BIOWIN MODELLING TO DEVELOP STRATEGIES TO MAXIMISE ENERGY GENERATION FROM SEVEN OF ANGLIAN WATER'S SLUDGE TREATMENT CENTRES

Smyth, M.[1], Kabir, M.M.[1] and Inman D.[2]
[1]Suez Advanced Solutions UK Ltd, trading as Aqua Enviro, [2] Anglian Water Services Limited
England
Corresponding Author Email matthew.smyth@aquaenviro.co.uk

Abstract

One tonne of dry solids contains anywhere between five and seven megawatt hours of energy; of this perhaps as little as 20% or as much as 80% may be recovered through anaerobic digestion. How much energy is recovered is a function of the AD process (advanced or conventional), digester retention time and organic loading rate and the feedstock's composition and biodegradability.

The best performing sites in the UK consistently produce 3-3.2 MWh/TDS as biogas (equivalent to ~1.25 MWh/TDS after CHP), but many operate at half of this figure, which means that as little as 25% of the total energy content of the feedstock may be converted to biogas.

In this study, BioWin models for seven Anglian Water Sludge Treatment Centres (STCs) were built and calibrated using historical site data and from a 3-week sampling period. COD fractionation is core to the BioWin model and has been used to rank different sludges in terms of their amenability to digestion. Investigation of the data showed that 'cycling' of sludges upstream of the sludge treatment centre or at the site itself can significantly worsen the characteristics of the sludge.

The calibrated model can be used to show numerous scenarios, including:

1. The difference between the energy a site is and should be producing, which can lead to short term improvement projects.
2. The increase in energy that could be achieved by improving the composition and biodegradability of the feedstock, resulting in 'spend to save' investment.
3. The energy benefit of employing pre-treatment.

Keywords

Anaerobic Digestion, BioWin Modelling, Energy Generation, Sludge degradability, COD fractionation

Introduction

As long ago as 2009 UK Water and Sewerage Companies (WaSCs) agreed to a voluntary target of 20 per cent renewable energy generation by 2020, recognising the potential to generate up to a quarter (DEFRA, 2009). Over 80% of sewage sludge produced in the UK is treated by anaerobic digestion (AD) and advanced anaerobic digestion (AAD).

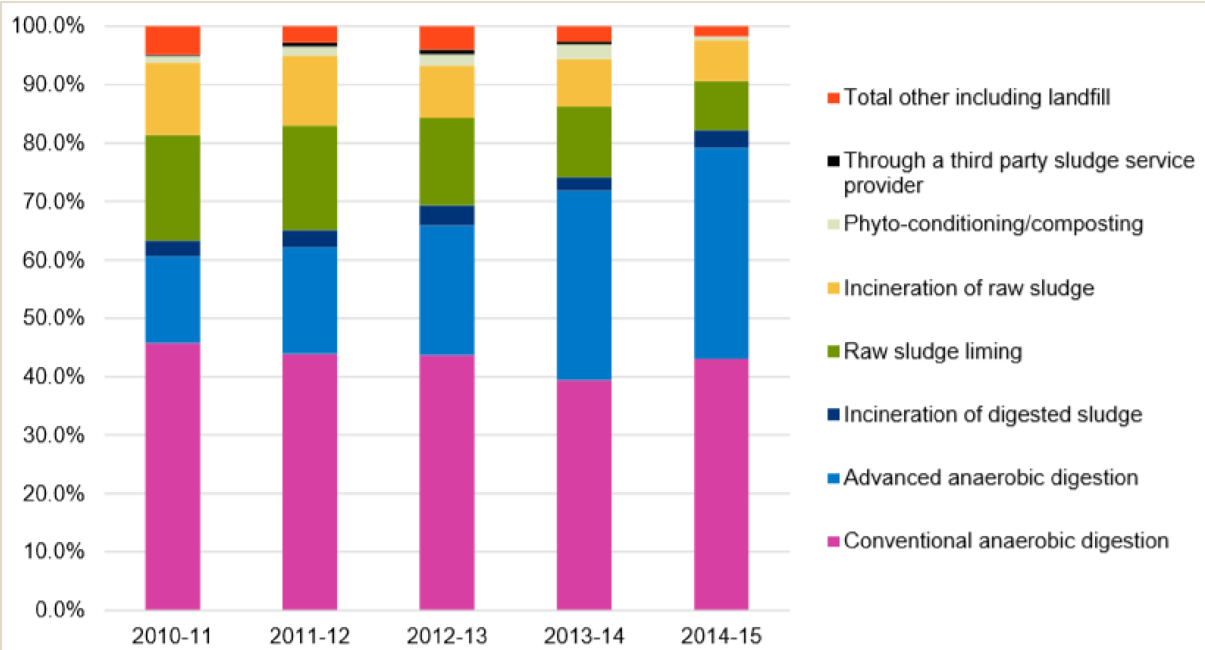

Figure 1 Sludge technology use over time (OFWAT, 2016)

The biogas produced is a renewable energy source and can be used to generate electricity and heat or converted into biomethane for grid injection.

The total energy produced can vary greatly from one site to another and depends upon the technology in situ and characteristics of the feed sludge (indigenous and imports). Two extremes, demonstrate the possible range:

1. Surplus activated sludge is challenging to digest, as little as 20% may be converted to biogas. If the energy content of the feedstock is 5 MWh per TDS, then 1 MWh of energy would be produced in the gas phase. Often, a WaSC may focus upon energy production post CHP (Combined Heat & Electricity Plant), but this hides what may be lost to flaring and also the efficiency of the engine.

2. Another site incorporates pre-treatment and digests a blend of sludge that is 80% primary sludge and 20% SAS. The combined feed has an energy content of 6 MWh/TDS and 68% of that is converted to biogas. The total energy production in the gas phase is 4.08 MWh / TDS.

And so, site 1 produces 1 MWH/TDS and site 2, 4.08 MWh/TDS, both in the gas phase. If the biogas were processed by CHP with an electrical efficiency of 38%, this would equate to 0.38 & 1.55 MWh_e/TDS.

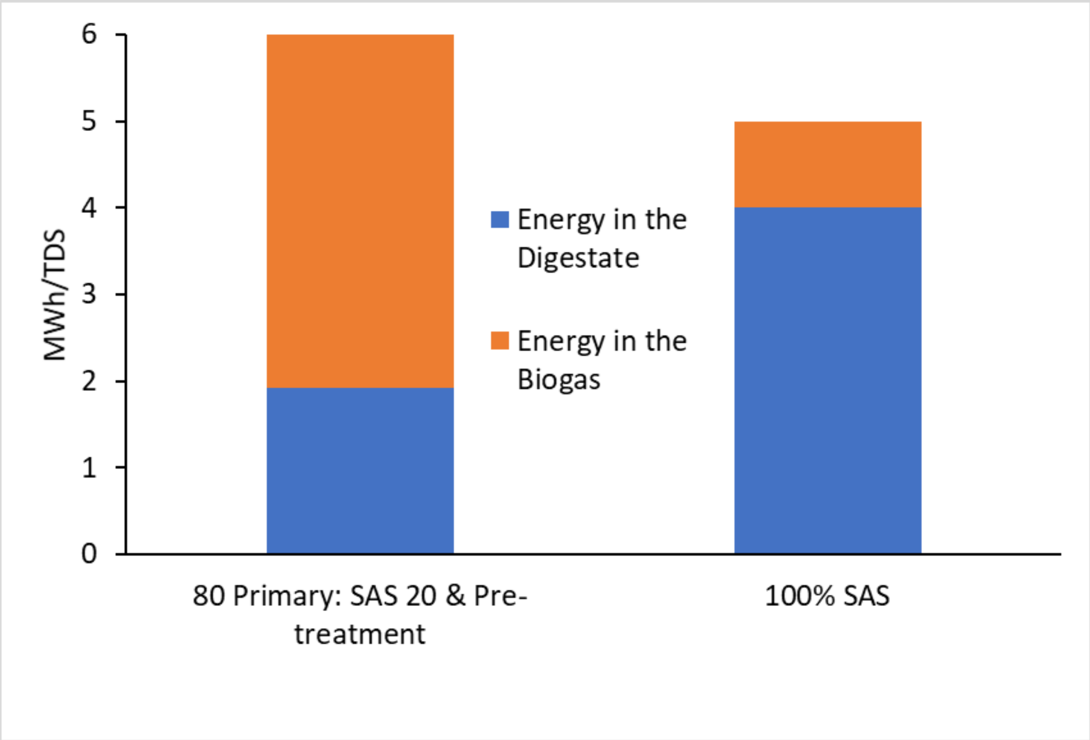

Figure 2 The fate of energy in sludge

In addition to the higher energy production, the 2nd site also produces a digestate that is more amenable to dewatering (as the percentage volatile solids in the digestate will be relatively lower) and the transportation and disposal costs are significantly reduced due to the greater solids and volume reduction.

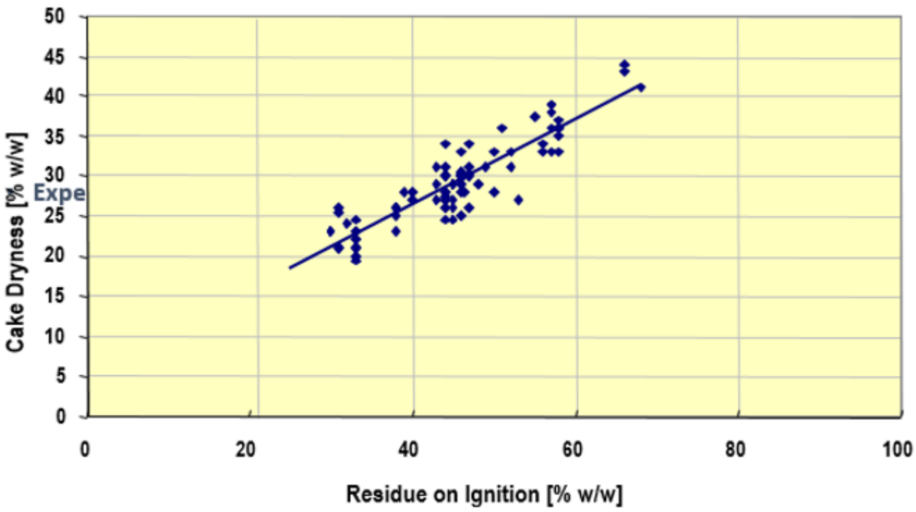

Figure 3 Cake dryness based on residue on ignition (Laughton, C. & Hallam, R., 2014)

This paper looks at the role of BioWin modelling in understanding the influence of sludge type and process on biogas production and once understood, how the contributing factors could be optimised to increase generation. The results are based upon data collected from seven of Anglian Water's STCs.

Simulation tool- BioWin Background

Simulation of the seven sites was carried using BioWin v. 5.3 (EnviroSim Associates Ltd., Canada) which is routinely used by Aqua Enviro's Technical Team. The BioWin software integrates the international ASM1, ASM2d and ASM3 models developed by the IWA with the anaerobic digestion model (ADM1). The integrated BioWin AS/AD model includes 50 state variables and 60 process expressions, which describe the processes occurring in activated sludge and anaerobic digestion systems, including biological, chemical, and physical processes, several chemical precipitation reactions, and gas–liquid mass transfer for six gases (Forgacs *et al*, 2017).

BioWin is a complete simulation tool for biological wastewater treatment plant design and analysis. It allows users to model a variety of treatment processes by selecting and connecting model elements, which represent different unit treatment operations or conveyance components within the treatment process. The large number of user variable inputs and parameters such as kinetic, stoichiometric, environmental, and process specification enables users to define and analyse the behaviour of treatment plants precisely.

Given the main aim of the project was determination of energy recovery through anaerobic digestion, the most relevant element was BioWin AD module. ADM-1 contains a set of state variables that are not consistent with activated sludge Models (Batstone et al., 2002), in BioWin modelling V3.1 onward, the activated sludge- Digestion Model ASDM has been integrated. Therefore, both the liquid stream and AD module are based on the same set of state variables and stoichiometry and process rate equations, allowing the 'whole plant' to be modelled on a consistent basis (Jones and Takács, 2004). Output from simulation modelling of the liquid stream processes, in the form of primary sludge and waste activated sludge, can be inputted into the AD modules within the same simulation model. This feature of the BioWin simulator thus enables modelling not only of anaerobic digestion performance, but also the impacts of digester liquor side stream returns on the liquid stream process.

Anaerobic digestion model in BioWin is designed based on the known anaerobic digestion stages and the production of intermediate products which are metabolised for the growth and reproduction of the subsequent groups of microorganisms. The basic functional categories are summarised below (EnviroSim Associates Ltd.):

(1) Heterotrophic growth through fermentation which achieves VFA generation. There are two biochemical pathways for the fermentation of readily biodegradable substrate to acetate, propionate, carbon dioxide, and hydrogen. The dominant pathway is governed by the dissolved hydrogen concentration. These processes are mediated by the ordinary heterotrophic organisms. This base rate is modified to account for nutrient limitations (ammonia, phosphate, other cations and anions) and pH inhibition.

(2) Growth and decay of propionic acetogens to conduct anaerobic digestion. These two processes describe the growth and decay of propionic acetogens, converting propionate to acetate, CO_2, and hydrogen. This base rate is modified to account for environmental conditions (anaerobic conditions, inhibition by hydrogen and acetate), nutrient limitations (nitrogen, phosphate, other cations and anions), and pH inhibition. The decay process has a rate that varies according to the electron acceptor environment.

(3) Growth and decay of methanogens in anaerobic digestion. These processes describe the growth and decay of two of the principal groups of obligate anaerobic microorganisms (acetoclastic methanogens), converting acetate or methanol and hydrogen to methane and water. Nutrient limitation (ammonia, phosphate, other cations and anions) and pH inhibition are taken into account for the growth rate, and for both microorganism the decay rate varies according to the electron acceptor environment.

A theoretical schematic of the anaerobic degradation process in the BioWin™ simulator is shown in Figure 4.

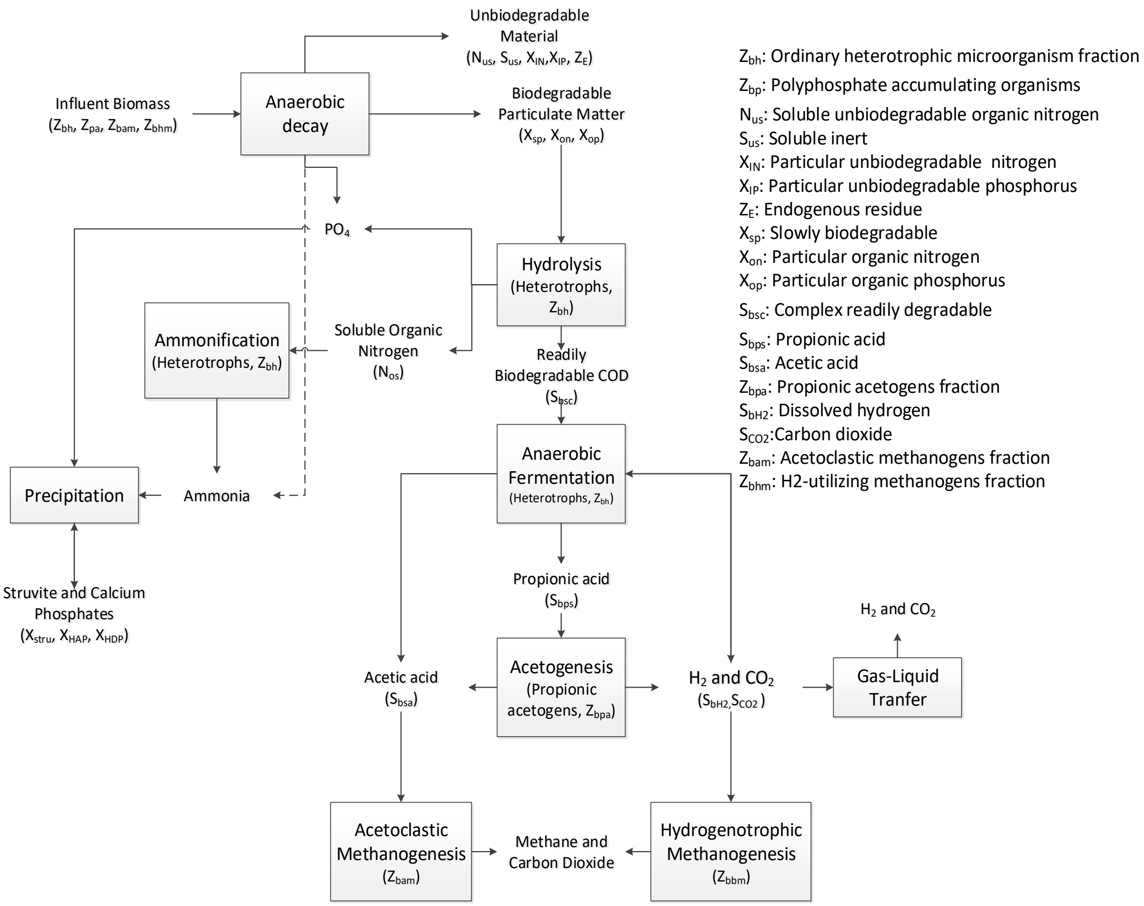

Figure 4. Conceptual Schematic of the BioWin Anaerobic Degradation Model (from Envirosim Associates, 2009).

Model development

The following process stages were taken for development and validation of the model:

- Data collection for the calibration of the BioWin model; historical data and arrangement for sampling and analysis of sludge sampling for a period of 3 weeks
- Configuration of the wastewater treatment process in BioWin
- Calibration of the BioWin model/ validation of a base model
- Application of the BioWin model to develop strategies for timely and cost-effective operation of the anaerobic digesters, achieved by generating site specific scenarios to provide bespoke solutions.

In the BioWin simulator, characterization of the carbonaceous material in municipal wastewater is in terms of Chemical Oxygen Demand (COD). Primarily, the reason for this selection is because COD provides a consistent basis for describing the activated sludge process, and is a suitable measurement for quantifying sludge production, oxygen demand, etc.

Biochemical Oxygen Demand (BOD) however, quantifies the portion of organic substrate utilized for energy generation and ignores the portion transformed into new cell mass. Therefore, the suitability of COD is established by considering the utilization of organic substrate and can be used as the basis for a mass balance.

COD measurement itself can be challenging on sludge and cake streams, therefore calorific value analysis can also be used in this case, although a back calculation to COD is required to obtain raw data for BioWin simulation.

Table 1. Energy and converting between units

COD (kg)	Calorific Value (MJ)	Methane (Nm^3)	Energy (kWh)
1.0	12.56	0.35	3.49

Sludge Characterisation

In addition to total COD, and its characterisation, information on flow rates, and values for nitrogen and phosphorus, alkalinity, pH of the input sludges are required.

The characteristic of the input sludge required for model development is shown in table 2.

Table 2. Characteristic 'typical' to raw sludge

Name	Raw sludge
Fbs - Readily biodegradable (including Acetate) [gCOD/g of total COD]	0.1600
Fac - Acetate [gCOD/g of readily biodegradable COD]	0.1500
Fxsp - Non-colloidal slowly biodegradable [gCOD/g of slowly degradable COD]	0.7500
Fus - Unbiodegradable soluble [gCOD/g of total COD]	0.0500
Fup - Unbiodegradable particulate [gCOD/g of total COD]	0.0130
Fna - Ammonia [gNH3-N/gTKN]	0.6600
Fnox - Particulate organic nitrogen [gN/g Organic N]	0.5000
Fnus - Soluble unbiodegradable TKN [gN/gTKN]	0.0200
FupN - N:COD ratio for unbiodegradable part. COD [gN/gCOD]	0.0350
Fpo4 - Phosphate [gPO4-P/gTP]	0.5000
FupP - P:COD ratio for unbiodegradable part. COD [gP/gCOD]	0.0110

Kinetic parameters

Kinetic parameters in the BioWin model are divided into the following categories: Ammonia Oxidising Biomass (AOB), Nitrite Oxidising Biomass (NOB), ANAMMOX, Ordinary Heterotrophic Organisms (OHOs), phosphorus accumulating organisms (PAOs), Acetogens, Methanogens, pH and switching functions. Although there are several different microbial groups involved in the anaerobic digestion process, the methanogens play the most important role in this process. Kinetic parameters of methanogens included in the model are shown in table 3.

Table 3. Kinetic parameters of methanogens

Name	Raw sludge
Acetoclastic max. spec. growth rate [d^{-1}]	0.3000
H_2-utilizing max. spec. growth rate [d^{-1}]	1.4000
Acetoclastic substrate half sat. [mgCOD/L]	100.00
Acetoclastic methanol half sat. [mgCOD/L]	0.5000
H_2-utilizing CO_2 half sat. [mmol/L]	0.1000
H_2-utilizing substrate half sat. [mgCOD/L]	0.1000
H_2-utilizing methanol half sat. [mgCOD/L]	0.5000
Acetoclastic propionic inhibition [mgCOD/L]	10000
Acetoclastic anaerobic decay rate [d^{-1}]	0.1300
Acetoclastic aerobic/anoxic decay rate [d^{-1}]	0.6000
H_2-utilizing anaerobic decay rate [d^{-1}]	0.1300

The process layout in Biowin is easy to follow and the input variable can be accessed by selecting individual units and linkages (figure 5).

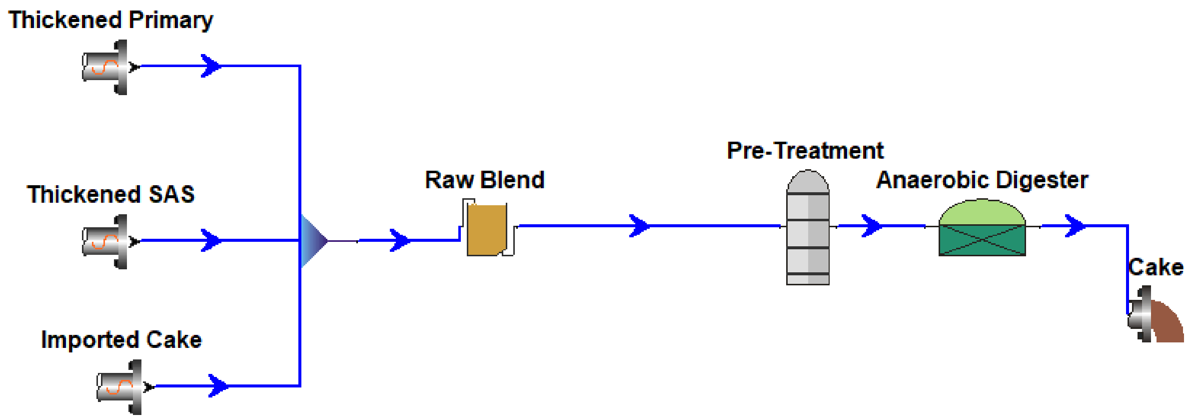

Figure 5. BioWin model developed for one of the seven sites

Results

Of the numerous input parameters one that influences the rate of biogas production greatly are the proportions of biodegradable and non-biodegradable COD in the feed sludge. There are several situations where a WaSC can influence the split, including:

1. Through a pre-treatment process
2. Primary: SAS. Influenced by a whole range of factors including sludge retention time and return liquor load and quality.

BioWin enables the user to quantify (and thus monetise) the benefit of pre-treatment and of changing the Primary: SAS (often assumed at 60: 40 is WaSC asset standards), which in turn can feed in to 'spend and save' investment.

Similarly, a calibrated model can be used to look at the benefit of increasing or decreasing the digester retention time on the specific biogas yield (m^3. biogas/TDS applied) and the overall quantity of biogas produced (m^3. biogas/m^3 of digester/d).

COD Fractionation

COD fractionation was undertaken in Aqua Enviro's purpose-built treatability laboratory, Wakefield. The testing provides:

Biodegradable COD – which is further subdivided in to Readily and Slowly biodegradable (particulate & colloidal) fractions. Non-biodegradable COD – with particulate and soluble fractions (Figure 6).

Readily biodegradable COD, such as volatile fatty acids, is readily degraded by microbial metabolism. Slowly biodegradable COD, composed of particulate organic matter, is degraded slowly by a series of microbial actions, such as adsorption, hydrolysis, and metabolism. Non-biodegradable soluble COD, which is refractory in biodegradation, is mainly contained in industrial wastewater. Non-biodegradable particulate COD are often referred as inert fraction that could be partly removed by sedimentation process (Wentzel et al., 1999; Henze et al., 2008).

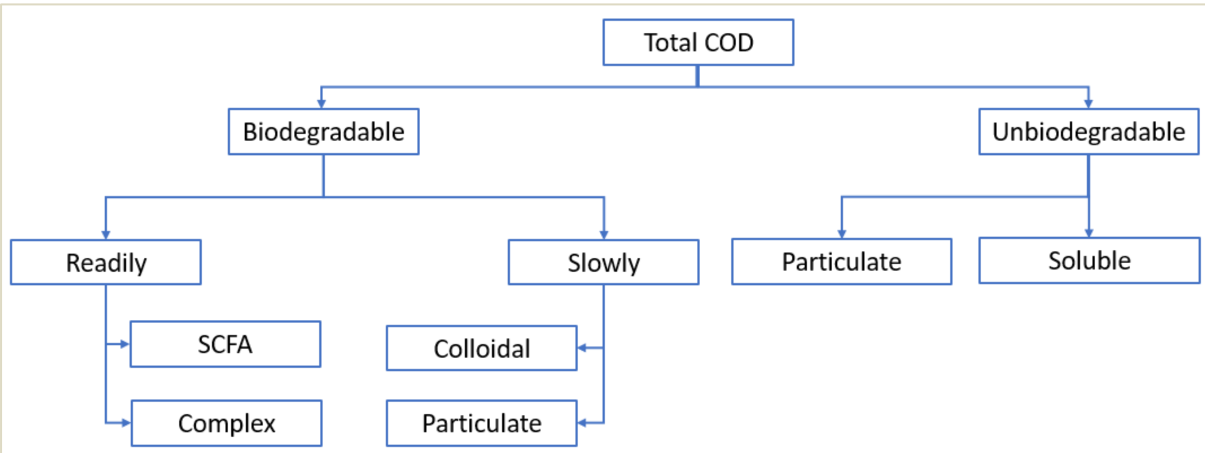

Figure 6. Different fractions of COD that can be determined through laboratory testing

It is important to understand that the different fractions aren't fixed through the treatment process and that operator actions can decrease as well as increase the biodegradable fractions and hence the energy generation potential. Table 4. Presents the quality of 'raw' sludges in terms of percentage biodegradability, prior to pre-treatment for each site and figure 7 the percentage increase in biodegradability through pre-treatment.

Table 4. Sludge quality ranking based upon COD biodegradability %

Thickened Primary			Thickened Secondary			Imports		
1-	**Site B**	81.84	**1-**	**Site E**	78.21	**1-**	**Site B**	65.75
2-	**Site D**	74.79	**2-**	**Site B**	66.38	**2-**	**Site E**	59.94
3-	**Site E**	74.72	**3-**	**Site C**	64.30	**3-**	**Site G**	52.02
4-	**Site A**	73.13	**4-**	**Site D**	61.60	**4-**	**Site C**	43.34
5-	**Site C**	70.95	**5-**	**Site G**	39.92	**5-**	**Site D**	40.83
6-	**Site F**	69.97	**6-**	**Site F**	37.26	**6-**	**Site A**	39.47
7-	**Site G**	60.74	7-	**Site A**	35.71	**7-**	**Site F**	30.32
	Average	**72.31**		**Average**	**54.77**		**Average**	**47.38**

The average for primary sludges is 72.31%, which means that 72.31% of the energy could be converted in to biogas. It does not mean that 72.31% will be converted, that is dependent upon the site's operation, digester retention time and organic loading rate.

Findings from the fractionation:

- Primary sludge, as expected is the most amenable to digestion, retention time in primary tanks influences the biodegradable fraction.
- SAS values are influenced by sludge age, secondary treatment technology and return liquor load & quality.
- Imports, although largely SAS, are least suited to AD, but there is an opportunity to transport the best sludges to those sites with the capacity to take advantage. The nature of the import (liquid or cake) influences biodegradability.

Fractionation can also be used to show the change in biodegradability through pre-treatment, which in turn enables the user to evaluate under which conditions pre-treatment can be optimised (Figure 7).

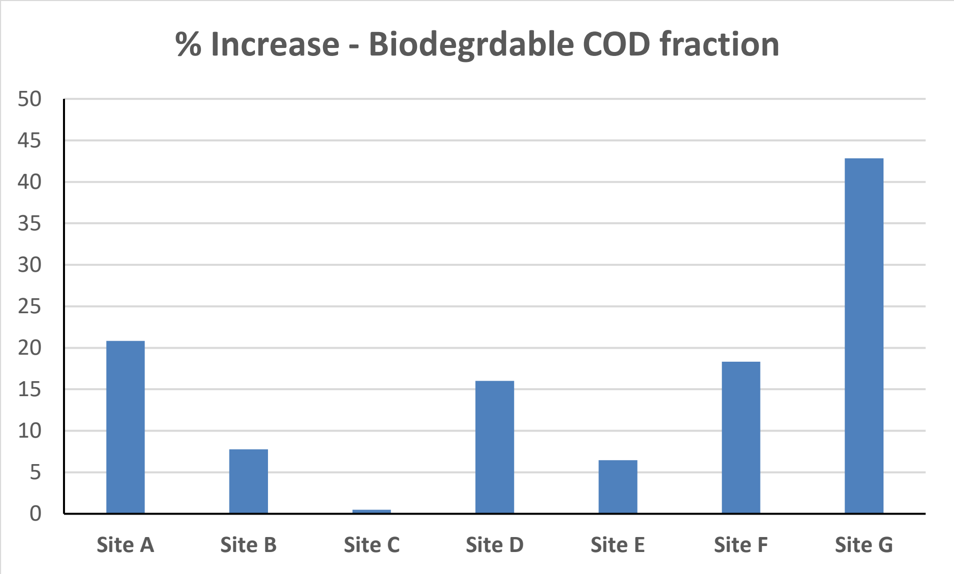

Figure 7. Impact of pre-treatment upon COD biodegradability

Model Output vs Actual Site Performance

Dynamic simulation was run to demonstrate the time-varying system response based on the time varying influent loading to the system (EnviroSim Associates Ltd.). The dynamic calibration was run for the data obtained over the 3-week sampling period for multiple process variables. The most important process outputs include: VFA, pH, Ammonium, and daily gas flow (figures 8-11).

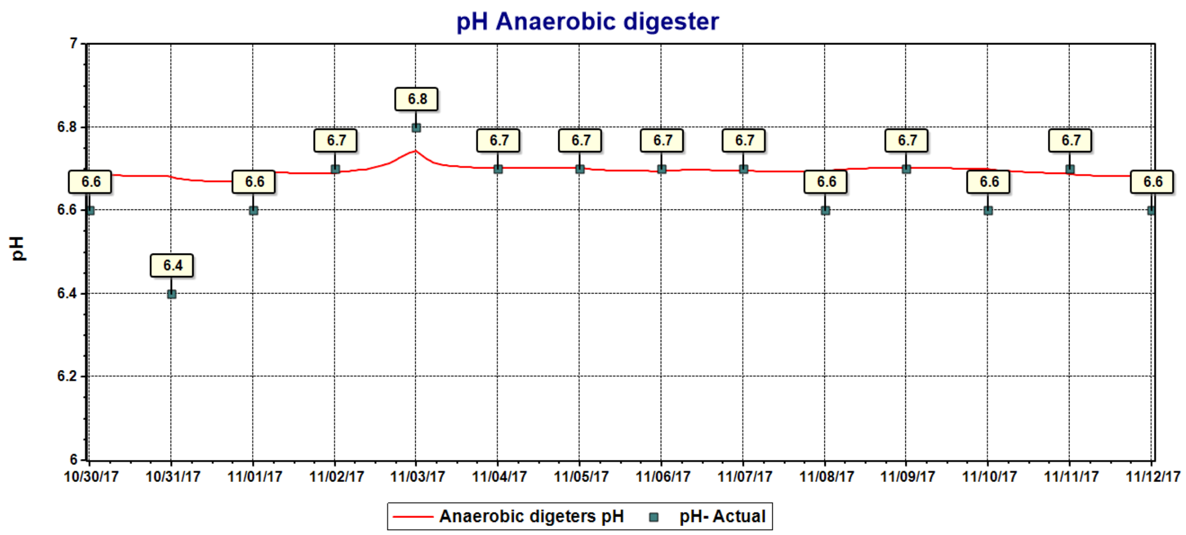

Figure 8. The model predicted pH values (solid lines) vs the measured values (squares).

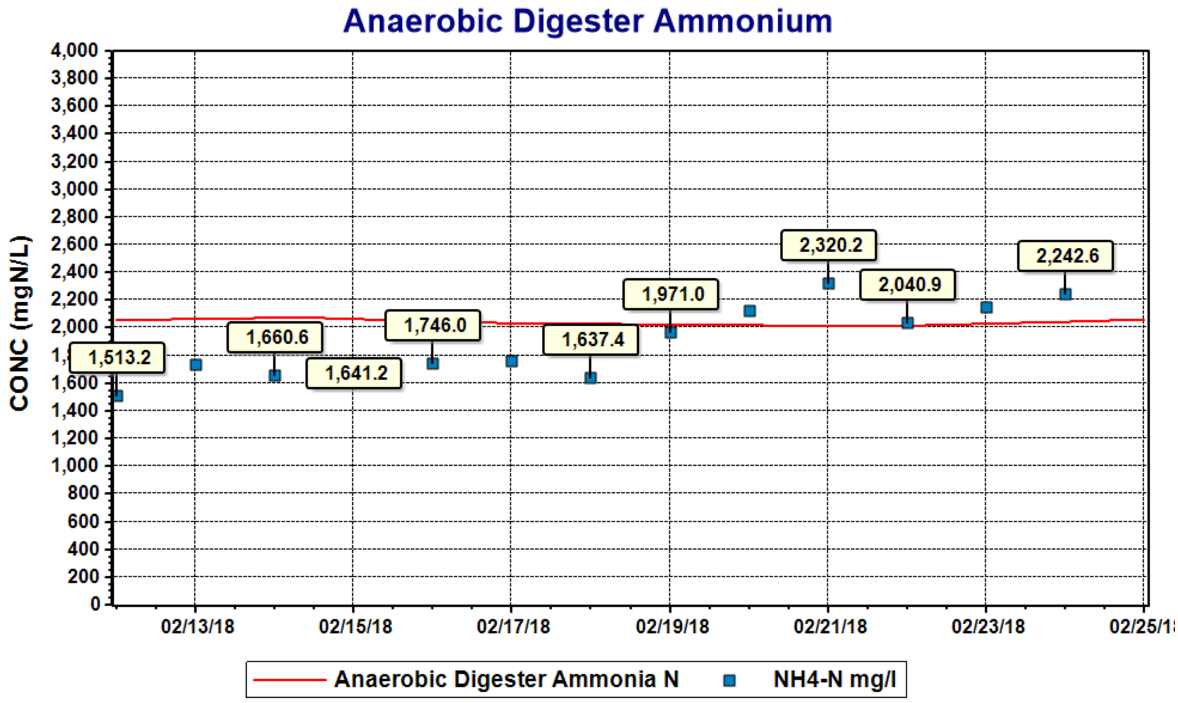

Figure 9. The model predicted Ammonium values (solid lines) vs the measured values (squares).

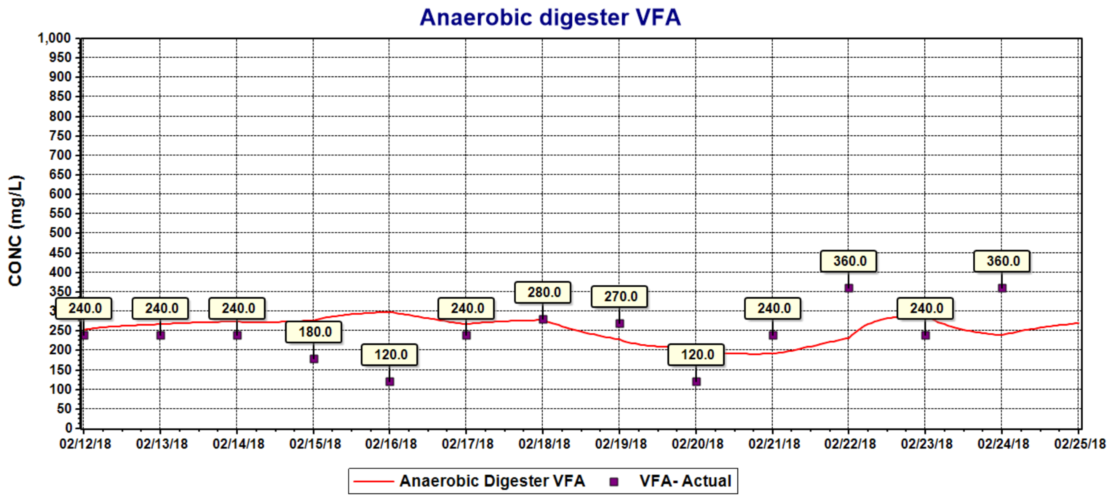

Figure 10. The model predicted VFA values (solid lines) vs the measured values (squares).

Once built model simulations are quick to run and parameters (e.g. COD fraction, split in primary: SAS, digester retention time) can be altered and the benefit/loss in terms of biogas production shown.

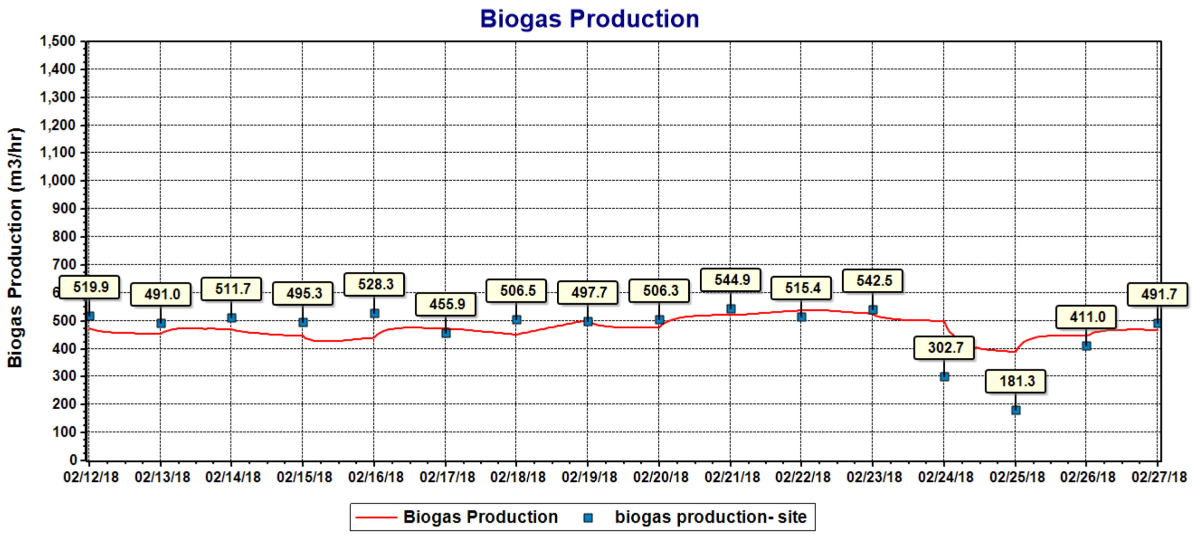

Figure 11. Shows the gas flow rate profiles. It demonstrates that the model predicted values (solid lines) fit the measured values (squares) for digesters operating on the site.

However, before that stage, the model output will first show if there is a difference between what the site is producing and what it should be producing, according to BioWin. If the site's actual performance is the same as BioWin, said site is doing as well as it can, it is optimised for its feedstock (Figure 11). A site that is not achieving the model output has the potential to be optimised (figure 12).

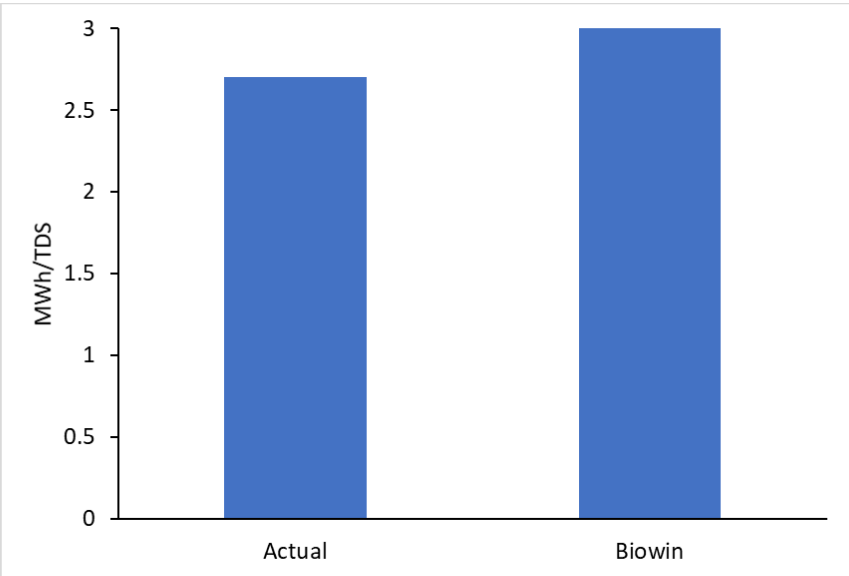

Figure 12. Site C, actual energy output is 2.7 MWh/TDS versus a BioWin model prediction of 3.0. (Values equivalent to 1.08 & 1.20 MWh/TDS after CHP, assuming 40% electrical efficiency)

The calibrated model can be used to determine the impact of process changes on digester performance by simulating future conditions with many different scenarios. This is found to be useful in predicting performance values for different operational alternatives and loading conditions. Model predictions can be used to determine the minimum HRT or temperature to reach a target biogas production and/or volatile solids loading rate.

As an example, Figure 13 shows for Site A, (which has low biodegradability values for SAS and imports), that by altering the characteristics of the feed sludges, energy production could be increased from 2.4 to 2.9-3.475 MWh/TDS.

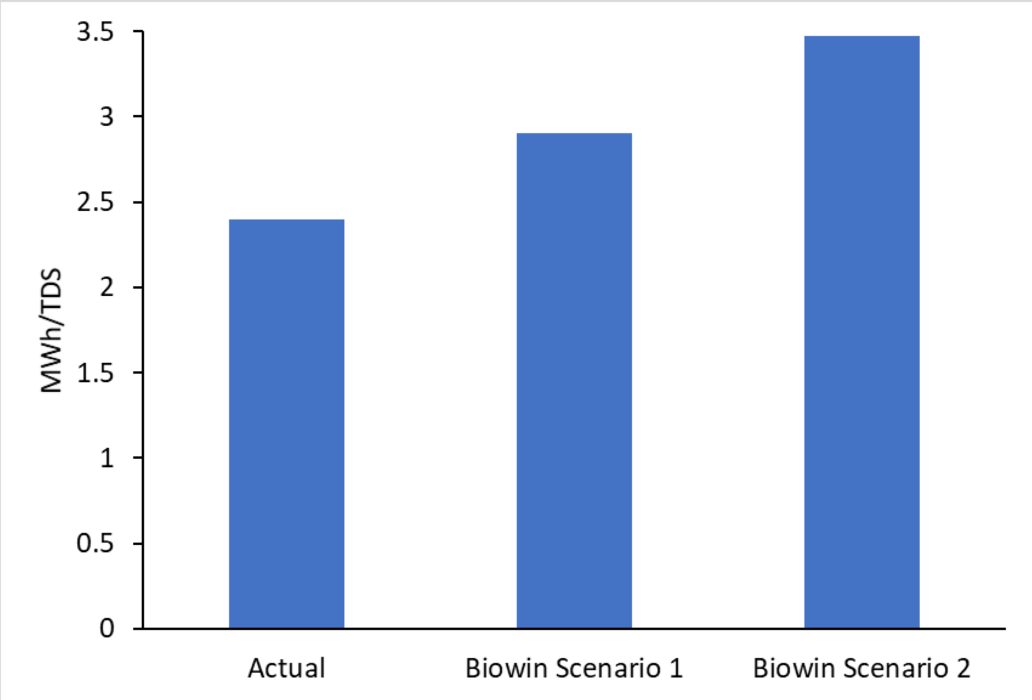

Figure 13. The impact of altering feedstock components on energy production at Site A

The opportunity to realise the values in figure 13 is site specific, requires buy-in from process and operational teams, and potentially modifications to pipework, mixers, tank operating levels and availability. On site workshops were used to develop site specific strategies for Anglian Water.

Energy Balances

For better understanding and demonstration of the opportunities for process optimisation, transferring the data generated in BioWin to an energy/Sankey diagram becomes worthwhile. A Sankey diagram is a simple illustration of energy flows. It provides a 'single shot' view of the overall energy balance and where optimisation efforts could focus. The energy diagram also incorporates elements that BioWin does not model (in terms of energy flow), which include return liquors, but was captured during the sampling and analysis programme.

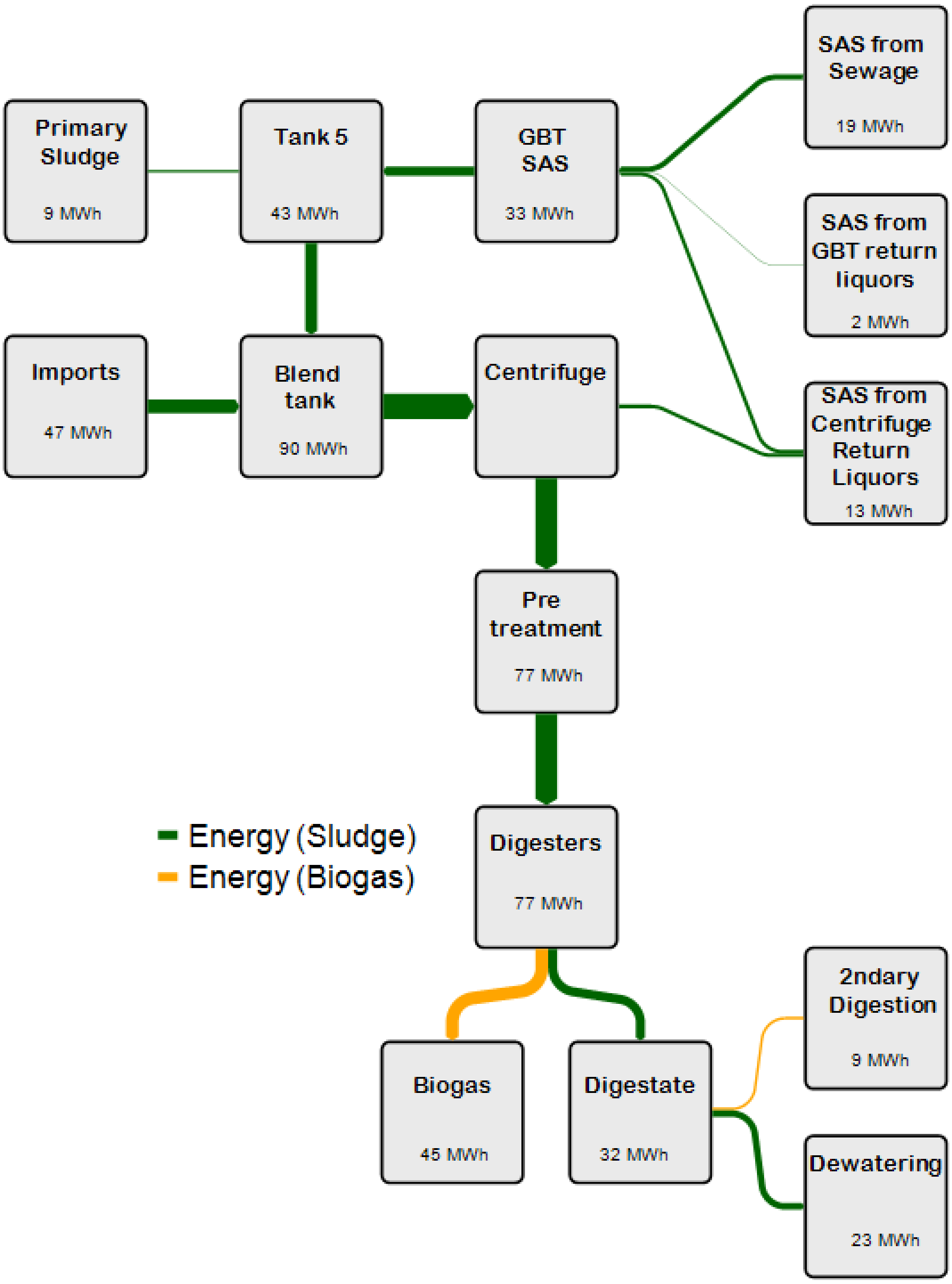

Figure 14. Energy diagram for Site A

Site A processes ~15 TDS/d, of which imports account for ~60% of the total load, equivalent to 47 of the total 77MWh processed through digestion (figure 14). Indigenous sludges are thickened and blended with imports, stored and then dewatered via centrifuge before pre-treatment (target of 8-10% dry solids), followed by digestion (theoretical HRT of 21 days). The SAS: primary is very high at 80: 20, the COD degradability of SAS is 35.71% and primary 73.13%, therefore rebalancing the SAS: primary offers significant energy benefit. Storage times post initial thickening (shown as Tank 5 & Blend Tank in figure 14) are long, which leads to solubilisation of COD and losses of readily biodegradable COD, mainly at the centrifuge (13MWh/d) before pre-treatment.

These liquors, as well as a small energy load from the SAS Gravity Belt Thickeners (2 MWh/d) are returned to the head of the works and due to the soluble, biodegradable nature, bypass the primary tanks and are converted to SAS, this largely accounts for the current SAS: primary (Figure 14).

The equivalent COD load of return liquors from these two streams is 3.49 tonnes. Based upon a COD: BOD of 2:1, an aeration system efficiency of 2 kilogrammes of oxygen per kilowatt-hour and 11pence/kWh this load incurs an aeration treatment cost of £174.50/d. Given COD lost in return liquors is readily biodegradable a high proportion would be converted to biogas, assuming an 80% conversion rate this would generate an additional 2.8 MWh of biogas each day; equivalent to 1.1 MWh_e ,assuming a CHP electrical efficiency of 40%.

The Sankey diagram also shows that from the digestate produced (labelled 2ndary digestion) there is the potential to generate an additional 9 MWh, equivalent to 17% of total biogas production. This is higher than anticipated, which offers an opportunity to recover biogas in the secondary digesters or could be an indicator of short circuiting in digesters. Further investigation, in the form of a lithium tracer will quantify digester mixing capacity and actual retention time.

Anglian Water are currently investing in plant modifications to deliver and measure the increase in energy production, which include:

- Bypassing storage tanks to reduce the overall HRT of the untreated sludge prior to centrifugation.
- Higher dry solids operation of the centrifuge and option to blend/dilute with biodegradable COD.
- Analysis of TSS, total, filtered and biodegradable COD to measure the impact of the changes.
- Digester cleaning to ensure that whole volume is available and to reduce losses from secondary digestion tanks.

We hope to be able to present an update of this work and from the other six sites next year!

Conclusions

1. BioWin modelling, supported by 3-week periods of sampling and analysis, was successfully deployed across seven Anglian Water STCs.
2. The model outputs show whether a site has the opportunity for optimisation and how changing the characteristics of the feed sludges can increase energy production.
3. Return liquors and the SAS: primary have a big impact on the energy balance.
4. COD fractionation can be used to rank sludges in terms of the amenability to digestion.
5. The nature of COD (biodegradable and non-biodegradable) can vary over time and at different stages of treatment, once understood there is the potential to control.
6. Modelled energy gains can be used to develop investment cases on a ‘spend to save’ basis.
7. All sludges are not the same! We knew that, but we can quantify!

Acknowledgements

Thanks to all those who helped in the Anglian Water Innovation, Operational and Optimisation teams.

References

Batstone, D.J; Keller, J.; Angelidaki, I.; Kalyuzhnyi, S.V.; Pavlostathis, S.G.; Rozzi, A.; Sanders, W.T.M.; Siegrist, H.; Vavilin, V.A. (2002) The IWA Anaerobic Digestion Model No 1 (ADM1) Wat. Sci. and Tech Vol 45(10) 65.

DEFRA (2009). DEPARTMENT FOR ENVIRONMENT, FOOD AND RURAL AFFAIRS, Future Water – The Government's Water Strategy for England, 2009. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/69346/pb13562-future-water-080204.pdf [accessed 22 August 2018]

Envirosim Asociates Ltd (2009) BioWin 3 Manual, Flamborough, Ontario, Canada.

EnviroSim Associates Ltd. Introductory topics with BioWin. Flamborough, Ontario: EnviroSim Associates Ltd.

Forgacs, G., Smyth, M., Law, I & Arnot, T.C. (2017). Co-digestion and Food Waste AD: BioWin Modelling to Optimise OLR & HRT on the Avonmouth Food Waste Digesters. *22nd European Biosolids and Organic Resources Conference*, November. Aqua Enviro, Wakefield.

Henze, M.; van Loosdrecht, M.C.; Ekama, G.A.; Brdjandnovic, D. (2008.) Biological Wastewater Treatment—Principles, Modeling and Design; IWA Publishing: London, UK.

Jones, R.; Takács, I. (2004) Modeling the Impact of Anaerobic Digestion on the Overall
Laughton, C. & Hallan, S. (2014). Selecting the right equipment for your sludge. *Making Dewatering Work.* Aqua Enviro, Wakefield.

Mills, N. (2015). Unlocking the Full Energy Potential of Sewage Sludge. University of Surrey & Thames Water.

OFWAT (2016). Water 2020: our regulatory approach for water and wastewater services in England and Wales. https://www.ofwat.gov.uk/wp-content/uploads/2015/12/pap_tec20150525w2020app2.pdf [accessed 22 August 2018]

Smith, S. (2014). How activated sludge sludge has been transformed from a waste to a resource, and the implications of this for the future of the activated sludge process. In ed. Horan, NJ, *Activated Sludge: Past, Present & Future*. Aqua Enviro Technology Transfer.

Wentzel, M.C.; Mbewe, A.; Lakay, M.T.; Ekama, G.A. (1999). Batch test for characterisation of the carbonaceous materials in municipal wastewaters. Water SA, 25, 327–336.