg ds/hr with the amounts of sewage sludge and wood in the fuel mix varying from all wood to a 50:50 mix i.e. fuel ratio of 1. The tar and ash results given in Figure 30 show that tar production remains fairly constant with change in fuel mix but the ash production increases as more sewage sludge is used as would be expected with its much higher ash content. The bulk gas compositions for both sewage sludges are shown in Figures 31 and 32. The

HCl, ammonia and H<sub>2</sub>S contents of the produced gas for both sewage sludges are shown in Figures 33-35. These figures generally show that increasing the sewage levels in the fuel mix increases the levels of these undesirable contaminants and therefore the amount of gas cleaning required. Gas cleaning strategies required to produce gas compositions suitable for use in gas turbines or IC engines would need to be used. The model includes modules for gas cleaning that are based on cleaning efficiency values.

### **7.3. Techno-economic Assessment**

#### **7.3.1. Model Scenarios**

In the preliminary process analysis (section 3.1) two distinct scenarios were chosen, a rural scheme (small to medium scale) and an urban scheme (medium to large scale) for both gasification and combustion. These four base cases were expanded on to allow for two levels of feedstock dry solids in the fuel and for screenings to be added to one combustion scenario.

The life cycle analysis was carried out using the base scenarios with two sewage sludge fuels, raw dewatered and digested sludge resulting in two sets of nine base scenarios as shown in Table 45.

#### **7.3.2. Model Development and Inputs**

The inputs for the techno-economic model are given in Table 46. Some of the input values, such as electricity price and wood purchase price are the current commercial values. Other input values, such as project cost, have been obtained by talking to sponsors, manufactures and other experts to get estimated values.

There are a number of economic outputs that the model can produce, but for simplicity the Net Present Cost (NPC) per tonne dry solids of sludge processed over a 20 year project life has been used for the comparisons. This value can be considered as the net present disposal cost per tonne dry solids of sludge and will enable comparison with the costs of alternative disposal routes.

##### **7.3.2.1. Electricity Price**

Electricity sale price is a key input to the model and is based on the average auction price for biomass fuelled generation from auction 8 (ended 19<sup>th</sup> August 2004) as given on the Non-Fossil Purchasing Agency (NFPA) website [38]. It should be noted that sewage sludge qualifies as biomass for the purposes of the Renewables Obligation and therefore any plant co firing clean biomass in combination with sludge will fully qualify for ROC's (Renewable Obligation Certificates). The average biomass price was 5.79 p/kWh in auction number 8, so for simplicity a value of 6p/kWh (£60MWh) has been used when this value is fixed in the analysis. The NFPA conducts green power auctions for the electrical output produced by NFFO generators biannually (covers six month period starting either 1<sup>st</sup> April or 1<sup>st</sup> October). The auction prices are for electrical output together with, depending on the generation technology, Climate Change

Levy Exemption Certificates (LECs) and Renewables Obligation Certificates (ROCs).

The average auction prices for biomass from the first auction in 2001 up to the latest are shown in Figure 36, the prices for landfill gas and municipal and industrial waste (MIW) are also shown for comparison. Historically, the average biomass price can vary considerably from one auction to the next and shows no obvious trends. As a major factor in the economics of all of the model scenarios this variability is a concern.

#### **7.3.2.2. Electricity Production and Additional Biomass Fuel Usage**

To set a basis for costing the various plant options the rural, (small scale) plant was set as 1.5 MW export and the urban, (larger scale) plant at 3MW export.

The model assesses the heat energy available from the sludge being modelled and supplements it with biomass (in our case wood) derived heat, in sufficient quantity, to enable the target net electricity production to be attained. Energy for thermal drying of both sludge and biomass feed-stocks is gained from recovered waste heat. The net available waste heat is calculated to check that adequate heat is available for drying purposes. Using a conservative approach all scenarios have sufficient waste heat for drying without using primary fuel.

The biomass feedstock used in the model is clean forest woodchips from whole trees inclusive of needles. This material is the most readily available and represents probably the most expensive fuel but with the lowest cost of handling equipment for the biomass fuel element. It is envisaged that the two feedstock's would be stored and handled separately right up to the point of injection into the combustor or gasifier.

The proportion by tonnage of additional biomass required varies according to the thermal efficiency of the process and the moisture level in the feedstock. Overall net energy efficiencies of 30% for gasification using engines, and 20% for combustion with steam cycle were used with a small increment for the larger plant.

For the urban combustion case on dry sludge the amount of additional biomass on a dry basis is a factor of 3 for raw sludge and a factor of 4 for digested sludge. The higher figure required for the digested case being due to the higher CV of raw sludge. These figures varied from factors of 2 to 5 across all the options considered.

#### **7.3.2.3. Technologies and Pricing**

The combustion options including feedstock handling, storage and drying have been estimated at a project cost of £7.5m/MWe installed and gasification on a similar basis at 12.5m/MWe installed. Both project costs are inclusive of civil engineering, buildings, facilities for 4 days storage of the feedstocks, development costs and grid connection.

There is very little information available on which to base these budget estimates and the figures for combustion plant were derived from recent biomass projects in the 10MWe range and then factored for size and the added process complexity. Overall the prices are approximately twice that of clean biomass fired grid connected power plant. The higher cost addresses multi-feedstock handling and drying and the requirement to comply with the Waste Incineration Directive as sludge is classified as waste. The prices are likely to be conservative especially taking into account the potential availability of site and infrastructure within existing utility sites. If this type of project is to be further developed specifications should be prepared and full prices obtained from equipment suppliers.

Proven gasifier fuelled power plant at these small sizes are rare and there is little commercially available information on those that exist. However, there are a number of small units in the proving stage and within the next couple of years it is likely that they will become commercially available for these applications. The lack of hard cost information on actual projects has meant that the cost of gasifier plant has been based on costs from development projects that may later be proven to be high.

The models do not include the transport costs of the sewage sludge but transport of biomass fuel is included.

The operating and maintenance cost is set at 20% of the engineering, procurement and construction (EPC (see appendix 1 for explanation)) cost, with the EPC cost assumed at 60% of the project cost. The operating and maintenance cost provides for full shift manning, operation and maintenance and overhead contribution with the plant considered as a separate business entity.

### **7.3.3. Analysis Results**

Figure 37 shows the effect of electricity price on the NPC/t ds of processed sludge over the project life. This Figure also gives the economic comparison between the nine scenarios. Overall, combustion on the urban scale at both dry solids levels (scenarios 8 and 9) has the best economics. All the rest of the scenarios are very similar apart from gasification on the rural scale (scenarios 1 and 3) which are significantly worse. Combustion is therefore predicted by the model to be the best option in both the rural and urban cases, but the latter case is the best overall at a cost of the order of £200/dry tonne. This figure when compared to typical costs for other potential disposal routes as shown in Table 47 is not the cheapest option. If the variability in electricity price and potential for biomass prices to increase in the future are considered along with the large capital investment required for this disposal route, it appears that co-firing is not yet a financially competitive disposal route compared to existing routes.

A 40% reduction in capital expenditure (CAPEX), i.e. a cost 10% higher than for non-waste biomass, results in an NPC of around £120 per dry tonne for the 3MWe combustion plant. Whilst this level of reduction may seem unrealistic

such savings may be achievable during engineering when infrastructure, feedstock handling, emissions and odour control requirements are fully identified.

Figure 38 shows the equivalent data for raw dewatered sludge and although the numbers are slightly different the same trends are seen as in Figure 37.

## 8. SUMMARY

The overall aim of the project was to assess the viability of using advanced solid fuel gasification and combustion technologies to co-fire sewage sludge and biomass (e.g. wood) as a route for sewage sludge utilisation combined with the production of heat and/or power generation with minimal environmental emissions, in terms of both system economics and process efficiency.

A preliminary process analysis of potentially viable biomass/sludge co-firing options has been carried out. The analysis assessed potential process routes and included details of the availability and compositions of both biomass and sewage sludge feed-stocks. The current legislation that would affect co-firing of sewage/biomass was reviewed. It was clear that many possible options for co-firing sewage sludge and biomass exist so distinct scenarios were identified for which technology and feedstock options can be defined.

Modifications were made to both the combustion and gasification test facilities at Cranfield University in order to co-fire the range of sewage sludge and biomass mixtures required during the course of the project. The modifications included the introduction of appropriate sludge and biomass handling, storage and feed systems and alterations to the rig control systems to ensure their safe operation. A co-firing test programme has been carried out in the combustion and gasification facilities using a range of sewage/biomass mixtures. Fuel feeding problems were a major problem during the testing particularly with the gasifier trials. It is not expected that this would be a major problem with a larger scale power plant. The test programme identified a limiting fuel CV required for co-firing to be viable operation. This limit identified is specific to the Cranfield combustor and it would be expected that a larger scale plant could use a lower CV fuel due to the lower heat losses associated with larger scale operations. Gas emissions and ash/char residue compositions have been obtained for the test fuel mixes. Operating constraints such as fuel moisture content have been identified and, where required, gas cleaning and disposal requirements highlighted.

A mass/energy flow and life cycle analysis has been carried out for both the combustion and gasification processes. In the combustion case the major potential emissions issue is mercury. It is likely that a mercury capture system would be required to clean the flue gas. The output from the gasifier model has demonstrated that the co-firing of sewage sludge results in an increased requirement for gas cleaning over firing with wood alone, although this

probably does not result in extra cleaning modules being required but a higher load than that required for wood alone.

A techno-economic model has been developed that can give predictions of the financial impact of building and running both combustion and gasification facilities that co-fire biomass and sewage sludge. To identify potential scales of operation, under which co-firing of biomass and sewage sludge may be economically viable an assessment was made of nine co-firing scenarios. The scenarios included both gasification and combustion at a rural and urban scale with two sewage sludges. Overall, combustion on the larger scale as modelled for the urban scenario gave the lowest disposal cost for sewage sludge. The variability in the price of electricity and the potential for biomass prices to rise make even the best option from the modelling an unlikely option as cheaper disposal routes exist which do not entail the capital outlay required for these options. Further legislation could remove these cheaper disposal routes and make combustion a more attractive option.

## **9. FURTHER WORK**

There are a number of areas of the programme that further work would build, they include the following:

- Investigation of alternative support fuels, such as coal or wastes, to co-fire with sewage sludge
- Development of improved gas cleaning strategies targeted at emissions problematic for co-firing of sewage sludge
- Generation of trace element partition data to be used to improve the mass/energy flow and life cycle model

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## **11. REFERENCES**

- [1] Spinoso L and Vesilind PA (2001) - Sludge production and characterisation. In: Sludge into Biosolids: Processing, Disposal and Utilisation. Editors Spinoso L and Vesilind PA. IWA Publishing, London, 3-19
- [2] Gendebien A, Carlton-Smith C, Izzo M and Hall JE (1999) - UK Sewage Sludge Survey: National Presentation. WRc plc R&D Technical Report P165, Medmenham, UK.

- [3] DTI (2002) Department of Trade & Industry Digest of UK Energy Statistics (2001) ISBN 0 11 515482 5
- [4] Chu CP, Lee DJ and Chang CY (2001) - Thermal pyrolysis of polymer flocculated waste activated sludge. *Wat. Res.*, 35 (1) pp49-56
- [5] Werther J and Ogada T (1999) Sewage sludge combustion. *Prog. En. Comb. Sci.* 25 pp55-116
- [6] Spleithoff H., Scheurer W and Hein KRG (2000) - Effect of co-combustion of sewage sludge and biomass on emissions and heavy metals behaviour. *Trans. IChemE* 78(B) pp33-39
- [7] OXERA (2002) Regional Renewable Energy Assessments: A report to the DTI and DTLR, OXERA Environmental and ARUP Economics and Planning, February 2002. 50pp.
- [8] SEERA (2002) Harnessing the Elements: a strategy for energy efficiency and renewable energy consultation draft, South East Regional Assembly. October 2002. ISBN 0-9543059-1-4.
- [9] Ofgem (2002) The review of the first year of NETA – a review document Volume 1 July 2002.
- [10] Promotion of Electricity from Renewable Energy Sources in the Internal Electricity Market EU - Renewable Energy Directive (2001/77/EC)
- [11] ROO (2002) Renewables Obligation Order 2002 (SI 914).
- [12] Council Directive on the Prevention of Air Pollution from New Municipal Waste Incineration Plants (89/369/EC), OJ L163, 14 June 1989
- [13] Council Directive on the Reduction of Air Pollution from Existing Municipal Waste Incineration Plants (89/429/EC), OJ L203, 15 July 1989.
- [14] Council Directive on the Incineration of Hazardous Waste (94/67/EC), OJ L365, 31 December 1994.
- [15] Directive 80/68/EEC - 17<sup>th</sup> December 1979 on the protection of groundwater against pollution caused by certain dangerous substances, The Council of the European Communities
- [16] Giegrich, J, Mohler, S. (in press). Environmental Assessment of Phytoremediation Systems. Submitted to *Journal of Biomass and Bioenergy*.
- [17] ISO (1997). Environmental management – principles and framework ISO14040.



- [18] ISO (1998). Environmental management — Life cycle assessment — Goal and scope definition and inventory analysis. ISO14041.
- [19] ISO (2000a). Environmental management - Life cycle assessment - Life cycle impact assessment. (ISO 14042:2000)
- [20] ISO (2000b). Environmental management – Life cycle assessment – Life cycle interpretation. (ISO 14042:2000)
- [21] Finnveden G and Ekvall T (1998) - Life-cycle assessment as a decision-support tool—the case of recycling versus incineration of paper. *Resources, Conservation and Recycling* 24 pp235–256
- [22] Spleithoff H, Scheurer W and Hein KRG (2000) - Effect of Co-combustion of Sewage sludge and Biomass on Emissions and Heavy Metals Behaviour. *Trans. IChemE* 78 (B) pp33-39
- [23] Nadziakiewicz J and Koziol M (2003) - Co-combustion of Sludge with Coal, *Applied Energy* 75 pp239-248.
- [24] Osborn GA (1992) - Review of Sulphur and Chlorine Retention in Coal-fired Boiler Deposits. *Fuel* 71 pp131-42
- [25] Sheng Ch, Xu M, Zhang J and Xu Y (2000) - Comparison of Sulphur Retention by Coal Ash in Different Types of Combustors. *Fuel Process Technology* 64 pp1-11
- [26] Folgueras MB, Díaz RM and Liberta J (2004) - Sulphur Retention during Co-combustion of Coal and Sewage Sludge. *Fuel* 83 p1315-1322
- [27] Werther J, Ogada T and Philippek CJ (1995) - N<sub>2</sub>O Emissions from Fluidised Bed Combustion of Sewage Sludges. *J Inst. Energy* 68 pp93-101
- [28] Philippek C, Knobig T and Werther J (1995) - In *Proceedings of the 14th International Conference on Fluidised Bed Combustion* (ed. Preto FDS), Vancouver, Canada, ASME, pp951
- [29] Hall JE and Dalimier F (1994) - *Waste Management- Sewage Sludge: Survey of Sludge Production Treatment, Quality and Disposal in the EC*. EC Reference no. B4-3040/014156/92
- [30] Sanger M, Werther J and Ogada, T (2001) - NO<sub>x</sub> and N<sub>2</sub>O Emission Characteristics from Fluidized Bed Combustion of Semi-Dried Municipal Sewage Sludge. *Fuel* 80 pp167-177
- [31] ETSU (1999) *New and Renewable Energy: Prospects for the 21<sup>st</sup> Century Supporting Analysis*. Report No. ETSU R-122. AEA Technology, Harwell.

- [32] Dennison FJ, Azapagic A, Clift R, Colbourne JS (1998) - Assessing management options for wastewater treatment works in the context of life cycle assessment. *Water Science and Technology* 38 (11) pp23-30
- [33] van Schijndel, P.P.A.J, Huisman, J, van Kasteren, J.M.N, Janssen, F.J.J.G. (1999). Environmental impact of different power production techniques using biomass. Paper presented at Entrée'99, Tampere, Finland, 10-13 November.
- [34] Edelmann W, Schleiss K, Joss A (2000) - Ecological, energetic and economic comparison of anaerobic digestion with different competing technologies to treat biogenic wastes. *Water Science and Technology* 41 (3) pp263-273.
- [35] Hellweg S, Mossner S and Hungerbuhler K (1999) - Life Cycle Assessment of Thermal Waste Processes. Paper presented at the R'99 Congress (Recovery, Recycling, Reintegration), Geneva, February.
- [36] Nair SA, Pemen AJM, Yan K, van Heesch EJM, Ptasiński KJ and Drinkenburg AAH (2003) - Chemical Processes in Tar Removal from Biomass Derived Fuel Gas by Pulsed Corona Discharges, *Plasma Chemistry and Plasma Processing*, 23 (4) pp665-680.
- [37] Milne TA, Evans RJ and Abatzoglou N - Biomass Gasifier "Tars": Their Nature, Formation and Conversion, National Renewable Energy Laboratory Report NREL/TP-570-25357, November 1998.
- [38] Non-Fossil Purchasing Agency website – <http://www.nfpa.co.uk>
- [39] Sonneson, U, Bjorklund, A, Carlsson, M, Dalemo, M. (2000). Environmental and economic analysis of management systems for biodegradable waste. *Resources, Conservation and Recycling* 28, 29–53
- [40] Goedkoop, M, Effting, S, Collignon, M. (2000). The Eco-indicator 99: A damage oriented method for Life Cycle Impact Assessment: Manual for Designers (2nd edn). PRé Consultants B.V, Plotterweg.
- [41] Phyllis database - <http://www.ecn.nl/phyllis>.
- [42] Asadi M – Personal communication, July 2005.
- [43] NAEI database - <http://www.naei.org.uk>.

**Table 1 Sludge characteristics from different WwTP processes**

Constituent		Sludge					
		Raw Primary		All		Digested	
		Range	Typical	Range	Typical	Range	Typical
Total solids (%)		2.0-7.0	4.0			2.0-6.0	3.5
Volatile solids (% of TS)		6.0-80	65			35-65	51
pH		5-8	6			7.2-7.8	7.5
Alkalinity (mg/l CaCO <sub>3</sub> )		500-1500	600			200-7600	4800
Total N (g/kg)		15-40	25	<1-176	33	1.6-4.0 <sup>a</sup>	2.7 <sup>a</sup>
Al	g/kg			1-135	4	4.1-61	9.6
As	mg/kg			1.1-230	10		
Ca	g/kg			1-250	39	44	26-27
Cd	mg/kg			3-3410	16	5-260	10
Cl	g/kg					1.7-190	7.1
Co	mg/kg			1-18	4.0	1-42	9.0
Cr				10-99000	500	200-1280	375
Cu				84-10400	850	280-2570	970
Fe	g/kg	20-40	25	<1-153	11	14-110	51
Hg	µg/kg			0.2-10600	5	0.43-4.7	2.1
K	g/kg	0-8.3	4	0.2-26.4	3	0.04-0.16	0.09
Mg				0.3-<19.7	4.5	3.1-11	6.8
Mn	mg/kg			18-7100	260	170-2090	320
Mo				5-39	30	7.0-97	12
Na	g/kg			0.1-30.7	2.4	0.07-0.42	0.16
Ni	mg/kg			2-3 520	82	23-410 <sup>b</sup>	120 <sup>b</sup>
P	g/kg	3.5-12.2	7	<1-143	23	14-57	24
Pb	mg/kg			13-19700	500	200-1280	375
Sn				2.6-329	14		
Zn				101-27800	500	400-5130	1600
Energy Content (MJ/kg)		19 - 29				9 - 14	

a: NH<sub>3</sub><sup>+</sup> Kjeldahl N in g/l, b: in mg/l

**Table 2 Sludge production, treatment processes and sludge quality data for both Thames Water and Severn Trent Water [2] (pe = population equivalent)**

		Operational Scale					
		Small pe<10000		Medium pe 10000 - 150000		Large pe>150000	
		Sludge produced (tds)					
Tham es	Annual data (96/97)	1800 n=13	1%	53300 n=60	19%	216100 n=34	80%
Sever n		1000 n=37	1%	50300 n=65	31%	111400 n=23	(69% )
	Process	Sludge Treatment (tds/a)					
Tham es	MAD			8300		104500	
	MAD + dewatered			6800		106200	
	Composting			1100		4000	
	Lime stabilisation			15000			
	Dewatered + stored	1000		9500			
	None – Now?	700		12700		1500	
Sever n	MAD			34900		20900	
	MAD + dewatered			1700		90600	
	Dewatered + stored	300		10400			
	None – Now?	600		3200			
	Median Sludge Quality (all UK outlets – mg/kg ds)						
	Zn	513		639		837	
	Cu	328		405		579	
	Ni	17		27		50	
	Cd	1.3		2.0		2.9	
	Pb	77		141		239	
	Hg	0/9		2.0		2.4	
	Cr	18		47		173	

**Table 3 Solids content and heating value of selected processed sludge types**

Type of sludge	Approximate solids content %	Heating value Range (MJ/kg)
Raw sludge (all process stages)	2 - 7	19 - 29
Anaerobically digested primary sludge	3 - 6	9 – 14
Anaerobically digested primary + activated sludge	1.5 – 6	
- gas produced from anaerobic digestion	-	22 MJ/m <sup>3</sup>
Aerobically digested primary sludge	2.5 – 7	
Aerobically digested activated + primary sludge	1.5 – 4	
Chemically precipitated primary sludge	10 – 35	14 – 19
Mechanically dewatered sludge	10 - 40	Same as previous process stage
Heat conditioned combined sludge	30 - 50	28 – 30
Thermal dried undigested sludge	Range of 95	20
Thermal dried digested sludge	Range of 95	15

**Table 4 Targets for electricity from wood combustion (South East) [8]**

Sub-region	Target for Installed capacity (MW)	Implied Annual energy output (GWh)
Thames Valley	15 – 30	112.5 – 225
Hampshire & IOW	0 – 25	0 – 187.5
Surrey/ East & West Sussex	0 - 30	0 – 225
Kent	0 – 10	0 – 75
<b>Total</b>	15 - 55	112.5 – 412.5

**Table 5 Targets for electricity for straw combustion (South East) [8]**

Sub-region	Target for Installed capacity (MW)	Implied Annual energy output (GWh)
Thames Valley	15 – 30	112.5 – 225
Hampshire & IOW	0 – 15	0 - 112.5
Surrey/ East & West Sussex	0 – 15	0 - 112.5
Kent	0 – 15	0 - 112.5
<b>Total</b>	15 - 30	112.5 – 225

**Table 6 Summary of benefits and drawbacks of broad categories of biofuels**

Category	Advantages	Disadvantages
<b>Wastes</b>	<ul style="list-style-type: none"> <li>• Available in large quantities</li> <li>• Widely distributed across the country</li> <li>• Available immediately</li> <li>• Collection and delivery systems readily initiated</li> <li>• Can charge gate fee</li> <li>• Few, if any competing uses</li> </ul>	<ul style="list-style-type: none"> <li>• Highly variable quality</li> <li>• Relatively high processing requirement</li> <li>• Tightly regulated</li> <li>• Poor public perception</li> <li>• Complex contractual environment</li> </ul>
<b>By-products</b>	<ul style="list-style-type: none"> <li>• Usually clean fuels</li> <li>• Additional processing for use as fuel relatively easily achieved</li> <li>• Point source availability</li> </ul>	<ul style="list-style-type: none"> <li>• May have competing markets/uses</li> <li>• Not primary activity of producer hence reduced supply security</li> <li>• Quantities available not large or widely distributed</li> </ul>
<b>Energy crops</b>	<ul style="list-style-type: none"> <li>• Clean &amp; homogeneous fuels</li> <li>• Highly controllable source Potentially widely available</li> <li>• Well supported through renewable energy development mechanisms</li> </ul>	<ul style="list-style-type: none"> <li>• Current availability low</li> <li>• Long lead in time to increased availability.</li> <li>• Potentially long transport distances to sludge production/power generation sites</li> </ul>

**Table 7 General summary of the characteristics of the principle biofuels**

Biofuel	Desirability	Homogeneity	Availability	Potential resource size	
				Short term <sup>1</sup>	Long term <sup>2</sup>
Forest thinnings	High	High	Low	Moderate	Moderate
SRC	High	High	Low	Low	High
Straw	Moderate	High	Moderate	Moderate	Moderate
Green waste	Moderate	Low	Moderate	High	High
Poultry waste	High	High	Moderate	Low – VL	Low
MSW	Low	Low	High	High	High
RDF	Moderate	High	Low	Moderate	High

<sup>1</sup> 0 -10 years, <sup>2</sup> 10-20 years, VL = very low

**Table 8 Estimated current & future forest residues in England (dt/yr) [31]**

Material		1998	2013
Residues and residuals		308,639	660,548
Dedicated woodfuel plants	In-forest	54,405	85,063
	Out-forest	93,834	294,804
	Broafleaf woodland	203,275	203,273
	Arboricultural arisings	484,000	484,000
Total		1,144,153	1,727,690

**Table 9 Regional distribution of straw production & use ('000 t @ 15%mc) [31]**

Region	Total straw produced	Straw currently un-used
Yorkshire & Humberside	1491	614
East Midlands	1938	1320
East Anglia	1840	1469
South East	2352	1603
West Midlands	950	213
Total	8571	5219

**Table 10 Targets for green waste combustion (SE) [8]**

Sub-region	Target for Installed capacity (MW)	Implied Annual energy output (GWh)
Thames Valley	0.5 – 1.75	3.8 – 13
Hampshire & IOW	0 - 0.5	0 – 3.8
Surrey/ East & West Sussex	0 – 0.25	0 – 9
Kent	1.25 – 2.5	9 – 19
<b>Total</b>	1.75 - 6	13 - 45

**Table 11 Materials for which data have been collected to date**

Wood	Agricultural wastes		Urban wastes
Beech logs	Wheat straw	Fresh &	Biological/activated sludge (paper industry)
Conifer logs		Weathered	anaerobically digested
Spruce logs	Barley Straw		aerobically digested
Conifer sawdust	Oats		thermally dried
Spruce chunks	Rapeseed		Sewage sludge
Briquette	Rape straw		raw
Conifer			Tyres
Pine Chips	Poultry litter		RDF with and without plastic
Pine sawdust			Paper mill waste
Pine bark			RDF
Forest residues			MSW
Bark (mixed)			MSW compost
Willow			Humus from digested MSW

**Table 12 Data type included in fuels database**



Analysis					
Proximate		Ultimate		Inorganic	
Material Description	Units	Material Description	Units	Material Description	Units
					mg/kg
Volatile matter	% dm	C	% dm	Al	dm
Dry matter	%	H		Ag	
	mg/kg	N		As	
Moisture content	%	S		B	
	g/kg	Cl-		Ba	
Bulk density	kg/m <sup>3</sup>	Cl	mg/kg	Be	
CO <sub>2</sub>	% dm	Cl <sup>-</sup> inorganic		Bi	
Fixed carbon	% dm	Cl <sup>-</sup> organic		Br	dm, daf, ar
	% daf	CO <sub>2</sub>		Ca	dm
		O (%dm)	% dm	Cd	
		O (diff.)		Co	
		Na		Cr	
		K		Cu	
			MJ/kg	F	dm, daf, ar
		CV	daf	Fe	dm
		LHV	dry	Hg	
			daf	La	
			ar	Li	
		GHV	-	Mg	
		HHV	dry	Mn	
			daf	Mo	
			ar	Ni	
		NHV	-	P	
		HHV <sub>Milne</sub>	dry	Pb	
			daf	Rb	
			ar	S	dm, daf, ar
			wt%	Sb	dm
		C	daf, ar	Sc	
		H		Se	
		N		Sr	
		S		Ti	
		Cl		Th	
		O		Tl	
				U	

				V
				Va
				W
				Y
				Zn

**Table 12 (cont.) Data type included in fuels database**

Organic compounds		Ash quality	
Material Description	Units	Material Description	Units
PCDD/F	ng TE/kg	Ash	% dm
PAH	µg/kg		% daf
B(a)P	µg/kg		% ar
		Ash @ 550 °C	%
		Ash @ 575 °C	
		Ash @ 900 °C	
		Ash fusion temperatures	
		Deformation	°C
		Softening	
		Hemisphere	
		Flow	
		Al <sub>2</sub> O <sub>3</sub>	
		CaO	
		Fe <sub>2</sub> O <sub>3</sub>	
		K <sub>2</sub> O	
		MgO	
		Mn <sub>3</sub> O <sub>4</sub>	
		Na <sub>2</sub> O <sub>3</sub>	
		P <sub>2</sub> O <sub>5</sub>	
		SO <sub>3</sub>	
		SiO <sub>2</sub>	
		TiO <sub>2</sub>	
		ZnO	

**Table 13 Summary of fuel quality data held on Phyllis database [41] for RDF**

Component	Unit	Value			Std dev (%)	Number Of Refs
		Mean	Min	Max		
Water content	wt% wet	18.7	4.2	38.7	69	14
Volatiles	wt% daf	86.7	74.6	99.4	6	11
Ash	wt% dry	18.5	4.4	44.2	52	20
HHV	kJ/kg daf	23331	13130	44029	24	22
LHV calc		21914	12126	40986	24	21
C	wt% daf	52.6	33.9	84.8	17	22
H		7.31	1.72	13.95	29	22
O		36.4	22.4	43.7	14	21
N		0.9	0.12	1.95	50	22
S		0.43	0.01	1.4	71	21
Cl		0.734	0.006	1.558	61	17
F		0.022	0	0.043	141	2
Br		0.001	0.001	0.002	84	2
Al	mg/kg dry	1600	1600	1600	0	1
As		4.9	1.5	10	76	4
B		-	-	-	-	0
Ba		-	-	-	-	0
Ca		-	-	-	-	0
Cd		8.3	1	20	107	4
Co		25.9	0.1	100	191	4
Cr		58.3	8	130	94	4
Cu		218.8	35	490	92	4
Fe		629	490	768	31	2
Hg		0.7	0.1	2	121	4
K		-	-	-	-	0
Mg		115	100	130	18	2
Mn		112.3	10	270	123	3
Mo		18.5	2	35	126	2
Na		-	-	-	-	0
Ni		37	1	120	153	4
P		395	40	750	127	2
Pb		215	50	350	58	4
Sb		10	10	10	0	2
Se		-	-	-	-	0
Si		-	-	-	-	0
Sn		0.1	0.1	0.1	0	1
Sr		-	-	-	-	0
Te		-	-	-	-	0
Ti		100	100	100	0	1
V		24.7	4	45	83	3
Zn		271.7	85	500	78	3

**Table 14 Summary of fuel quality data held on Phyllis database [41] for willow**

Component	Unit	Value			Std dev (%)	Number Of Refs
		Mean	Min	Max		
Water content	wt% wet	10.9	2.4	43.5	78	21
Volatiles	wt% daf	83.6	80.3	88.2	3	19
Ash	wt% dry	1.9	0.4	4.6	48	25
HHV	kJ/kg daf	19849	18315	21717	4	21
LHV calc		18495	17011	20393	4	22
C	wt% daf	50	48.5	51	1	22
H		6.11	5.9	6.74	3	22
O		42.9	39.1	45	4	22
N		0.63	0.1	1.49	48	22
S		0.06	0	0.13	54	17
Cl		0.02	0.004	0.102	116	15
F		0.003	0	0.01	157	4
Br		-	-	-	-	0
Al	mg/kg dry	59.5	30	100	54	4
As		1.3	1	1.4	12	5
B		9.8	8.8	12	15	4
Ba		4	4	4	0	1
Ca		5720	4000	7700	23	5
Cd		2.4	1.7	3	39	2
Co		0.6	0.3	0.9	35	5
Cr		13.7	2.9	45	129	5
Cu		13.2	3.6	44	132	5
Fe		67.5	39	110	51	4
Hg		0.1	0.1	0.1	0	1
K		2894	2000	4058	27	7
Mg		524	360	700	25	5
Mn		9.7	7.9	13	23	5
Mo		0.5	0.5	0.5	0	1
Na		209.6	37	510	73	7
Ni		26.2	4.9	78	114	5
P		708	640	860	12	5
Pb		237.5	135	340	61	2
Sb		2.5	1	4	85	2
Se		1	1	1	0	2
Si		617.6	88	1800	115	5
Sn		1.7	0.3	3	116	2
Sr		14	14	14	0	1
Te		1	1	1	0	1
Ti		4	1.3	9	86	4
V		0.3	0.2	0.6	64	5
Zn		97.4	62	130	34	5

**Table 15 Summary of fuel quality data held on Phyllis database [41] for bark**

Component	Unit	Value			Std dev (%)	Number Of Refs
		Mean	Min	Max		
Water content	wt% wet	24.4	0	90	101	91
Volatiles	wt% daf	81	48.9	117.5	11	101
Ash	wt% dry	8.5	0.1	57	128	181
HHV	kJ/kg daf	20627	12575	38134	16	138
LHV calc		19077	10585	27907	13	123
C	wt% daf	50.6	30.1	67.4	11	143
H		6.25	3.2	9.25	13	142
O		41.9	19.7	59.7	15	142
N		1.25	0	12.05	168	138
S		0.46	0	8.19	292	118
Cl		0.194	0	1.162	160	74
F		0.005	0.001	0.012	123	3
Br		0.02	0.02	0.02	0	1
Al	mg/kg dry	240.8	22	2150	133	51
As		0.5	0	6.3	192	49
B		-	-	-	-	0
Ba		143.1	1.3	540	93	44
Ca		15512.9	260	57000	101	58
Cd		0.4	0	3.2	127	90
Co		3.5	1.8	10	102	5
Cr		8.9	0.1	296	493	45
Cu		13.3	1	437	321	107
Fe		244.6	15	2000	185	54
Hg		0.1	0	1.7	289	41
K		5892.7	88	34200	126	28
Mg		832	80	3800	85	54
Mn		218.6	1.1	840	101	48
Mo		1.5	1	2	47	2
Na		46536.8	22	191000	169	21
Ni		4.8	0.3	140	437	43
P		2249.5	50	29600	258	46
Pb		9.4	0	652	721	92
Sb		1.1	1	1.2	13	2
Se		0.9	0.8	1	16	2
Si		1027.6	18	7000	153	54
Sn		1.3	1	1.5	28	2
Sr		31	31	31	0	1
Te		1	1	1	0	1
Ti		29.5	19	40	50	2
V		1	1	1	0	1
Zn		80.9	4	1228	196	61

**Table 16 Summary of fuel quality data held on Phyllis database [41] for wheat straw**

Component	Unit	Value			Std dev (%)	Number Of Refs
		Mean	Min	Max		
Water content	wt% wet	10.8	6	18	29	37
Volatiles	wt% daf	81.4	76.5	87	3	30
Ash	wt% dry	6.7	1.3	22.8	56	65
HHV	kJ/kg daf	19516	16627	21742	5	51
LHV calc		18160	15202	20487	5	47
C	wt% daf	49.1	46.5	52.6	3	53
H		5.92	3.2	6.61	9	53
O		43.7	39.4	50.1	4	53
N		0.75	0.29	2.08	51	54
S		0.17	0	0.46	63	48
Cl		0.523	0.021	2.316	110	46
F		0.001	0.001	0.001	14	5
Br		-	-	-	-	0
Al	mg/kg dry	528.5	117	940	110	2
As		1.2	0.2	2.5	101	3
B		5.3	5.3	5.3	0	1
Ba		50.3	23	74	51	3
Ca		5066.7	2900	9500	50	6
Cd		0.2	0.1	0.6	80	11
Co		1.4	1	1.6	24	3
Cr		7.7	3.1	12	58	3
Cu		4	1.9	11.4	70	11
Fe		1457	48	3200	98	4
Hg		0	0	0	50	8
K		11234.7	4300	24400	54	17
Mg		1738	440	3200	67	5
Mn		17.5	17	18	4	2
Mo		1.4	0.9	2.3	53	3
Na		988.4	60	10000	252	16
Ni		3.6	1.3	6	65	3
P		691.7	300	920	34	6
Pb		1.1	0.1	3.1	109	11
Sb		1.7	0.3	3	116	2
Se		2	2	2	0	1
Si		19740	9000	34000	55	5
Sn		0.9	0.4	2	99	3
Sr		25	25	25	0	1
Te		-	-	-	-	0
Ti		21.2	5.4	37	105	2
V		1.7	1.7	1.7	0	1
Zn		15	12	18	20	3

**Table 17 Technology ranking (individual score between 1 (low) and 5 (high), S = small scale, M = medium scale)**

Technology	Maturity	Suitability		Fuel flexibility	Electrical efficiency	Flexibility of Output	Total Score	
		S	M				S	M
Combustion								
Underfeed	5	5	2	3	3	2	18	15
Travelling grate	5	3	5	3	3	2	16	18
Rotary drum	5	3	2	5	2	2	17	16
Fluidised bed	5	2	5	5	3	2	17	20
PF / Cyclone	5	1	2	1	3	2	12	13
Gasification								
Fixed bed	4	5	2	2	4	4	19	16
Fluidised bed	3	2	5	5	4	4	18	21
Pyrolysis								
	1	4	?	?	4	4	?	?

**Table 18 Water Industry accreditation for the Renewables Obligation/CCL**  
(1,2)

Operator	No. of sites	Total installed generating capacity (kW)
All UK water utilities	47	44673
Thames Water	14	15488
Severn Trent Water	6	12609

(1) Accurate as of 16/12/02) (2) Source: Ofgem

**Table 19 Example functional unit definitions**

<b>Authors</b>	<b>Study aim</b>	<b>Functional unit</b>
[32]	Analysis of different sewage sludge centralisation schemes	Treatment of 9.48kg raw wastewater and subsequent sludge disposal
[33]	Analysis of power production techniques using biomass	Thermal treatment of an amount of biomass equal to 966TJ LHV and joined production of 424.8TJ electricity in one year
[34]	Comparison of different waste treatment technologies	Treatment of 1kg organic household waste
[35]	Comparison of different thermal waste treatment processes	Treatment of 1kg of municipal waste of an average composition
[36]	Analysis of different wastewater sludge treatment scenarios	Treatment of 1ton of mixed sludge on a dry basis resulting from municipal wastewater treatment in France

**Table 20 Nominal operating conditions of combustion facility with coal firing**

<b>Parameter</b>	<b>Units</b>	<b>First combustor</b>	<b>Second combustor</b>
Coal	kg / hour	2 - 5	6 – 10
Air	Normal m <sup>3</sup> / hour	18 – 42	42 – 72
Energy input	kW	19 – 51	57 – 102

**Table 21 Nominal operating conditions of gasification facility with coal firing**

<b>Parameter</b>	<b>Units</b>	<b>Range</b>
Coal	kg / hour	4 – 6
Air	Normal m <sup>3</sup> / hour	8 – 25
Energy input	kW	36 – 57



**Table 22 Analysis of component materials used in composted sludge**

Analysis	Raw Sludge	Woodchip
ds (%)	25 - 30	73 - 90
VM (%)	71 - 77	84 - 96
Density (kg/m <sup>3</sup> )	789 - 840	470 - 490
Nitrogen (%)	9.1 - 15.9	0.3 - 1.5
TOC (%)	26.4	50.9

**Table 23 Fuel mixtures in the combustion experiments**

Sewage	Source	wt% as received	Biomass	wt% as received	Comments
Composted sludge	Thames Water	50	Willow wood chips	50	-
		100		0	Laboratory dried
Digested sludge	Severn Trent	20		80	-
		50		50	Cancelled, problems feeding
		30		70	Replacement experiment
Raw dewatered	Thames Water	20		80	-
		30		70	Long test
		40		60	-
Dried raw dewatered	Severn Trent	30		70	Long test
		50		50	-
		100		0	-
Screenings	Thames Water	40		60	-
		20		80	-

**Table 24 Fuel mixtures in the gasification experiments**

Sewage	Source	wt% as received	Biomass	wt% as received	Comments
Composted sludge	Thames Water	50	Willow wood chips	50	-
		100		0	Laboratory dried
Digested sludge	Severn Trent	20		80	-
		30		70	-
Raw dewatered	Thames Water	20		80	-
		40		60	-
Dried raw dewatered	Severn Trent	30		70	Long test
		50		50	-
		100		0	
Screenings	Thames Water	40		60	-
		20		80	-

**Table 25 Proximate analysis, ultimate analysis (as received) and calorific value (CV) for the fuels used in the co-firing experiments. (% values (by wt as-received) refer to amount of sludge, screenings etc. in blend, balance is willow wood chip).**

Measure	Unit	Maltby coal	Willow wood chip		Composted sludge		
					100%		50%
Moisture	%	1.3	10.6	18.6	52.8	57.1	34.9
Ash	% (db)	5.1	1.2	2.0	41.9	45.4	15.0
Volatile	%	9.4	-	67.0	-	22.1	-
Sulphur		0.76	0.11	0.09	0.65	0.49	-
Chlorine		0.07	0.01	0.01	0.02	0.01	-
Carbon		86.26	43.16	39.00	13.30	6.13	-
Hydrogen		3.14	4.82	4.15	1.68	1.01	-
Nitrogen		1.29	0.49	0.30	1.63	0.85	-
Oxygen*		2.2	39.7	36.2	10.1	14.9	-
Gross CV	kJ/kg	33436	17404	13991	5496	4845	11941
Net CV†		32642	16114	12598	3797	3082	-
DAF CV*		35680	19710	17550	20070	20650	21590

Measure	Unit	Digested sludge				Raw dewatered			
		100%		20%	30%	100%		20%	40%
Moisture	%	62.0	69.3	37.8	27.2	77.4	73.3	41.9	49.4
Ash	% (db)	44.1	45.5	4.4	8.5	36.3	24.5	3.5	4.1
Volatile	%	19.9	15.9	52.6	60.4	13.5	18.1	45.2	38.8
Sulphur		0.52	0.43	0.14	0.23	0.26	0.20	0.13	0.09
Chlorine		0.02	0.01	-	-	0.01	0.01	-	-
Carbon		11.26	9.55	-	-	8.63	13.14	-	-
Hydrogen		1.57	1.20	-	-	1.26	1.67	-	-
Nitrogen		1.52	1.27	-	-	0.81	1.33	-	-
Oxygen*		6.4	4.2	-	-	3.4	3.9	-	-
Gross CV	kJ/kg	4977	3857	12100	14074	3909	4698	11200	9720
Net CV†		3109	1884	10378	12470	1767	2603	9482	7909
DAF CV*		23460	23030	20350	21120	27150	23340	20510	20900

Table 25 - Continued

Measure	Unit	Raw dewatered predried			Screenings		
		100% wt		50% wt	100% wt		40% wt
Moisture	%	21.5	38.8	23.7	86.6	73.3	53.4
Ash	% (db)	29.6	29.9	10.4	5.2	4.3	1.7
Volatile	%	51.9	39.8	52.7	11.4	22.8	37.6
Sulphur		0.75	0.60	0.46	0.06	0.09	0.09
Chlorine		0.04	<0.01	-	0.01	0.01	-
Carbon		32.57	24.09	-	7.05	14.05	-
Hydrogen		4.85	3.62	-	0.94	1.90	-
Nitrogen		2.77	2.15	-	0.28	0.50	-

Oxygen *		14.4	12.4	-	4.4	9.1	-
Gross CV	kJ/kg	15169	11314	14246	3781	4262	9355
Net CV†		13682	9642	12836	1450	2161	7477
DAF CV*		27430	26370	20830	29770	16780	20430

DAF = dry ash free, db = dry basis, \* calculated using determined values,  
† calculated using Seyler Parr Formula

**Table 26 Ash elemental analysis (mg/kg as received) for co-firing test fuels (\*values calculated from ash elemental oxide data)**

Element	Coal	Wood Chip		Composted sludge		Digested sludge	
Silicon	8717	359	1197*	30118	43083*	47183	62533*
Aluminium	5715	159	550*	13336	18020*	21115	21190*
Iron	5350	336	126*	53546	71447*	67812	68104*
Titanium	179	50	36*	1912	2450*	2631	3000*
Calcium	3037	3336	6389*	40810	59378*	40493	43900*
Magnesium	874	369	446*	2308	3012*	4571	4939*
Sodium	445	214	89*	710	1010*	1480	1350*
Potassium	954	737	1195*	2118	3392*	3312	5288*
Phosphorus	720	832	724*	30487	45171*	29949	34548*
Lithium	2	2	<2	3	<2	17	11
Boron	17	7	21	121	55	157	135
Vanadium	84	0.6	0.3	6.6	6.5	37.2	26.1
Chromium	6	13	0.7	18.7	22.2	246	121
Manganese	61	60	44.3	317	421	579	501
Cobalt	10	0.2	0.2	2.6	4.1	43	54.8
Nickel	72	42	1.1	16.4	26.9	104.2	152
Copper	21	7	5.6	319	534	286	404
Arsenic	2.1	0.1	<0.1	2.6	2.8	9.2	7.1
Cadmium	0.13	2.24	2.11	0.63	1.26	6.9	2.36
Antimony	0.3	<0.1	<0.1	3.6	7.2	52.8	33.4
Tungsten	27	0.5	1.2	0.8	1.3	1000	300
Mercury	0.05	0.15	0.02	1.46	1.52	6.7	4.91
Thallium	<0.1	<0.1	<0.1	<0.1	<0.1	<1	<0.1
Lead	6.9	2	0.8	95.8	108	306.1	156
Zinc		-	41.6	-	723	-	772

**Table 26 Continued (Ash elemental analysis (mg/kg as received) for co-firing test fuels)**

Element	Raw dewatered		Raw dried pellets		Screenings	
Silicon	29651	25884*	36806*	36061*	4205*	5287*
Aluminium	14017	11540*	15352*	15349*	1871*	1388*
Iron	49171	17993*	45961*	45172*	1928*	2256*
Titanium	2156	1322*	1775*	1972*	2120*	954*
Calcium	44404	35895*	26021*	27780*	10406*	8881*
Magnesium	2169	3103*	3927*	3967*	784*	596*
Sodium	728	727*	878*	887*	617*	351*
Potassium	1629	5695*	2703*	2482*	475*	928*
Phosphorus	31823	22452*	24155*	26748*	3767*	2458*
Lithium	1.8	<2	5	<2	13	<2
Boron	47	22	44	43	<1	5
Vanadium	12	3.9	14.4	16.8	0.7	0.6
Chromium	20	12.7	35.4	31.7	37.1	6.6
Manganese	375	94.9	593.5	391	18.5	16.0
Cobalt	5	1.3	7.2	11.5	0.9	0.7
Nickel	26	16.3	19.6	20.0	18.7	6.9
Copper	641	327	238.4	193	56.9	25.4
Arsenic	3	1.4	7.1	6.3	0.2	0.3
Cadmium	1.4	0.88	3.0	2.78	0.68	0.21
Antimony	8	4.8	8.9	6.9	13.0	12.0
Tungsten	4.6	1.3	9.4	10.0	0.5	5.9
Mercury	1.54	0.97	2.84	0.80	0.08	0.10
Thallium	<1	<0.1	0.1	0.1	<0.1	<0.1
Lead	78	34.3	97.6	67.6	2.9	4.3
Zinc	-	292	-	1120	-	64.2

**Table 27 Experimental conditions in combustion experiments (SO<sub>2</sub>, NO<sub>x</sub>, HCl from fuel input). (% wt values refer to amount of sludge, screenings etc. in blend, balance is willow wood chip).**

Fuel	Unit	Composted sludge t(dried)		Digested sludge		Raw dewatered	
		50%	100%†	20%	30%	20%	40%
Feeding rate	kg/h	12.5	11	11.5	13	11	16
Nat. gas	l/min	10	15	20	20	20	15
Air		1100	1300	1300	1140	1180	1190
Comb. Temp.	°C	835	980	940	915	972	920
CO <sub>2</sub>	%	11.75	8.79	11.91	13.12	12.43	13.19

SO <sub>2</sub>	pp m	522	1390	170	700	400	950
NO <sub>x</sub>		3320	7980	1485	5400	3172	3300
HCl		18.5	38	16	25	16	33
fly ash	%	29.7	50.5	39.8	59.7	81.5	73.3
C in fly ash		3.4	4.9	24.6	20.7	19.2	14.2

**Table 27 Continued (Experimental conditions in combustion experiments)**

Fuel	Unit	Raw dewatered (predried)		Screenings	
		50%	100 %	20%	40%
Feeding rate	kg/h r	11.34	6.5	12	11.5
Nat. gas	l/mi n	20	14	20	20
Air		1300	1400	1300	1400
Comb. Temp.	°C	920	880	800	750
CO <sub>2</sub>	%	12.16	6.31	10.59	9.91
SO <sub>2</sub>	pp m	566	573	358	704
NO <sub>x</sub>		4885	4840	1571	2354
HCl		29	27	14	23
fly ash	%	40.1	55.3	25.5	53.6
C in fly ash		10.2	7.3	3.0	1.9

**Table 28 Experimental conditions in gasification experiments. (% wt values refer to amount of sludge, screenings etc. in blend, balance is willow wood chip). † calculated.**

Fuel	Unit	Composted sludge		Digested sludge		Raw dewatered	
		50%	100%	20%	30%	20%	40%
Feeding rate	kg/hr	12.5	8.6	10	10	9.7	11.1
Moisture		3.96	0.17	2.08	-	-	-
Air/N <sub>2</sub> total	l/min	200	200	210	250	250	250
ER	-	0.29	0.52	0.39	-	-	-
H/C	-	2.59	1.64	2.20	-	-	-
Energy input	kW	41	39	42	-	-	-
Gasification T	°C	900	875	850	800	850	830
CO <sub>2</sub>	% vol. dry	10.44	12.23	14.81	12.97	14.66	14.98
CO		10.76	12.53	11.38	12.75	17.63	11.06
CH <sub>4</sub>		3.26	2.73	4.48	-	-	-

H <sub>2</sub> †		12.79	12.49	17.37	-	-	-
HHV gas (dry)†	MJ/m <sup>3</sup> dry	4.27	4.25	5.54	-	-	-
Char	kg/kg fuel	0.065	0.086	0.080	-	-	-

**Table 28 - Continued**

Fuel	Unit	Dried raw dewatered			Screenings	
		30%	50%	100%	20%	40%
Feeding rate	kg/hr	11.5	8.5	13	9	8
Moisture		-	1.38	2.79	1.66	-
Air/N <sub>2</sub> total	l/min	250	250	350	210	250
ER	-	-	0.46	0.43	0.39	-
H/C	-	-	2.30	3.15	2.27	-
Energy input	kW	-	34	54	38	-
Gasification T	°C	820	900	750	850	870
CO <sub>2</sub>	% vol. dry	11.21	8.84	12.61	13.87	13.57
CO		12.27	8.05	6.95	11.38	10.13
CH <sub>4</sub>		0.62	1.78	4.77	4.34	-
H <sub>2</sub> †		-	13.74	19.26	17.67	-
HHV gas (dry)†	MJ/m <sup>3</sup> dry	-	3.46	5.21	5.39	-
Char	kg/kg fuel	-	0.116	0.087	0.055	-

**Table 29 Percentage of fly ash in the experiments and carbon content. (% wt values refer to amount of sludge, screenings etc. in blend, balance is willow wood chip).**

Samples		% Fly ash*	% Carbon content	
			bed	fly ash
Wood chips		20	0.18	9.60
Composted sludge	50% wt	29.7	0.11	3.43
	100% wt	50.5	0.18	4.93
Digested sludge	20% wt	39.8	0.38	24.55
	30% wt	59.7	0.35	20.71
Raw dewatered	20% wt	81.5	0.40	19.18
	30% wt†	80.0	0.38	16.15
	40% wt	78.3	0.35	14.22
Dried raw dewatered	30% wt†	45.6	0.20	6.49
	50% wt	40.1	0.20	10.20

	100% wt	55.3	0.20	7.26
Screenings	20% wt	35.5	0.21	2.95
	40% wt	53.6	0.24	1.91

\*This value is fly ash including its carbon content, † long tests

**Table 30 Ash elemental analysis from the fly ash samples in the co-firing experiments. Analysis basis: As analysed (mg/kg). (% values (by weight) refer to amount of sludge, screenings etc. in blend, balance is willow wood chip). (\*values calculated from ash elemental oxide data)**

Element	Composted sludge		Digested sludge		Raw dewatered		
	50%	100%	20%	30%	20%	30%	40%
Silicon	10105 2	11302 8	32567	67094	76695*	86574*	86213*
Aluminium	40293	39749	16179	28755	31651*	33262*	34502*
Iron	12359 8	12428 6	40776	85082	85923*	83230*	97796*
Titanium	5072	4393	1279	2917	3392*	3517*	4114*
Calcium	14108 2	11980 4	27033 6	19243 4	170974 *	117986 *	158784 *
Magnesium	9069	7180	3859	6357	7798*	10108*	7760*
Sodium	3487	3398	1055	2407	2998*	3108*	3182*
Potassium	25750	23572	7673	14810	17444*	25740*	18515*
Phosphorus	75480	66357	16755	42824	46554*	60338*	57647*
Lithium	13	1	20	29	4.6	<2	4.0
Boron	469	378	124	56	118	125	143
Vanadium	81	93	56	55	59	0.5	35.9
Chromium	495	509	179	306	487	3.3	471
Manganese	1500	1200	313	699	1286	16.4	1198
Cobalt	32.0	31.0	17	38	28	0.4	20
Nickel	528	613	159	346	473	4.8	545
Copper	1290	649	160	391	738	10.6	918
Arsenic	24.2	23	11	12	21	0.2	18
Cadmium	21.7	14.9	7.7	13.4	22.7	0.76	19.2
Antimony	19.0	13.8	8	23	20	0.2	14
Tungsten	9.8	27	290	410	170	22	100
Mercury	0.45	0.69	0.77	2.15	1.50	2.38	1.15
Thallium	1.2	0.3	<1	<1	<1	<0.1	<1
Lead	203	190	58	160	145	7.4	137
Zinc	-	-	-	-	-	22.8	-



**Table 30 - Continued**

Element	Dried raw dewatered		Screenings	
	50%	100%	20%	40%
Silicon	104946*	92735*	87846*	125193*
Aluminium	41822*	53475*	39136*	45687*
Iron	130015*	126434*	110749*	137229*
Titanium	5384*	6669*	6259*	5881*
Calcium	104613*	106003*	118761*	89743*
Magnesium	10831*	12858*	13642*	11832*
Sodium	3331*	2751*	2582*	3639*
Potassium	14909*	10774*	11556*	13030*
Phosphorus	75239*	82928*	66439*	73632*
Lithium	22	17	61	<2
Boron	40	71	<1	138
Vanadium	53.4	71.3	22	2.2
Chromium	207.3	164.7	122	16.4
Manganese	1430	1250	712	73.8
Cobalt	32.5	30.0	16	1.8
Nickel	173.3	123.1	157	22.5
Copper	578.1	523.2	297	33.3
Arsenic	6.2	90.8	11	1.1
Cadmium	20.2	18.4	7.6	0.72
Antimony	1.9	2.7	14	1.1
Tungsten	43	58.0	26	110
Mercury	0.47	0.92	0.42	0.53
Thallium	0.2	1.8	<1	<0.1
Lead	306.7	323.7	116	13.9
Zinc	-	-	-	177

**Table 31a Ash fusion temperatures for the different fuel mixtures (°C), analyses conditions: Reducing Atmosphere. (% wt values refer to amount of sludge, screenings etc. in blend, balance is willow wood chip).**

Samples		Ash Fusion Temperatures (°C)			
		Initial	Sphere	Hemisphere	Flow
Composted sludge	50% wt	1130	1150	1160	1200
Digested sludge	20% wt	1120	1220	1230	1300
	30% wt	1250	1260	1280	1300
	100% wt	1040	1060	1070	1150
Raw dewatered sludge	20% wt	1230	1250	1260	1300
	40% wt	1190	1220	1230	1260
	100% wt	1100	1140	1150	1200
Dried raw dewatered	50% wt	1060	1070	1080	1100
	100% wt	1050	1070	1080	1110
Screenings	40% wt	1240	-	1270	1300

**Table 31b Ash fusion temperatures for fly ash samples (°C), analyses conditions: Reducing Atmosphere. (% wt values refer to amount of sludge, screenings etc. in blend, balance is willow wood chip).**

Samples		Ash Fusion Temperatures (°C)			
		Initial	Sphere	Hemisphere	Flow
Wood chips		1140	1160	1180	1240
Composted sludge	50% wt	1200	1240	1250	1270
	100% wt	1170	1190	1200	1240
Digested sludge	20% wt	1380	+1400	+1400	+1400
	30% wt	1230	1270	1300	1390
Raw dewatered sludge	20% wt	1170	1200	1210	1270
	30% wt	1300	-	1390	+1400
	40% wt	1150	1200	1220	1360
Dried raw dewatered	50% wt	1100	1110	1130	1170
	100% wt	1070	1090	1110	1180
Screenings	20% wt	1180	-	1210	1240
	40% wt	1130	-	1140	1180

**Table 32 Proximate analysis, ultimate analysis (as received) and calorific value (CV) for the gasifier char from co-firing experiments. (% wt values refer to amount of sludge, screenings etc. in blend, balance is willow wood chip).**

Measure	Unit	Compost ed sludge	Raw dewatered		Raw dried pellets		
		100%	30%	50%	30%	50%	100%
Moistur e	%	0.9	1.4	1.0	1.1	1.2	1.0
Ash	% (db)	95.7	73.7	92.0	76.8	61.0	88.4
Volatile	%	5.8	9.8	6.0	7.9	15.6	9.0
Sulphu r		1.61	0.40	1.64	0.42	0.91	0.57
Chlorin e		0.03	0.04	0.05	0.05	0.05	0.04
Carbon		6.24	25.08	12.91	31.76	31.55	10.45
Hydrog en		0.07	0.42	0.30	0.58	0.84	0.24
Nitroge n		0.36	0.70	0.75	0.83	1.60	0.91
Oxygen *		<0.1	<0.1	<0.1	<0.1	3.6	<0.1
Gross CV	kJ/kg	1413	8290	3300	7820	11940	3160

Net CV†		1115	7851	2958	7406	11394	2810
DAF CV*		32860	32010	41250	34150	31010	27480

DAF = dry ash free, db = dry basis, \* calculated using determined values,  
† calculated using Seyler Parr Formula

**Table 32 - Continued**

Measure	Unit	Screenings	Digested
		20%	20%
Moisture	%	0.4	1.1
Ash	% (db)	88.8	87.0
Volatile Sulphur	%	8.9	9.2
Chlorine		0.58	0.83
Carbon		0.04	0.04
Hydrogen		10.37	11.33
Nitrogen		0.28	0.30
Oxygen*		0.92	0.99
Gross CV	kJ/kg	<0.1	<0.1
Net CV†		2980	3680
DAF CV*		2648	3318
		26610	28530

**Table 33 Ash elemental analysis from the gasifier char samples in the co-firing experiments. Analysis basis: As analysed (mg/kg). (% wt values refer to amount of sludge, screenings etc. in blend, balance is willow wood chip). \*values calculated from ash elemental oxide data**

Element	Compos ted sludge	Screeni ngs	Digest ed sludg e	Raw dried pellets			Raw dewatered sludge	
	100%	20%	20%	30%	50%	100 %	30%	50%
Silicon*	110499	115400	10411 4	9765 2	672 96	1090 95	857 86	1191 29
Aluminium*	31908	45116	45582	3495 4	248 58	4444 4	335 43	4674 1
Iron*	158638	126704	12474 4	1090 45	789 31	1267 52	953 65	1241 92
Titanium *	4016	5324	5737	4604	292 6	5300	397 6	4964
Calcium*	82075	70446	70261	7739 3	658 30	7012 9	679 48	9928 5
Magnesium*	6926	11246	11018	1111 6	846 1	1119 6	102 23	5548
Sodium*	2840	3294	3227	2849	226 3	3279	328 0	2048
Potassium*	6356	8109	7945	1912 7	151 92	8072	201 90	5346
Phosphorus*	70577	67426	68717	6300 7	460 51	6789 4	549 96	7547 7
Lithium	<2	<2	<2	<2	<2	<2	<2	<2
Boron	100	131	130	114	103	131	108	113
Vanadium	0.7	0.6	0.6	0.9	0.4	0.3	1.8	0.9
Chromium	140	1.4	1.4	8.4	1.8	0.5	8.5	2.5
Manganese	81.9	17.0	15.4	28.9	18.5	7.4	69.7	42.7
Cobalt	2.5	0.4	0.4	0.9	0.3	0.2	1.4	0.6
Nickel	313	1.0	0.9	27.8	2.3	0.6	11.9	4.2
Copper	47.6	7.8	7.9	13.0	6.2	5.2	32.5	57.0
Arsenic	1.3	0.2	0.2	0.3	0.2	0.1	0.8	0.5
Cadmium	0.12	0.12	0.10	0.26	0.25	0.06	0.50	0.15
Antimony	0.9	0.2	0.2	0.2	0.1	0.1	0.6	0.7
Tungsten	3.7	9.4	0.5	0.7	6.0	12.0	4.8	0.8
Mercury	0.12	0.29	0.28	0.30	0.14	0.30	0.19	0.04
Thallium	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

Lead	12.0	3.8	3.6	4.1	5.2	2.6	9.3	17.0
Zinc	88.7	42.6	41.7	78.7	28.4	22.5	181	70.1

**Table 34 Gas quality requirements for power generation [37]**

Contaminant	Units	Gas engine	Gas turbine
Particles	mg/Nm <sup>3</sup>	50	30
Particle size	µm	10	5
Tars	mg/Nm <sup>3</sup>	100	40

**Table 35 Tar concentrations measured in gasifier gas. (% wt values refer to amount of sludge, screenings etc. in blend, balance is willow wood chip).**

Compound (mg/Nm <sup>3</sup> )	Raw dried Pellets		Digested Sludge		Raw Dewatered		Screenings	
	30%	100 %	20%	30%	20%	40%	20%	40%
Phenol	391.8	-	211.2	-	200.7	375.6	92.4	111.3
2-Methylphenol	110.2	-	60.2	-	57.1	106.6	22.8	26.7
3- & 4-Methylphenol	219.4	-	100.5	-	73.2	145.6	-	-
Naphthalene	296.0	222.2	237.7	271.5	430.4	619.3	221.8	452.0
2-Methylnaphthalene	79.5	27.9	52.2	61.0	110.6	186.0	39.7	69.5
1-Methylnaphthalene	60.4	25.8	41.6	43.4	79.9	132.6	29.4	48.4
Biphenyl	32.0	13.0	21.4	18.3	29.1	54.2	18.9	28.6
Acenaphthylene	80.9	22.6	40.6	57.0	76.0	157.5	57.5	72.3
Acenaphthene	-	-	-	-	6.1	12.2	-	-
Fluorene	15.1	-	10.2	9.1	13.6	29.0	14.7	9.5
Phenanthrene	15.9	-	16.4	14.2	20.0	40.0	19.0	19.4
Anthracene	-	-	-	-	6.1	12.4	-	-
Fluoranthene	-	-	-	-	5.7	10.7	-	6.1
Pyrene	-	-	-	-	6.0	10.7	-	5.59
bis(2-Ethylhexyl)phthalate	69.1	-	731.2	-	17.9	26.7	32.0	-

**Table 36 Fuel properties for combustion model**

Parameter	Units	Willow wood	Digested sludge (sludge 1)	Raw dried pellets (sludge 2)	Screenings
Moisture content	%	50	75	25	65
Volatile matter	% ds	82.3	51.8	66.1	85.2
Ash		2	45.5	29.6	4.8
C		47.9	31.1	41.5	52.6
H		5.1	3.9	6.2	7.1
O		44.5	13.7	18.3	34.5
N		0.4	4.1	3.5	2.0
S		0.1	1.4	1.0	0.4
Cl		0.01	0.03	0.05	0.05
F		0	0.02	0.02	0.02
HHV	MJ/kg ds	19468	12564	19324	22090
Cd	mg/kg ds	2.24	6.9	3.0	0.5
Tl		0.1	1	0.1	0.1
Hg		0.15	6.7	2.84	0.09
Sb		0.1	52.8	8.9	12
As		0.1	9.2	7.1	0.2
Pb		2	306.1	97.6	33.6
Cr		13	246	35.4	21.9
Co		0.2	43	7.2	0.8
Cu		7	286	238.4	41.2
Mn		60	579	593.5	17.3
Ni		42	104.2	19.6	12.8
V		0.6	37.2	14.4	0.6

**Table 37 Other fuel specific parameters for combustion system model**

Parameter	Unit
Combustion loss	%
Fuel N to NO	%
Fuel N to N <sub>2</sub> O	%
<b>% trace elements in bottom ash</b>	
Cd	%
Ti	%
Hg	%
Sb	%
As	%
Pb	%
Cr	%
Co	%
Cu	%
Mn	%
Ni	%
V	%

**Table 38 Process parameters required for combustion system model**

Parameter	Unit
Sludge feed rate	kg DS/h
Wood feed rate	
Sludge gas drier- exit moisture content	%
Wood gas drier- exit moisture content	
<b><i>Sludge transport</i></b>	
Return distance	km
% urban	%
% rural	
% motorway	
Capacity	t/vehicle
<b><i>Wood transport</i></b>	
Return distance	Km
% urban	%
% rural	
% motorway	
Capacity	t/vehicle
<b><i>Flue gas dryer (wood)</i></b>	
Exit moisture content	%

Efficiency	
<i>Flue gas dryer (sludge)</i>	
Exit moisture content	%
Efficiency	
<i>Combustion</i>	
Excess air	%
Casing loss	
<i>Steam usage</i>	
% steam to steam turbine	%
Steam turbine efficiency	
Generator efficiency	
External heat supply efficiency	
<i>Flue gas clean-up</i>	
Flue gas particle removal efficiency	%
Flue gas SO <sub>2</sub> removal efficiency	
Flue gas HCl removal efficiency	
Flue gas HF removal efficiency	
Flue gas stack temperature	°C

**Table 39 Fuel properties for gasification model**

Parameter	Unit	Willow wood	Digested Sludge (sludge 1)	Raw dried Pellets (sludge 2)	Screenings
Moisture content	%	50	50	25	65
Volatile matter	% ds	82.3	51.8	66.1	85.2
Ash		2	45.5	29.6	4.8
C		47.9	31.1	41.5	52.6
H		5.1	3.9	6.2	7.1
O		44.5	13.7	18.3	34.5
N		0.4	4.1	3.5	2.0
S		0.1	1.4	1.0	0.4
Cl		0.01	0.03	0.05	0.05
F		0	0.02	0.02	0.02
HHV measured	MJ/kg ds	17.2	12564	19324	22090
Cd	mg/kg ds	2.24	6.9	3.0	0.5
Tl		0.1	1	0.1	0.1
Hg		0.15	6.7	2.84	0.09
Sb		0.1	52.8	8.9	12
As		0.1	9.2	7.1	0.2
Pb		2	306.1	97.6	33.6
Cr		13	246	35.4	21.9



Co		0.2	43	7.2	0.8
Cu		7	286	238.4	41.2
Mn		60	579	593.5	17.3
Ni		42	104.2	19.6	12.8
V		0.6	37.2	14.4	0.6
<i>Chars</i>					
C	% daf	88	88	88	88
H		0.46	0.46	0.46	0.46
O		9.53	9.53	9.53	9.53
N		1.91	1.91	1.91	1.91
S		0	0	0	0
Cl		0.1	0.1	0.1	0.1
F		0	0	0	0

Table 40 Other fuel specific parameters for gasification system model

Parameter	Unit
<b>Sludge</b>	
Volatiles to tar	%
Volatile N to NH <sub>3</sub>	
Volatile O to CO	
<b>Wood</b>	
Volatiles to tar	%
Volatile N to NH <sub>3</sub>	
Volatile O to CO	
Char C CO <sub>2</sub> : H <sub>2</sub> O ratio	
Volatiles burned	
<b>Gas property</b>	
CV C <sub>10</sub> H <sub>8</sub> (tar)	MJ/kg
<b>% trace elements in bottom char</b>	
Cd	%
Ti	
Hg	
Sb	
As	
Pb	
Cr	
Co	
Cu	
Mn	
Ni	
V	

**Table 41 Process parameters required for gasification system model**

Parameter		Unit	Parameter		Unit
Sludge	feed rate	kg DS/h	<b>Gasification</b>		
Wood			Fuel:air ratio		%
Sludge	gas drier exit moisture content	%	Casing loss		
Wood			<b>Gas cooler and clean-up</b>		
<b>Sludge transport</b>			cooler 1 exit temperature	°C	
Return distance		km	particle removal filter efficiency	%	
% urban		%	cooler 2 exit temperature	°C	
% rural			scrubber tar removal efficiency	%	
% motorway			Scrubber outlet temp	°C	
Capacity		t/vehicle	Water in exit gas†	kg/kg dry gas	
<b>Wood transport</b>			<b>Gas usage</b>		
Return distance		km	Gas engine used (y/n)		y / n
% urban			<b>Gas engine</b>		
% rural			gas engine	excess air	%
% motorway				exit gas temperature	°C
Capacity		t/vehicle	% jacket heat loss		%
<b>Steam dryer (sludge)</b>			generator efficiency		
Exit moisture content		%	<b>Gas turbine</b>		
Sludge inlet temperature		°C	compressor	inlet pressure	bar
Vapour exit temperature				outlet pressure	
Efficiency		%		outlet temperature	°C
<b>Steam dryer (wood)</b>			gas turbine	efficiency	%
Exit moisture content		%		excess air	
Wood inlet temperature		°C		exit temperature	°C
Vapour exit temperature					
Efficiency		%	generator efficiency		%
			<b>HRSG performance</b>		
<b>NOTES</b>			HRSG casing loss		%
			HRSG exit temperature		°C
† specific humidity			<b>Steam usage</b>		
			% steam to steam turbine		%
			Inlet enthalpy		MJ/kg

	Outlet enthalpy	%
	steam turbine efficiency	
	generator efficiency	
	External heat supply efficiency	

**Table 42 Vehicle emissions (based on NAEI vehicle emissions database [43])**

Emission	Type	Value	Units
Consumption	Urban	0.2106	kg/km
	Rural	0.1997	
	Motorway	0.2188	
CO <sub>2</sub>	Urban	661	g/km
	Rural	627	
	Motorway	687	
NO <sub>x</sub>	Urban	4.41	
	Rural	3.98	
	Motorway	4.15	
PM10	Urban	0.117	
	Rural	0.092	
	Motorway	0.092	

**Table 43 Waste Incineration Directive limits**

Item	Limit	Units
Dust	10	mg/m <sup>3</sup>
NO <sub>x</sub>	200	
SO <sub>2</sub>	50	
HCl	10	
HF	1	
Hg	0.05	
Cd + Tl	0.05	
Sb +As + Pb + Cr + Co + Cu + Mn + Ni + V	0.5	

**Table 44 EI 95 weightings**

Item	Value	Description
Dust	1	Winter smog
SO <sub>2</sub>	1	Acidification potential & winter smog
N <sub>2</sub> O	11	Global warming potential
CO <sub>2</sub>	1	
CO <sub>2</sub>	1	
NO <sub>x</sub>	0.7	Acidification potential
HCl	0.88	
HF	1.6	
Cd	50	Heavy metals
Hg	1	
Pb	1	
Mn	1	

**Table 45 Base scenarios for life cycle analysis**

Cas e No.	Process	Sludge (tds/day )	Delivere d ds (%)	5% (wet) screening s*	Numbe r of units
1	Gasificatio n†	10 (rural)	25	No	2
2	Combustio n‡				1
3	Gasificatio n†		90		2
4	Combustio n‡				1
5	Gasificatio n±	27 (urban)	25		5
6	Combustio n‡				1
7	Gasificatio n±		90		5
8	Combustio n‡				1
9	Combustio n‡			Yes	1

†Semi-downdraft gasifier

‡Bubbling fluidised bed or spreader stoker combustor

±Fluidised bed gasifier

\*5% of sludge (ds) input

**Table 46 Inputs for techno-economic model**

No.	Input	Unit
1	Sludge input	t/day ds
2	Delivered dry solids	% ds
3	Target dry solids after drying	% ds
4	NCV sludge dry	GJ/t
5	NCV screenings dry	GJ/t
6	Screenings input as % of sludge input	%
7	Target sludge NCV	GJ/t
8	Target net output	MWe
9	Efficiency heat to power net	factor
10	Target sludge dry solids after drying	% ds
11	Wood as-received dry solids	% ds
12	Fuel blend dry solids	% ds
13	Target wood dry solids	% ds
14	NCV wood dry	GJ/t
15	Operating and Maintenance cost as % of EPC	%
16	Electricity sale price	£/MWh
17	Gate Fee Sludge	£/tds
18	Gate Fee Screenings	£/tds
19	Wood Price delivered	£/wet t
20	Disposal cost for ash	£/t
21	Project cost / MWe export installed, increase factor	-
22	Prices index	%
23	Discount rate	%

**Table 47 Indicative Disposal Costs Expressed as NPC per tonne of dry solids for a medium size plant (~200000 pe)**

Treatment	NPC (all in unit cost, £/dt)
Pre-pasteurization	156
Lime stabilisation	161
Compliant treatment	235
Additional drying to 30% ds	240
Thermal drying	297

Screenings disposal costs are £30-40 per wet tonne plus landfill tax

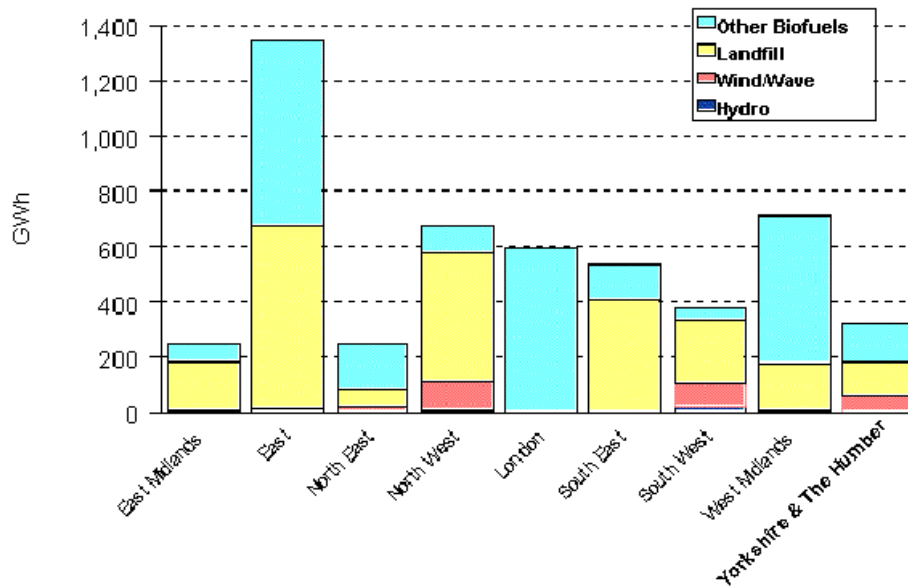


Figure 1 Regional renewable energy capacity (GWh) in 2000 [7]

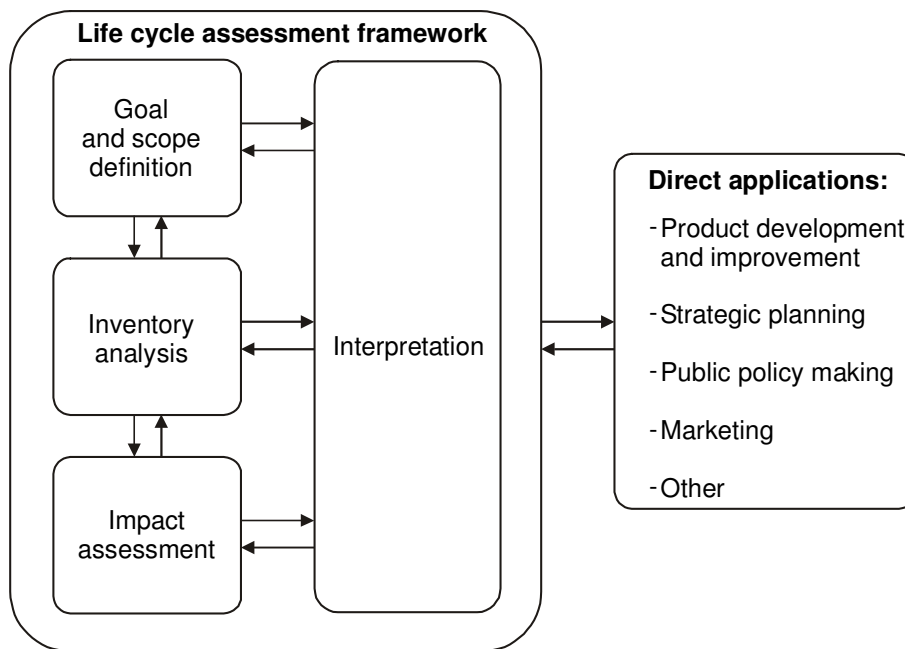


Figure 2 Life cycle assessment framework [17]

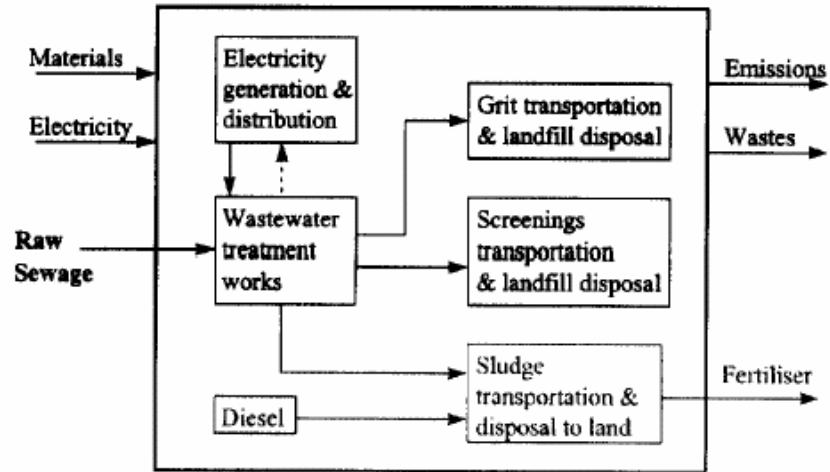


Figure 3 Boundary definition for analysis of sludge treatment centralisation options [32]

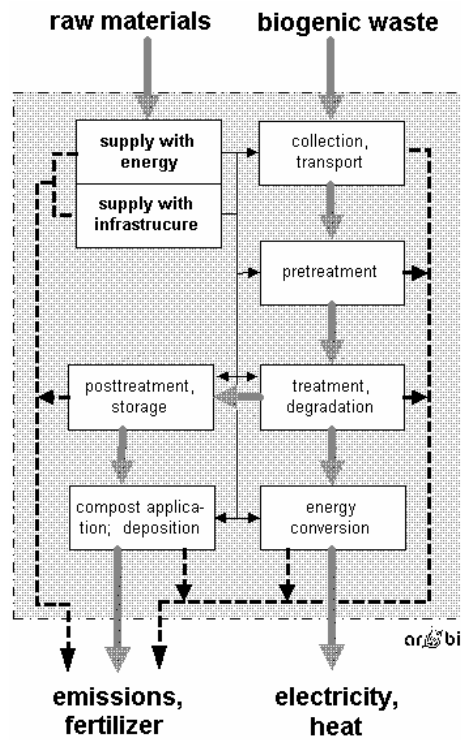


Figure 4 Boundary definition for a study of treatment systems for organic household waste [34]

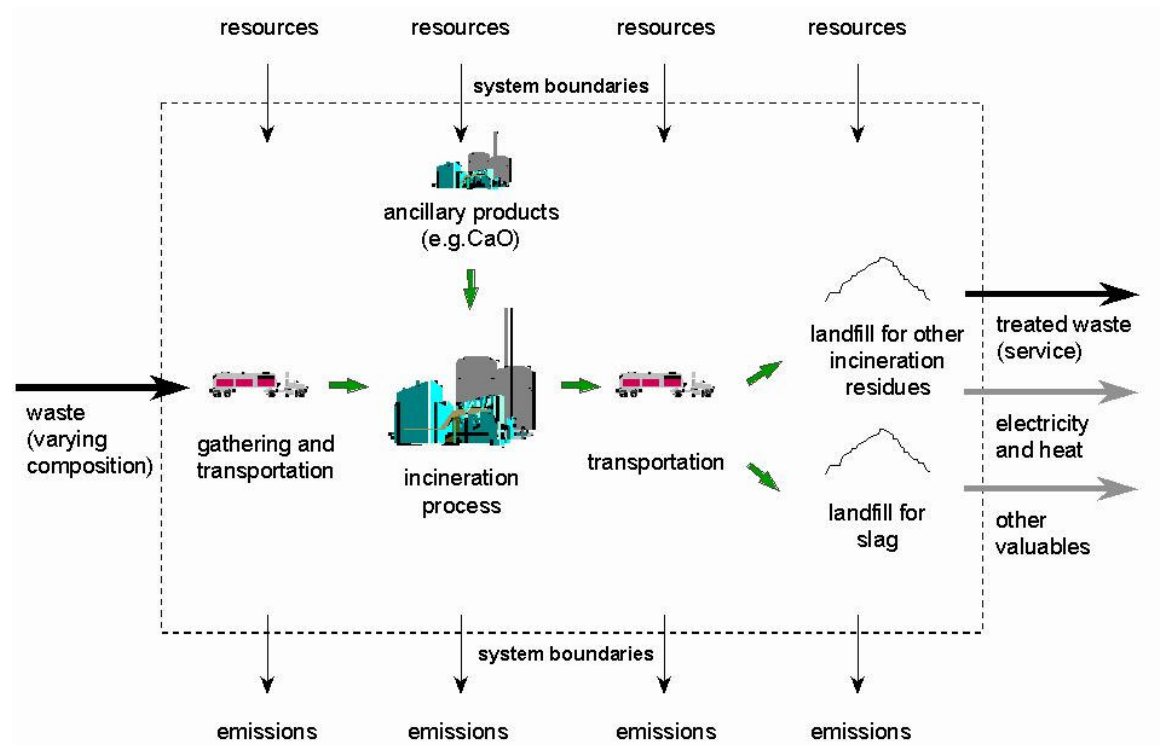


Figure 5 System boundary definition for waste incineration process [35]

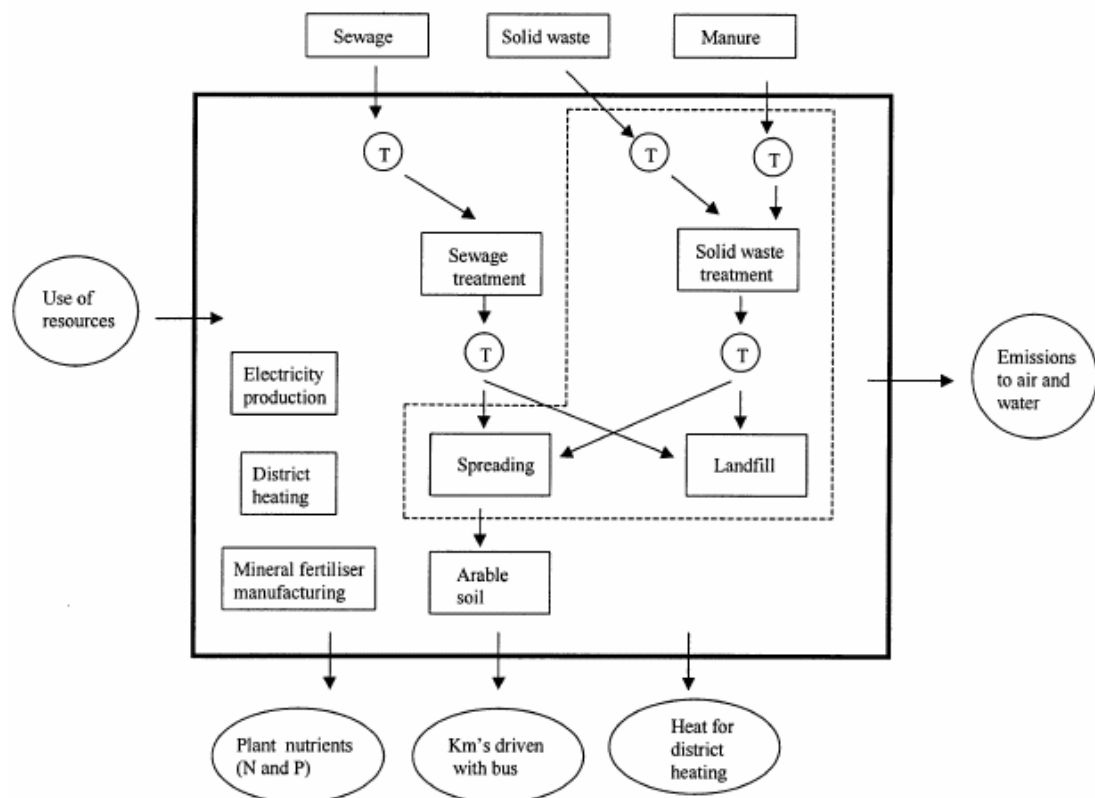


Figure 6 System boundary for a study of management systems for biodegradable waste [39]



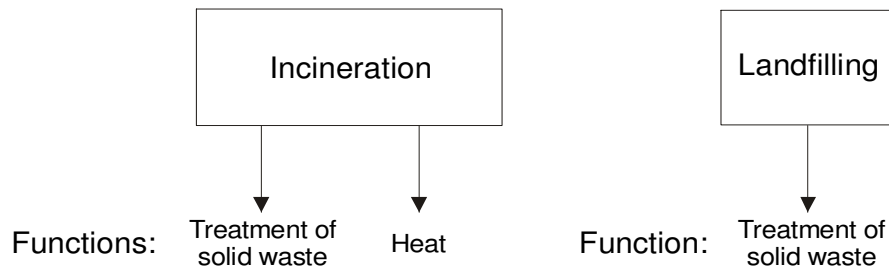


Figure 7 Allocation problem in waste treatment [21]

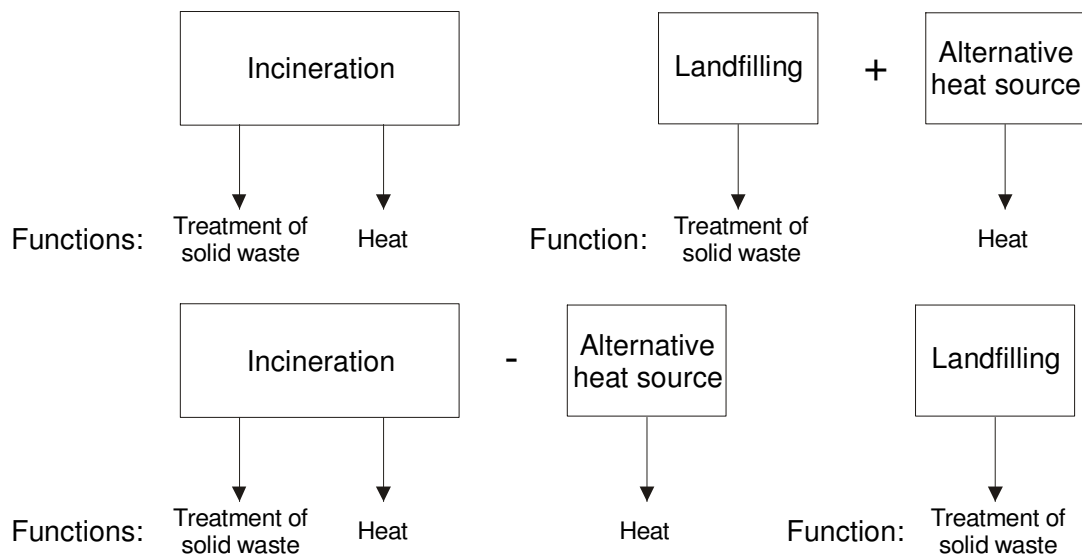


Figure 8 Allocation avoidance by broadening the system [21]

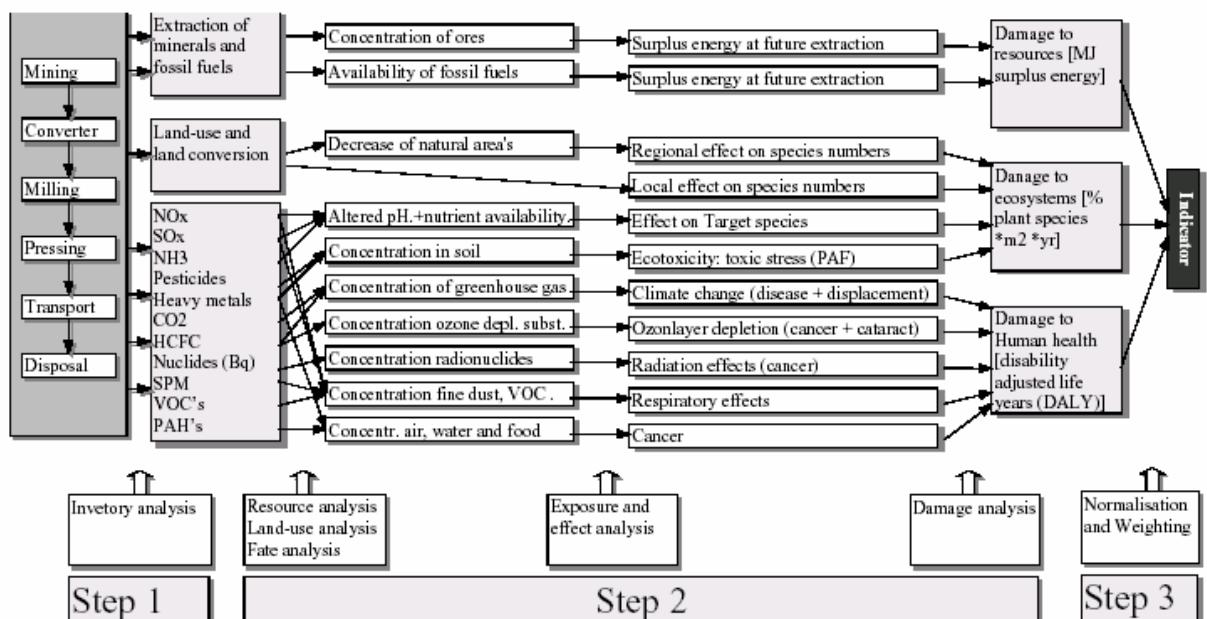
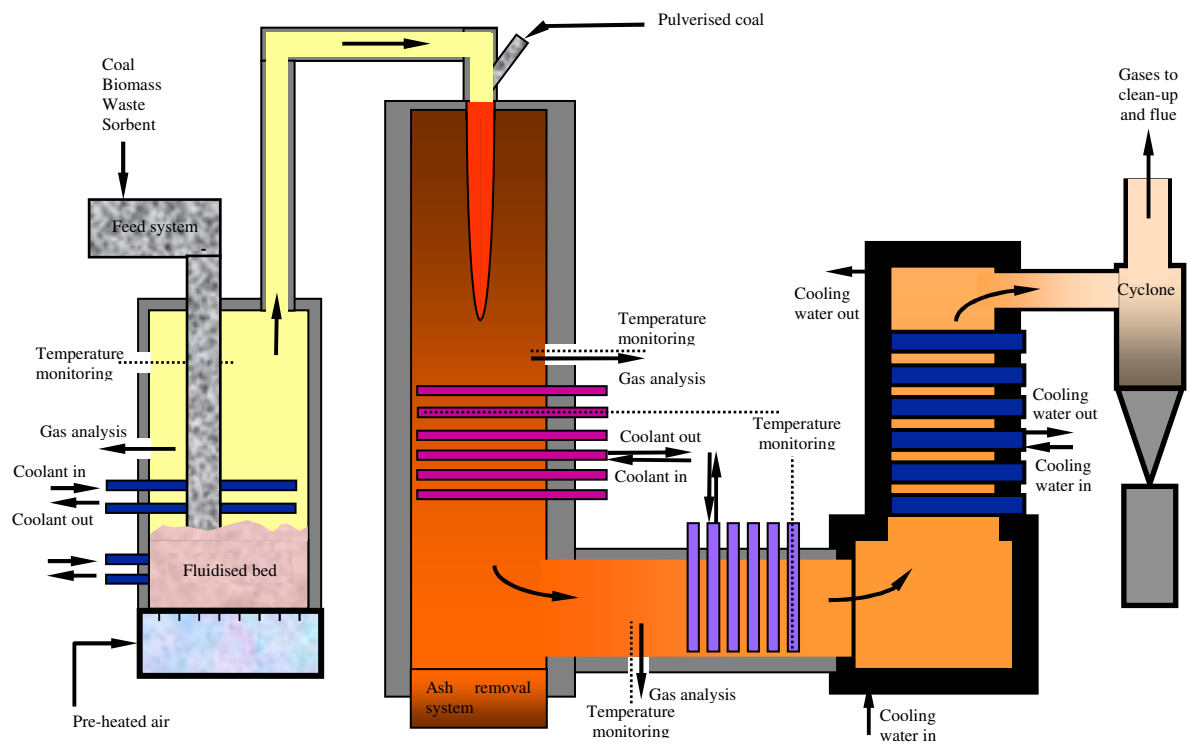


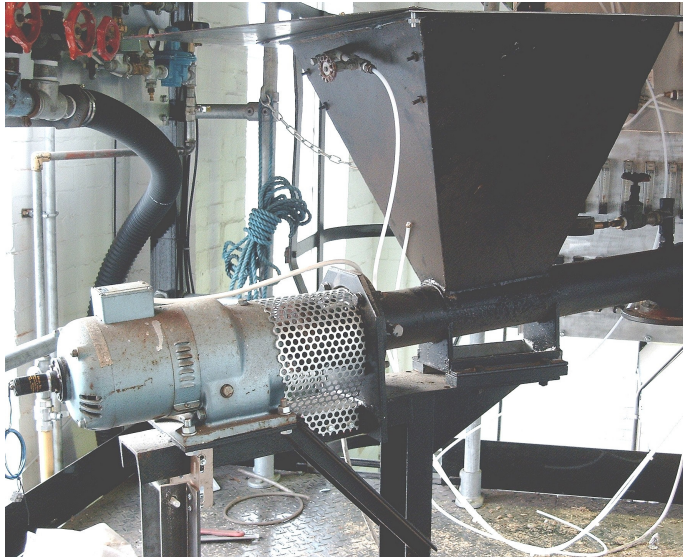
Figure 9 Steps involved in calculation of the Eco-Indicator 99 [40]



**Figure 10 Schematic diagram of combustion pilot plant facility**



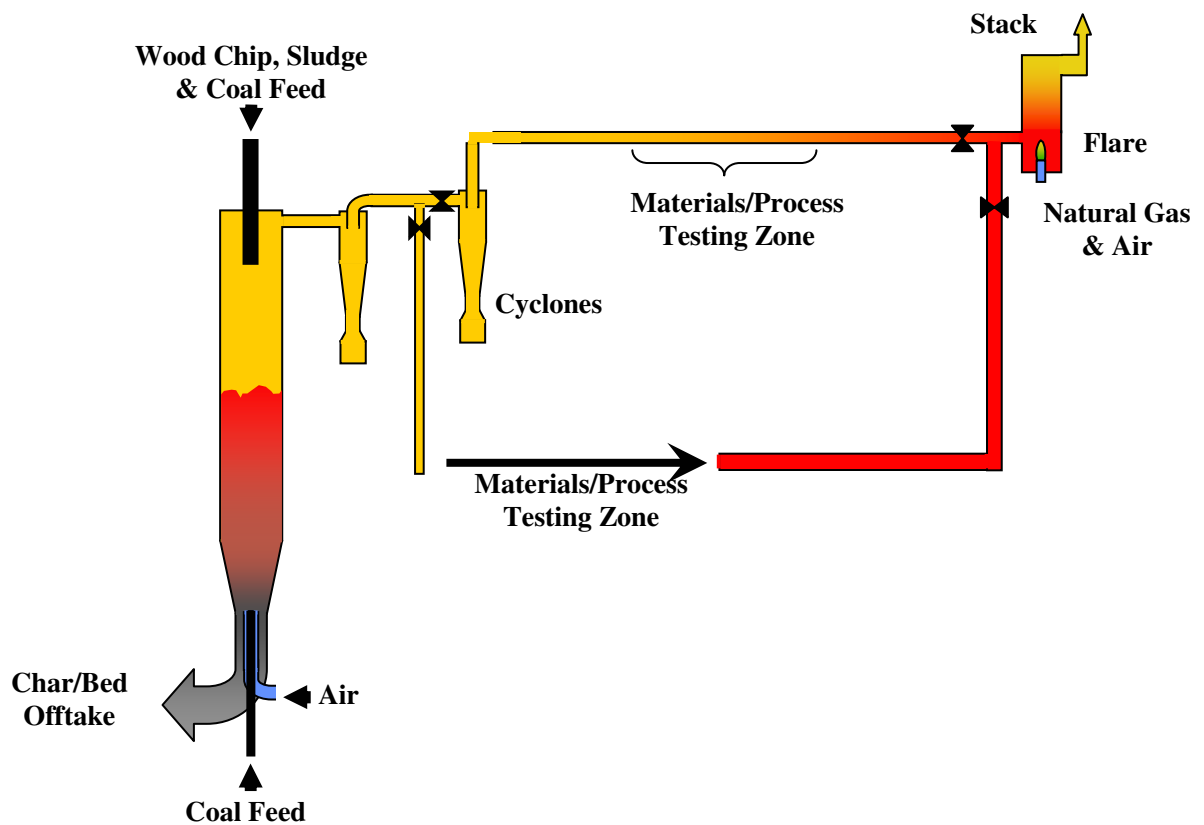
**Figure 11 Photographs of the combustion test facility: in both pictures the fluidised bed combustor is on the right hand side**



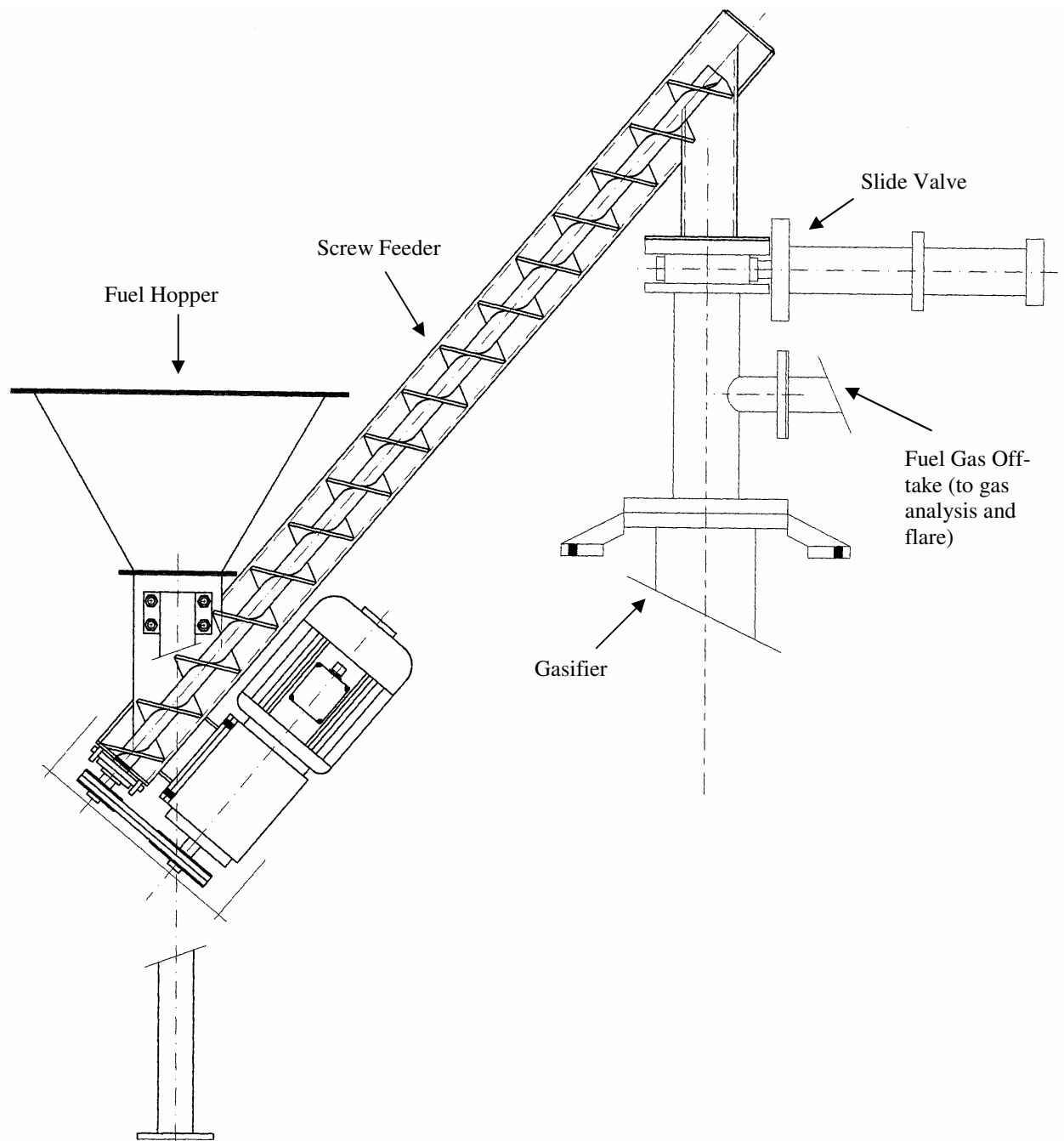
**Figure 12 Photograph of combustor fuel storage and feed system for FBC operation**



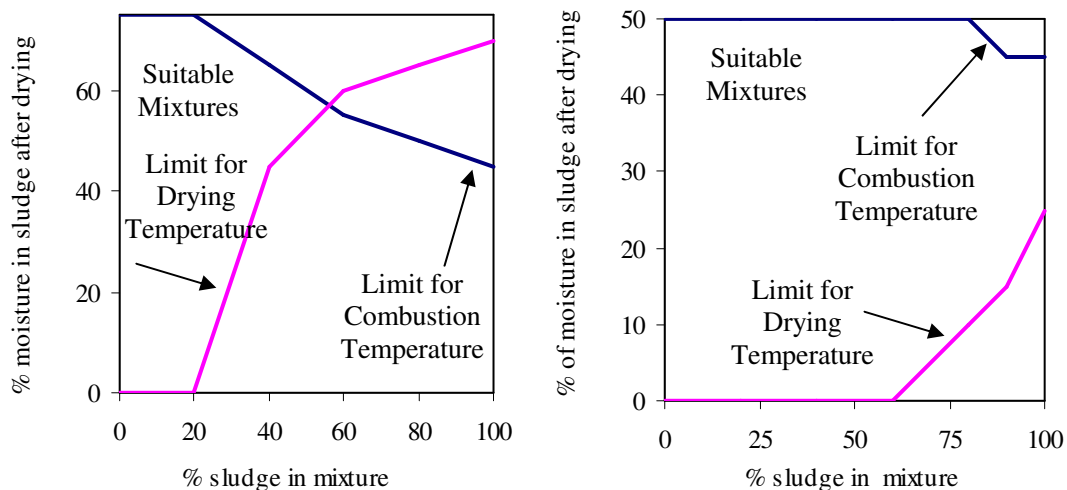
**Figure 13 Photograph of fuel storage hopper from above**



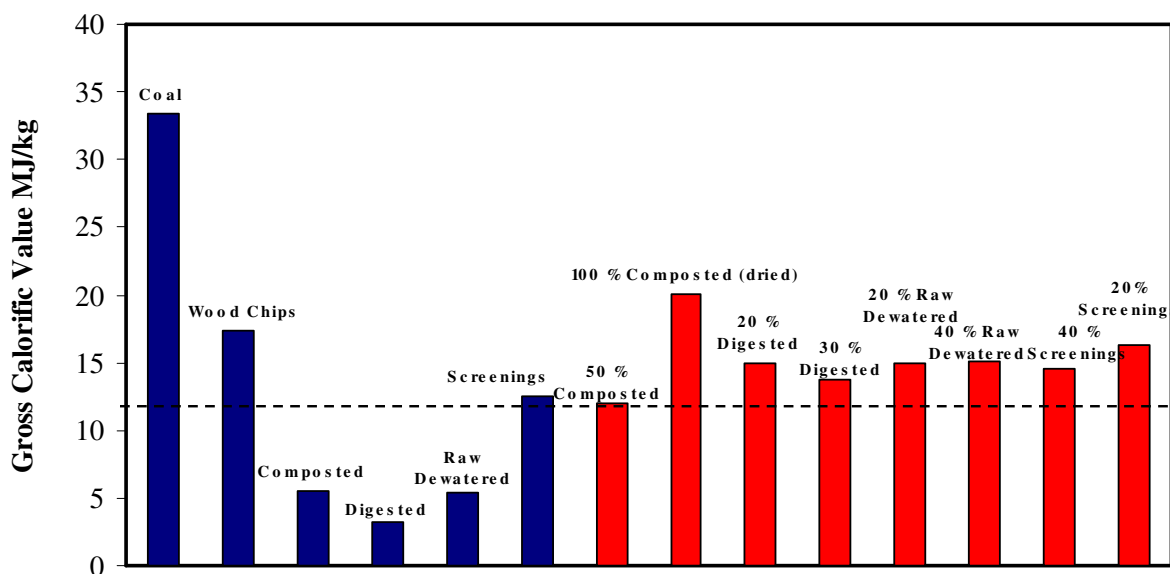
**Figure 14 Schematic diagram of gasification pilot plant facility**



**Figure 15 Design of fuel storage hopper, screw feed system and interlocking valve for gasification pilot plant**



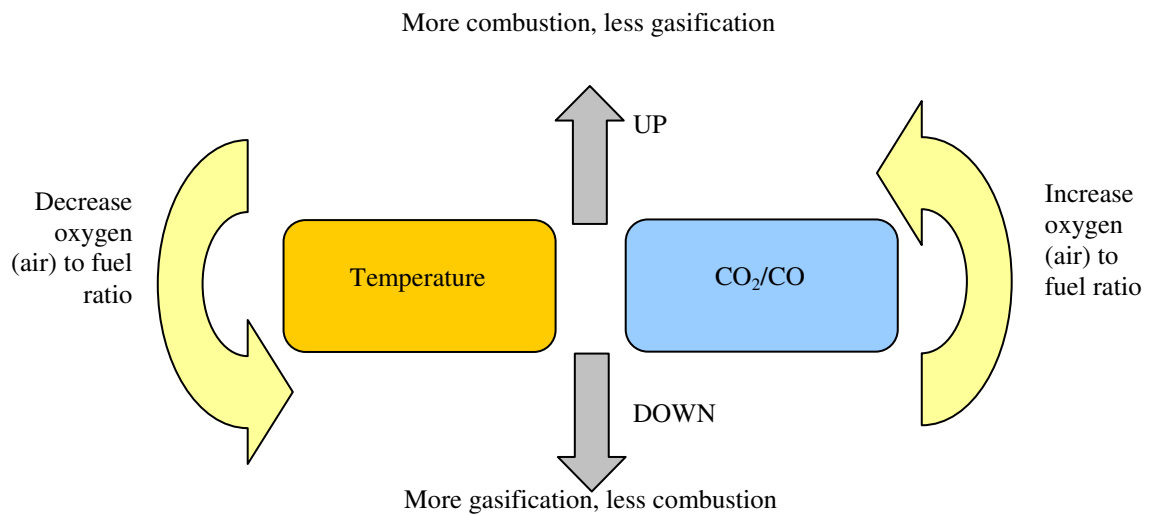
**Figure 16** Diagram showing the impact of moisture content on the ratio of fuels in a biomass-sewage sludge co-firing plant, for two types of sewage sludge - a) digested sludge, b) composted sludge.



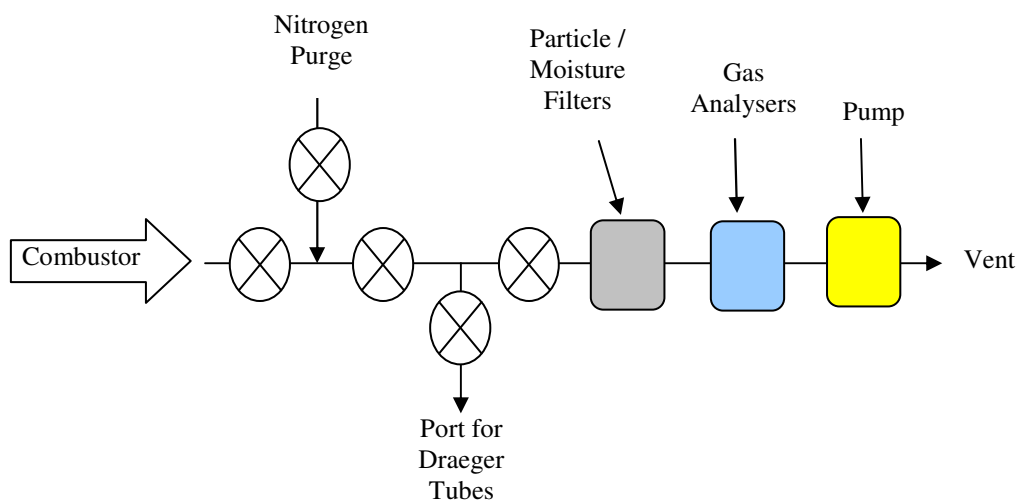
**Figure 17** Gross calorific values (GCV) from the original fuels used in the co-firing tests and from the mixtures. Dotted line is lower limit for CV – see section 5.4.2.3.



**Figure 18 Picture of the mixture of 50/50% wt digested sludge/wood chips**

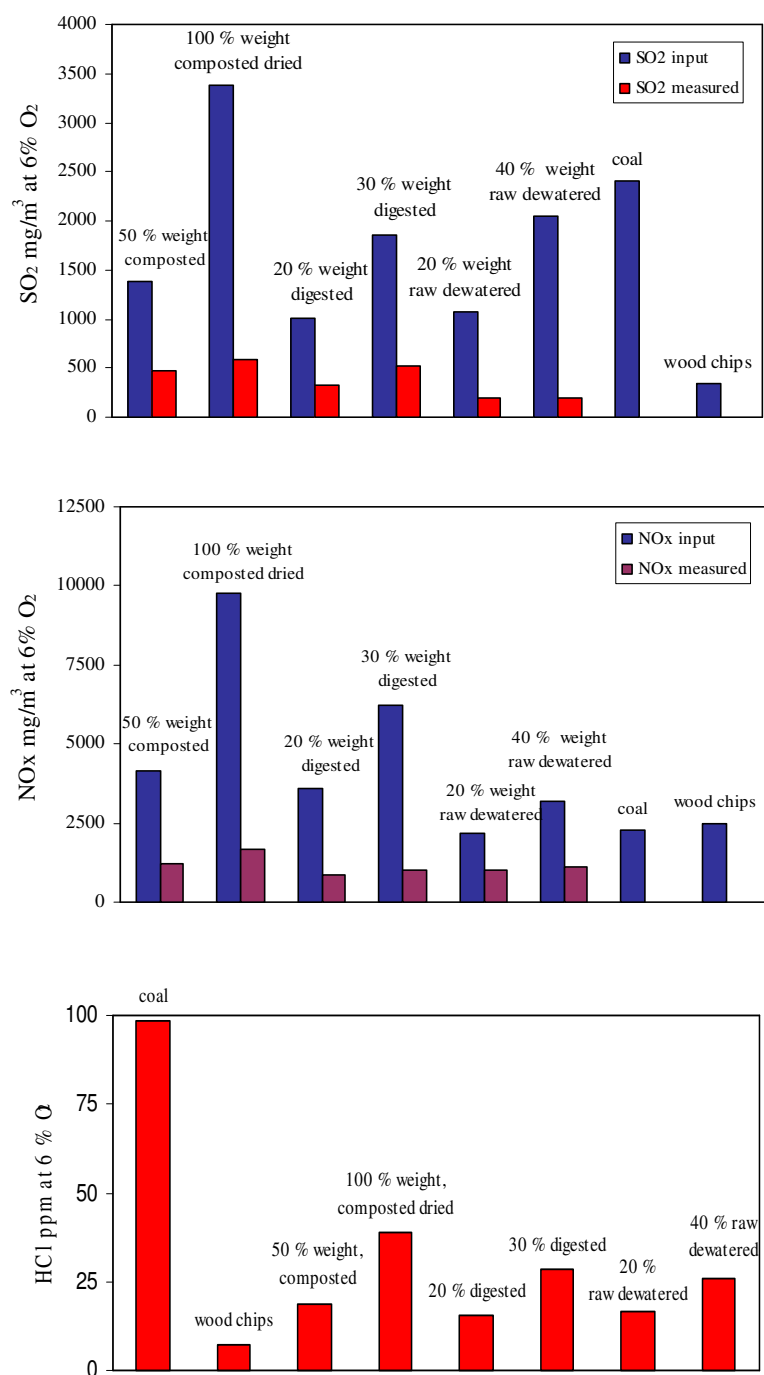


**Figure 19 Schematic of Balance between Gasification and Combustion during gasifier Tests**

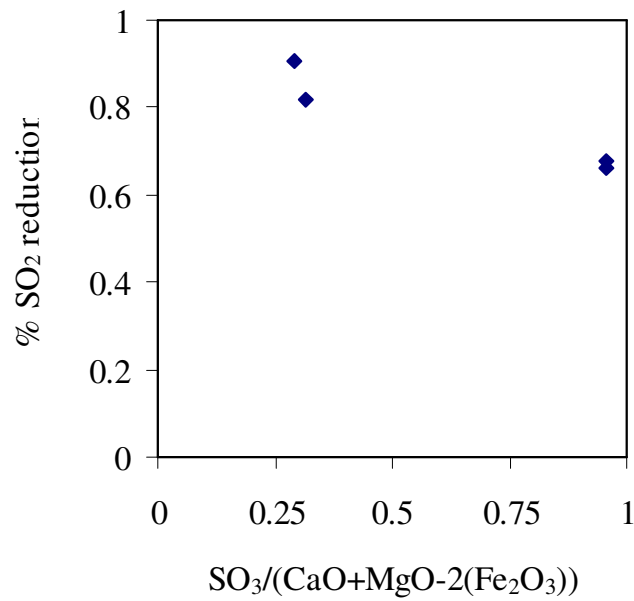


**Figure 20 Schematic of Combustor Gas Sampling Train**

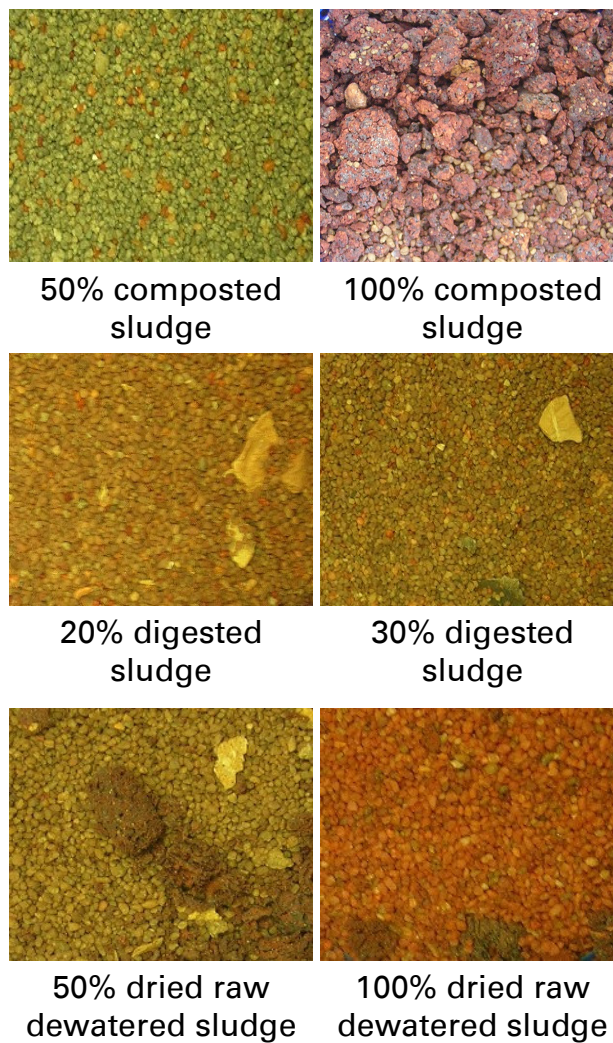




**Figure 21 Emissions comparison for the different experiments carried out in the combustion co-firing experiments (SO<sub>2</sub> and NO<sub>x</sub> input values indicated above are levels of species if all fuel sulphur is converted to SO<sub>2</sub> and all fuel nitrogen converted to NO<sub>x</sub> in flue gas)**

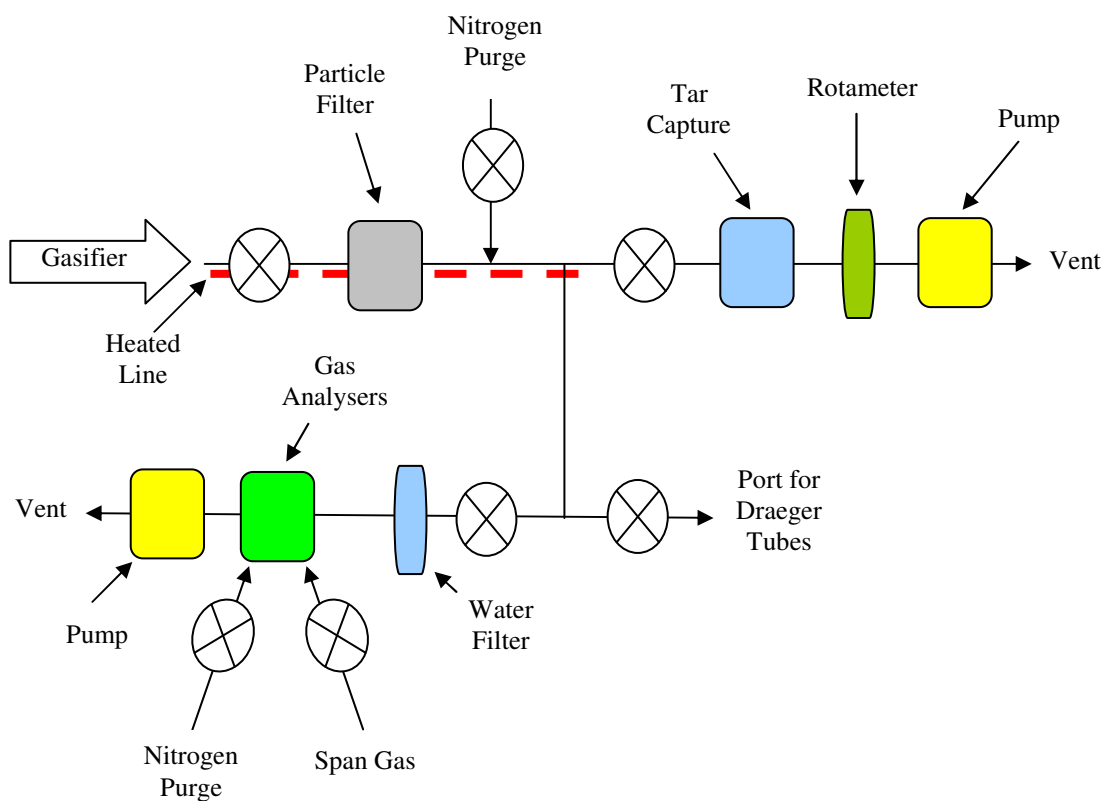


**Figure 22 Influence of  $\text{Fe}_2\text{O}_3$  content of ashes on the active  $\text{CaO} + \text{MgO}$  in sulphur capture**

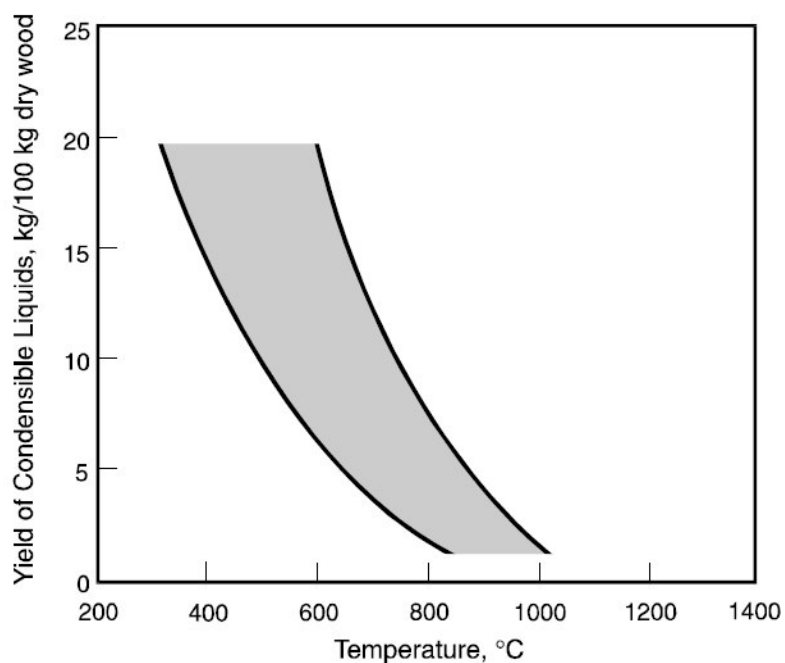


**Figure 23 Photographs of bed material after different experiments**

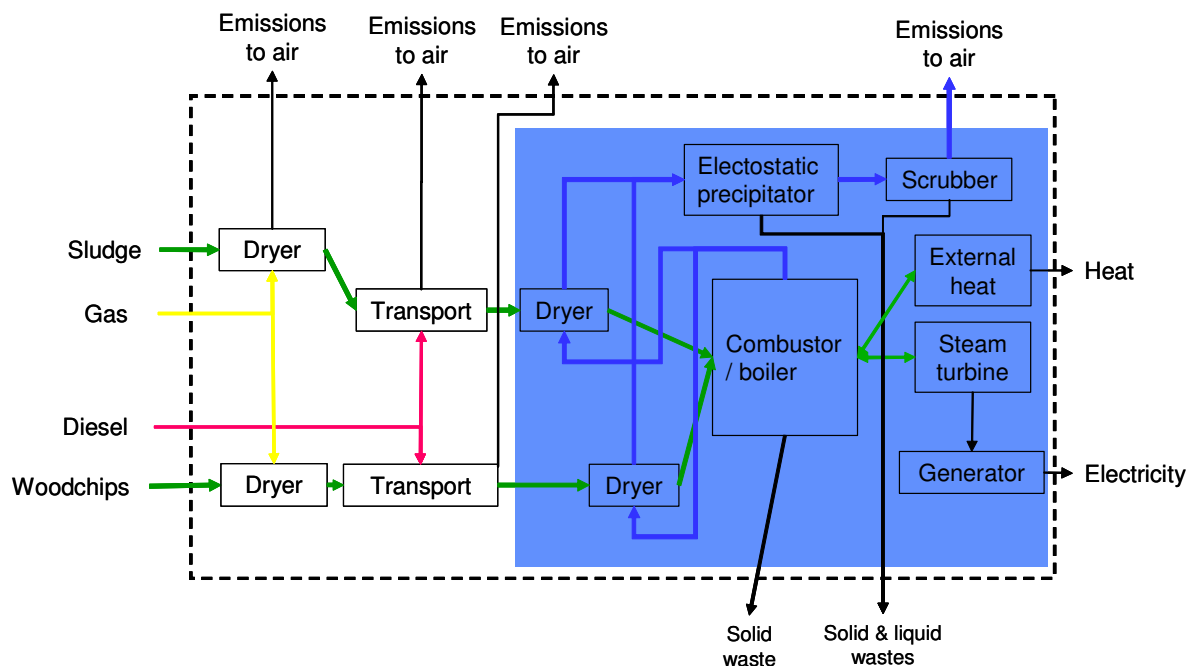




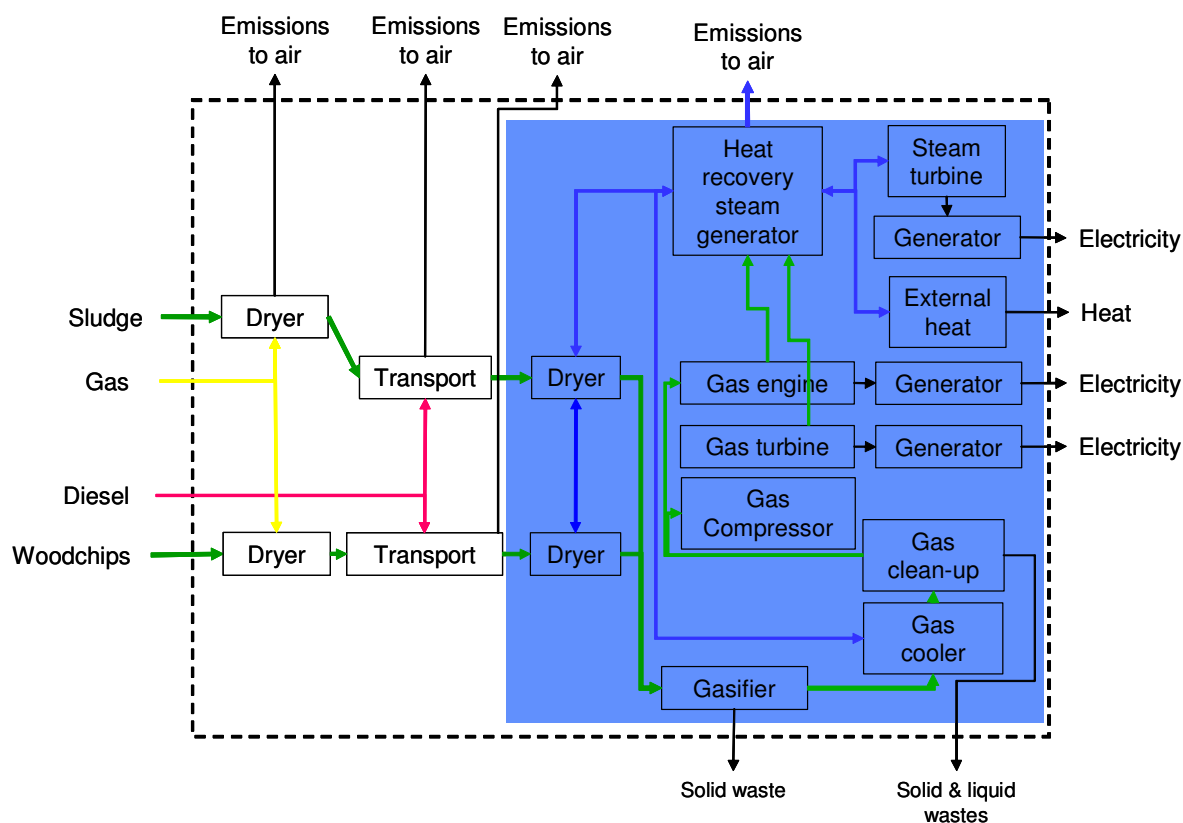
**Figure 24 Schematic of Gasifier Gas Sampling Train**



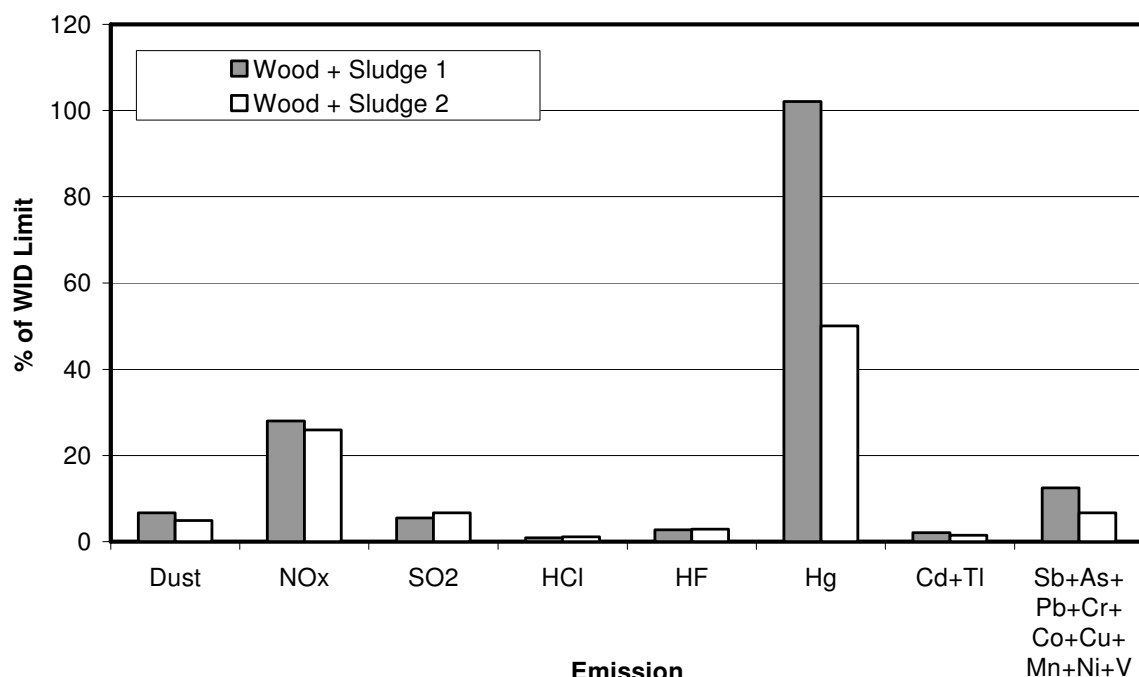
**Figure 25 “Tar” yield as a function of the maximum temperature exposure [37]**



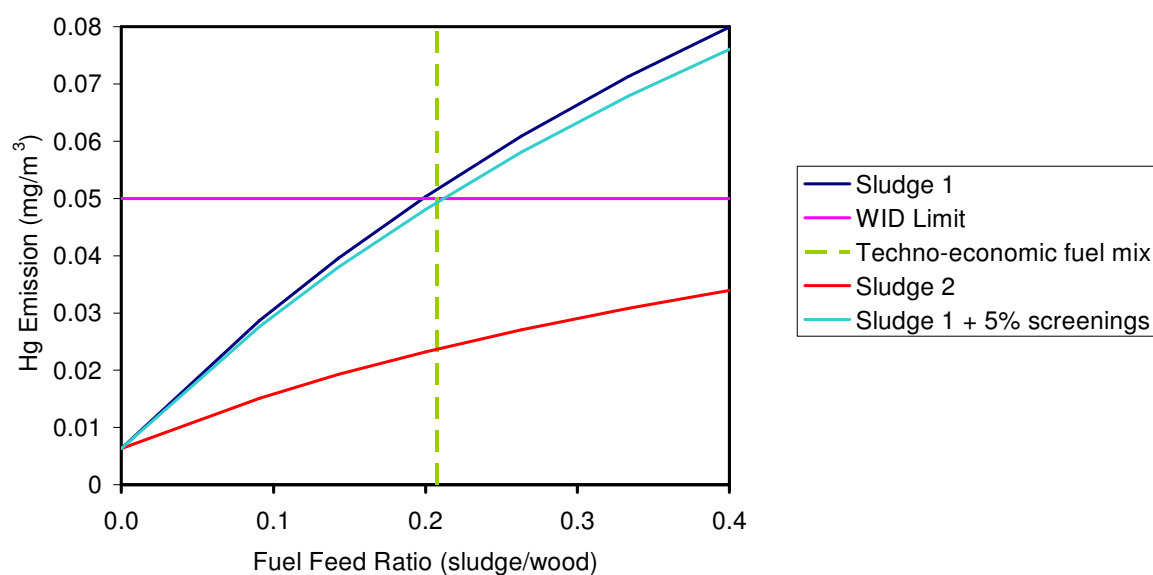
**Figure 26 Schematic representation of combustion mass and energy balance model**



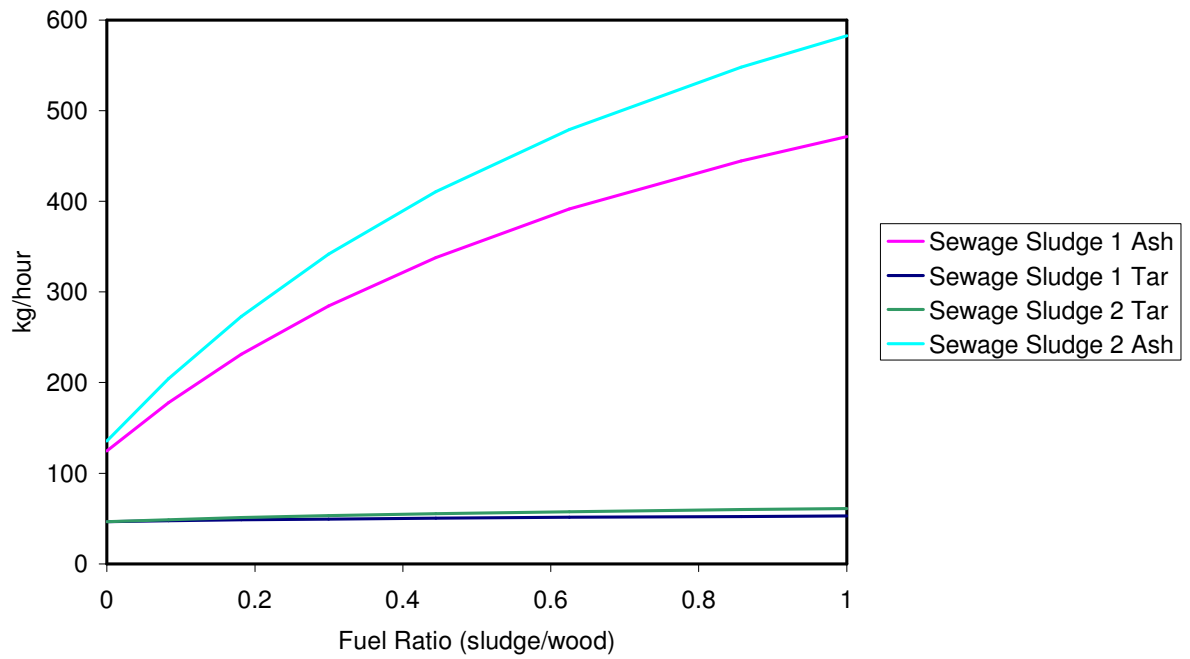
**Figure 27 Schematic representation of gasification mass and energy balance model**



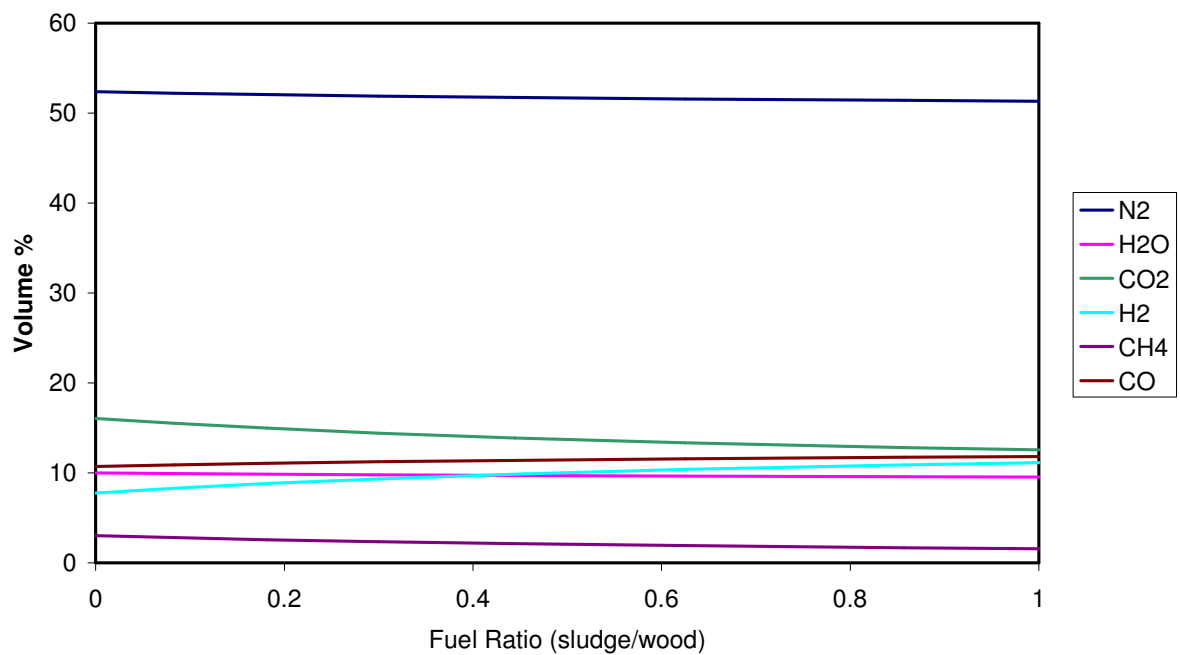
**Figure 28 % of WID limit used by each emission predicted by combustion mass and energy balance model for two sludge/wood fuels at fuel feed ratio (sludge/wood) of 0.2.**



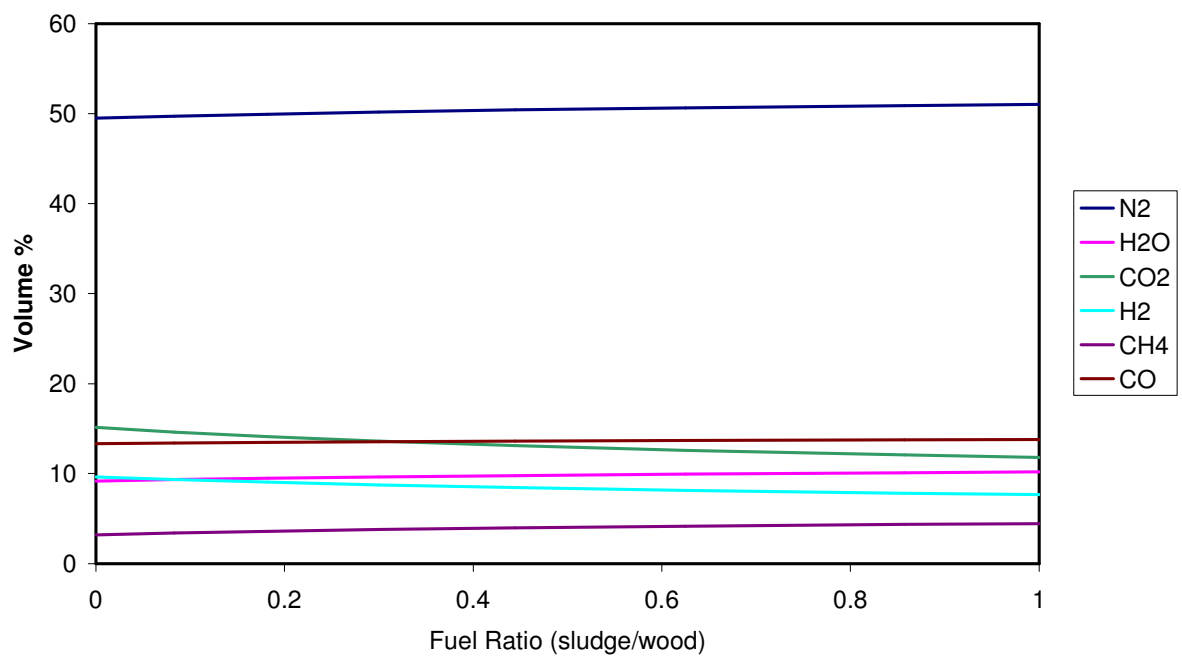
**Figure 29 Mercury Emission versus fuel feed ratio predicted by combustion mass and energy balance model for a number of sludge/wood fuels. Also indicated is the WID limit for mercury and the fuel feed ratio used in the techno-economic model. Data for the fuels modelled are given in Table 39. NOTE - not all fuel feed ratios indicated were viable in this work.**



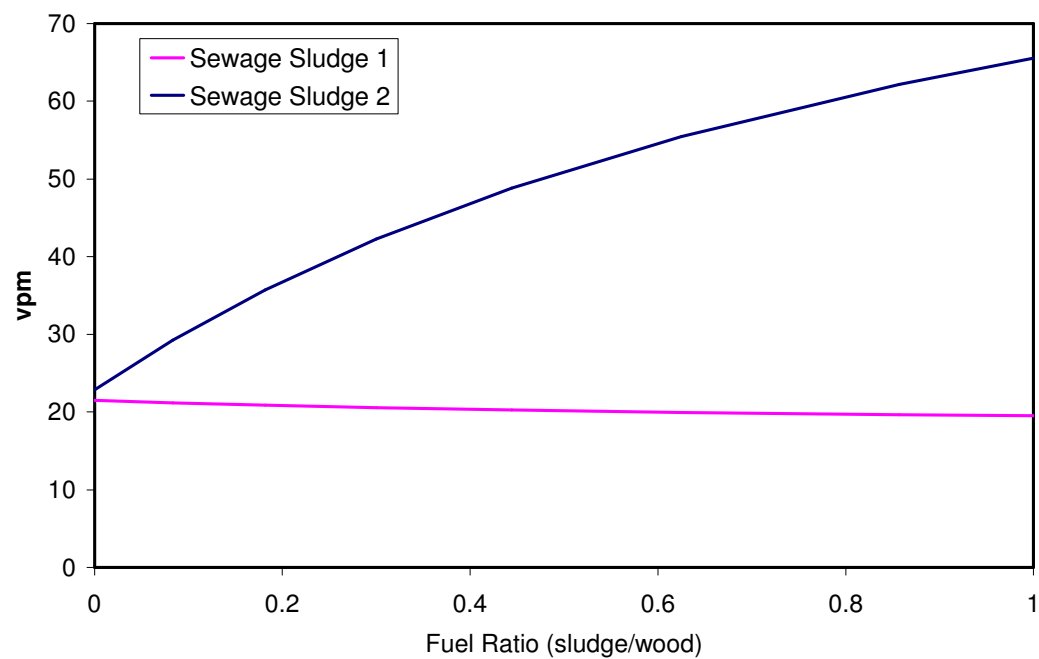
**Figure 30 Tar and ash production versus fuel ratio as predicted by gasifier mass and energy balance model for two sludges.**



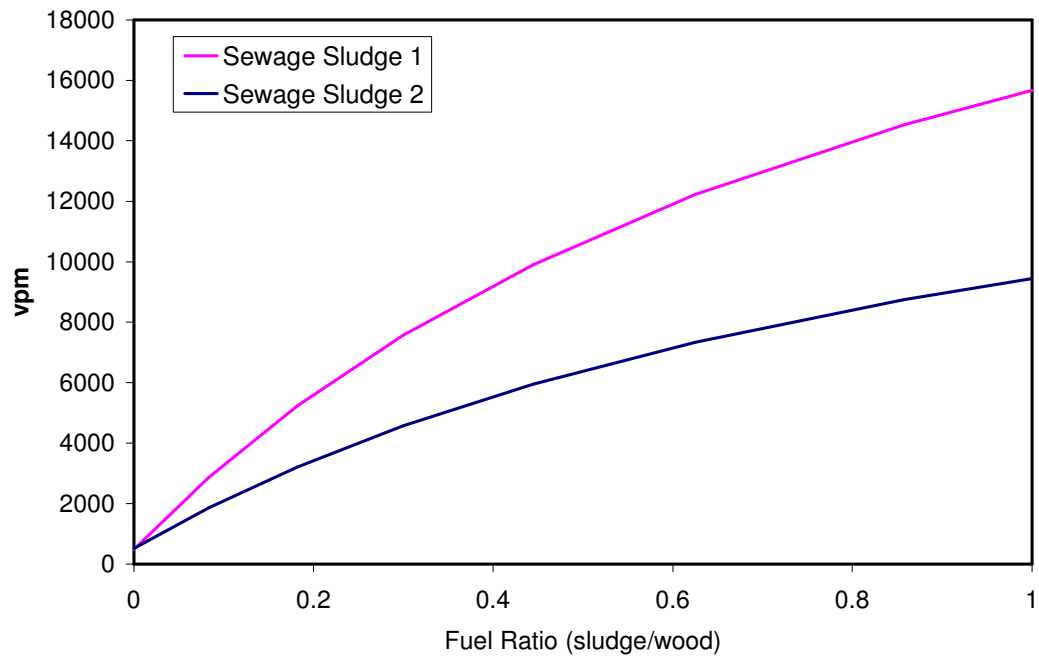
**Figure 31 Bulk gas composition versus fuel ratio as predicted by gasifier mass and energy balance model for sewage sludge 1.**



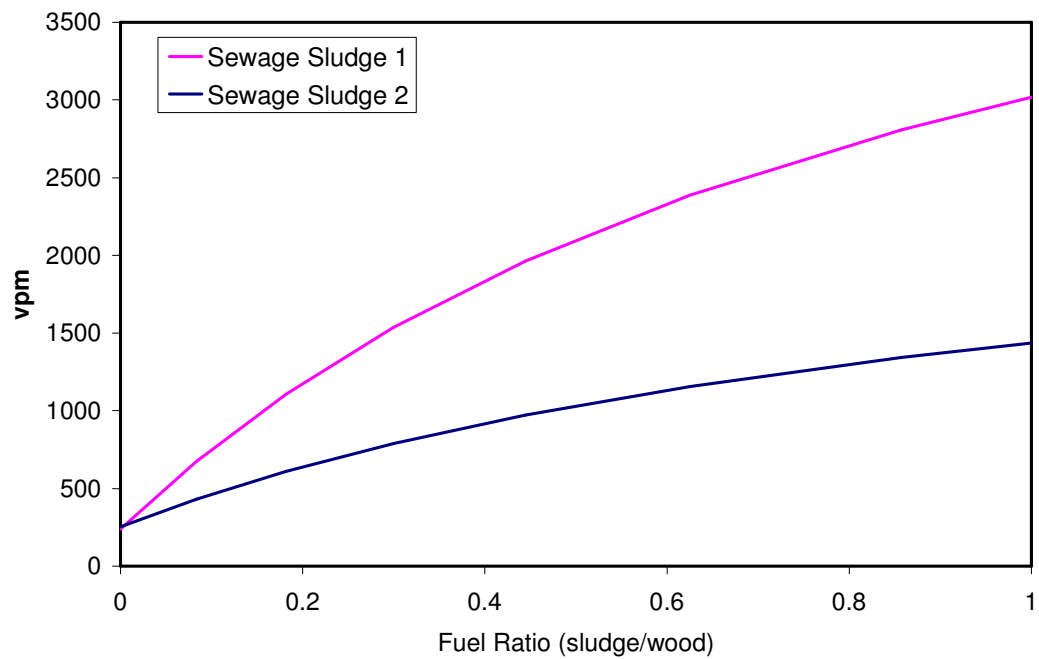
**Figure 32 Bulk gas composition versus fuel ratio as predicted by gasifier mass and energy balance model for sewage sludge 2.**



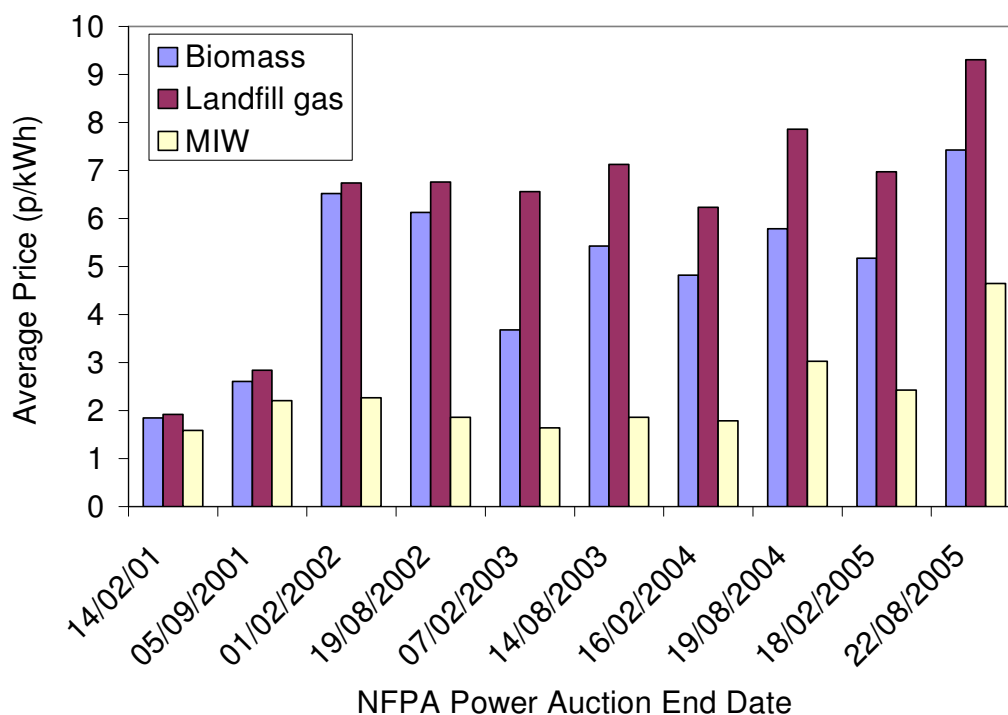
**Figure 33 HCl content of gas versus fuel ratio as predicted by gasifier mass and energy balance model for two sludges.**



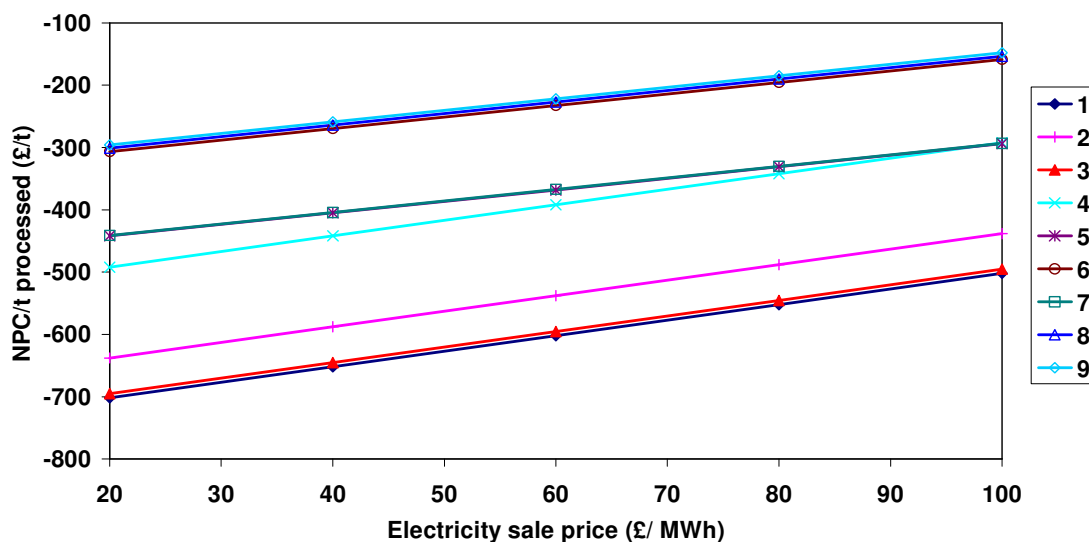
**Figure 34 Ammonia content of gas versus fuel ratio as predicted by gasifier mass and energy balance model for two sludges.**



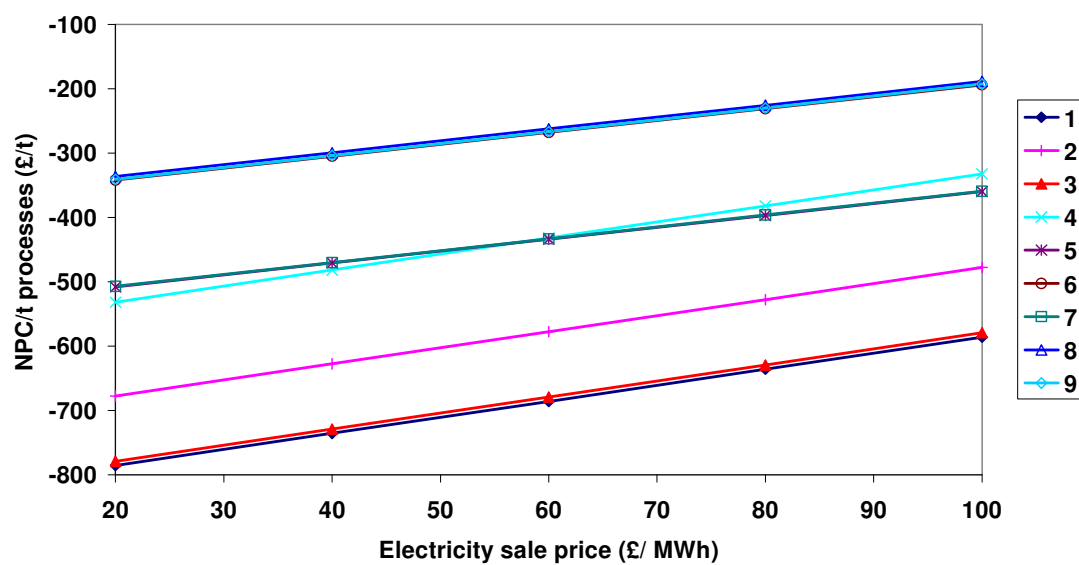
**Figure 35 Hydrogen sulphide content of gas versus fuel ratio as predicted by gasifier mass and energy balance model for two sludges.**



**Figure 36 Average Price for Green Power from NFPA Auctions (MIW is Municipal & Industrial Waste)**



**Figure 37 Effect of Electricity price on NPC/t ds of sludge processed over project life for Digested sludge (see Table 36 for explanation of scenario number in legend).**



**Figure 38 Effect of Electricity price on NPC/t ds of sludge processed over project life for Raw dewatered sludge (see Table 36 for explanation of scenario number in legend).**



## APPENDIX 1 – GLOSSARY OF TERMS

AD	Anaerobic digestion
Ash fusion	see appendix 3
ar	As received
B(a)P	benzo(a)pyrene
CAPEX	Capital expenditure
CCA	Climate change Agreements
CCL	Climate change levy
CHP	Combined heat and power
CV	Calorific Value of a fuel is the quantity of heat produced by its combustion at standard conditions.
DAF or daf	Dry Ash Free basis is an analysis expressed on the basis of a sample from which the total moisture and the ash have been removed
DAF CV	The Dry Ash Free (DAF) Calorific Value refers to the fuel when dry and without the ash.
db	dry basis is an analysis expressed on the basis of a sample from which the total moisture has been removed.
dm	Dry matter
EfW	Energy from Waste
EPC	Engineering, Procurement and Construction - The EPC cost is the cost to the owner of building the facility, on top of which the costs of land, development, electrical connection, interest during construction and financing costs have to be added to come up with a total project cost.
GCV	Gross Calorific Value (or Higher Calorific Value) supposes that the water of combustion is entirely condensed and that the heat contained in the water vapour is recovered.
GHV	Gross Heating Value – same as GCV
HHV	Higher Heating Value – same as GCV
HHV <sub>Milne</sub>	Calculated HHV using Milne formula: $\text{HHV}_{\text{Milne}} = 0.341C + 1.322H - 0.12O - 0.12N + 0.0686S - 0.0153\text{ash}$ where C, H, etc. are the mass and the ash fractions in wt% dry and HHV in MJ/kg. Using the hydrogen and ash fractions (wt% dry) and moisture fraction (wt% ar) other HHV's and LHV's can be calculated.
IGCC	Integrated gasification combined cycle
LHV	Lower Heating Value – same as NCV
MAD	Mesophilic anaerobic digestion
MIW	Municipal & Industrial Waste
MSW	Municipal solid waste

NCV	Net Calorific Value (or Lower Calorific Value) supposes that the products of combustion contain the water vapour. The heat contained in the water vapour is not recovered.
NETA	New energy trading arrangements
NHV	Net Heating Value – same as NCV
NPC	Net Present Cost
PAH	Polycyclic Aromatic Hydrocarbon
PCDD/F	Polychlorinated dioxins and furans
pe	Population equivalent
RDF	Refuse derived fuel
SCR	Selective catalytic reaction
SRC	Short rotation coppice
tds	Tonnes of dry solids
TOC	Total Organic Carbon
VM	Volatile matter
WID	Waste incineration directive
wt	weight
WwTW	Waste water treatment works

## APPENDIX 2 – ASH ELEMENTAL OXIDE DATA

**Table A2-1 Ash elemental oxide analysis (mg/kg as received) for co-firing test fuels (\*values calculated from ash elemental data – Table 26)**

Compound (%)	Coal	Wood Chip		Composted sludge		Digested sludge	
SiO <sub>2</sub>	40.1*	7.7*	12.8	21.2*	20.3	26.5*	29.4
Al <sub>2</sub> O <sub>3</sub>	23.2*	3.0*	5.2	8.3*	7.5	10.5*	8.8
Fe <sub>2</sub> O <sub>3</sub>	16.5*	4.8*	0.9	25.2*	22.5	25.4*	21.4
TiO <sub>2</sub>	0.6*	0.8*	0.3	1.1*	0.9	1.2*	1.1
CaO	9.1*	46.7*	44.7	18.8*	18.3	14.9*	13.5
MgO	3.1*	6.1*	3.7	1.3*	1.1	2.0*	1.8
Na <sub>2</sub> O	1.3*	2.9*	0.6	0.3*	0.3	0.5*	0.4
K <sub>2</sub> O	2.5*	8.9*	7.2	0.8*	0.9	1.0*	1.4
P <sub>2</sub> O <sub>5</sub>	3.5*	19.1*	8.3	23.0*	22.8	18.0*	17.4

**Table A2-1 Continued**

Compound (%)	Raw dewatered		Raw dried pellets		Screenings	
SiO <sub>2</sub>	20.8*	22.6	26.6	25.8	17.3	26.3
Al <sub>2</sub> O <sub>3</sub>	8.7*	8.9	9.8	9.7	6.8	6.1
Fe <sub>2</sub> O <sub>3</sub>	23.0*	10.5	22.2	21.6	5.3	7.5
TiO <sub>2</sub>	1.2*	0.9	1	1.1	6.8	3.7
CaO	20.3*	20.5	12.3	13	28	28.9
MgO	1.2*	2.1	2.2	2.2	2.5	2.3
Na <sub>2</sub> O	0.3*	0.4	0.4	0.4	1.6	1.1
K <sub>2</sub> O	0.6*	2.8	1.1	1	1.1	2.6
P <sub>2</sub> O <sub>5</sub>	23.9*	21	18.7	20.5	16.6	13.1

**Table A2-2 Ash elemental oxide analysis from the fly ash samples in the co-firing experiments. Analysis basis: As analysed (mg/kg). (% values (by weight) refer to amount of sludge, screenings etc. in blend, balance is willow wood chip). (\*values calculated from ash elemental data – Table 30)**

Compound (%)	Composted sludge		Digested sludge		Raw dewatered		
	50%	100%	20%	30%	20%	30%	40%
SiO <sub>2</sub>	24.1*	27.9*	11.8*	19.8*	20.3	22.1	21.5
Al <sub>2</sub> O <sub>3</sub>	8.5*	8.7*	5.2*	7.5*	7.4	7.5	7.6
Fe <sub>2</sub> O <sub>3</sub>	19.7*	20.5*	9.8*	16.8*	15.2	14.2	16.3
TiO <sub>2</sub>	0.9*	0.8*	0.4*	0.7*	0.7	0.7	0.8
CaO	22.0*	19.3*	63.8*	37.2*	29.6	19.7	25.9
MgO	1.7*	1.4*	0.8*	1.5*	1.6	2	1.5
Na <sub>2</sub> O	0.5*	0.5*	0.2*	0.4*	0.5	0.5	0.5
K <sub>2</sub> O	3.5*	3.3*	1.6*	2.5*	2.6	3.7	2.6
P <sub>2</sub> O <sub>5</sub>	19.2*	17.5*	6.5*	13.6*	13.2	16.5	15.4

**Table A2-2 Continued**

Compound (%)	Dried raw dewatered		Screenings	
	50%	100%	20%	40%
SiO <sub>2</sub>	25	21.4	21.6	27.3
Al <sub>2</sub> O <sub>3</sub>	8.8	10.9	8.5	8.8
Fe <sub>2</sub> O <sub>3</sub>	20.7	19.5	18.2	20
TiO <sub>2</sub>	1	1.2	1.2	1
CaO	16.3	16	19.1	12.8
MgO	2	2.3	2.6	2
Na <sub>2</sub> O	0.5	0.4	0.4	0.5
K <sub>2</sub> O	2	1.4	1.6	1.6
P <sub>2</sub> O <sub>5</sub>	19.2	20.5	17.5	17.2

**Table A2-3 Ash elemental oxide analysis from the gasifier char samples in the co-firing experiments. Analysis basis: As analysed (mg/kg). (% wt values refer to amount of sludge, screenings etc. in blend, balance is willow wood chip).**

Compound (%)	Composted sludge	Screenings	Digested sludge	Raw dried pellets			Raw dewatered sludge	
	100%	20%	20%	30 %	50 %	100 %	30 %	50 %
SiO <sub>2</sub>	24.7	27.8	25.6	27.2	23.6	26.4	24.9	27.7
Al <sub>2</sub> O <sub>3</sub>	6.3	9.6	9.9	8.6	7.7	9.5	8.6	9.6
Fe <sub>2</sub> O <sub>3</sub>	23.7	20.4	20.5	20.3	18.5	20.5	18.5	19.3
TiO <sub>2</sub>	0.7	1	1.1	1	0.8	1.0	0.9	0.9
CaO	12	11.1	11.3	14.1	15.1	11.1	12.9	15.1
MgO	1.2	2.1	2.1	2.4	2.3	2.1	2.3	1
Na <sub>2</sub> O	0.4	0.5	0.5	0.5	0.5	0.5	0.6	0.3
K <sub>2</sub> O	0.8	1.1	1.1	3	3	1.1	3.3	0.7
P <sub>2</sub> O <sub>5</sub>	16.9	17.4	18.1	18.8	17.3	17.6	17.1	18.8

### APPENDIX 3 – ASH FUSION TEST

Standard ash fusion test methods have been developed to investigate the fusion properties of coal ash [1-5]. The tests involve heating the ash at a specified rate in controlled mildly reducing or oxidizing atmospheres generally over a temperature range of 900°C to 1600°C. Each standard test uses ash formed into a defined shape of specified dimensions (ASTM, BS, ISO [1-3] use triangular pyramids (cones) with height 12mm and base 6mm). The temperatures at which a number of defined stages of fusing and flow occur are recorded, normally the initial deformation temperature, softening temperature, hemisphere temperature and fluid (flow) temperature. These temperatures when recorded using a reducing atmosphere (CO present) are generally lower or equal to those recorded with an oxidizing atmosphere (like air). This can be due to the oxidation behaviour of iron atoms. Reduced iron lowers the melting and fusion temperatures of ash much better than the oxidized form. Of the characteristic temperatures the initial deformation and flow are generally the most difficult to reproduce.

There are not distinct melting points for ash so as temperature increases there is a decrease in viscosity. When ash 'melts' it occurs on both a large scale and a microscopic scale. On the large or bulk scale the ash behaves like a glass. As the temperature of the material increases, its viscosity decreases. On a microscopic scale several minerals may have all ready melted, but their concentrations are low when compared to other minerals with higher melting temperatures. As the temperature is increased the ash becomes less viscous or more liquid like. Many reactions are now occurring between the minerals as they melt and become more fluid. As the molten components mix they become more like molten glass. This molten material starts to dissolve the non molten materials like quartz and other minerals. In this way the melting temperature of minerals such as sandstones and shales are lowered by other minerals such as pyrite and limestone. It should be noted that even at the fluid temperature there may be solid or non-melted minerals such as quartz.

- [1] ASTM D1857-04 - Standard Test Method for Fusibility of Coal and Coke Ash
- [2] BS 1016-113:1995 - Methods for the Analysis and Testing of Coal and Coke - Determination of ash fusibility
- [3] ISO 540:1995 - Solid mineral fuels - Determination of fusibility of ash - High-temperature tube method
- [4] DIN 51730 - Determination of fusibility of fuel ash
- [5] AS 1038 – Coal and coke – Analysis and testing

#### APPENDIX 4 – FULL RAW TAR DATA

Target Analytes mg/l	Raw dried Pellets		Raw Dewatered		Digested		Screenings	
	100%	30%	20%	40%	20%	30%	20%	40%
Solvent volume (cm <sup>3</sup> )	600	600	400	400	600	400	600	400
Gas capture volume (Nm <sup>3</sup> )	0.1	0.05	0.09	0.06	0.1	0.05	0.1	0.08
Phenol	<20	29.4	45.2	56.3	35.2	<10	15.4	20.9
bis(2-Chloroethyl)ether	<5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
2-Chlorophenol	<20	<10	<10	<10	<10	<10	<10	<10
1,3-Dichlorobenzene	<5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
1,4-Dichlorobenzene	<5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
Benzyl alcohol	<5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
1,2-Dichlorobenzene	<5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
2-Methylphenol	<5	8.3	12.9	16.0	10.0	<2.5	3.8	5.0
bis(2-Chloroisopropyl)ether	<5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
Hexachloroethane	<5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
N-Nitroso-di-n-propylamine	<5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
3- & 4-Methylphenol	<20	16.5	16.5	21.8	16.8	<10	<10	<10
Nitrobenzene	<5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
Isophorone	<5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
2-Nitrophenol	<20	<10	<10	<10	<10	<10	<10	<10
2,4-Dimethylphenol	<20	<10	<10	<10	<10	<10	<10	<10
Benzoic Acid	<100	<50	<50	<50	<50	<50	<50	<50
bis(2-Chloroethoxy)methane	<5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
2,4-Dichlorophenol	<20	<10	<10	<10	<10	<10	<10	<10
1,2,4-Trichlorobenzene	<5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
Naphthalene	37.0	22.2	96.8	92.9	39.6	30.5	37.0	84.8
4-Chlorophenol	<20	<10	<10	<10	<10	<10	<10	<10
4-Chloroaniline	<5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
Hexachlorobutadiene	<5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
4-Chloro-3-methylphenol	<5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
2-Methylnaphthalene	4.5	6.0	24.9	27.9	8.7	6.9	6.6	13.0
1-	4.3	4.5	18.0	19.9	6.9	4.9	4.9	9.1

Methylnaphthalene								
Hexachlorocyclopentadiene	<5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
2,4,6-Trichlorophenol	<20	<10	<10	<10	<10	<10	<10	<10
2,4,5-Trichlorophenol	<20	<10	<10	<10	<10	<10	<10	<10
2-Chloronaphthalene	<2	<1	<1	<1	<1	<1	<1	<1
Biphenyl	2.2	2.4	6.6	8.1	3.6	2.1	3.1	5.4
Diphenyl ether	<2	<1	<1	<1	<1	<1	<1	<1
2-Nitroaniline	<5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
Acenaphthylene	3.8	6.0	17.1	23.6	6.8	6.4	9.6	13.6
Dimethylphthalate	<5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
2,6-Dinitrotoluene	<5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
Acenaphthene	<2	<1	1.4	1.8	<1	<1	<1	<1
3-Nitroaniline	<5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
2,4-Dinitrophenol	<10	<5	<5	<5	<5	<5	<5	<5
Dibenzofuran	<5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
4-Nitrophenol	<50	<25	<25	<25	<25	<25	<25	<25
2,4-Dinitrotoluene	<5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
Fluorene	<2	1.1	3.1	4.3	1.7	1.0	2.5	1.8
Diethylphthalate	<5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
4-Chlorophenylphenylether	<5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
4,6-Dinitro-2-methylphenol	<50	<25	<25	<25	<25	<25	<25	<25
4-Nitroaniline	<5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
N-Nitrosodiphenylamine	<5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5

#### APPENDIX 4 – FULL RAW TAR DATA CONTINUED

Target Analytes mg/l	Raw dried Pellets		Raw Dewatered		Digested		Screenings	
	100%	30%	20%	40%	20%	30%	20%	40%
Solvent volume (cm <sup>3</sup> )	600	600	400	400	600	400	600	400
Gas capture volume (Nm <sup>3</sup> )	0.1	0.05	0.09	0.06	0.1	0.05	0.1	0.08
Phenanthrene	<2	1.2	4.5	6	2.7	1.6	3.2	3.6
Anthracene	<2	<1	1.4	1.9	<1	<1	<1	<1
Di-n-butylphthalate	<5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
Fluoranthene	<2	<1	1.3	1.6	<1	<1	<1	1.1



Pyrene	<2	<1	1.3	1.6	<1	<1	<1	1.0
Butylbenzylphthalate	<5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
Benzo[a]anthracene	<2	<1	<1	<1	<1	<1	<1	<1
Chrysene	<2	<1	<1	<1	<1	<1	<1	<1
3,3'-Dichlorobenzidine	<20	<10	<10	<10	<10	<10	<10	<10
bis(2-Ethylhexyl)phthalate	<5	5.2	4.0	4.0	121.9	<2.5	5.3	<2.5
Di-n-octylphthalate	<2	<1	<1	<1	<1	<1	<1	<1
Benzo[b]fluoranthene	<2	<1	<1	<1	<1	<1	<1	<1
Benzo[k]fluoranthene	<2	<1	<1	<1	<1	<1	<1	<1
Benzo[a]pyrene	<2	<1	<1	<1	<1	<1	<1	<1
Indeno[1,2,3-cd]pyrene	<2	<1	<1	<1	<1	<1	<1	<1
Dibenzo[a,h]anthracene	<2	<1	<1	<1	<1	<1	<1	<1
Benzo[g,h,i]perylene	<2	<1	<1	<1	<1	<1	<1	<1