THE PROSPECTS FOR REPLACING SLUDGE INCINERATION WITH ADVANCED ENERGY RECOVERY SYSTEMS AND THE POTENTIAL BENEFITS TO U.K. WATER AND SEWAGE COMPANIES

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Abstract

For U.K. water and sewage companies (WASCs), rising operating costs are a critical risk. Energy costs are a key component of rising WASC OPEX and energy demand is presently a predominant contributor to operational carbon footprint. Optimising and maximising renewable energy recovery is key to WASCs minimising OPEX, reducing carbon emissions and optimising TOTEX.

Sewage sludge is the key resource for renewable energy generation for U.K. Water and Sewage Companies (WASCs). U.K. WASCs operate mesophilic anaerobic digestion for energy recovery from sewage sludge but this technology has limits to how much energy it can recover, even when operating in the form of advanced digestion. Some WASCs also operate sludge incineration with limited energy recovery, which can recover energy downstream of digestion. However, the efficiency of the latter is also limited by steam turbine efficiency.

More efficient energy recovery from sewage sludge that could be deployed more flexibly than incineration would increase the energy recovery in large scale wastewater processing at minimum and reduce operating costs. This paper illustrates the opportunity available to U.K. WASCs to replace strategically replace incineration with Advanced Energy Recovery technologies to recover more energy downstream of digestion.

We describe the potential treatment works and corporate operating cost benefits that are available from deployment of advanced energy recovery technologies; compare the thermodynamic and operating performance of the technologies, their end products and carbon footprint and the effects of investment subsidies and wastewater asset base profile on their deployment.

Keywords

Reducing operating costs, **Advanced Energy Recovery**, Median Water, Virtual Works, carbon footprint reduction, operating cost risks.

Introduction

In 2013 the U.K. water industry is experiencing the effects of global macroeconomic trends that will increase its operating costs for a prolonged period. Energy cost is the most single significant price increase risk but cost risk over the near future is not confined to energy prices alone. Although energy costs do feed through to most areas of resource exploitation via mechanisation and its energy demands, material resources are also coming under pressure.

The basic materials used by water companies have also been under pressure from persistent energy and raw materials price increases. Chemical prices have increased significantly, especially in the last decade when energy prices have continued to increase. It is therefore no coincidence that some chemical suppliers reported to the WERF/UKWIR/AWWA/WRF teams compiling their joint 2009 report (1) into water industry chemical price increases that energy costs were a major factor in their price increases. The water industry also has to compete with other industries for its chemical material resources. Iron is used in construction and manufactured goods; organic polymers may be derived from oil.

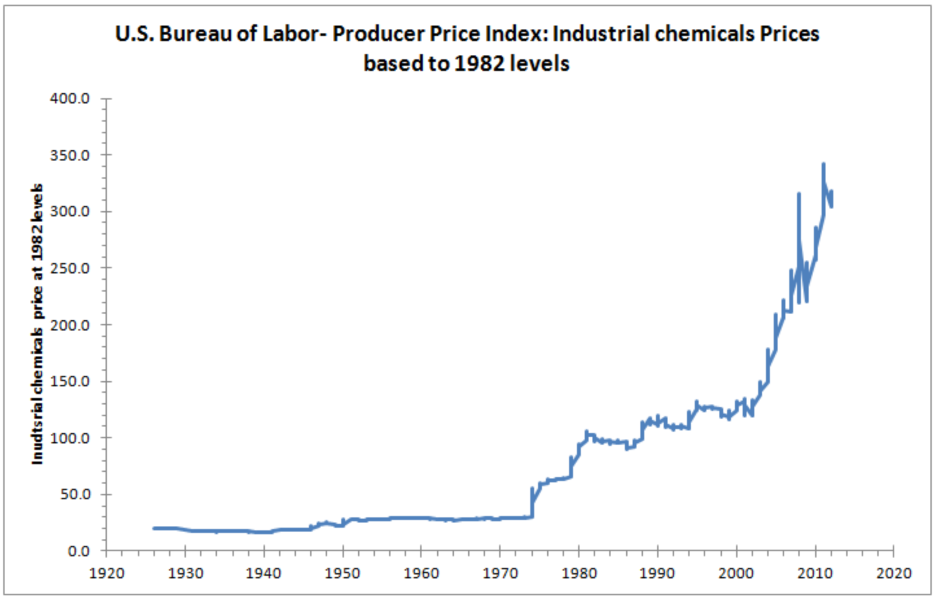


Figure 1: U.S. Chemical Price increases as reported by the U.S. Bureau of Labor Producer Price Index.

The wider picture includes issues reported on by the OECD in 2012 (2) (Figure 2.), which includes food price increases. The World Bank data for commodity prices been very inelastic with respect to its relationship to energy prices and food and energy price increases create underlying latent pressure on staffing costs in the U.K. as the value of incomes is eroded.

Energy is a critical component of GDP growth (3).

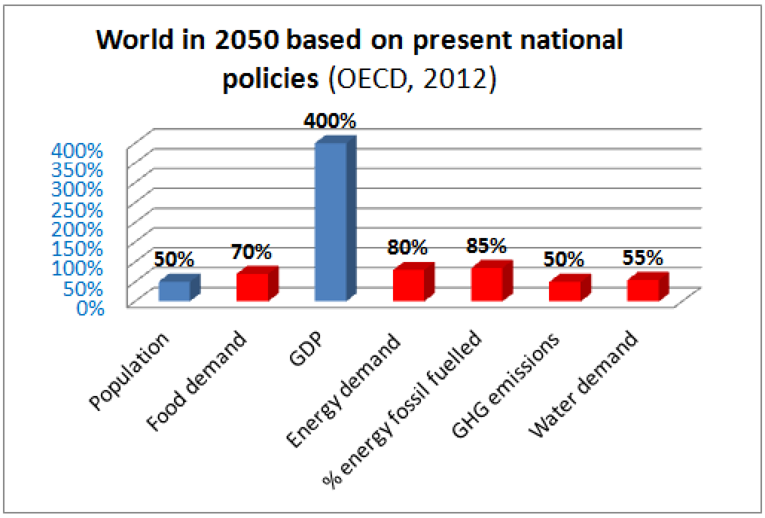


Figure 2: **OECD Environmental Outlook to 2050 (2). GDP growth will create significant resource demand. Present aggregate national policies imply the world will still be predominantly fossil fuelled in 2050, which creates energy price risks as well as risk to climate.**

Consequently there is a range of resources for which supply and demand imbalances may occur over the next four decades and contribute to rising operating cost for WASCs. MWH have modelled this risk using the Median Water WASC model. Median Water projections suggest that the profile of the U.K. WASC operating cost burden will alter significantly by 2030 with commodity costs energy and materials) occupying far more of WASC operating budgets and energy and materials costs replacing salary and service costs as the bulk of WASC operating cost (Figure 2a).

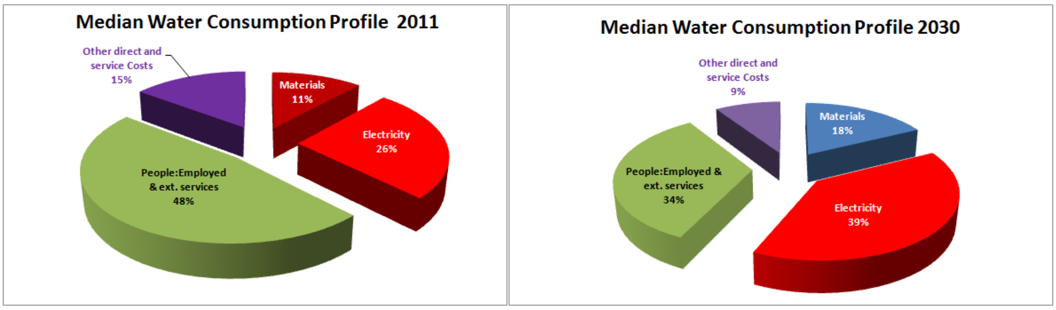


Figure 3a: **Projected WASC Operating Cost Profile changes by 2030 for the Median Water U.K. Water and Sewage Company (WASC) model.**

The inflation risk profile of a water company is different to that of an individual, because their consumption profiles does not have the same consumption profile of such resources as an individual are significantly different (Figure 3a). Consequently, inflation indices such as RPI-X or CPI may not provide the true risk profile for corporate costs; especially when WASC operating cost profile is less predominated by staff/salary costs.

This explains why a Median Water derived ‘cost of operations’ index for a water company differs from RPI-X or CPI.

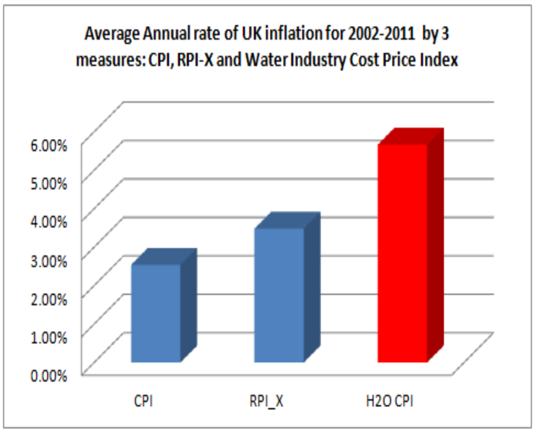


Figure 3b: **Commodity price inflation for UK WASCs for 2002-2011 compared to public consumer price indices in the same period.**

Figure 3b shows that the inflation risk profile for a U.K. WASC was significantly greater for 2002-2011 than the CPI or RPI-X indicates for individuals, based on patterns of WASC consumption.

Most UK WASCs are also committed to significant reductions in their operational carbon footprint. The large OFWAT category 6 sewage works are responsible for most corporate wastewater emissions. These emissions arise predominantly from Scope 1 (wastewater and sludge processing) emissions and Scope 2 (electricity purchased associated) emissions. In situ energy generation from sewage sludge is renewable and therefore can be used to reduce or eliminate (at energy neutral status for the treatment works) Scope 2 emissions.

Renewable energy generation from sewage sludge is therefore both a cost benefit and an emissions benefit to U.K. WASCs.

Sewage sludge is the key resource for renewable energy generation for U.K. Water and Sewage Companies (WASCs). Most WASCs use mesophilic anaerobic digestion to recover energy from sewage sludge via biogas, which is then often used for electricity generation. Some WASCs have begun to deploy advanced digestion to maximise this route for energy recovery but it has ultimate limits dictated by digester detention (and hence ultimately, by CAPEX). Even after advanced digestion, substantial calorific value and mass for disposal remains. Some WASCs operate sludge incineration which reduces the final disposal mass significantly, literally down to ash. Incineration as initially deployed by the UK Water industry lacked energy recovery. More recent incineration capacity and upgrades have introduced incineration with energy recovery. The technology typically deployed is steam turbine which has a typical generating efficiency of around 32%. Incinerators also have a high parasitic load. These factors limit the returns from incineration.

Over the last two decades, development (Refs. 4,5,6,7,8,9 and 10) and deployment of full scale of gasification for energy recovery for organic waste and municipal waste has provided an opportunity for WASCs to deploy alternative technology for energy recovery from sewage.

In the same period substantial work has been done to advance pyrolysis as a waste to energy technology for organic wastes (Refs. 10,11,12,13,14,15,16,17,18). For sewage sludge this has included full scale material recovery of oils by pyrolysis of sewage sludge, in the Enersludge process by Bridle *et al* (17) and significant research and development in sewage sludge pyrolysis (4,5,10,14).

Like incineration, gasification and pyrolysis offer a U.K. WASC the potential to absolutely minimise the waste mass for ultimate disposal from processing sewage sludge for its Sludge Treatment Centres (STCs) and largest treatment works. These alternative technologies also offer the prospect of greater energy recovery and/or lower operating cost than that offered by incineration. This paper reports the results of models of a large wastewater treatment works for advanced energy recovery and its comparison with existing technology options.

This papers considers energy recovery only and not valuable material recovery (*e.g.* oil production from sewage sludge by pyrolysis). Our models have been developed from gasification and pyrolysis publications of the last 2 decades, including references 4 to 18 inclusive.

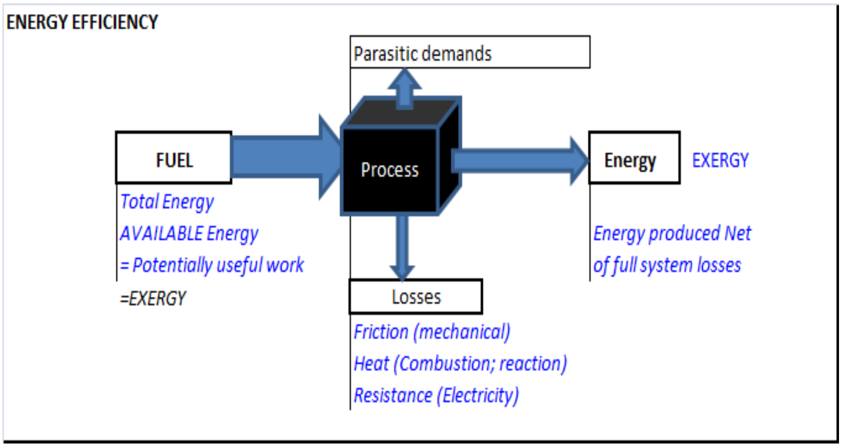


Figure 4: **Maximising energy recovery as part of energy efficiency measures.**

Figure 4 presents the basic thermodynamic requirements for maximising energy recovery.

Exergy is a more accurate term than energy when assessing energy efficiency. The limits of energy efficiency are set by thermodynamics, so a thermodynamic approach is essential for an accurate assessment of energy efficiency options.

Exergy is the maximum amount of useful work that can be extracted from a material as it approaches thermodynamic equilibrium. The quest for increased energy recovery from sewage sludge is therefore an investigation of competing energy recovery technologies to establish which can recover the most sewage sludge exergy (20).

The second law of thermodynamics implies that it is impossible to have a process that is 100% efficient; there will always be losses. Maximising energy recovery from sewage sludge requires:

- A definition of the fuel quality of the sludge;
- An understanding of the factors affecting sludge fuel quality and how these can be managed to maximize fuel quality,
- Understanding the total parasitic demands and losses across sludge processing and treatment,
- Using knowledge of parasitic demands and losses to minimize their level and effects.

This analysis then needs to provide value for the energy recovered. If modelling is used to examine the exergy potential of gasification and pyrolysis in terms of the operational risks associated with sewage sludge processing, it should then report in metrics that are independent of throughput so that users can assess the potential for their own applications.

Consequently, our approach included the development of several key metrics for exergy potential and its value in treatment plant operational terms as follows:

Sludge Processing Cost Metrics:

- Unit Cost Of Treatment for Sludge

  £ /tonne plant total Dry Solids fed (to treatment)

- Optimization measure

  £ /tonne initial Dry Solids fed after technology benefits to OPEX

Sludge Processing Quality Metrics:

- Unit Energy Demand and Yield
- kWh generated / tonne DS fed to generating process(es)
- kWh demand / initial TOTAL tonne DS sludge processed

The AER (Advanced Energy Recovery) technologies assessed in this study include gasification (of raw sludge; with conventional digestion and with advanced digestion) and pyrolysis (also of raw sludge; with conventional digestion and with advanced digestion).

The existing technology for post-digestion energy recovery is incineration, which is unrestricted combustion of sewage sludge. Incinerators recover energy from use of excess heat through steam generation and hence energy recovery via steam turbine. This keeps power generation around 32% for modern plant. Incineration also has a high parasitic load and generates significant heat from combustion. The process has off-gas treatment which is itself quite complex.

The apparent simplicity of combustion is misleading. Sewage sludge incineration is in fact a complex multi-stage process (21, 22 & 23) (Figure 5).

	Incinerator COMBUSTION Reaction SEQUENCE	
1	$H_2O_{(liquid)} \rightarrow H_2O_{(gas)}$	***DEHYDRATION*** *~180° C*
2	$C_mH_nO \rightarrow H_2 + CO + CO_2 + C_mH_n + C_{(CHAR)}$	***DEVOLATILISATION*** *~350° C*
3	$H_2O + C_{(CHAR)} \rightarrow H_2 + CO; H_2 + C_{(CHAR)} \rightarrow CH_4, CO_2 + C_{(CHAR)} \rightarrow CO$	***AUTOGASIFICATION*** *Major reaction for **wet (** e.g. 30% DS) rather than dry (i.e. 90%DS) sludge*
4	$C_mH_n + O_2 \rightarrow CO_2 + H_2O$	***VOLATILES COMBUSTION*** *~500° C* *Principal reaction for sewage sludge*
5	$C_{(CHAR)} + O_2 \rightarrow CO_2$	***CHAR COMBUSTION*** *> 500° C* ***Minimal reaction for sewage sludge** due to low Char formation*

Figure 5: Principal reactions in the combustion of sewage sludge.

Gasification is also a complex process but is not a combustion process. In gasification of sewage sludge, the organic components react in a gas stream of steam, steam and air or steam and oxygen top form a syngas, whose principal component is initially carbon monoxide.

There is a large range of reactor types and applications. Successful reactor design is based on full consideration of the fuel properties, including its handling properties. The reactor type and gasifying agent selected depend on the fuel characteristics and outputs required from the reactor. A gasifier's outputs include char; syngas and heat. Syngas produced usually needs cleaning to assure reliable CHP/gas engine operation on it as electricity generating fuel.

Summary of Gasification Characteristics:

- Design of reactor/ reactor type depends on fuel characteristics operation and mixing affect efficiency
- Most reactors using biomass do run with a combustion zone (e.g. updraft where char formed is combusted at the reactor base and the heat required is generated in this zone).
- Reactor types include updraft, downdraft and crossdraft; fixed, trained, spouted and fluidised bed
- The gasifying agent pumped into the reactor may air and steam, oxygen and steam or steam
- Gasification of the waste biomass still generates significant heat; which represents a loss in exergy from the volatile mass available for syngas

Other forms and related technologies include Plasma gasification, Induction furnace gasification and Supercritical wet oxidation.

Pyrolysis is no less complex than incineration or gasification. It is the thermal decomposition of organic material, in which the organic fraction devolatilises to form either a condensate (liquid product) or gas (syngas). The end product required determines the operating temperature range for Pyrolysis with liquids (e.g. oil recovery) occurring at lower temperatures and syngas being the principal product at higher temperatures. Higher operating temperature also favours production of cleaner syngas. However, as is the case with gasification, some degree of gas cleaning is normally required for reliable gas engine –CHP operation.

Summary of Pyrolysis Characteristics:

- The thermochemical decomposition of organic material in the absence of oxygen. Pyrolysis can be a fast or slow process, depending on method & application
- For optimal syngas production, higher temperature (>550°C) pyrolysis required
- For CHP applications, maximising syngas volume and quality provides the highest generating potential
- Syngas power generation efficiency potentially 35%
- Gas cleaning required

Pyrolysis can be modelled on the basis of the work done on the devolatilisation of sewage sludge (18, 11) including the effect of calorific value (10, 12, 18 & 24).

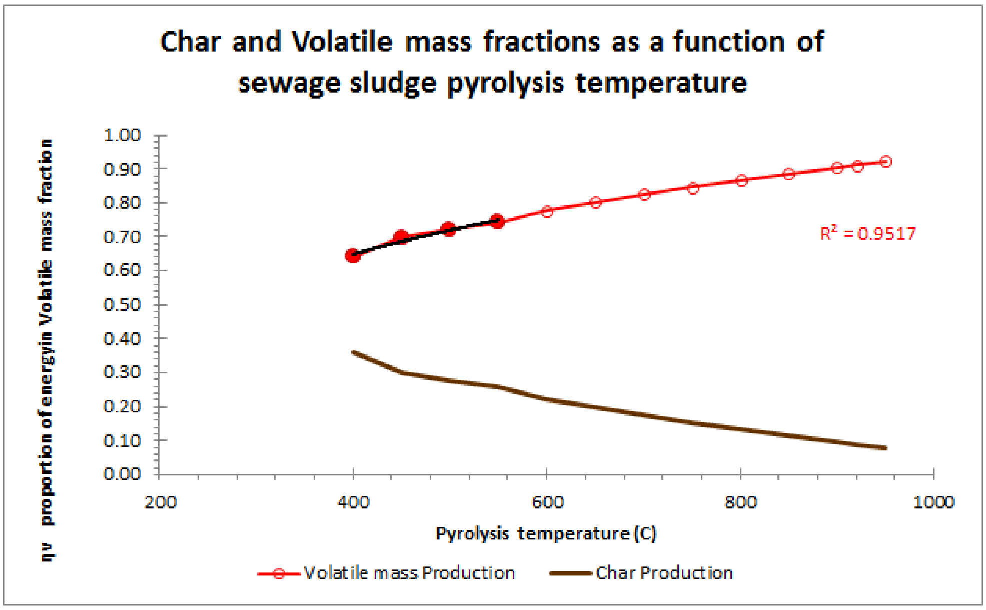


Figure 6: **Sewage sludge pyrolysis and char production (Ref 18).**

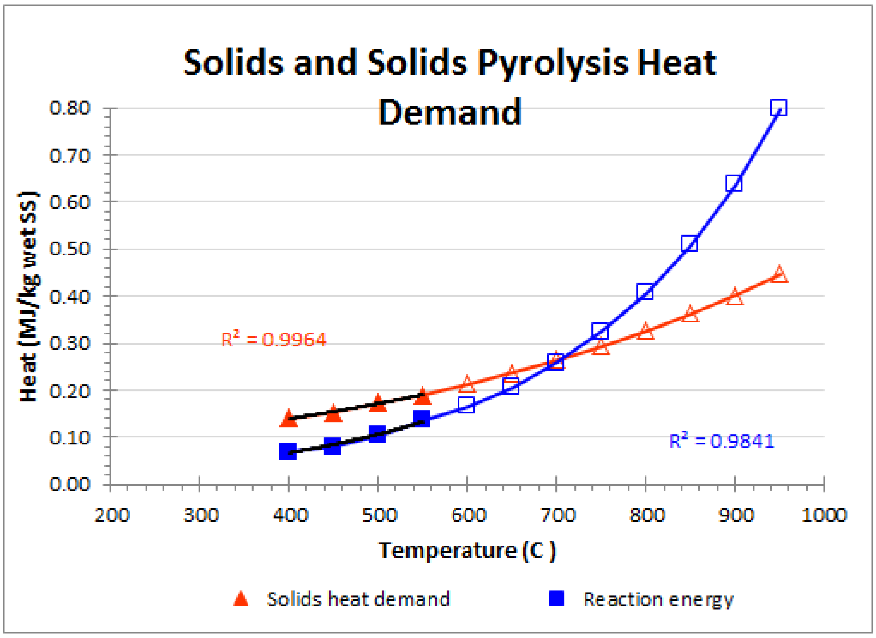


Figure 7: **Sewage sludge pyrolysis and char production (Ref 18).**

When sewage sludge is pyrolysed, the principal heat demand will arise from evaporation until sewage sludge moisture content drops below a threshold level. The other two main energy sinks are the solids heat demand and reaction (decomposition) heat. The former overtakes the latter as the principal heat demand at above 700°C if evaporation is not more significant.

Method

A MWH Virtual works model was constructed for a large OFWAT category 6 wastewater treatment works of 500,000PE with sludge imports.

The Virtual Works model is a combined PFD, mass balance and associated energy balance, supplemented by a UK industry standard Carbon Accounting Tool from WRc/UKWIR (2011: Version 5), with steady state models for grit removal, primary treatment and biological treatment and chemical and transport accounting datasheets.

The mass and energy balance was based on the Process Flow Diagram for the hypothetical works. The mass balance incorporates the full range of wastewater quality determinants and assumes the works operating at a steady state. In other words, the mass balance approach provides a state variable $x_i \, (i = 1, \dots, n)$ for each determinant of interest – in this case sewage pollutants monitored in the overall treatment plant influent and discharge. The state equations of a mass balance describe a flow and material load thus:

$$x'_i = r_i - q_i + p_i$$

Where p_i is inflow, (rate) q_i is outflow and η_i is the process removal or transformation rate (process efficiency). The mass balance process stages included were those described in the works description provided above.

The principal elements are preliminary and primary sedimentation, biological treatment and sludge processing and treatment, but the balance also includes all significant recycles such return activated sludge and return flows to treatment such as sludge liquor returns, as well as additional streams such as chemical dosing.

The Virtual Works built for this study serves 500,000PE with an annual daily average flow of 150Mld and sludge imports. In the first instance, liquid sludge imports of 6.75tDS/day were assumed for the existing works. Upgrades with conventional digestion, advanced digestion, incineration and AER of raw sludge and in combination with conventional digestion and advanced digestion have all been modelled in this study.

The Virtual Works model used for this study had the following technology profile:

- Fine screens
- Grit removal by detritors
- Storm treatment in mixed storm tanks
- Primary treatment in circular radial flow sedimentation tanks
- Biological treatment by mechanically aerated activated sludge
- Separate sludge thickening for primary and waste biological sludge
- Sludge imports (initially 6.75tDS/day liquid sludge for the baseline model; then 40tDS/day of 25% sludge cake after plant sludge processing uprated
- Sludge dewatering liming (liming prior to works upgrades; on upgrades liming abandoned)

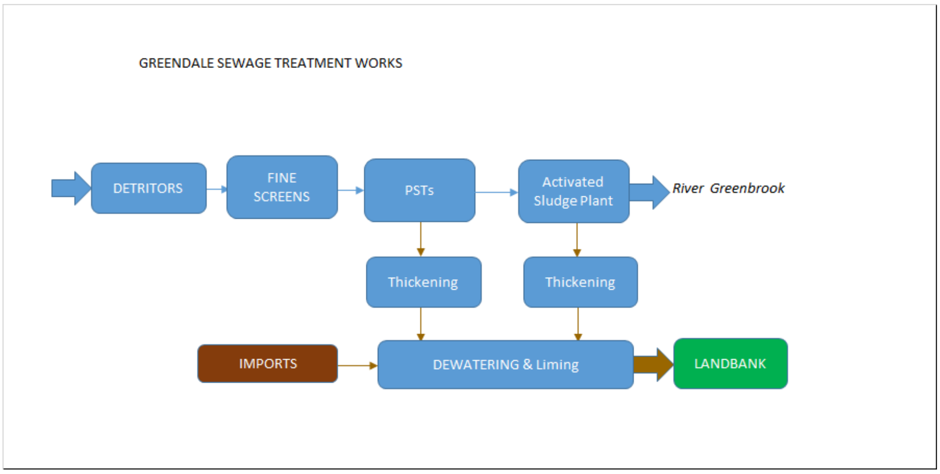


Figure 8: **Baseline (initial, non-upgraded) Virtual Works Model prior to upgrades to STC (Sludge Treatment Centre).**

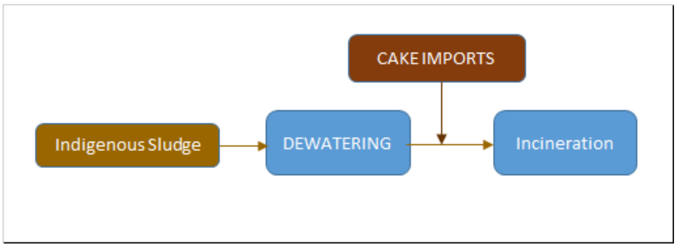


Figure 9: **Incineration Sludge Processing Upgrade in Virtual Works Incineration Models.**

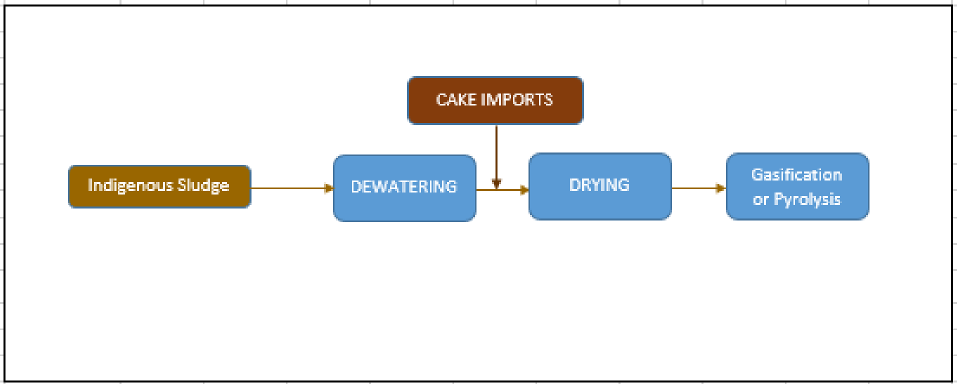


Figure 10: **AER Sludge Processing Upgrades in Virtual Works Incineration Models.**

The model uses primary, waste biological sludge and inert and chemical mass fractions to calculate sludge quantity and quality in volatile solids and CV (calorific value) terms, including assessment of primary tank performance (Refs. 24,25,26,27).

Each model was the used to derive the Unit Cost of treatment for the whole sludge processing train and unit cost of treatment adjusted for benefit; both independent of sludge throughput *i.e.* as £/tonne Dry Solids (£/tDS) (of sludge processed).

The costs included:

- Power costs,
- Carbon fees,
- Chemical costs,
- Sludge disposal costs,
- Staffing,
- Services.

The benefits available included

- Power import cost defrayed by in situ generation
- Power exports (where generation exceeds total site demand)
- ROCs
- Reductions in carbon fees
- Reduction in sludge disposal costs

Each model also generated the sludge processing energy demand and energy generation, independent of sludge throughput *i.e.* kWh/tDS.

Two of us (Ord and Maclaren) have also been researching the optimum design point for CHP plant and one of our key our findings in this regard was included in this modelling exercise; namely, that CHP should be designed to operate at 85% availability on average.

The CHP plant for conventional and advanced digestion and for AER syngas, was based on processing 100% of design fuel load at 85% availability. Operational CHP availability was assumed as 85%.

The form of advanced digestion modelled in this exercise was Thermal Hydrolysis. Sludge cake imports for the fictional plant upgraded to a Sludge Treatment Centre were assumed to average 25% and indigenous sludge was assumed plate pressed to 35%.

AER carbon emission were based on the full scale study of sewage sludge gasification by Takahashi in Japan in 2007, where gasifier emissions were found to be 55% of sewage sludge emissions under combustion in a fluidised bed incinerator (30).

The UCT, energy and carbon baseline were first establish for the fictional plant baseline which lacks any form of energy recovery (Table 1).

Table 1: ‘Greendale Sewage Treatment Works’ (Virtual Works) Performance Baseline.

SCENARIO	UCT with benefits £/tDS	Initial UCT £/tDS	Generation kWh/tDS to generation	Demand kWh/tDS (total)	Operational Carbon tCO_2e/yr
Baseline: Greendale STW 2012	128.72	128.72	0	203	11205

Results

The power demand and generating potential of each of the options is presented in Figure 11. The AER options are able to generate more power than incineration options, which appears to be due to the greater electrical power generating efficiency associated with gasification and pyrolysis.

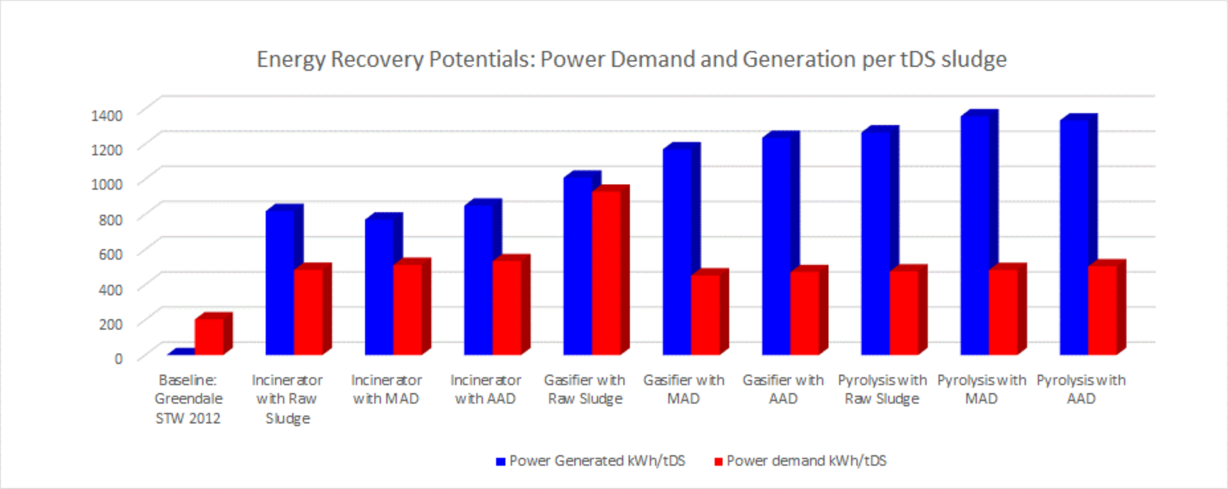


Figure 11: **Modelling outcomes for energy production potential from sewage sludge for the fictional 'Greendale Sewage Treatment Works' upgraded to energy recovery by incineration and AER.**

When gasification is compared to pyrolysis, there is an advantage to pyrolysis for electricity generation associated with better syngas quality and quantity potential, part of which ,may be attributed to a higher parasitic load for the gasification options examined.

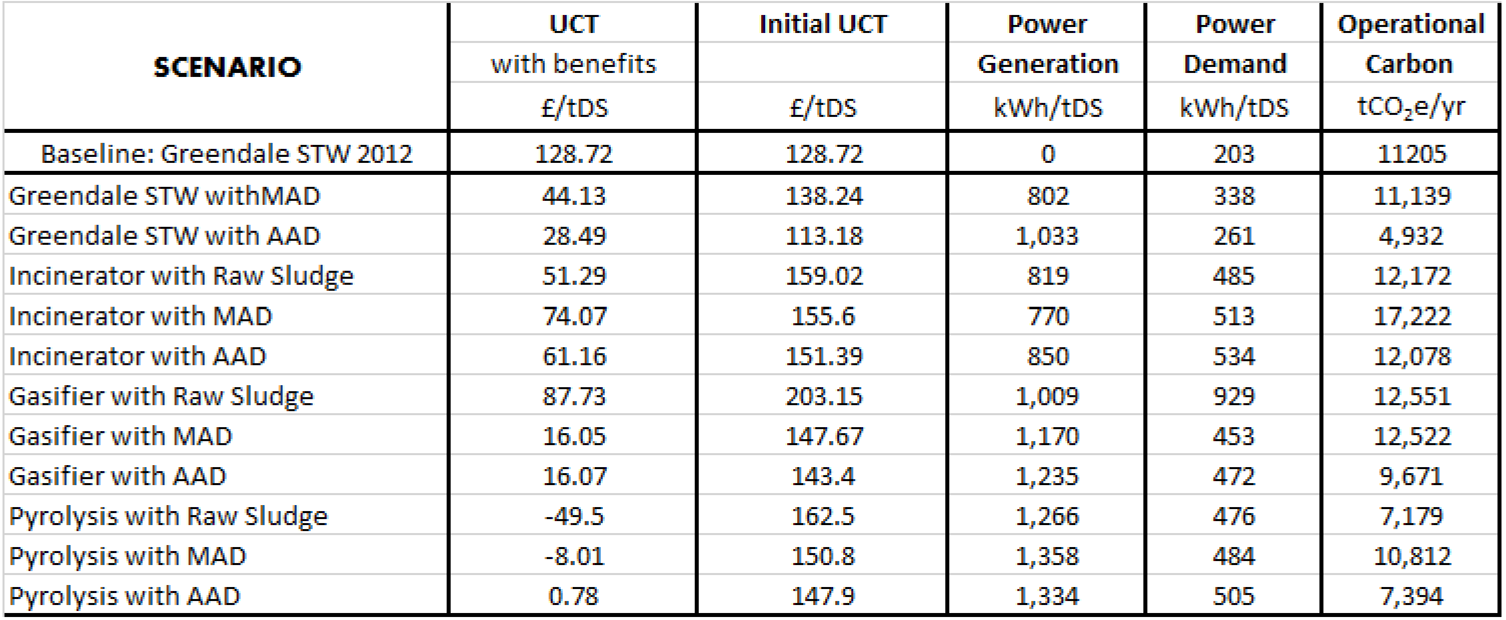
Taking this factor into account, gasification fares better when combined with digestion and especially with advanced digestion if a low carbon outcome is sought. Similar to combining incineration with digestion, the combined technologies maximise the low parasitic load of biological treatment while using the brute force of incineration, or gasification, to release most of the remaining energy that digestion is unable to access.

Gasification does this more efficiently than incineration, but also may produce a better outcome than the non-optimised AAD-Gasifier system in this study, as it has waste heat that could be used better than in this study in combination with AAD. This is a separate investigation that remains to be undertaken and reported on.

Table 1 also provides the outcomes for upgrading the plant to conventional digestion and advanced digestion, to provide a context for the upgrades that include incineration, gasification and pyrolysis paired with conventional digestion and advanced digestion.

The full detail of the modelling outcomes are summarised in Table 2, below.

Table 2: **Energy Recovery Options (including AER options) and their associated Unit Costs for Treatment, before and after technology associated benefits are accounted for, for a 500,000PE Wastewater Treatment Works with sludge imports.**



SCENARIO	UCT with benefits £/tDS	Initial UCT £/tDS	Power Generation kWh/tDS	Power Demand kWh/tDS	Operational Carbon tCO$_2$e/yr
Baseline: Greendale STW 2012	128.72	128.72	0	203	11205
Greendale STW withMAD	44.13	138.24	802	338	11,139
Greendale STW with AAD	28.49	113.18	1,033	261	4,932
Incinerator with Raw Sludge	51.29	159.02	819	485	12,172
Incinerator with MAD	74.07	155.6	770	513	17,222
Incinerator with AAD	61.16	151.39	850	534	12,078
Gasifier with Raw Sludge	87.73	203.15	1,009	929	12,551
Gasifier with MAD	16.05	147.67	1,170	453	12,522
Gasifier with AAD	16.07	143.4	1,235	472	9,671
Pyrolysis with Raw Sludge	-49.5	162.5	1,266	476	7,179
Pyrolysis with MAD	-8.01	150.8	1,358	484	10,812
Pyrolysis with AAD	0.78	147.9	1,334	505	7,394

Advanced energy Recovery (AER) Options include Gasification options and Pyrolysis Options, where the baseline for electricity generating efficiency is related to syngas conversion to electricity in CHP gas engines at 33-36% efficiency at full fuel load.

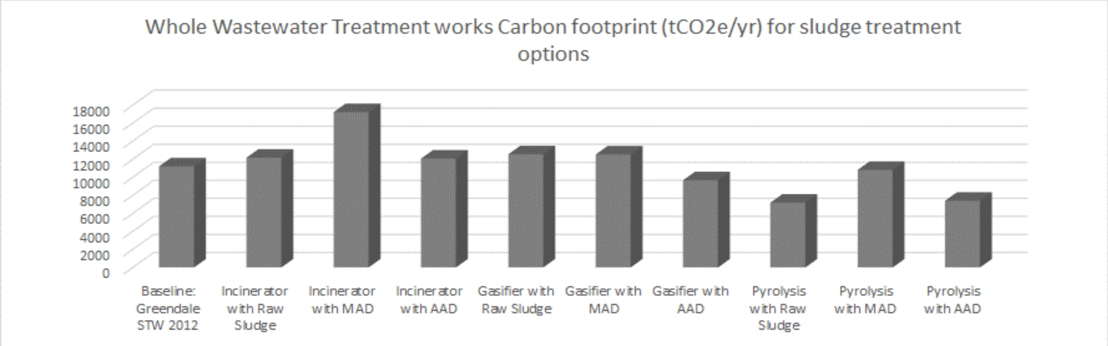


Figure 12: **Modelling outcomes for carbon footprint reduction from sewage sludge renewable energy recovery for the fictional 'Greendale Sewage Treatment Works' upgraded to energy recovery by incineration and AER. The existing plant (first column on left) with no energy recovery sets a carbon baseline of 11,205 tonnes CO_2 equivalent *per annum*. Values below this in Figure 12 imply a carbon footprint reduction.**

The most significant carbon footprint reductions arise from gasification paired with AAD; raw sludge pyrolysis and pyrolysis paired with AAD. Incineration has significant NOx emissions which contribute to a GHG load in the UKWIR/WRc carbon accounting method to a significant carbon equivalent load from sludge incineration. It is assumed in this study that the UKWIR/WRc approach *does* take standard incinerator NOX emissions equipment into account, but we have not confirmed this. This emission is the principal source of the carbon footprint associated with sludge processing for incineration options.

For carbon footprint reduction, raw sludge pyrolysis or AER technology paired with AAD provides the best outcomes.

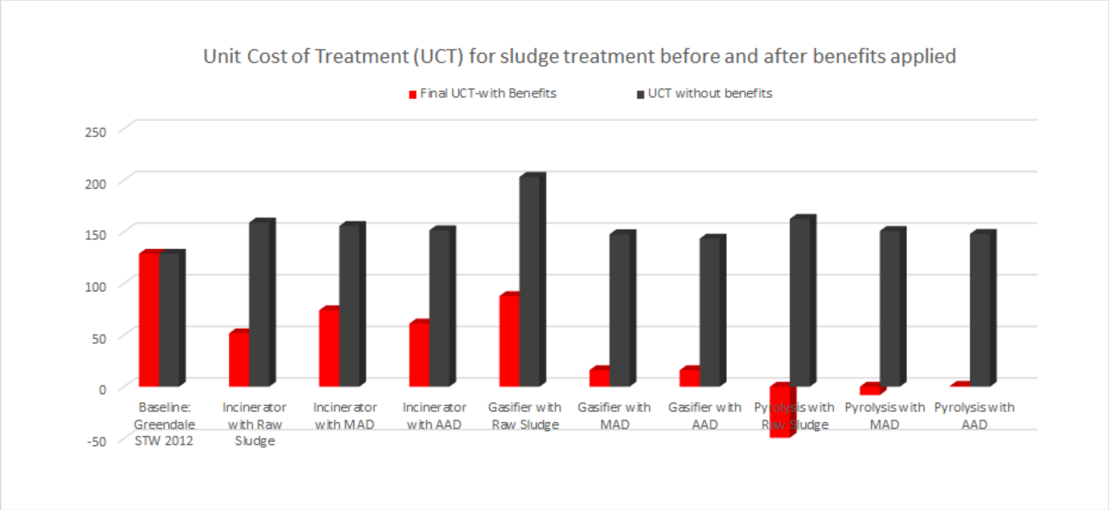


Figure 13: **Modelling outcomes for Unit Cost of Treatment from sewage sludge renewable energy recovery for the fictional 'Greendale Sewage Treatment Works' , when upgraded to energy recovery by incineration and AER. The grey left hand column is the unit cost of sludge processing prior to benefits listed in the Method section being taken into account. The red right hand column is the benefits adjusted outcome. Five AER solutions significantly reduce cost compared to incineration.**

Figure 13 shows the final (benefits adjusted) unit cost of treatment outcomes. Five AER solutions; gasification with MAD, gasification with AAD, raw sludge pyrolysis, pyrolysis with MAD and Pyrolysis with AAD, each provide a better net energy production outcome (Figure 10) and consequently, a significantly lower unit cost of treatment than incineration based alternatives.

The final Unit Costs of Treatment presented in Table 2 can only be secured while the operating risks that underpin them are adequately managed. If energy production recovery practice becomes sub-optimal, a UCT set as a target will not be maintained.

The great advantage of Virtual Works based modelling is that the Virtual Works model can be used to describe the entire operational envelope associated with a UCT. This means that a UCT has context which can be presented to an operator, allowing them to manage the risks to attaining the UCT. The following examples have been derived for this modelling exercise for primary tank efficiency, dewatering efficiency, CHP availability and incinerator Oxygen control setpoint/operating temperature.

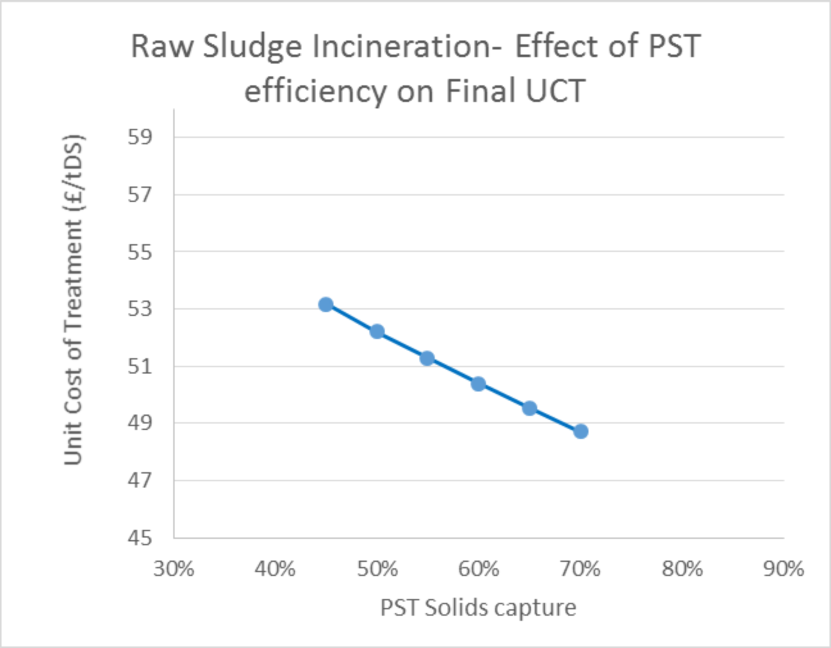


Figure 14: **Risks to Unit Cost of Treatment from Virtual Works Modelling of energy recovery: Risk 1-Primary treatment efficiency. This factor affects sludge Calorific Value and operation significantly above or below the norm can have a significant effect on periodic *i.e.* annual operating cost, especially if underperformance on this factor occurs simultaneously with that on another. Multiple minor underperformance can result in cost significant performance deterioration over time.**

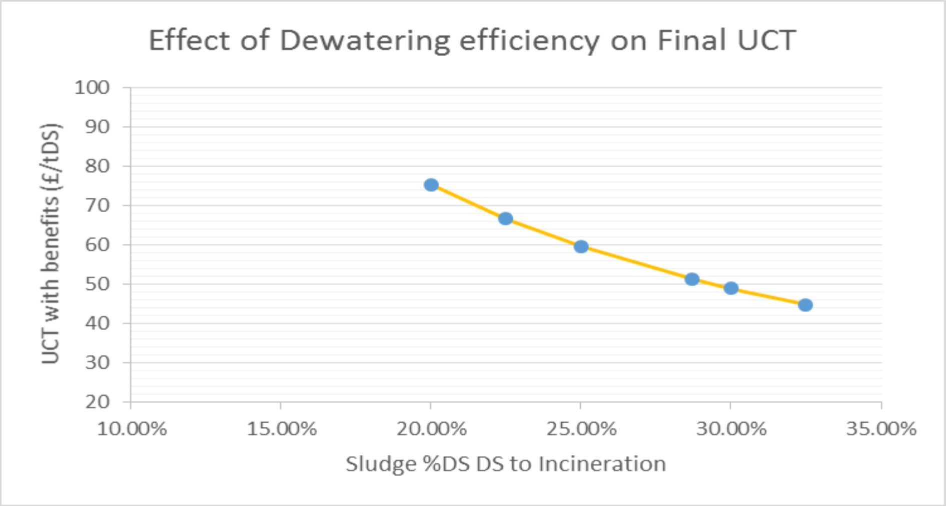


Figure 15: **Risks to Unit Cost of Treatment from Virtual Works Modelling of energy recovery: Risk 2-dewatering efficiency. Depending on the downstream equipment (*i.e.* presence or absence of a sludge dryer and its capacity, this can be a major or moderate risk. Without drying present for an incinerator, it is a major risk.**

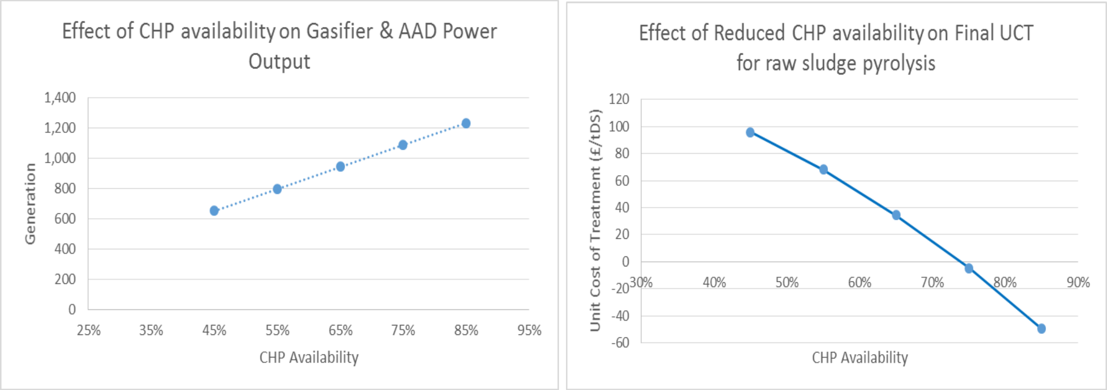


Figure 16: **Risks to Unit Cost of Treatment from Virtual Works Modelling of energy recovery: Risk 3-CHP availability. This is a major risk factor for all AER energy recovery options as they depend on CHP/gas engine capacity being available to generate. The optimum operational availability is 85% (29).**

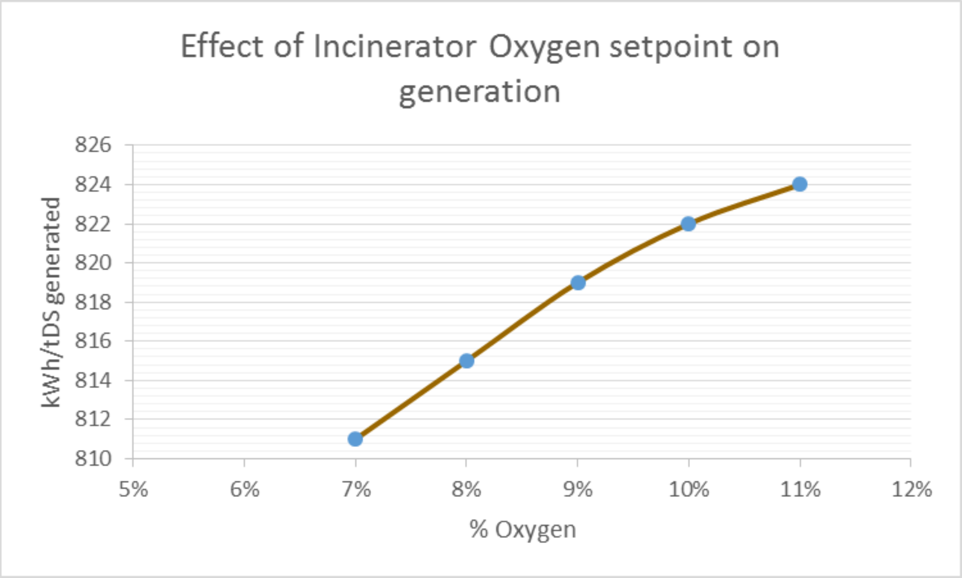


Figure 17: **Risks to energy recovery and hence Unit Cost of Treatment from Virtual Works Modelling of energy recovery: Risk 4-Incinerator oxygen setpoint. This has a limited, but notable effect over a long period. However, the operating temperature range of the incinerator may also be restricted by other factors such as the off gas treatment equipment used for NOx control.**

These examples of risks to Unit Cost of Treatment (UCT) attainment are not exhaustive, even for this fictional study, but do represent the ability inherent in the right (meaning thermodynamically based, calibrated and validated) modelling approach to assure appropriate UCTs are firstly identified and secondly, presented in a holistic whole plant context that allows their practical value as a viable operational UCT to be assessed.

Without offering operational staff that context, a UCT can become quickly undermined as it becomes perceived as an unattainable/unrealistic target. The Virtual Works success in modelling and identifying UCTs also works in reverse. The description of the whole plant operating envelope allows the context of a given UCT to be understood and its probability of achievement to be estimated. This facility ensures that unrealistic UCTs are not set as targets and draws engineers and operations staff together as a single team.

Conclusions

Unit Cost of Treatment derivation for investment options into Advanced Energy Recovery offer U.K. WASCs a method of analysis that secures a bottom down commercial model by Models like Median Water, converging on a thermodynamic and engineering based bottom up modelling to secure a more accurate basis for TOTEX based on engineered system limits and operating costs. This approach is currently unique but offers insights and investment risk appreciation we have not found with any other technique.

Reporting this data as unit cost per tonne Dry Solids also provides an assessment which is transferrable to similar schemes because the reported metric is independent of throughput. The use of Virtual Works models for the bottom up assessment of operating costs allows for calibration of the model in a real life application. This means that the OPEX derivation is completely verifiable for an investor, which raises project confidence. In this paper, the Virtual Works approach allows us to model emerging technologies with a high degree of confidence due the thermodynamic first principle basis we are modelling on- which is the formally defined correct approach to establishing exergy potential (20).

Based on a Virtual Works model serving 500,000PE, we found that Advanced Energy Recovery by gasification offered better energy recovery prospects and lower operating costs than incineration when paired with digestion or advanced digestion. This appears to arise from the better overall energy balance from the non-combustion process. The range of gasification technologies available is large and at present we suspect that there are further synergies that can be derived for a digestion or advanced digestion/ gasification AER system, with regard to recovering heat for digester and/or THP/E(E)H heating.

We will in future use the techniques presented in this paper to further investigate this potential gasification/MAD/AAD synergy to a detailed design/ optimised design level and also address an option we have not looked into detail for – super critical wet oxidation.

Although the U.K. Renewable Heat Incentive (RHI) legislation and regulation RHI does not presently cover this technology in this application, it might be eligible in future. If so, this may also further advance the prospects of this combination of technologies for energy recovery at lower Unit Cost of Treatment.

The second AER option Pyrolysis offers further advantage than the gasification options considered here, which appears to arise form it providing a better syngas product than gasification, favouring more effective gas engine/CHP power generation.

For carbon footprint reduction, raw sludge pyrolysis or AER technology paired with AAD provides the best outcomes.

By using the Median Water model, we have been able to value the operational saving returns arising from systematic deployment of the leading AER/combined AER solutions at the largest sewage treatment works and all Sludge Treatment Centres of a typical UK WASC at least £35MM per annum, based on a UK average WASC asset base.

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