Comparison of thermal destruction technology for complete biosolids processing

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Abstract

Sewage sludge production is rising around the world. This is due to population growth, stricter legislation, and new investment in wastewater infrastructure. Whilst, typically considered a nuisance, sludge has numerous benefits which can be exploited, such as the reuse of nutrients or extraction of energy. Previously in Europe, reluctance for land recycling of sludge coupled with cheap energy led to the development of sludge treatment strategies which were heavily reliant on energy intensive processing. However, increasing energy costs, mounting importance of nutrient recovery and growing influences of sustainability have led to the development of new sludge strategies. This paper highlights a number of case study options available for sludge and includes results of a study looking at optimal energy recovery strategies. The study suggests that use of anaerobic digestion is preferable (to no use) when dewatered cake is processed further for energy recovery (for example co-firing at power station) with regards to overall energy balance. When drying options are also considered, use of anaerobic digestion with thermal hydrolysis gives the greatest overall energy recovery potential. This is due to a large decrease in drying requirements as a result of greater solids destruction (less to dry) coupled with better dewaterability (less water to evaporate). Drying and energy recovery of raw sludge gives a negative energy balance.

Keywords

Sewage sludge; anaerobic digestion; incineration; super critical wet air oxidation; co-digestion; biomethane

INTRODUCTION

Sewage sludge, an inevitable by-product of wastewater treatment, is a valuable renewable resource. Not only does it contain energy which can be recovered in various ways, but it also contains important nutrients which can be used to displace fossil-fuel rich fabricated fertilisers. However, in spite of its value, legislation surrounding its use varies widely resulting in some cases, the requirement of increasingly energy and carbon intensive processing. The production of sludge is increasing worldwide. As well as a growing population and greater urbanisation requiring wastewater treatment, the rise in sludge generation is also fundamentally influenced by tightening environmental legislation. Using published data, sludge generation can be anything between 10 and 75 grams/person/day depending on quantity of infrastructure installed.

Sludge is formed during wastewater treatment and exists in a number of forms which have different properties (see Table 1 later). Figure 1 shows a standard configuration of a wastewater treatment plant. Typically wastewater, industrial effluent and run-off enter a sewage works where they are initially screened prior to going to onto primary treatment. During this stage solids and other material settle out and these form what is known as primary sludge. The supernatant from this stage passes to a second stage of treatment where nutrients are removed from the wastewater. This is achieved via a number of facultative and aerobic bacteriological reactions in the presence of air or oxygen and is accomplished in a large variety of configurations. The effluent leaving this process is generally clean enough for discharge; otherwise a tertiary stage may be added (not shown). The solid material leaving this secondary treatment stage constitutes mainly bacteriological material and is known via a number of names including: secondary; bacteriological; waste or surplus activated sludge (WAS or SAS). Other variations of wastewater treatment include: Biological Nutrient Removal (BNR) and phosphorous precipitation using a variety of compounds. Both of these processes lead to further types of sludge. Once formed, sludge is typically thickened to approximately 5% solids prior to further treatment. This dry solids content is typical due to the non-newtonian flow characteristics which make handling of sludge infinitely more difficult as it becomes progressively thicker (Dawson, *et al.*, 2009). Following the thickening process, sludge can be processed via a myriad of ways, some of which are shown in Figure 2.

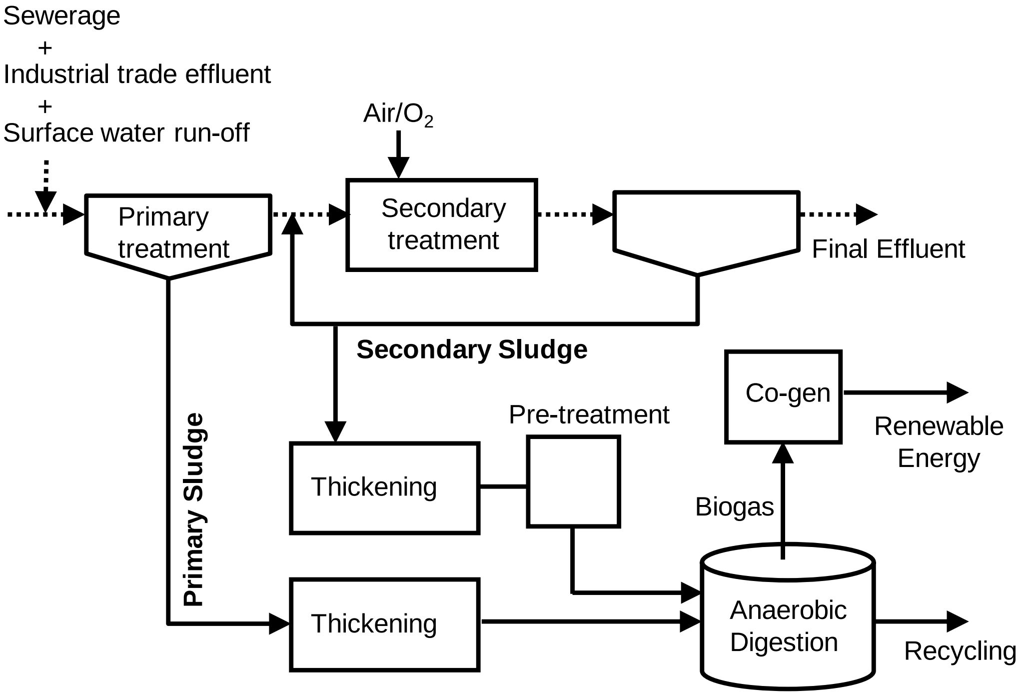

Figure 1. Typical layout of a wastewater treatment plant

Biosolids Trends

Several factors and trends have resulted in the increase of sludge volumes in Europe and the UK, including implementation of the European Union’s Urban Waste Water Treatment Directive (UWWTD – 91/271/EEC) and similar legislation, however, the options available for sludge recycling on land (as shown in Figure 2) have become more restrictive. Strict rules on nitrogen application; concerns over metals and organic compounds; changes to farming practices; public perception, and reduction in brownfield reclamation have historically limited this recycling option in Europe. Consequently, Water Utilities in the UK generated sludge treatment strategies to reduce reliance (and therefore risk) of land application of biosolids. This, along the traditionally available cheap energy prices ten years ago, resulted in developing approaches to sludge management involving energy intensive technologies such as drying.

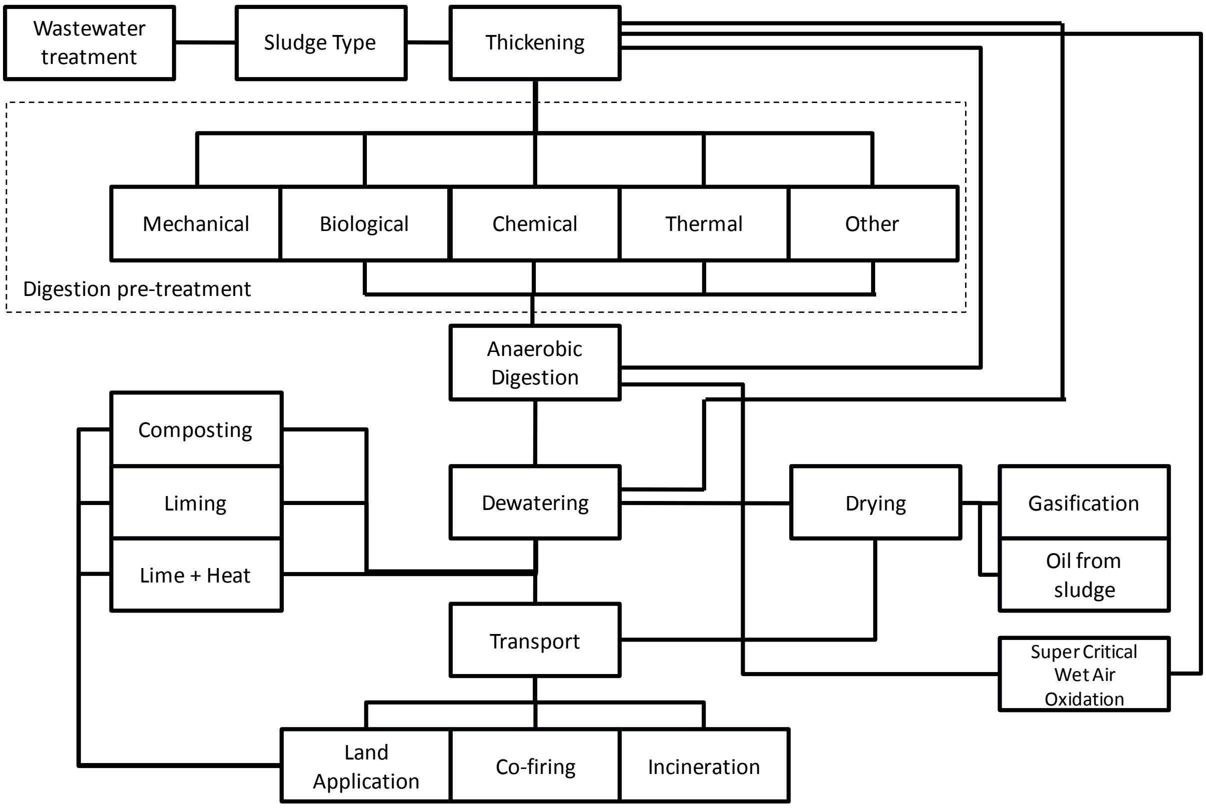

Figure 2. Some of the treatment options available for sewage sludge

However, in subsequent years a number of the drivers have evolved with sustainability and carbon impact becoming more prominent in decision making. Being heavily reliant on fossil-fuels, the cost of fertilizer has also increased significantly making treated sludge more economically attractive in the short term. Phosphorous, which is vital to food production, is in dwindling supply. Various estimates put the reserves of (easily mined) phosphorous at anything from as little as 30 to 100 years. Global demand for phosphorous is following an opposite trend as countries change eating habits resulting in more intensive farming practices which require increasing amounts of phosphorous fertiliser. China has placed a self imposed export tax on its phosphorous of between 7 and 110% in excess of base price (Xiamen Terrabetter Chemical Co. Limited) to discourage its export. In addition, whilst sludge treatment emits greenhouse gases, fertilizer manufacturing generates carbon footprint by consuming fossil fuels. Published work (Kroiss and Zessner, 2007) has shown that every 1 kg N fertilizer requires approximately 10 kWhr of energy during manufacture. In the meantime, world energy prices are continuing to increase significantly. Oil has topped $100 USD/barrel and this has made energy intensive sludge processing options very expensive to maintain. In combination with the factors mentioned above, these have caused a revision of their original strategies for the UK Water Companies. The Water Companies have now moved away from energy intensive processing (especially drying) to lower energy processes involving enhanced anaerobic digestion with increased recycling of treated sludge to land (Riches *et al.*, 2010; Bowen *et al*., 2010; Barber, 2009b).

Energy in sludge

Sewage sludge comprises a number of volatile and inert components. The volatile fraction is primarily composed of carbon, hydrogen, oxygen, nitrogen and sulphur, whilst the inert fraction may contain a number of metals such as iron, copper, nickel, selenium and others (Metcalf and Eddy, 2004). From knowledge of the composition of the volatile fraction it is possible to determine various characteristics such as molecular formula and its energy content (Barber, 2007). An analysis of this data for primary, secondary and mixed sludge is shown in Table 1. The data in this table have been determined from over 100 measurements of both elemental analysis and calorific value.

Table 1. Sludge composition and energy data

		Primary Sludge	Secondary Sludge	Mixed Sludge
Molecular Formula		$C_{23}H_{35}O_8N$	$C_7H_{11}O_3N$	$C_{13}H_{20}O_5N$
Calorific Value of volatile fraction	[kJ/kg VS*]	25,700	21,800	23,400
COD equivalence		1.91	1.53	1.75
Biogas composition	[%CH_4:%CO_2]	63:37	68:32	64:36
Biogas Yield	[Nm^3/kg CODdestroyed]	1.06	0.78	0.95

The energy values given in Table 1 refer to the energy contained within the volatile fraction. The quantity of inert material in sludge differs depending on global region. For instance, European and North American sludge usually contains approximately 25% inerts compared with (occasionally) as little as 10 – 15% in Australasian sludge and as much as over 50% for Chinese sludge. Assuming European properties, the energy content of sludge inclusive of the inert fraction is therefore in the region of 17,500 kJ/kg dry solids of sludge. This compares favourably with a number of materials such as: lignite (16,500 kJ/kg); domestic waste (<14,000 kJ/kg), or glycerine (19,000 kJ/kg).

Energy extracted from sludge is considered renewable and can therefore attract a number of financial incentives whilst simultaneously reduce carbon footprint by displacing fossil fuel energy. This energy is generally extracted via production of methane rich biogas (see Table 1) produced during anaerobic digestion and/or thermal treatment. With thermal treatment, the sludge is either burnt directly for energy with or without other fuels or dried prior to energy recovery.

Energy generation – Anaerobic Digestion

Anaerobic digestion is an intricate compilation of series and parallel biological reactions which degrade the organic material within the sludge into a methane-rich biogas in the absence of oxygen. The biogas is typically converted to electricity and heat using gas engines via co-generation. However, the gas can also be further processed to meet natural gas standards enabling it to be injected directly to the gas grid. Once upgraded in this fashion, biogas is known as biomethane.

A number of gas clean-up technologies exist in various forms of development. These include: water wash; amine wash (common in Germany); cryogenic; pressure swing adsorption, and (lesser developed) membrane systems (Brown, 2010). Whilst the technology to produce biomethane is well established and used extensively in some parts of Europe, a number of legislative issues exist in other counties which can potentially hamper its widespread application. These issues are compounded by different European States having significantly different biomethane standards (Huguen & Le Saux, 2010; Edgington & Tattersall, 2010). As well as grid injection, biomethane can be compressed and used in vehicles, and both of these applications are well established in Northern Europe and the UK is seeing its first two installations near London and in Manchester (New Energy Focus, 2010; Edgington & Tattersall, 2010).

The use of anaerobic digestion in the Water Industry can be traced back over a hundred years. However, the original driver for its use was not one of energy generation, but one of sewage stabilisation. Subsequently, the designs of sewage digestion plants are typically not-optimised for energy generation, or by default, carbon footprint reduction. In spite of this, use of the technology in the UK Water Industry has enabled it to provide a tenth of its energy requirement as renewable energy, a figure which far exceeds both, the renewable generation of other industries and also government targets for renewable generation (Water UK, 2007). The performance of anaerobic digestion is normally described by its ability to destroy the volatile (energy containing) component of the sewage sludge. This is known as volatile solids destruction or reduction and may be calculated in a variety of ways. Volatile solids destruction can range from below 30% to in excess of 60%. Typically a tonne of sludge anaerobically digested using co-generation facilities will produce anything from 0.3 to 0.8 kWhr of electricity per kg sewage sludge anaerobically digested before biological enhancement. A typical sankey diagram based on standard anaerobic digestion using co-generation engines is shown in Figure 3.

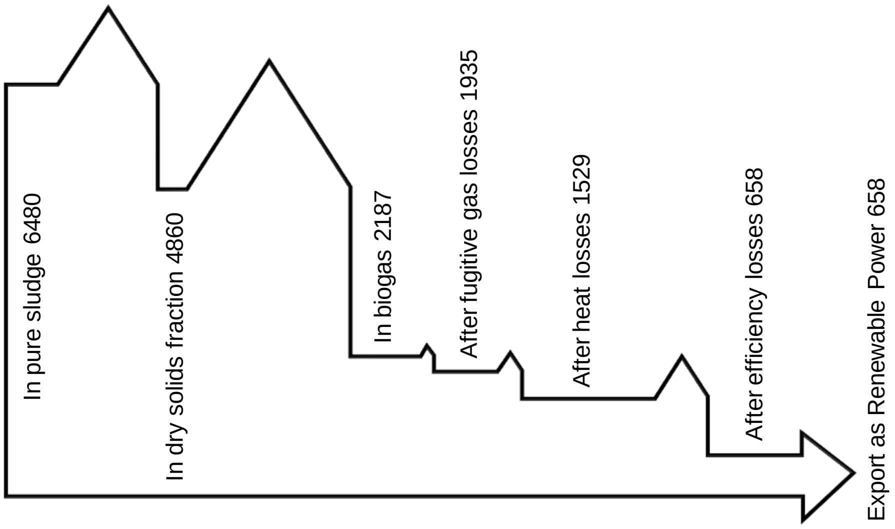

Figure 3. Sankey diagram showing energy flows for 1 tonne of typical (European) sludge being anerobically digested using biogas engines for co-generation. [Energy units in kWhr]

The range of figures is dependent on a wide variety of factors, most important of which is the type of sludge itself. Ironically, the sludge type is itself dependent on the level and type of wastewater treatment required. However, increasingly strict environmental drivers for wastewater treatment, such as the European Union's Water Framework Directive (WFD – 2000/60/EC) and the Urban Waste Water Treatment Directive (UWWTD – 91/271/EEC) will impact the type of sludge produced and will encourage the production of sludge which is increasingly difficult to digest or has high inorganic content with little energy available for extraction.

Fortunately, there is a plethora of technology available which enhance the biodegradability of sewage sludge. Most of these technologies work to improve the biodegradability of secondary sludge (that produced by secondary wastewater treatment such as Activated Sludge processing). Secondary sludge digestion can be described by first order kinetics (Tong and McCarty, 1991) and it is the hydrolysis of this sludge which generally controls the anaerobic digestion of sewage sludge. These pre-treament technologies improve a variety of parameters over standard digestion including: enhancing volatile solids destruction (and inherent biogas production and energy generation); loading rate; dewatering, and some of the processes can also pasteurise and sterilise the sewage sludge. The pre-treatment technologies aim to improve the hydrolysis of the secondary sludge and broadly fit into five categories as follows: biological; mechanical; thermal; chemical and other (as shown in Figure 2).

Biological systems aim to improve digestion by altering the biology of digestion itself. These may include plug-flow systems (the most famous of which is known as acid-phase) and others where biological agents are added to aid performance. Mechanical systems cover a wide range of technologies (including the application of ultrasound and sludge compression/decompression) but mainly rely on mechanical shear to break or disrupt sludge flocs in order to release their contents, including short chain volatile fatty acids. The contents are then used by other organisms for biogas production.

Thermal processes can be further divided into those which apply heat only to pasteurise the sludge (up to 70°C) to meet pathogen destruction requirements, or those systems which work at higher temperatures to sterilise the sludge and fundamentally alter the sludge characteristics. The latter systems operate under medium pressure and temperatures up to 175°C. At these temperatures a number of physical adjustments take place, including altered solubilities of components and changes in the sludge rheology itself. Changes in sludge rheology can result in sludge being processed at higher concentrations which has impacts on size of digestion plant required for new facilities. Thermal hydrolysis is being widely used as a retrofit to existing works to enable additional digestion capacity to be realised without additional digestion expenditure (Panter and Kleiven, 2005).

Finally, other processes include those which are not described above. These rely on a number of different mechanisms to improve sludge digestion. These technologies include chemical lysis (where chemicals are used to break down cell structures) and the application of electric pulses (Banaszak, *et al.*, 2010).

However, the two processes which are gaining a most interest recently are biological and also thermal hydrolysis technologies (an example of which is shown in Figure 6 later). As mentioned previously, many sludge strategies in the UK are moving away from energy intensive processing, such as raw sludge drying, to the use of these advanced pre-treatment technologies. These, and similar technologies, will become increasingly important with respect to upgrading existing facilities and also in becoming a standard technology to be considered for the building of new facilities. However, as has been experienced worldwide, choice of technology is not straight forward and is dependent on a large number of parameters and drivers and the technology which may be appropriate for one site may not be suitable for another.

Energy generation – Co-firing

As previously mentioned, sewage sludge has a calorific value similar to that of lignite (brown coal). Consequently, it has been used as a fuel both in mono- and co-firing plants, with examples of it being supplemented to coal in power stations or as a fuel source for cement manufacture found in Europe. One plant which has successfully exploited this is Heilbronn in Germany (Barber, 2002). Heilbronn (Figure 4) is a coal-fired Power Station and burns coal in four roller mills which consume approximately 240 t/h at full load.

Figure 4. Heilbronn coal-fired power station. It has successfully co-fired sewage sludge since 1996

Its furnace operates at 1200°C, and is equipped with SCR (Selective Catalytic Reduction) -DeNOx plant, electrostatic precipitators (to reduce dust emissions) and a desulphurisation plant based on the limestone/gypsum method for the reduction of oxides of sulphur. It has successfully co-combusted both dewatered and dried municipal sewage sludge since 1996. A maximum of 4% sewage sludge (2% as dewatered cake and 2% dried sludge pellets) totalling 40,000 tonnes dry material per year are added to the coal on a dry solids basis. The quantity of sludge added is controlled by the exit air temperature exiting each of four mills, which must not drop below 80°C. Tests showed that, at the levels of sludge added there were no adverse impacts on air emission quality from the plant when compared with coal-only combustion. Initially, there were problems at the site with methane release from the sludge, but these were overcome by adding infrastructure at the site to enable that the methane concentration did not exceed 50% of the lower explosion limit value.

Traditionally, power stations would charge a gate fee to receive the sludge based on a minimum dry solids or calorific value. However, co-firing may become increasingly viable in the future as energy companies are obliged to provide a certain quantity of energy from renewable sources and may even attract economic incentives to burn other, non-fossil materials. Longannet, in Scotland, was the first coal-fired power plant in the UK to qualify for renewable energy credits for burning other materials including 55,000 tonnes of dried sewage sludge from Glasgow. In addition, more power plants are upgrading their flue gas abatement systems which will further increase the potential for co-firing. However, in spite of the obvious benefits of combining sewage burning with power generation, there are a number of legislative and other hurdles to overcome. In Europe for example, sludge burning is covered by the Waste Incineration Directive (2000/76/EC) which may conflict with legislation surrounding power generation from fossil fuel and may require the installation of expensive upgrades to enable co-firing. Additionally, co-firing requires the long term co-operation of at least two partners which in itself, may provide sufficient incentive to prevent it from occurring. Other potential disadvantages are described in Table 2 later.

Energy generation – Incineration with thermal hydrolysis

Other than co-firing, the sludge can also be burnt in a purpose built incineration facility (Figure 5), and this has successfully been achieved around the world for a number of years. The basic components of a sewage sludge incineration facility are: sludge reception; pre-drying (if required) incinerator; energy recovery; flue gas clean up for the removal of acid gases, mercury, trace contaminants, dioxins and furans; gas monitoring systems and stack. Whilst most of the core infrastructure for incineration is robust, the two most common issues causing downtime at incineration plants are, the availability of ancillary equipment, and the sludge not having the expected characteristics. For incineration to work efficiently, and also to meet legislative requirements in many countries, the sludge have sufficient calorific value to be autothermic – i.e. it should not require a supplemental fuel source to aid its burning. Traditionally, when incinerating sewage sludge, it was preferable to burn raw undigested sludge. Digestion processes (see later) extract some of the energy from sludge and subsequently reduce the sludge's energy content. However, when considering incineration as part of a wider strategy, the decision whether or not to include digestion becomes less clear. Since, virtually all of the requirements of incineration are directly related to throughput, i.e. quantity of flue gas produced; power required; consumption of chemicals; production of effluent from flue-gas abatement, it becomes evident that upstream processing capable of reducing sludge quantity may be beneficial.

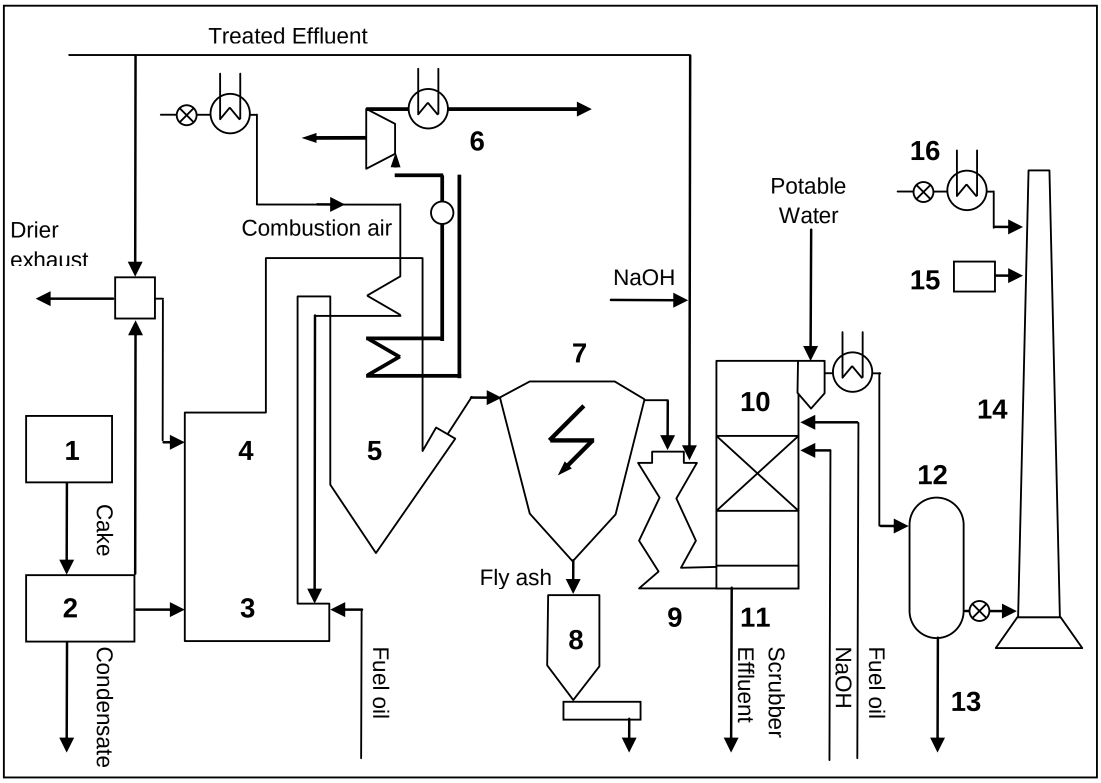

Figure 5.

Typical Layout of a sewage sludge incineration plant. Key: 1. Dewatering; 2. Pre-drying; 3. Incinerator; 4. Freeboard; 5. Heat recovery; 6. Power generation; 7 – 12. Flue gas clean-up; 11 and 13. Waste streams from flue gas clean up; 14. Exhaust stack; 15. Continuous monitoring, and 16. Flue gas reheat

Furthermore, whilst more energy is generated from raw sludge than digested at the incineration plant, when the energy extracted from digestion is also considered, it then becomes evident that more energy is recovered by combining digestion with incineration, as shown in Figure 6.

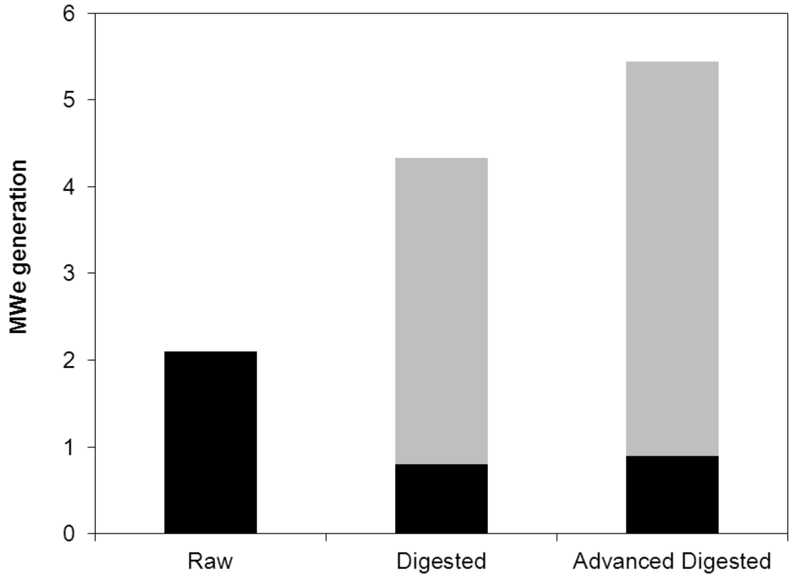

Figure 6. Energy recovery from raw, digested and advanced digested (based on thermal hydrolysis) sludge for treatment of 50,000 tonnes dry solids raw equivalents of sludge. Key: (■) energy recovered from incineration phase; (▒) energy recovered from digestion phase.

Figure 6 can be explained by the fact that energy recovery from co-generation at a digestion plant is more efficient than that at an incineration plant. Furthermore, dewatering (which is employed to thicken the sludge to reduce downstream processing and transport requirements) appears to be more influential in controlling the energy content of sludge than volatile solids destruction caused by digestion (Barber, 2009b). For the advanced digestion case in Figure 6, based on thermal hydrolysis, a combination of enhanced solids destruction and improved dewatering results in a further increase in energy recovery from anaerobic digestion coupled with a reduction in energy generation. However, as less material is being burnt, energy and consumable requirements at the incinerator are lower resulting in a smaller incinerator with a lower carbon footprint.

Subsequently, a sludge strategy involving a combination of thermal hydrolysis followed by both anaerobic digestion and incineration was developed by United Utilities, a UK Water Company (Barber, 2009b). A thermal hydrolysis facility capable of processing 121,000 tonnes dry sludge matter annually is being installed at Davyhulme in Manchester (see Figure 7) and this will enable the Water Company to double the throughput of its largest digestion facility whilst enabling it to burn more at its existing incineration plant (connected via a pipeline) without the requirement of either, more digestion or incineration facilities. The solution allows recycling or burning and has resulted in a drop in the Water Company’s carbon footprint of 8%.

Figure 7. Early installation photograph of Cambi thermal hydrolysis plant being installed in Davyhulme, Manchester. It will have a processing capacity of 121,000 tonnes dry sludge per year. [Photo: Cambi]

Energy generation – Wet air oxidation

Regardless of their success, incineration plants attract large quantities of negative press both amongst the general public and politicians who are generally opposed to their installation. One approach to incineration which may provide an interesting alternative is the use of Wet Air Oxidation. The principle of Wet Air Oxidation (WAO) is based on the thermal oxidation of contaminants in a material in the liquid phase. The system developed in the chemical and oil industries and subsequently transferred to the municipal wastewater treatment industry. WAO is an option for final destruction of sludges, which are either, too dilute to incinerate and/or too concentrated for further biological treatment. It can be summarised as the oxidation of organic and inorganic material present in wastewater using oxygen (or air) at elevated temperatures and pressures as the oxidising agent. At the operating temperatures for wet oxidation, pressure is needed to maintain water in the liquid phase (as superheated water) and to provide an over-pressurisation to maintain sufficient soluble oxygen. This enhanced solubility of oxygen in aqueous solutions at elevated temperatures provides a strong driving force for oxidation of the different species. The elevated pressure also keeps the products of the oxidation reactions predominately in solution in the liquid phase. Typical conditions for wet air oxidation range from 160° C at 20 bar to 320° C at 140 bar. A variant of the process known as super critical wet air oxidation (SCWAO) exists based on similar principles but run under conditions where water exists as neither a gas nor a liquid but in its supercritical state (i.e. >374°C and 221 bar). Based on published information, the performance of Super Critical wet air oxidation is significantly better than that of the sub critical variant (Sloan *et al*., 2008; Gilbert *et al*., 2004). Figure 8, shows the typical process steps of a SCWAO process.

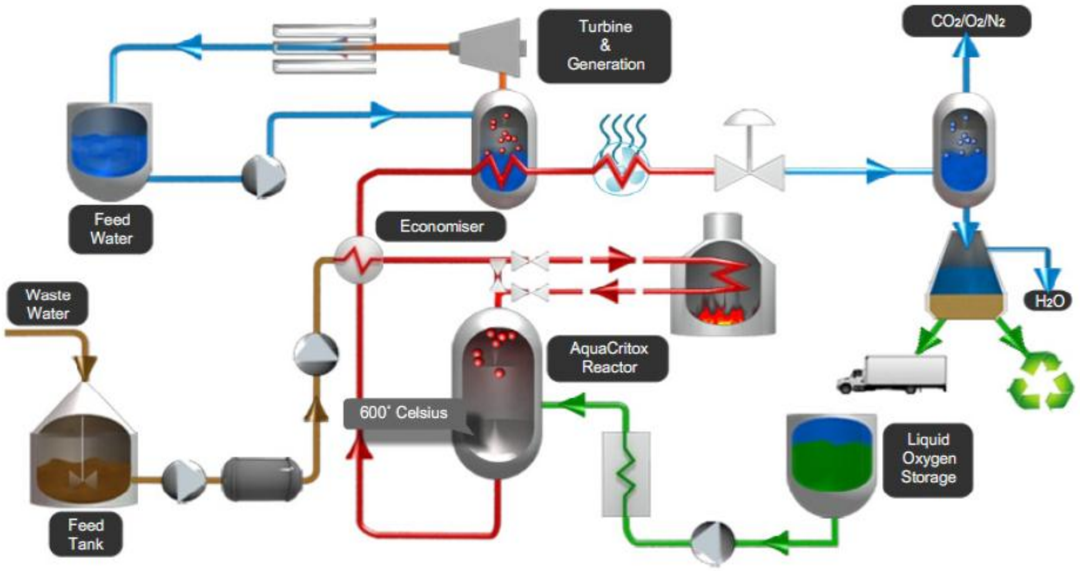

Figure 8. Process steps for super critical wet air oxidation process [Courtesy: Scfi]

As for incineration, it is advised that wastewaters for processing are thickened and digested to reduce the oxygen and downstream processing demands. The effluents from the process with regards sludge oxidation are a solid mineral complex, a liquid effluent (containing the residual COD not converted by the process, BOD and ammonia) and a controlled gas release to atmosphere. Retention times within a WAO reactor may range from 15 to 120 minutes depending on the required degree of destruction, but these times are reduced to seconds when in a super critical range. The degree of the oxidation achieved is a function mainly of temperature, oxygen partial pressure, residence time and the susceptibility of the pollutants to oxidation. Consequently the chemical oxygen demand (COD) removal may typically be between 75% to 90% for standard oxidation and close to 100% for super-critical oxidation. The result of sludge wet oxidation is that, insoluble organic matter is converted to simpler soluble organic compounds which are in turn oxidised and eventually converted to carbon dioxide and water (if the reactions were left to completion). The last residual organic compounds to be oxidised are fatty acids, especially acetic acid. Organic amine nitrogen is converted to ammonia, but only a limited amount of nitrogen elimination is obtained (10 – 20 %) due to the solubility of ammonia.

Regulation of WAO can be achieved by adjusting the water content of the feed sludge. The volatile matter concentration of the feed sludge will determine the oxygen demand and the heat yield from the overall exothermic reactions. Therefore sludge with more dilute organic residuals can be processed at higher concentrations up to 8% dry solids. This makes sludge exiting thermal hydrolysis and digestion an ideal input stream for wet air oxidation. It is further complemented by the ability of wet oxidiation to provide the steam required for the upstream thermal hydrolysis process. This configuration has been used successfully in Europe at full-scale as an alternative to incineration.

Promising results have been obtained from a pilot-scale project being operated at Cork in Ireland.

Figure 9. Photos of supercritical wet air oxidation plant treating sludge. [Courtesy Scfi]

The facility is rated at 250 litres/hr and is fed sludge at a range of 12% -15% dry solids depending on its calorific value. The calorific value is critical in keeping the reactor temperature in excess of > 540 °C. At that temperature ammonia is completely destroyed and effluent COD is below 20 mg/l. This is in stark contrast to sub-critical wet air oxidation which can suffer from high COD (10,000 – 13,600 mg/l) and ammonia (1,500 – 3,000 mg/l) levels in the effluent (Chauzy, 2012) due to operation at a lower temperature. At Cork, the feed is pumped to pressure and then taken through an economiser where its temperature is raised to approximately 380°C . The stream then enters the tubular reactor where oxygen is introduced in one or more positions. Oxygen is added in a quantity slightly above stoichiometric requirements. The effluent is cooled to 30 °C in a final cooler before passing through the pressure let down system. This reduces the pressure to slightly above ambient and the flow is directed to the gas/liquid separator. The off gas is free from NOx and SOx and is carbon dioxide rich (>70% CO_2). Phosphate content in the inert residue is significant and will be typically in the region of 15% P_2O_5 and can provide a useful starting material for phosphorous recovery.

Overall Energy Recovery

In order to determine the best combination of energy recovery based on the options which have been described above a model was set up to look at the major energy inputs and outputs of: anaerobic digestion; dewatering; drying and energy recovery (whether at a coal-fired power station; chemical factory; purpose built mono-incinerator or supercritical oxidation process). Six distinct options were modelled as follows:

1. Dewatering + energy recovery;
2. Anaerobic digestion + dewatering + energy recovery;
3. Thermal hydrolysis + anaerobic digestion + dewatering + energy recovery;
4. Dewatering + drying + energy recovery;
5. Anaerobic digestion + dewatering + drying + energy recovery;
6. Thermal hydrolysis + anaerobic digestion + dewatering + drying + energy recovery.

It was assumed that the sludge dewatered to 25% dry solids unless thermal hydrolysis was present where the assumption was 35% dry solids. For drying options, thermal drying was assumed with an output dry solids of 90%. Calorific value for raw cake was considered to be 18 MJ/kg dry solids and this figure was recalculated depending on performance of anaerobic digestion. The baseline for calculation was 10,000 tonnes dry solids processed per year.

The main energy flows are shown in Figure 10 below:

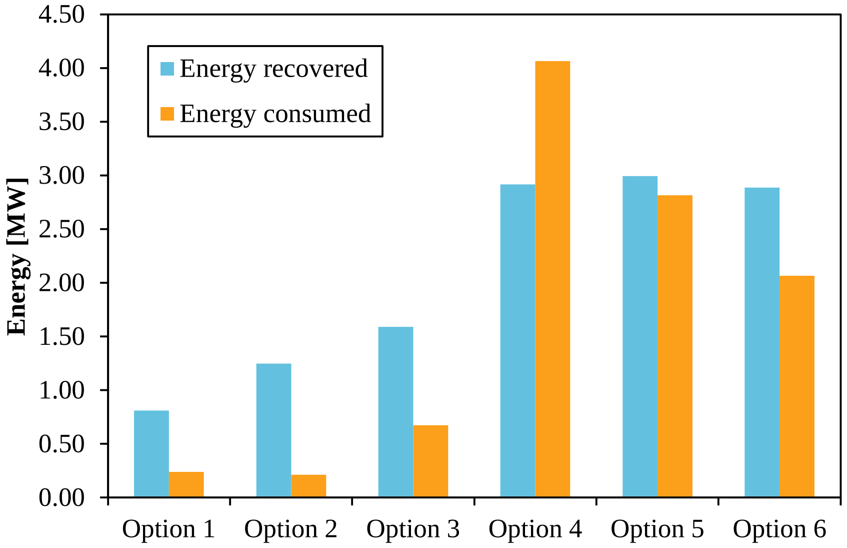

Figure 10. Energy recovered (blue bars) and energy consumed (orange bars) for options modelled

In order to appreciate the total energy requirements, it is necessary to compare the difference between energy recovered and consumed. This is shown in Figure 11 below:

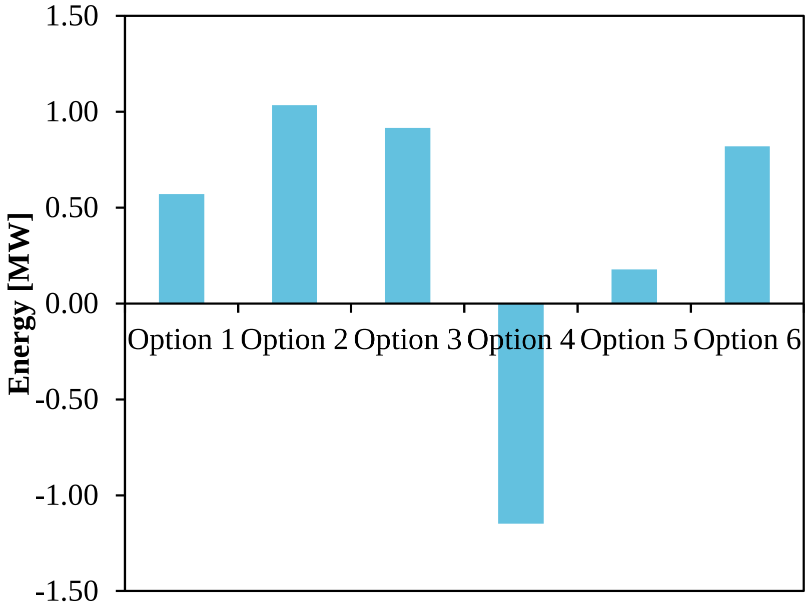

Figure 11. Overall energy balance for options modelled

Analysis of Figures 10 and 11 show the following:

- When recovering energy from dewatered cake, energy recovery is far better when anaerobic digestion is included in spite of the cake having lower calorific value. This is due to the higher energy recovery efficiency during cogeneration than compared with burning;
- Although the use of thermal hydrolysis with anaerobic digestion increases energy recovery compared with use of anaerobic digestion alone (Figure 10, Options 3 and 2), the overall energy balance is similar (Figure 11 Options 3 and 2) due to the energy demand of the thermal hydrolysis system;
- When drying of sludge is added to the equation, use of anaerobic digestion significantly enhances the energy balance compared to when digestion is absent. In that case, the energy balance is lower than 1 MW consumed per 10,000 tonnes dry solids of sludge processed;

- If drying is considered prior to energy recovery off-site, it is far better to employ thermal hydrolysis than not to. This is due to a combination of enhanced volatile solids destruction coupled with and better dewaterability. This combination reduces energy demand of the dryer by half when compared to anaerobic digestion where thermal hydrolysis is absent, and by two thirds when no anaerobic digestion is considered.

Summary

Sludge production is rising around the world. However, rather than being a nuisance, sludge has numerous benefits which can be exploited. For example, sludge contains energy which can be extracted in a variety of ways. Originally, reluctance for land application coupled with cheap energy led to the development of sludge treatment strategies which were heavily reliant on energy intensive processing such as drying. However, increasing energy costs, the mounting importance of nutrient recovery and growing influences of sustainability have led to the development of new sludge treatment strategies which involve advanced anaerobic digestion – especially the deployment of thermal hydrolysis – followed by land recycling. Subsequently, in the UK, many drying plants have been shut down due to high carbon footprint and energy requirements to accommodate the new strategies. As well as anaerobic digestion, energy can be successfully extracted via a number of various means including: co-firing at coal fired power stations; incineration and also super critical wet air oxidation. If drying is absent, anerobic digestion preceeded by energy recovery is preferable to absence of digestion. When digestion is present energy recovery is approximately twice that compared to when digestion is absent. If drying is also considered prior to energy recovery, then the greatest energy recovery can be achieved with the additional installation of thermal hydrolysis to an anaerobic digestion plant. In this instance, energy demands of drying are vastly reduced due to a combination of improved digestion performance resulting in less biosolids to dry and enhanced dewaterability resulting in a lower water evaporation requirement.

Acknowledgements

The author would like to thank John O'Regan of SCFI for invaluable help regarding super critical wet air oxidation.

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