A spreadsheet calculator for estimating biogas production and economic measures for UK-based farm-fed anaerobic digesters

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Abstract

This paper presents a spreadsheet calculator to estimate biogas production and the operational revenue and costs for UK-based farm-fed anaerobic digesters. There exist sophisticated biogas production models in published literature, but the application of these in farm-fed anaerobic digesters is often impractical. This is due to the limited measuring devices, financial constraints, and the operators being non-experts in anaerobic digestion. The proposed biogas production model is designed to use the measured process variables typically available at farm-fed digesters, accounting for the effects of retention time, temperature and imperfect mixing. The estimation of the operational revenue and costs allow the owners to assess the most profitable approach to run the process. This would support the sustained use of the technology. The calculator is first compared with literature reported data, and then applied to the digester unit on a UK Farm to demonstrate its use in a practical setting.

Keywords

Anaerobic digestion; Biogas production estimation; Economic calculator; Mathematical modelling.

1. Introduction

Anaerobic digestion (AD) is a biological process that breaks down biodegradable material in the absence of oxygen and produces biogas and digestate. Biogas is mostly methane and carbon dioxide and can be used as an energy source for generating heat and electricity. Digestate contains fibrous material and minerals and can be used as a soil fertiliser. AD is considered a renewable technology, as the feed material is often regarded as a waste to be landfilled or incinerated. Farm-fed anaerobic digesters (up to 500kWe) are logistically practical due to the proximity to feed materials and the availability of farmland to spread the digestate onto.

The AD sector in the UK has grown significantly in the last few years, and currently, there are over 185 farm-fed AD units in the UK, with over 500 being developed (NNFCC, 2015). However, the overall increase in AD capacity in the UK has led to the gradual reduction in government incentives, upon which farm-fed AD units depend to be profitable. Given the many benefits of the technology, there is a motivation for the sustained use of farm-fed AD units. To this end, a simple mathematical model based tool, often conveniently termed “calculator” that can reliably estimate the biogas production and associated economic measures would be desired, for it can assist the owner to better manage and optimise the operation of the process.

Academic research on biogas production modelling have largely focused on kinetic models which estimate bacteria growth inside the digester. These require measurements not normally available in farm-fed AD units and are complicated for non-experts to understand and maintain, making them impractical. Empirically based approaches have focused on the use of biogas yields. They are more straightforward to understand and can be calculated from existing measurements, making them practically viable. In the literature, two freely available AD calculators (Jones & Salter, 2013) (Anderson, et al., 2013) have been reported; they will

be discussed in detail in section 2.2.2. Briefly, these calculators were developed for particular application scenarios. The scenario in (Jones & Salter, 2013) is that the farmland is a “utility” supporting the AD unit, where the farmers decide on how the farmland should be used to maximise the AD unit profit. In (Anderson, et al., 2013), the focus is on when the combined heat & power (CHP, which is downstream of the AD) unit should operate relative to local electricity demand to maximise profits. Under such scenarios, biogas yields are taken as fixed values (Jones & Salter, 2013) (Anderson, et al., 2013), despite the fact that the yields are affected by the operating conditions, including retention time, temperature and dead time (Kim, et al., 2006) (Chae, et al., 2008).

In contrast, the scenario considered in this paper is that the AD unit is not a core part of the farmers’ business; rather it is an additional facility to make use of the existing biodegradable waste produced on the farm. The farmers are non-experts in the AD process. This is a typical use case of AD in UK farms and widely seen in other countries. The existing calculators (Jones & Salter, 2013) (Anderson, et al., 2013) are not directly applicable because of using fixed biogas yields, which should depend on the operating conditions that vary significantly under the scenario considered in this paper.

A spreadsheet tool proposed in this paper is to assist operators in the day-to-day management of farm-fed AD units and maximising the long-term process profitability of the unit. The tool has two main components: a steady state model to estimate biogas production, and financial estimations of the operational revenue and costs of the unit. Farm-fed AD units have a limited number of process measurements; the installation of additional devices/laboratory equipment is financially impractical. This restricts the sophistication of process models that can be developed. The proposed model estimates the biogas yield (the biogas produced per unit mass of a particular material) as a function of the retention time, operating temperature, dead time and a broad classification of the type of feedstock. Details

on the biogas yield estimation are discussed in section 2.3. The operational revenue and costs are location sensitive. This calculator is designed for common farm-fed AD units in the UK. The site location affects the utility prices, product value, government incentives etc. The factors included in the financial calculations are detailed in section 2.4. The prediction performance of the developed tool is first compared with literature data, and then its use is demonstrated in a 500kWe AD unit at a working UK Farm.

The Microsoft Excel spreadsheet that implements the calculator has been made publicly available for non-commercial use [as Supplementary Materials](#). Currently this tool is being incorporated with a tablet app being developed at Perceptive Engineering Ltd. for practical use by farm owners and operators.

2. Materials and Methods

2.1. Summary of the calculator

The calculator consists of two parts: a biogas production model, and an operation economic estimator that calculates the operating revenue and costs for the unit. A summary of the two parts is given below.

In the biogas production model, the production is estimated using biogas yield, which is estimated from the volatile solids destruction (VSD) rate. Empirical studies, including (Bolzonella, et al., 2005) and (Metcalf & Eddy, Inc., 2003), represented VSD as a function of retention time (RT). Other studies indicated that operating temperature, dead time, and imperfect mixing also affect VSD; therefore the proposed model estimates VSD as a function of retention time, temperature, dead time and mixing profile. This modification to the VSD was applied to the models proposed by (Bolzonella, et al., 2005) and (Metcalf & Eddy, Inc., 2003), and a weighted average between the two estimated VSD is taken.

In the economic calculation part, the biogas produced is converted to heat (using a thermal boiler), and/or to heat and electricity (using a combined heat and power unit or refined to biomethane and injected to the gas grid). The revenue and costs of these approaches are considered. This part requires a lot of site-specific information such as the number of employees, the amount of heat/electricity reused on site, gate fees and transport costs for feed materials, etc. For this study, the tariffs and government incentives are based on what applies to the UK; but these values can be easily changed by the user. The estimated economic measures in operation can then be used to estimate the long-term revenues and costs for the unit, providing useful information to decision making on how the unit should be operated.

2.2. Scope of Work

The AD calculator proposed is designed to work for UK based farm-fed AD units. The common configurations for AD units used in the UK are shown in Table 1. The proposed AD calculator is designed to work for the shaded configurations.

Table 1 – Common configuration of AD units in the UK (biogas-info.co.uk, 2014)

{PLACEHOLDER FOR **Table 1**, PLEASE REFER TO SEPARATE FILE}

A simplified illustration of a farm-fed anaerobic digester and the typically available process measurements are shown in Figure 1. The number of measured process variables, especially inside the digester tank, is limited. The installation of additional measuring devices/laboratory equipment is financially impractical. This greatly limits the applicability of more sophisticated biogas production models available in the literature, such as kinetic models. The emphasis in this paper is the development of a biogas production model that is based on the available measurements found on a typical farm-fed AD unit. For many farmers, AD is not a core part of their business, and they are non-experts in the operation. The use of biogas yield is conceptually simple and easy to follow, and operating conditions can be accounted for by modifying how that yield is calculated.

{PLACEHOLDER FOR **Figure 1**, PLEASE REFER TO SEPARATE FILE}

Figure 1 – Illustration of a farm-fed scale anaerobic digester and the process variables that are typically measured.

The biogas production model takes reported values of potential biogas yields to allow for preliminary calculations. Reported case studies of farm-fed AD units are used to assess the accuracy of the uncalibrated model. The owners in the UK Farm AD unit used in this study have provided daily sample data over a period of 11 months. This data is used to assess how suited the biogas production model is as a tool to benchmark biogas production for day-to-day

operation. This AD unit takes a variety of feed materials from two different farms, including pig slurry, chicken litter, maize silage and grass silage.

2.2.1. Overview of existing biogas production models

The simplest and most common approach to estimate biogas production is using fixed biogas yields (FNR, 2010) (Jones & Salter, 2013) (Anderson, et al., 2013). Biogas yield is the expected biogas produced per unit mass of feed material (or volatile solid). The yield is multiplied by the feed mass flow rate to estimate the biogas production from that particular feed (Eqn. 1). Assuming linear superposition, the summation of the biogas produced from all the feed materials would give the overall biogas production of the unit (Eqn. 2).

$$\dot{V}_{BG,i} = \dot{m}_{VS,i} \times Y_{BG,i} \quad \text{Eqn. 1}$$

$$\dot{V}_{BG} = \sum_i \dot{V}_{BG,i} \quad \text{Eqn. 2}$$

where: $\dot{V}_{BG,i}$ is the estimated biogas production rate associated with feed material i (m^3 biogas/day); $\dot{m}_{VS,i}$ is the mass flow rate of volatile solids contained in feed material i (kg volatile solid/day); $Y_{BG,i}$ is the biogas yield of feed material i (m^3 biogas/kg volatile solid); $\dot{V}_{BG}$ is the total estimated biogas produced from the AD unit.

Some publications (discussed later) present the biogas yield as a function of other process parameters, but fixed biogas yields are a constant value assigned to each feed material type. Fixed biogas yields are widely published in the literature, and are often used in preliminary calculations. However, it is also recognised that operating parameters including temperature (Chae, et al., 2008) and retention time (Kim, et al., 2006) (El-Mashad & Zhang, 2010) affect how much biogas is produced (and hence the biogas yield). Fixed biogas yields are measured under certain operating conditions, and if they are used, it is implicitly assumed that the process is operating under the same or similar conditions as that reported. Report case studies of farm-fed AD units are used to verify the proposed AD calculator (see Table 5), and they show a variety of different operating conditions.

Some empirical studies have presented biogas yield as a function of retention time, including (Bolzonella, et al., 2005), (Eddy & Metcalf, 2003) and (Bilgili, et al., 2009) . An intermediate term is introduced, called the volatile solids destruction (VSD) rate. Volatile solids (VS) are the particulate, biodegradable material within the feed. VSD is the percentage of VS entering the digester tank that is consumed by bacteria. The relationship is represented in a number of ways, but the plot of biogas yield against retention time shows a logarithm relationship.

The VS removed is multiplied by a constant to estimate the biogas produced (Bolzonella, et al., 2005). It is therefore assumed that VSD and biogas production exhibit a linear correlation. Using the same assumption, an alternative description is that there is a theoretical maximum for the biogas yield (called the potential biogas yield) and that the VSD is a fraction of this potential yield. This is expressed in Eqn. 3.

$$Y_{BG,i} = Y_{BG,i}^p \times [VSD]_i \quad \text{Eqn. 3}$$

where: $Y_{BG,i}^p$ is the potential biogas yield obtainable from feed material i (m^3 biogas/kg volatile solid); $[VSD]_i$ is the volatile solids destruction for material i (%).

Biogas yields are an easy concept to apply, particularly for non-experts. Eqn. 3 allows the biogas yield to be used as before in Eqn. 1 and Eqn. 2, but it is now a function of VSD (which is, in turn, a function of retention time). Retention time is a calculated term based on the volume feed flow rate and the active volume of the digester tank, as shown in Eqn. 4.

$$[RT] = V_{Dig}/\dot{V}_{feed} \quad \text{Eqn. 4}$$

where: V_{Dig} is the active volume in the digest tank (m^3); $\dot{V}_{feed}$ is the volume flow of feed material (m^3/day).

While published literature noted the effects of operating temperature on biogas production, this is not incorporated in the biogas yield based models. Temperature effects are considered in kinetic models, which are the next level of model sophistication. Monod-kinetic

models are used to describe bacteria growth in the digester tank, and the associated material component consumption. Variations include additional terms to represent the concentrations of different inhibiting compounds (Angelidaki, et al., 1999); the representation of feed materials not as volatile solids but rather as organic component groups (Tomei, et al., 2009); and the effects of operating temperature. While kinetic models are useful academically, it is very difficult to apply these to farm-fed AD units due to the lack of measurements taken inside the digester tank (refer to Figure 1). While literature reported parameter values can be used for preliminary estimations, kinetic models are more complicated and harder for non-experts to understand and maintain.

2.2.2. Comparison with other AD calculators

The term AD calculator is rather broad. The general aim to these calculators is to provide a tool for AD unit owners to assess the different modes of operation and to pick the most profitable option. However, there are differences in how the biogas production is estimated, and what process variables the owner can change. The calculators by (Anderson, et al., 2013) and (Jones & Salter, 2013) are discussed briefly here to highlight the differences. The calculator presented in (Jones & Salter, 2013) was developed for AD units generating heat and electricity using a Combined Heat & Power (CHP) unit. The key difference is that it is achieved by changing what the available farmland is used for. The farm business would be centred around the AD unit, with the farmland functioning as a support facility to the AD unit.

The calculator presented in (Anderson, et al., 2013) was also focused on AD units which generated electricity in a CHP. The focus there was on the choice of CHP engine, and when to generate electricity. It considered peak demands for electricity in an area and used that to determine when to run the unit. By comparison, this calculator assumes that the farmland's intended use is not changed; the AD unit is an added facility to make use of the animal/agricultural waste already generated on the farm or nearby. Revenue generated from

electricity is calculated based on available subsidies in the UK. The biogas yield is estimated as a function of the operating conditions, as opposed to taking a fixed value.

2.3. Biogas production estimation

2.3.1. Base model structure

This biogas production model proposed is based on the empirical models by (Bolzonella, et al., 2005) and (Eddy & Metcalf, 2003), shown in Eqn. 5 and Eqn. 6 respectively. The correlation between [RT] and [VSD] is logarithmic.

$$[VSD]_{i,A1}^{RT} = \frac{k_1 \times [RT]}{1 + k_1 \times [RT]} \times 100\% \quad \text{Eqn. 5}$$

$$[VSD]_{i,A2}^{RT} = (k_2 \ln([RT]) + k_3) \quad \text{Eqn. 6}$$

where: $[VSD]_i^{RT}$ is the estimated VSD of feed material i at retention time $[RT]$ (%); $[RT]$ is the retention time (days); $k_{1\sim3}$ are model parameters. Subscripts $A1$ and $A2$ denote the two different base models used: $A1$ is from (Bolzonella, et al., 2005), $A2$ is from (Eddy & Metcalf, 2003).

Some published studies observing the relationship between biogas yield and retention time also observed a logarithmic-like relationship, but with a noticeable curve at low retention times (5 days or less). These include the studies by (Zhang, et al., 2007) and (Ge, et al., 2014). This discrepancy is likely due to organic composition of the material being digested (some organic component structures are more difficult to break down). For farm-fed systems, the effect of this is less significant, as the typical retention time that these units operate at is much greater (30 days and longer, see Table 5).

2.3.2. Inclusion of dead time

Bacteria require time to process feed material entering tank before biogas is produced. This delay is known as the dead time. This is added as a shift factor to the retention time factor, shown in Eqn. 7.

$$[VSD]_{i,A1}^{RT} = \frac{k_1 \times ([RT] - [DT])}{1 + k_1 \times ([RT] - [DT])} \times 100\% \quad \text{Eqn. 7}$$

$$[VSD]_{i,A2}^{RT} = (k_2 \ln([RT] - [DT]) + k_3) \quad \text{Eqn. 8}$$

Where: $[DT]$ is the dead time (days).

2.3.3. Inclusion of temperature effects

Temperature affects how active the bacteria groups are, and how quickly they consume feed material and generate biogas from it. Each bacteria group has a temperature range that they are most active in; outside this range, the activity rapidly drops. (Lier, et al., 1996) expressed the relationship between bacteria activity and temperature as a double Arrhenius equation, shown in Eqn. 9. See also Figure 2, which show how the relative bacterial activity factor relates to the operating temperature.

$$B = k_4 \times \exp(k_4 \times (T - k_6)) - k_7 \times \exp(k_8 \times (T - k_6)) \quad \text{Eqn. 9}$$

where: B is the relative bacterial activity factor (dimensionless); T is the operating temperature ($^{\circ}\text{C}$); k_{4-8} are model parameters.

For a finite amount of feed material, higher activity means that the material is processed more quickly. However, the total amount of biogas produced is limited to how much material is in the digester. Therefore, the effects of temperature become increasingly less significant at higher retention times (Gavala, et al., 2003) (Seadi, et al., 2008). It is incorporated as shown in Eqn. 10 and Eqn. 11 to reflect these characteristics.

$$[VSD]_{i,A1}^{RT,T} = \frac{B \times k_1 \times ([RT] - [DT])}{1 + B \times k_1 \times ([RT] - [DT])} \times 100\% \quad \text{Eqn. 10}$$

$$[VSD]_{i,A2}^{RT,T} = (k_2 \ln(B \times [RT] - [DT]) + k_3) \quad \text{Eqn. 11}$$

where: $[VSD]_i^{RT,T}$ is the VSD for feed material i evaluated at retention time $[RT]$ and temperature $[T]$ (%); B is the relative bacterial activity factor (dimensionless).

The model parameters k_{4-8} are estimated using the data presented in (Lettinga, et al., 2001). The reference contained information on both mesophilic and thermophilic conditions,

and so the two sets of modelling parameters (one set for each temperature region) are estimated (using the same form as Eqn. 9), but scaled such that the value of B in the mesophilic regime is equal to 1 at 35°C. This is because k_1 is initially set to 0.2 as reported in (Bolzonella, et al., 2005), and that experiment was carried out at 35°C. The relationship between the relative bacterial activity factor and the operating temperature is shown in Figure 2.

{PLACEHOLDER FOR Table 12, PLEASE REFER TO SEPARATE FILE}

Figure 2 - The effect of temperature on the relative bacterial activity B

2.3.4. The effects of imperfect mixing

Vertical tank digesters are the most common form of digesters in the UK. The average retention time calculated in Eqn. 4, however the mixing regime for a vertical tank digester does not give a consistent retention time. A study on the mixing profile on vertical AD units concluded that 39% of the feed would leave the digester tank before reaching half the average retention time, and 13% of the influent leaves after spending over double that (Aqua Enviro, 2010). The correlation between retention time and VSD is not linear and so this was evaluated after taking into the effects of temperature. The calculation was simplified to evaluate the VSD under three conditions: at half retention time, at the specified retention time and at double the retention time. A weighted average of these determines the VSD, as shown in Eqn. 12. Eqn. 12 is applied to both calculation approaches.

$$[VSD]_{i,A1 \text{ or } A2} = k_9 \times [VSD]_i^{0.5 \times RT, T} + k_{10} \times [VSD]_i^{2 \times RT, T} + (1 - k_9 - k_{10}) \times [VSD]_i^{RT, T} \quad \text{Eqn. 12}$$

where: $[VSD]_i^{0.5 \times RT, T}$ is the VSD for feed material i evaluated at half the calculated retention time $[RT]$ and temperature $[T]$ (%); $[VSD]_i^{2 \times RT, T}$ is the VSD for feed material i evaluated at

twice the calculated retention time $[RT]$ and temperature $[T]$ (%); k_7 and k_8 are the averaging weights, where $0 \leq (k_9 + k_{10}) \leq 1$.

The retention time for a plug flow reactor is, by design, much more consistent, and so the imperfect mixing adjustment should be omitted: the $[VSD]_i^{RT,T}$ then calculated from Eqn. 10 and Eqn. 11 would be used instead.

2.3.5. *Weighted average of the two approaches*

The VSD calculation was carried out using two base models resulting in the estimated VSD in Eqn. 12 (or Eqn. 10 and Eqn. 11 for horizontal digesters). The effects of the process conditions are non-linear, and so the calculations had to be carried out separately. A weighted average is taken to estimate the VSD. The factor k_{11} has been used as a tuning parameter to ensure a good fit against observed data.

$$[VSD]_i = k_{11} \times [VSD]_{i,A1} + (1 - k_{11}) \times [VSD]_{i,A2} \quad \text{Eqn. 13}$$

where: k_{11} is the weighted average factor, where $0 \leq k_{11} \leq 1$.

This VSD is then used in Eqn. 1 and Eqn. 2 to estimate the biogas produced from the AD unit. A possible simplification when implementing these calculations would be to use only one of the approaches (A_1 or A_2) and adjust the parameters of k_1 or k_2 and k_3 .

To clarify the different approaches the following notation is used: Base approach 1 is shown in Eqn. 5 (Bolzonella, et al., 2005); modified approach 1 is calculated from Eqn. 10 and Eqn. 12; modified approach 2 is calculated from Eqn. 11 and Eqn. 12. The difference in the proposed approach compared to the base is that the base approach modelled VSD as a function of the retention time, whereas in the modified VSD is a function of retention time, dead time, temperature and mixing profile. The actual VSD estimation proposed in this paper is a weighted average of modified approach 1 and modified approach 2.

2.3.6. Methane production estimation

Methane is the energy component of the biogas. It was estimated using the same model with VSD and potential methane yield. A simpler approach is to estimate the average methane content contained in the biogas and multiply it with the estimated biogas production (Eqn. 14). The effects of temperature and retention time are therefore included within the biogas production calculations already. The total methane production is the summation of all the methane production rates for every type of feed material (Eqn. 15). The linear superposition approach assumes that the digester remains in an operating mode free from methane inhibitory factors, such as low pH.

$$\dot{V}_{CH_4,i} = \dot{V}_{BG,i} \times C_{CH_4,i} \quad \text{Eqn. 14}$$

$$\dot{V}_{CH_4} = \sum_i \dot{V}_{CH_4,i} \quad \text{Eqn. 15}$$

where: $\dot{V}_{CH_4,i}$ is the methane production rate of feed material i ($\text{m}^3 \text{CH}_4/\text{day}$); $C_{CH_4,i}$ is the biogas content associated with feed material i (%); $\dot{V}_{CH_4}$ is the total methane production rate ($\text{m}^3 \text{CH}_4/\text{day}$).

2.3.7. Summary of model parameter values

A number of model parameters are introduced in the previous subsections. Table 2 is a summary of the parameter values k_{1-11} and the source references for these parameters. An experienced user can adjust these values. To allow for preliminary estimations, literature reported values for the potential biogas yield and methane content are included, as summarised in Table 3. Verification of the literature values in Table 3 is always advised to eliminate as much uncertainty as practical for the calculations; the properties of feed material can vary widely from site to site.

Table 2 – Fixed parameter values used in the biogas production estimation calculations

{PLACEHOLDER FOR **Table 2**, PLEASE REFER TO SEPARATE FILE}

Table 3 – Initial parameter values associated with the feed materials

{PLACEHOLDER FOR Table 3, PLEASE REFER TO SEPARATE FILE}

2.4. AD operation economic estimation

The second part of the AD calculator considers biogas usage, and estimates the operational revenue and costs associated with each scenario. Much of the information is site specific and requires specific configurational inputs. This section explains which inputs are considered and how they are calculated.

2.4.1. Feed material value

Feed material value is the unit cost to acquire the feed material and transport onto the site. Typically, the material comes from the farm itself, but the unit may also take biodegradable waste from nearby facilities. In many cases, AD owners are paid a gate fee to process certain feeds, which means that the feed acquisition is a form of income. In such an instance, the estimated cost should be negative.

2.4.2. Biogas usage options

Biogas is typically used in one of three ways: generating heat via a gas boiler, generating heat and electricity using a CHP unit or with further enhancement (scrubbing, CH₄ enriching) converted to biomethane to inject to the gas grid. The export value and government incentives are measured by the energy content of the biogas or biomethane. For UK farm-fed AD units, the most common use for the biogas is heat and electricity generation using a CHP unit. Heat and electricity generation depend upon unit efficiency (i.e. the fraction of energy from biogas that is converted). The energy content of the biogas is estimated from the calorific value of methane.

The UK has limited capacity for biogas enhancement to biomethane, it is much more prevalent in other European countries, particularly Germany (EBTP, 2016). Biogas enhancement to biomethane can be carried out using a number of approaches. The calculation

used the reported values on methane purity and recovery, and electricity consumption from (Biomethane Regions, 2012). Biomethane production is estimated using Eqn. 16. The energy content of the biomethane is estimated from the calorific value of methane.

$$\dot{V}_{biomethane} = \dot{V}_{BG} \times \frac{[CH_4 \text{ recovered in biomethane}]}{[CH_4 \text{ purity in biomethane}]}$$
 Eqn. 16

where: $\dot{V}_{biomethane}$ is the volume flow of biomethane (m³/day).

2.4.3. Heat and electricity consumption and savings

Heat is consumed by the AD unit to heat up the feed material and from general heat loss from the digester tank to the surroundings (parasitic heat loss). Sensible heat transfer (i.e. no phase change) is used to estimate the heat required to heat up the feed material Eqn. 17. Specific heat capacity is not normally evaluated for individual feed materials, but as the combined feed material is mostly water, the specific capacity of water is used.

$$\dot{Q}_{feed} = \dot{M} \times C_p \times (T - T_{amb})$$
 Eqn. 17

where: $\dot{Q}_{feed}$ is the heat consumed to heat up the feed material (kJ); $\dot{M}$ is the total feed mass flow rate (kg/day); C_p is the specific heat capacity of the feed (kJ/kg K).

The heat loss to the surroundings is calculated from the general heat transfer equation, evaluated at each surface. The heat transfer coefficient U depends on material properties, material thickness, the fluid characteristics etc. Values of U can be obtained from the literature.

$$\dot{Q}_{loss,j} = U \times A_j \times (T - T_{amb})$$
 Eqn. 18

where: $\dot{Q}_{loss}$ heat transfer (lost) per unit time across the area A_j (W); U is the overall heat transfer coefficient (W/m² °C); A_j is the heat transfer area of surface j (m²); T_{amb} is the ambient temperature (°C).

Electricity is consumed in the AD unit by the various pumps and mixers that support the process operation. The calculation is based on material flow (how much there is to pump/mix). An AD unit may have a surplus or deficit of heat and electricity. Electricity and heat is imported if there is a deficit, and this is calculated against the retail price of electricity and gas. If the AD process is used to generate heat and electricity, the energy may be reused on site instead of being sold. This is considered a saving and is calculated based on the retail price of electricity and heat. The distinction between electricity/heat being reused and being sold affects some government incentives.

2.4.4. Government incentives

AD units encouraged in the UK by the following incentives:

- Feed-in-Tariffs (FiTs) are paid for the generation of electricity, determined by the AD capacity, even if the electricity is reused on site;
- Electricity Export Tariff is a floor price for the electricity exported from renewable sources;
- Renewable Obligations Certificates (ROCs) are certificates issued to owners based on the amount of electricity exported, (the value is not fixed, rather the certificates are tradable, and their value is based on supply and demand); and
- Renewable Heat Incentives (RHI) is a guaranteed payment for the generation of renewable heat and biomethane injection.

ROCs cannot be taken in conjunction with FiT or with RHI.

2.4.5. Digestate value, labour costs and other factors

Digestate is used as a soil fertiliser substitute for a farm-fed AD unit. The digestate value is the fertiliser it replaces, though this is difficult to determine without on-site data as it would depend on the minerals available in the feed material. The cost of labour is the man-

hours required to maintain the process multiplied by the hourly wage of an employee. The estimated amount of man-hours needed is provided (see Table 4).

2.4.6. Summary of reference values used

Table 4 contains the reference values used in the financial calculations previously described.

Table 4 – Summary of the factors considered for the AD operation economic estimation

{PLACEHOLDER FOR Table 4, PLEASE REFER TO SEPARATE FILE}

2.5. Biogas production estimation on a UK Farm AD

The biogas production model predicts steady-state biogas production. It is intended to evaluate the average biogas production over a few months, and not for a day-to-day basis unless if the AD unit operated consistently under the same operating conditions. The day-to-day biogas production estimate provides a benchmark for the farmers to assess how well the unit is performing. There is an interest in assessing if the steady state biogas production model can be applied (or adapted) to provide day-to-day biogas production estimation. The daily sample from the UK Farm AD is used to assess this.

The UK Farm's AD unit store biogas in the digester as a buffer to be drawn to meet the demand of the CHP, or when the gas holder reaches a certain pressure. This buffering makes it harder to distinguish the biogas produced from the feed material. Additionally, because biogas is removed from the tank if the pressure is increased (e.g. through an increase in feed flow), the dead time may not be observable. Some assumptions are made to enable to steady model to be applied. It is assumed that the process does not undergo significant variations in the feed flow and that the tank level remains constant. A 5-day average is applied to the feed flow rate to smooth out small fluctuations. The approach taken is to estimate the biogas production for the averaged feed flow rate and compare that with the biogas produced at that same daily sample.

3. Results and Discussion

3.1. Assessment of the biogas production model

The proposed biogas production model requires information on the feed flow rates $\dot{M}_i$ (which determine the retention time and potential biogas yield), the operating temperature T and some information about the digester itself (vertical or horizontal, active volume, materials etc.). The above information should be available for a typical AD unit, so the model should be readily usable for most sites.

The key difference in the proposed model for biogas production estimation was that VSD estimation accounted for temperature, retention time, dead time and imperfect mixing effects. Some of these can be observed in Figure 3a and b. Figure 3a show the effects of temperature and retention time on the VSD estimated. VSD (and by extension biogas yield and biogas production) increased with retention time, up to an upper limit of the feed potential biogas yield of the material. This corresponded with the behaviour observed from (Kim, et al., 2006) (El-Mashad & Zhang, 2010) and (Nayono, et al., 2010). Model calibration on site involves measuring the potential biogas yield, $Y_{BG,i}^p$, for each feed material. Figure 3b showed how the biogas yield show the biogas yield estimations for different feed materials evaluated at $T = 35$, $k_1 = 0.2$, $[DT] = 4$. An experienced operator could adjust the parameters k_{1-3} & τ and dead time $[DT]$.

{PLACEHOLDER FOR Figure 3a, PLEASE
REFER TO SEPARATE FILE}

{PLACEHOLDER FOR Figure 3b, PLEASE
REFER TO SEPARATE FILE}

Figure 3 – The effects of temperature, retention time and feed type on biogas production; (a) shows the effects of temperature and retention time on the VSD for mesophilic conditions (imperfect mixing and dead-time effects already included); (b) Biogas yield estimations for different feed materials evaluated at $T = 35$, $k_1 = 0.2$, $[DT] = 4$

3.1.1. Model comparison on case studies reported in literature

Reported case studies of AD units (up to 500kW in scale) were used to compare the model estimations of the proposed model (Eqn. 13) against the base empirical models (Eqn. 5 and Eqn. 6); The proposed model was not calibrated, so this comparison would assess the model's ability to make accurate preliminary steady-state estimations. The comparison is summarised in Table 5. Of the case studies evaluated, the preliminary biogas production estimations were within $\pm 21\%$ of the case reported. With the notable exception of one case, the modified VSD generally improved the biogas estimations over the base approach. In the cases reviewed, the biogas production estimated using the modified approach 1 is comparable to the proposed model (which is a weighted average between that and the modified approach 2).

Table 5 – Comparison between AD calculator estimation (uncalibrated) against literature reported case studies

{PLACEHOLDER FOR Table 5, PLEASE REFER TO SEPARATE FILE}

3.1.2. Day-to-day biogas production estimation at the UK Farm AD unit

11 months of daily sample data (331 samples) from the UK Farm's AD unit was used to evaluate the performance of the proposed model for day-to-day biogas production estimation. The AD operators benefit from having a performance benchmark of the expected biogas production to compare against the measured biogas production. Figure 4 shows the feed material profile over during the 11-month period. The mass flow rate of material varied significantly over that period, which conflicted with the assumption of steady state operation. Still, the biogas production model was applied to assess how well it was able to predict biogas production.

{PLACEHOLDER FOR Figure 4, PLEASE REFER TO SEPARATE FILE}

Figure 4 – Feed flow rates for the UK Farm's AD unit

The uncalibrated biogas production model was applied, and this was shown in Figure 5. Based on the literature case study comparisons, the uncalibrated model had a prediction error of up to 21%; this was applied as confidence boundary for the prediction, and shown as the shaded area on the trend plot. The biogas production estimated using base approaches 1 (Bolzonella, et al., 2005) and 2 (Metcalf & Eddy, Inc., 2003) have been included for comparison. Known faults have been highlighted, and those samples were not used in the data analysis. Root mean squared error is used to assess the model accuracy (lower means the model estimation has a better fit to data).

{PLACEHOLDER FOR **Figure 5**, PLEASE REFER TO SEPARATE FILE}

Figure 5 – Biogas production estimation for a UK farm-fed AD unit using an uncalibrated model. Root mean squared error (omitting known faults) for the proposed model = 646; Base approach 1 = 557; Base approach 2 = 974

Visual observation of Figure 5 suggested that some of the biogas yield potentials for the feed materials used on site were higher than that used in the preliminary estimation. The proposed model (and even the base approach 1) generally under predicted the biogas production. This further emphasised the importance of model calibration when applied on-site for day-to-day biogas production estimations.

There were notable “spikes” observed in the estimated biogas production that did not appear in the measured values. These “spikes” were caused by sharp changes in the feed flow rates, which were smoothed out by the biogas held in the tank. An interesting point to note is the deviation observed from about sample 220 onwards. It suggested that there was a change in the process conditions. If the uncalibrated model was used as a benchmarking tool, this would prompt the operators to investigate the process to find the cause.

Simple model calibration could be carried out to get better estimates of the biogas yield potentials. The first 60 days of samples were used to calibrate the potential biogas yields

of the feed materials, and the calibrated model was used to estimate biogas production across the same data set. The accuracy of the calibrated biogas model was also considered. This is shown in Figure 6. The confidence bound would no longer be justified, and was removed in this case. The decrease in the root mean squared error showed a significant improvement in the accuracy of the predicted biogas production.

{PLACEHOLDER FOR Figure 6 , PLEASE REFER TO SEPARATE FILE}

Figure 6 – Biogas production estimation for a UK farm-fed AD unit using a calibrated model. Calibration carried out using the first 60 days of data. Root mean squared error (omitting known faults) for the proposed model = 407; Base approach 1 = 491; Base approach 2 = 564

3.2. Operational revenues and costs

AD unit owners are generally reserved about publishing financial data of their process. There were not many available financial reports for operating AD units and those that do only provide a limited summary and not a breakdown of the calculations. The comparison on the operational revenue and costs is limited. The electricity sales for Glebe Farm's AD unit was reported in 2011 (Gas Data, 2012) was assessed here.

In 2011, the AD unit is fed: 35t/day pig slurry; 5t/ day chicken litter; 2t/day bio-waste and 6t/day maize silage. It operated at 40°C at about 70 days' retention time. The unit had a capacity of 500kW, though only generated 300kW of electricity (250kW exported; 50 used on site). The revenue from electricity sales was about 16.5p/kWh, so the unit generated £29,700/month in electricity sales. Based on the government incentives at that time (FiT of 10.66p/kWh¹, electricity export tariff of 3.1p/kWh), the calculator estimated (with FiT) the operational revenue to be £28,000 from electricity sales in that same month (£22,500 from FiTs and £5,500 from electricity export). For this case, the electricity sales estimation is

¹ Based on historical value of tariffs, FiTs are much more favourable to that of ROCs, so it was assumed that Glebe Farm's AD opted for FiT over than that of ROCs.

within an acceptable range. A side point to note is that about 80% of the revenue came from government incentives. This illustrates the financial challenges for the AD technology. Because the government incentives will decrease over time with the increase in overall capacity (tariff digression), there is a need to find ways to better manage and improve the process.

3.2.1. Analysis of alternative modes of operation

The AD calculator was also intended to be able to evaluate the long-term revenue of running the AD unit. This allowed farmers to assess the possible modes of operation and identify the most profitable choice. This calculator would estimate the revenue and costs of a particular configuration, including the financial breakdown. This is to aid the owners in understanding the financial aspects to the unit and allow them to make better-informed decisions on how to operate their process.

The following hypothetical example was considered: A farm-based AD unit took pig slurry and grass silage as feed material to generate electricity in a CHP. 50kW of the generated electricity is reused on site, and the remaining is exported to the gas grid. The owner is interested in looking for ways to increase his profits. He does not have more waste on the farm, but he can reduce the amount fed to increase the retention time. He has been offered to take sludge from a nearby wastewater treatment site, and will be paid £10/t sludge processed. Due to the toxic nature of the sludge, no more than one-third of the total feed flow can be sludge. He considered the following scenarios:

- Case 1 – Operate the AD unit as usual (base case);
- Case 2 –Decrease the feed flow by 20%, and increase his retention time by 20%
- Case 3 – Operate at the base retention time, but with 1/3 of the feed as sludge
- Case 4 – Import an extra 10t/day sludge and reduce retention time
- Case 5 – Import the maximum extra 20t/day sludge and reduce retention time

Table 6 – Summary of the hypothetical case scenarios

{PLACEHOLDER FOR Table 6, PLEASE REFER TO SEPARATE FILE}

Table 6 summarises the revenue estimated for each scenario. In the particular cases considered, case 5 was the most profitable. Because the sludge is of a lower quality than the other feedstock, it produces less electricity and has a much lower yield. But the gate fee offered is able to offset the losses in sales and tariffs. The comparison between case 1 and 2 is also important; while a higher yield can be obtained by leaving the material in the tank to digest for longer, the gain may not offset the loss in material fed.

The table also highlights a conflict of interest in terms of sustainable practices. From an environmental perspective, there is an interest to increase the biogas yield and extract as much biogas as possible from the feed material (any volatile solids not consumed will eventually release the methane/carbon dioxide into the atmosphere, contributing to greenhouse gas emissions). But from an economic perspective, it is actually more profitable (at least in the cases evaluated) to process more material and accept the loss in yields.

3.2.2. Digestate value

Digestate is the other major output of the AD process and can be used soil fertiliser. However, it is very difficult to estimate a financial value of the digestate. In terms of legislation, in particular the EU's waste framework directive, there is a motivation to use anaerobic digestions as part of the waste management of animal manure and other agricultural waste. However, digestate is rarely sold above its cost-recovery price (Saveyn & Eder, 2014). This is attributed to the limited market for the digestate, the cost associated with developing markets (Pell Frischmann Consultants Ltd , 2012), and the perceived value of digestate for the customers (Edwards, et al., 2015). In the proposed calculator, the digestate is valued as the amount of fertiliser it replaced on the farm, which is site dependent. If the UK market for digestate developed in later years, this may allow for a better estimate for the digestate.

4. Conclusions

An AD calculator is proposed to estimate biogas production for day-to-day and long-term operation in farm-fed AD units. The uncalibrated model was compared against case study reports of other farm-fed AD units, and it was able to predict within $\pm 25\%$ of the reported values. The application of the biogas production estimation for the day-to-day operation was demonstrated on an operating UK Farm AD unit. The use of operational revenue and cost estimations are designed to allow owners to make long-term decisions on how to operate the unit. This was evaluated the UK Farm's AD unit and by hypothetical scenarios.

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{FIGURE 1 - Common configuration of AD units in the UK}

* Literature sourced values are used in the calculator for preliminary estimates

** Used in this calculator for verification

Figure 2

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Figure 3a

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Figure 3b

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Figure 4
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Figure 5
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Figure 6
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Table 1

{Table 1 – Common configuration of AD units in the UK (biogas-info.co.uk, 2014)}

Design	Most common mode in the UK	Alternative(s)
Configuration		
Operating temperature	Mesophilic (25-45°C)	Thermophilic (50-60°C)
Wet or dry	Wet (5-15% dry matter in the digester)	Dry (>15% dry matter in the digester)
Flow of feed material	Continuous flow (or approximately continuous flow)*	Batch cycles
Number of digesters	Single/double	Multiple
Tank design	Vertical tank	Horizontal plug flow

The AD calculator can be used for the shaded applications.

* Some AD units, including the UK Farm AD unit analysed in this paper, is actually operated discontinuously; the AD unit is fed in small amounts once per hour. But relative to the dynamics of the process, this can be considered to be continuous.

Table 2

{TABLE 2 – Fixed parameter values used in the biogas production estimation calculations}

Parameter	Value	Reference & Notes
$[DT]$	4	(Appels, et al., 2008)
k_1	0.2	(Bolzonella, et al., 2005)
k_2	13.7	(Eddy & Metcalf, 2003)
k_3	18.9	
k_4	(m) 0.494; (t) 22.8	Estimated using data presented in
k_5	(m) 0.0704; (t) 0.107	(Lier, et al., 1996)
k_6	(m) 0.00233; (t) 21.0	(m) mesophilic; (t) thermophilic
k_7	(m) 0.323; (t) 0.113	Scaled such that parameter $B=1$ at
k_8	(m) 23.8; (t) 58.6	35°C, using parameters (m)
k_9	0.39	(Aqua Enviro, 2010)
k_{10}	0.13	
k_{10}	0.8	Empirically determined from data at the UK Farm AD

Table 3

{TABLE 3 - Initial parameter values associated with the feed materials}

Feed material	VS content % of fresh feed *	Biogas yield	CH ₄ content	Density kg/m ³	Reference
		$Y_{BG,i}^p$ m ³ BG/kg VS [#]	$C_{CH_4,i}$ %		
Biological Sludge	4.6%	0.406	62.9%	1,000	(Peu, et al., 2012)
Bio-waste	32.0%	0.550	60.0%	502	(Seadi, et al., 2008)
Brown Grease	24.8%	1.200	61.0%	899	(Seadi, et al., 2008)
Cattle Slurry	7.5%	0.340	55.0%	986	(Seadi, et al., 2008)
Fodder Beet	14.4%	0.625	55.6%	540	(FNR, 2010)
Food Waste	24.8%	0.720	65.0%	500	(Seadi, et al., 2008)
Grass Silage	34.2%	0.656	55.0%	485	(Seadi, et al., 2008)
Maize Silage	30.5%	0.611	53.0%	613	(Seadi, et al., 2008)
Pig Slurry	6.0%	0.400	58.0%	1,026	(Seadi, et al., 2008)
Poultry Manure	30.0%	0.467	64.3%	496	(FNR, 2010)
Poultry Slurry	16.0%	0.425	60.0%	1,000	(Seadi, et al., 2008)

Sugar					(FNR,
	20.7%	0.628	55.4%	540	
Beet					2010)

* Volatile solids content is generally represented as a % of total solids; total solids are also represented as a % of fresh feed. The table represents the two terms as one

Potential yields are sometimes presented as m³ biogas/kg fresh feed. Divide this by the VS content to convert the unit equivalent to m³/kg VS

Table 4

{TABLE 4 - Summary of the factors considered for the AD operation economic estimation}

	Initial value	Reference
Calorific value of methane	11.06kWh/m ³	(The Engineering ToolBox, 2015)
CHP efficiency	50% to heat 30-40% to electricity	(The Andersons Centre, 2010)
Gas boiler efficiency	85% to heat	(The Andersons Centre, 2010)
Electricity consumption by AD unit	6kWh/tonne of feed	(The Andersons Centre, 2010).
Gas retail price	4.21p/kWh	(UK Power Ltd., 2014)
Electricity retail price	10.27p/kWh	
Electricity export price	4.85p/kWh	(Feed-In Tariffs Ltd., 2015)
Biomethane export price	7.3 p/kWh	(Wood Energy Ltd., 2015)
FiT – electricity generation	10.13p/kWh (< 250kW) 9.36p/kWh (250-499kW) 8.68p/kWh (500-5000kW)	(Ofgem, 2015)
ROC – electricity export	2 ROC/MWh exported £42.12/ROC	(ePower, 2015)
RHI – biogas combustion	7.3 p/kWh (< 200kW)	(Wood Energy Ltd., 2015)
Maintenance man-hours	1.6 hours/day	(AFBI, 2011)

{TABLE 5 - Comparison between AD calculator estimation (uncalibrated) against literature reported case studies }

Case study	Feedstock flowrates	T & RT	Output	Reported and estimated study report
499kW AD unit (WRAP, 2014)	3,250 t/yr cattle slurry 11,712 t/yr grass silage	35°C* 50 days	BGP (m ³ /yr)	Reported: 1,960,000; Proposed model: 2,270,000 (+16%); {1} 2,480,000 (+27%); {2} 1,580,000 (-19%) {1b} 2,380,000 (+21%); {2b} 1,870,000 (-5%); {3} 859,000 (-56%); {4} 2,690,000 (+37%)
Schmack Biogas (The Andersons Centre, 2010)	8,000 t/yr cattle slurry 4,500 t/yr maize silage 4,000 t/yr grass silage	35°C* 55 days	BGP (m ³ /yr)	Reported: 1,740,000; Proposed model: 1,660,000 (-5%) {1} 1,800,000 (+3%); {2} 1,160,000 (-33%) {1b} 1,740,000 (~); {2b} 1,370,000 (-21%) {3} 1,070,000 (-39%); {4} 2,080,000 (+20%)
Ribe CAD (The Andersons Centre, 2010)	352 t/day cattle manure 68 t/day bio-waste	53°C 10 days	BGP (m ³ /yr)	Reported: 4,800,000; Proposed model: 3,840,000 (-20%) {1} 5,310,000 (+11%); {2} 3,670,000 (-24%) {1b} 3,900,000 (-19%); {2b} 3,600,000 (-25%) {3} 10,600,000 (+121%); {4} 8,610,000 (+79%)
Lindrup CAD (The Andersons Centre, 2010)	410 t/day cattle manure 137 t/day bio-waste	53°C 10 days	BGP (m ³ /yr)	Reported: 5,700,000; Proposed model: 6,260,000 (+10%) {1} 8,660,000 (+52%); {2} 5,990,000 (+5%) {1b} 6,350,000 (+11%); {2b} 5,870,000 (+3%)

{3} 13,900,000 (+144%); {4} 14,400,000 (+153%)				
Copys Green Farm (RASE, 2011)	2,500 t/yr cattle slurry 2,500 t/yr maize silage	39°C 45 days	BGP (m ³ /day)	Reported: 1,680; Proposed model: 1,360 (-19%) {1} 1,470 (-13%); {2} 928 (-45%) {1b} 1,420 (-15%); {2b} 1,120 (-33%) {3} 966 (-41%); {4} 1,838 (+9%)
Hill Farm (RASE, 2011)	80 dairy cows**	38°C 26 days	BGP (m ³ /day)	Reported: 100; Proposed model: 100 (~) {1} 113 (+13%); {2} 70 (-30%) {1b} 105 (+5%); {2b} 80 (-20%) {3} 360 (+260%); {4} 149 (+49%)
Lodge Farm (RASE, 2011)	30 t/day cattle slurry 3 t/day poultry manure	40°C 28 days	BGP (m ³ /day)	Reported: 1,200; Proposed model: 952 (-21%) {1} 1,070 (-11%); {2} 664 (-45%) {1b} 999 (-17%); {2b} 767 (-36%) {3} 2,500 (+108%); {4} 1,343 (+12%)
			CHP electricity	Reported: 88; Proposed model: 97 (+10%)
			output (kW)	{1} 108 (+23%); {2} 67 (-23%)

				{1b} 101 (+15%); {2b} 78 (-12%)
				{3} 4,020 (+4,450%) ¹ ; {4} 124 (+41%);
				{5} 15 (-83%)
AFBI AD unit	20 t/day cattle slurry	37.1°C	BGP (m ³ /day)	Reported: 303; Proposed model: 418 (+38%)
(AFBI, 2011)		27 days		{1} 473 (+56%); {2} 294 (-3%)
				{1b} 438 (+45%); {2b} 336 (11%)
				{3} 1,500 (+395%); {4} 595 (+96%)

** estimated as 4.8 t/day cattle manure (Biomass Energy Centre, 2006)

Abbreviations: {1} Base approach 1 (Bolzonella, et al., 2005) ; {2} = Base approach 2 (Metcalf & Eddy, Inc., 2003); {1b} = Modified approach 1, VSD estimation includes effects of temperature, dead-time and mixing; {2b} = Modified approach 2, VSD estimation includes effects of temperature, dead-time and mixing; {3} = (FOV Biogas, 2015); {4} = (PlanET, 2016); {5} = (Renewable Energy Concepts , 2009)

¹ Due to the significantly high % error, the report author used the biogas production estimated by (FOV Biogas, 2015) to estimate the electricity produced using the calorific value of methane (the proposed approach by this paper) to check. The estimated electricity production was 253kW (180% over).

{TABLE 6 - Summary of the hypothetical case scenarios}

	Base scenario	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Feed material (t/day)	Pig slurry: 25	Pig slurry: 20	Pig slurry: 17	Pig slurry: 25	Pig slurry: 25
	Grass Silage: 15	Grass Silage: 12	Grass Silage: 10	Grass Silage: 15	Grass Silage: 15
	Sludge: 0	Sludge: 0	Sludge: 13	Sludge: 10	Sludge: 20
Retention Time (days)	30	36	30	24	20
Biogas production (m ³ /day)	3,140	2,620	2,290	3,080	3,010
Methane yield (m ³ /t feed)	43.5	45.4	30.9	34.4	28.1
Revenue per month	£29,200	£24,000	£23,000	£31,700	£34,200
Electricity export	9,100	7,300	5,600	8,900	8,700
FiT Tariff	20,100	16,700	13,500	19,800	19,500
Sludge gate fee	0	0	3,900	3,000	6,000

Operating conditions and unit design is consistent with all cases: operating temperature 35°C, 40% CHP efficiency for electricity generation;

50kW electricity generated used on site, the surplus is exported at 4.64p/kWh; FiT is at 8.68p/kWh generated