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Overview of Anaerobic Digestion and Power and Gas to Grid Plant CAPEX and OPEX Costs

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Abstract

Anaerobic Digestion (AD) is a four-stage biological process used extensively around the world to treat a range of organic feedstocks to produce biogas, a methane rich gas that can be used for cooking, fuel for a gas engine to generate electricity, or upgraded to biomethane as a substitute for natural gas that can be injected into the natural gas grid, replacing/supplementing natural gas supplies as a 'fossil-free' gas source. The residual solid material, post digestion, is termed digestate and has valuable properties as both a soil improver and fertiliser when spread to land.

As part of a move in the UK/EU and North America to reduce the greenhouse gas emissions associated with the disposal of organic wastes to landfill, while simultaneously producing renewable electricity and heat and biomethane, both regulatory controls and fiscal incentives have been applied to promote the use of AD to treat organic wastes.

This paper provides a brief background of the use of AD in the UK/EU and examines the variation in capital and operating costs of a range of AD projects, based on a different technology providers and end-uses. The object of the paper is to assist developers and investors to compare the capital and operating costs of potential projects with operational AD plants by evaluating of a range of simple metrics and assessing their statistical validity.

Introduction

Application of the biological process of Anaerobic Digestion (AD) to treat a wide range of organic materials to produce biogas, is used widely around the world.

AD is a typically a four-stage process;

- Hydrolysis of the input materials that breaks down insoluble organic polymers, such as carbohydrates, fats and proteins, into soluble derivatives such as glucose/sugars, fatty acids and amino acids that become available for other bacteria
- Acidogenesis is where bacteria breakdown or convert the glucose/sugars, fatty acids and amino acids into volatile fatty acids and alcohols
- Acetogenesis converts the volatile fatty acids and alcohols into H_2, CO_2 and NH_3
- Methogenesis is where the methanogenic bacteria convert the acetogenesis products into mostly CH_4 and CO_2 i.e. biogas.

Each stage uses a diverse range of microflora that operate under different conditions.

AD is a major source of fuel for cooking in rural India and China, replacing woody biomass that is both in short supply and poses health issues to users. It has been used for many years to treat animal wastes and in addition to use as a fuel for cooking, biogas can be used to fuel gas engines to generate electricity, or be upgraded to biomethane. Biomethane has a methane content and calorific value equal to natural gas that allows it to be injected into the natural gas grid, replacing/supplementing natural gas supplies as a 'fossil-free' gas source.

The residual material post digestion is termed digestate, which has valuable properties as a soil improver and fertiliser when applied to land. The types of organic materials that can be processed includes a wide range of animal slurries/manures, food wastes (consumer and post-production) and purpose grown energy crops.

In both the EU and North America, AD is used as a technology to treat a variety of high organic content wastes that would otherwise be landfilled. Landfilling such wastes leads to the production and (often) uncontrolled release of landfill gas - a type of biogas - to atmosphere. Recognition of the environmental harm caused by the release of landfill gas to atmosphere due to its methane content, prompted the adoption of regulations to both control landfill gas and latterly to offer fiscal incentives for processes that treat household and post-production food wastes to produce electricity and biomethane as an alternative to landfill.

The aim of this paper is to provide a brief background to the use of AD in the UK/EU and to examine the variation in capital (Capex) and operating (Opex) costs of a variety of AD projects, based on a range of different technology providers and end-uses, with the object of identifying a simple metric to assist developers and investors compare the Capex/Opex costs of potential projects against operational AD plants.

Background

Recognition of biogas as a useful source of renewable energy has led to a significant increase in the number of AD plants within the European Union (EU), particularly in the UK and Germany and increasingly in North America and other parts of the world, as part of a move to reduce the greenhouse gas emissions associated with the disposal of organic wastes, while simultaneously producing renewable heat, electricity and biomethane.

Legislation relating to controlling greenhouse gas emissions has shaped EU renewable energy policy. In 1997 the European Council and European Parliament adopted the "White Paper for a Community Strategy and Action Plan" at a time when the share of renewable energy was 6% of gross internal energy consumption [1]. An integrated Energy and Climate Change package on the EU's commitment to change (Energy policy for Europe (COM (2007) 1 final) [2] and Limiting Global Climate Change to 2 degrees Celsius - The way ahead for 2020 and beyond (COM (2007) 2 final) were published by the European Commission in 2007 [3], which included an EU commitment to achieve a reduction at least a 20% of GHG emissions by 2020 compared to 1990 levels and a mandatory EU target of 20% renewable energy [4].

The Renewable Energy Directive (RED) 2009/28/EC on the promotion of renewable energy sources [5] requires Member States (MS) to increase to 20% the gross final energy consumption from renewable energy and a 10% contribution from renewable energy in transport in each MS by 2020. Directive 2015/1513 sets a 7% limit on the final consumption of energy in transport in the Member States in 2020 for the biofuels produced from food or feed crops grown for energy purposes on agricultural land. A target of 0.5% was set for 2020 for the share of energy from renewable sources in transport, to be achieved by biofuels produced from feedstocks that are not in competition with food crops and biofuels made from feedstocks such as wastes, residues, non-food cellulosic material or lignocellulosic materials.

A further series of regulations specify national objectives and legally binding targets for the share of renewable energy amongst MS. In response to their obligations under EU legislation the UK implemented a series of regulatory requirements and fiscal incentives that impact the viability of AD projects and promote its use as a means of reducing the environmental impacts associated with energy production. Key to the success of an AD project producing electricity/biomethane is the mix of available types and quantity of feedstocks, process technology used, government regulations and fiscal incentives and importantly, capital and operating costs.

The predominant AD technology in use operates in the mesophilic temperature range, optimally between 30-35 ^{0}C, making it a stable, resilient process. AD can operate in the range 50-55 ^{0}C, termed thermophilic digestion and while it has a faster conversion rate of volatile solids to biogas than mesophilic digestion, it is less generally resilient to process variations. While not used widely in the manure/energy crops/food waste sectors, it is used for treating sewage sludge and wastewaters etc.

In view of the availability of numerous reviews of different AD process types the focus of this paper is to provide an overview of the Capex/Opex costs of mesophilic AD plants producing electricity and biomethane using a wide range of solid and liquid feedstocks. A database has been derived from the technical due diligence undertaken on 46, separate AD projects designed to process solid/liquid feedstocks, comprising consumer/post-production food wastes, purpose grown energy crops and animal slurries/manures and mixtures of these feedstocks.

The residue from digestion is termed digestate, a mixture of solid and liquid fractions, with the proportions determined by the dry solids content of the feedstock and duration of digestion. The application of digestate to land in the UK is determined by a set of rules that prohibits application of liquid digestate during a 'closed period', typically November to March, to prevent the runoff of liquid into streams and rivers causing pollution. If the digestate is separated into its liquid and solid fractions, solid digestate can be applied to land at any time but at an increased operational cost.

Project Parameters

As mentioned in the preceding section, key aspects that influence the success of a potential AD project producing electricity and/or biomethane are the types/quantities of feedstocks, process technology used, regulatory requirements, fiscal incentives and importantly the capital and operating costs. A brief overview and description of the above parameters is presented below.

Fees stocks

The chosen feedstock and quantity to be processed are the principal design parameters that determine both the likely technical performance and financial success of an AD project, as they govern the biogas yield, determine the suitability of the process technology and plant configuration and the overall treatment capacity. Of the three main types of feedstock referred to previously, each has its pros/cons, as described briefly below:

Manures

usually cow-based manure is used but chicken and pig manures are also used. Cow manure is a self-contained feedstock, with no significant process issues that can arise with chicken/pig manures due to the (usually) high levels of hydrogen sulphide and ammonia present in the biogas that need to be removed, requiring additional process stages and increased capital and operating costs. A key advantage of using manures is that the feedstock cost is zero/near zero, while the main disadvantage (especially for cow and pig slurries) compared to energy crops/food wastes, is the low biogas yield e.g. 15-25m^3 biogas/te. The digestate output is liquid and can be applied to land as a fertiliser when appropriate

Energy Crops

purpose grown crops such as silage maize, sugar beet pulp, rye, grass silage etc. have known high solids contents and a consistent potential biogas output per tonne of input, at levels of 200-220m^3/te for maize silage, 390-410m^3/te for rye grass and 160-200m^3/te for grass silage [6]. Due to the higher dry solids compared to manures, additional liquid is needed to achieve the design dry solids content of c. 10-15%, for digestion. Typically, this is water but can also be other liquid wastes, such as milk whey, beverage wastes etc. that attract a gate fee. The mixing of a dry feedstock with additional liquid requires selection of a suitable mixing technology, to ensure the dry solids are wetted adequately to prevent formation of a floating top layer in the digester that can lead to both poor biogas production and operational problems associated with blockages etc. The major disadvantages of using energy crops are their purchase cost and ensuring adequate mixing of the dry solids with the digester contents. The preferred solution to ensure adequate mixing is to pre-mix the input dry solids with digestate and to then add the pre-mixed, wetted mixture to the digester. The digestate output is a mix of solid and liquid and can be applied to land directly when allowed, or separated into its solid and liquid components. In the UK solid digestate can be applied to land at any time of the year, while the liquid fraction must be stored until application to land is permitted.

Food wastes

use of solid/liquid food wastes, either household (mixed or source segregated), or commercial (post-production and out of date products) wastes, serves to both divert organic wastes from landfill and to return to land the nutrients inherent in the digestate. While these sources can have good/very good biogas yields e.g. household food waste at 100-125m^3/te and fats +1,000m^3/te, handling such food wastes in the EU/UK also requires specific process and operational requirements that add to both the Capex/Opex costs. The issues relate to potential health concerns associated with using animal by-products, which include the need for a fully closed reception hall for accepting waste deliveries and pasteurisation of either the food waste or digestate, in accordance with the Animal By-Products Regulations (ABPR), both of which add to the costs compared to processing manures and energy crops only. As with energy crops the digestate is a mix of solid and liquid components and once pasteurised as necessary, can be applied to land when permitted, or separated into its solid and liquid components as discussed previously. In this paper the total feedstock treatment capacity only is considered, not the potential impact of different types of feedstock.

Process Technology

The choice of AD process technology and process configuration for a mesophilic plant is determined primarily by the need for either single stage digestion, involving only a single digester i.e. animal manures, or two stage digestion, requiring two (or more) digesters i.e. energy crops and food wastes.

The digester [height x diameter] ratio influences selection of the mixing process required, to ensure adequate mixing of the digester contents and prevention of 'floating layers' forming in the digester. Floating layers arise due to inadequate mixing of the dry solids input with the digester contents, or inadequate mixing of liquid feedstocks with densities different to that of the digester contents. In both cases the existence of a layer of 'undigested' material can lead to blockages, or the sudden production of a large volume of biogas when mixing finally takes place, which can then overload the pressure release valve, leading to biogas being vented to atmosphere i.e. lost.

For some feedstocks specialist equipment is used to assist the breakdown of recalcitrant components, such as wheat straw, which otherwise is not very digestible due to the outer layer of lignin. Other equipment use ultrasound on organic suspensions in water, with the cavitation produced in the liquid helping to breakdown both the cell walls of bacteria and plants and agglomerations of fibres and cell structures, resulting in increased availability of the biological substrate and nutrients for digestion. Some plants also dry the digestate, which allows long-term storage of the dry matter for use as a fertiliser, or as a fuel in a biomass combustion unit.

All of the above issues can be addressed satisfactorily, once the proposed feedstock mixture and quantity is determined and importantly, then adhered to. It is important to appreciate that if a plant is designed to process specific types of feedstock, subsequently changing the feedstocks can lead to operational problems that result in poor plant performance, if the properties of the new feedstock are not assessed adequately for their suitability with the extant processing arrangement

Energy Production Technology

The main drivers determining the choice of energy production technology are primarily governmental regulations and any fiscal incentives. Thus, utilisation of biogas in the UK and EU was focussed initially on electricity generation, with use of the waste heat produced but in the UK the emphasis has shifted latterly to grid injection of biomethane, with a subsequent decline in large scale power generation. Most electricity generation is now sized only to provide the plants parasitic load.

Power Generation

The predominant power generation technology is based on spark ignition, reciprocating gas engine generator sets (genset), a proven technology, widely available around the world and importantly, available in a range of power outputs from 10-20kW$_e$ unit, to +3-5MW$_e$. AD plants producing electricity tend to be in the range of a few hundred kW$_e$, up to 2-5MW$_e$, with the larger capacity plants comprising multiple units, which enables both flexibility of operations for maintenance and future expansion of the plant output capacity etc.

Biomethane

The move to producing biomethane was driven by regulations and fiscal incentives, with only sufficient electricity produced to provide the plants parasitic load. There are currently a number of different technologies available commercially for upgrading biogas, with the overall process comprising drying of the raw biogas and removal of carbon dioxide and other trace gases, leaving a +95% methane content gas. Each technology below is both well proven and has an extensive operational track record in the petrochemical sector

Absorption

the principle of separation using absorption is based on the different solubilities of the various gas components in a liquid scrubbing solution. In a biomethane upgrading plant using this technique the raw biogas is contacted with a liquid within a scrubbing column filled with plastic packing to increase the contact area between the phases. Currently, three different upgrading technologies embodying this physical principle are available:

- **physical absorption:** usually based on pressurised water scrubbing, whereby the absorbed gas components are bound physically to the scrubbing liquid, in this case water;
- **organic physical absorption:** similar to water scrubbing but uses an organic solvent solution (e.g. polyethylene or glycol) instead of water as the scrubbing liquid;
- **chemical absorption:** characterised by physical absorption of the gaseous components in a scrubbing liquid, followed by a chemical reaction between the scrubbing liquid components and the absorbed gas components within the liquid phase and based typically on amine scrubbing.
- **Adsorption:** separation using adsorption is based on the adsorption behaviour of the different gas components on the adsorbent solid surface at an elevated pressure. After adsorption at high pressure the saturated, loaded adsorbent material is regenerated by a stepwise decrease in pressure and flushing with raw biogas or biomethane;
- **Membrane technology:** separation membranes used for upgrading biogas are made of materials permeable to carbon dioxide, water and ammonia, allowing the methane to be separated from the carbon dioxide and other unwanted gases in the raw biogas.

Grid Connection

Connection to the electricity grid for exporting the electricity generated, or the natural gas grid for injecting biomethane, is a key facet of any AD energy project. The location of a suitable grid connection point, able to take the proposed output, can be a problem and in some cases, leads to relocation of a proposed plant to a more suitable connection point.

In the UK it is usually easier to find a suitable gas grid injection point local to a planned plant than a suitable electricity grid connection point. In some cases, the distance to the nearest low voltage (i.e. 11kV) electricity connection point can be +1-2km and cost over £0.5M, a significant capital item for a modest 200-500kW$_e$ farm-based AD plant. For larger output plants the option to increase the output voltage to enable connection to the (usually nearer) High Voltage (HV) transmission system, may be possible but the increased costs of cabling and transformer etc. need to be taken into account.

In contrast to the electricity grid, it is usually easier in the UK to connect to a suitable capacity, gas grid connection point. Unless the plant has a very high output, or is sited in a remote rural location, injection into the Medium Pressure (MP) gas grid is likely to be possible. Where this is not the case, plants have been designed to compress the biomethane and store it in pressurised cylinders that are then transported by truck to either a suitable grid injection point, or to an end-use location e.g. vehicle refuelling point, or gas engine CHP plant at an industrial user site.

It is essential that a proposed plant should be located in close proximity to a suitable capacity grid connection point.

Regulatory Requirements and Fiscal Incentives

A number of different regulatory requirements apply to the operation of AD plants in the UK/EU, based around ensuring the operational safety of plants producing electricity and biomethane.

All AD operators in the UK must also comply with regulations concerning environmental protection, animal by-products, duty of care, health and safety and waste handling.

Environmental Permitting (EP) [7] is a scheme in England and Wales for regulating business activities that could have an impact on the environment and human health. All AD plants are required to obtain either a permit, or an exemption, to operate and to spread digestate to land, by completing an application with relevant technical information and demonstrating they are competent to operate the plant. To apply for environmental permit operators must demonstrate their technical competence.

Digestate material can be processed to meet regulatory standards that mean it is no longer regarded as a waste and can be spread to both agricultural and non-agricultural land to confer benefit or ecological improvement. The requirements are covered by achieving the PAS 110 [8]. standards using the appropriate

Quality Protocol [9]. Quality protocols explain when a waste derived material can be regarded as a non-waste product and no longer subject to waste controls and aim to produce high quality products from waste materials to promote greater recovery and recycling. Prior to achieving PAS110 accreditation, application of digestate to land requires either an environmental permit, or registration for an exemption.

The European Union's Animal By-Products (ABP) Regulations (Regulation No 1069/2009) [10] allows for the treatment of some ABP in composting and biogas plants. ABPs are animal carcasses, parts of carcasses, or products of animal origin not intended for human consumption and the Regulations permit their treatment in approved composting and biogas premises of low-risk (category 3) ABPs and catering waste that contain meat or which comes from a premises handling meat. High risk (Category 2) ABPs cannot be used as feedstock in biogas plants, except where they have first been rendered to the 133 °C/3 bar/20minute EU pressure-rendering standards.

Biomethane injected into the UK gas network must meet the specifications outlined in the Gas Safety (Management) Regulations (GS(M)R) [11]. The GS(M)R approach was initially developed by the UK Health and Safety Executive (HSE) and uses the Wobbe Number, a measure of the energy input through an appliance based predominantly on the discharge through a burner nozzle, as the main parameter to compare between different gas qualities. Thus before acceptance for injection into the gas grid the gas properties are checked and CV measured and if there is a need to increase the CV to match the properties of the gas already in the grid, a small quantity of propane is added.

The UK government incentive schemes are designed to support deployment of renewable energy generation in the UK, allowing producers to compete with fossil fuel generated technologies that may be cheaper in the short term. AD has been supported by a number of incentive schemes depending on how the biogas is use; Feed In Tariff (FIT) for electricity generation [12], Renewable Heat Incentive (RHI) [13] for supplying heat or injecting biomethane into the gas grid, or the Road Transport Fuel Obligation (RTFO) [14] for use as a transport fuel.

Plant Database

As referenced in section 2, data from 46, individual AD plants provide the database used in this paper. The main characteristics of the plants, in terms of output and feedstocks, are shown in Table 1.

Energy Output	**%**
Power to grid plants [15]	64
Gas to grid plants [16]	36
Feedstock Type	**%**
Animal manure feedstock only	5
Animal manure and energy crops	39
Food wastes only	15
Energy crops only	18
Food wastes and energy crops	15
Manures, food wastes and energy crops	8

Table 1: Plant Output Type and Feedstocks.

A number of clarifications are needed however to explain fully the above broad descriptions.

Cow manure is a 'stabilising' feedstock that provides the full range of microflora and trace elements to enable anaerobic digestion to take place at a constant rate. Plants using only food wastes, or energy crops, are deficient in some of these essential components and require addition of supplements to be able to operate stably and maintain constant biogas production. Therefore, most energy crop-based AD plants include some cow manure as part of the feedstock mix, to ensure continuous, stable digestion takes place. When categorising an AD plants feedstock the small amount of cow manure added is often discounted.

In a similar manner some plants use a complex mixture of feedstocks, reflecting both what is available locally and the relative cost of the feedstock i.e. energy crops have to be purchased, whereas food wastes usually provides a revenue i.e. a gate fee can be charged. The definition of 'food wastes' includes both household-derived, post-production solid and liquid wastes e.g. fats and oils and post-consumer 'out of date' food.

In practise some plants use a combination of all the above waste types, which can lead to complications when seeking to categorise the effect of feedstocks on plant performance. In such cases the plant is usually categorised based on the feedstock that contributes the largest proportion of biogas.

Examples of complex feedstock mixtures used by some plants in the database are listed in Table 2.

• Post production food wastes, sludges and silage;
• Slurry, stomach contents, food wastes, green wastes;
• Vegetable wastes, fat, slurry, myceliun protein, brewer's grain, bakery wastes, blood;
• Chicken/cow manure, slurry, sugar beet, maize/grass silage;
• Manure, slurry, energy crops, food/green waste;
• Silage maize/grass, FYM, reeds, permeate, brewery wastes, apple pomace, potato peelings

Table 2: Examples of Complex Feedstock Mixtures.

Categorising plants by their feedstock mix is thus somewhat problematic, which leads inevitably to a lack of precision in the results of any subsequent analysis. Notwithstanding this issue, a 'pragmatic' approach has been adopted to using the database, as outlined in the previous paragraphs. The definitions of Capex and Opex costs comprise a range of elements that differ between project developers, depending on the lenders/funders requirements and whether some/all maintenance aspects are undertaken in-house or are contracted out etc. Definitions of Capex and Opex costs used in this review are described below. Assessing the significance of different metrics is to try to identify a simple metric that allows comparison of seemingly similar plants utilising different technologies and feedstock mixtures. The chosen method is regression analysis, a set of statistical processes for estimating relationships among variables. The resulting best fit trend line and highest value correlation coefficient R^2, is then deemed to provide the best correlation [18]. The least-squares method minimizes the variance of the unbiased estimators of the coefficients, under the conditions of the Gauss–Markov theorem [19].

Although the number of data points in some cases is limited, statistical assessment using regression analysis and the correlation coefficient R^2 is considered the simplest means to compare the different metrics.

Capex

The capital cost of an AD project comprises many different elements, including not only the obvious costs of process equipment, civil engineering costs for the digester and building foundations, access road and bunding etc. but also grid connection costs, professional fees, financial transaction costs, working capital and possibly, land purchase costs. As a general guide the typical breakdown of an AD plant Capex is shown in Table 3.

Capital Cost Item	% CAPEX
Pre-development	8%
Construction	82%
Grid Connection	6%
Other Infrastructure	4%

Table 3: Typical CAPEX Breakdown.

Each project therefore has a unique set of feedstocks and site-specific factors that impact on the final capital cost, such that identical AD plants sited at different location may have (significantly) different capital costs. The AD plant database used in this review includes a range of different Capex and Opex costs for what appears to be plants with similar capacity/outputs but which reflect the use of different feedstocks and the subsequent impact on the cost of the associated equipment to be able to handle/process the feedstock etc. The potential metrics selected for assessment to identify the most useful indicator for estimating the Capex of an AD plant are shown in Table 4. The metrics were chosen to assess whether the variations in Capex are explained by the relationship to processing capacity and the energy type and output

Capex £: capital cost expressed as the plant design feedstock capacity
Capex £/tpa: capital cost expressed per tonne per annum processing capacity of the design feedstock capacity
Capex £/MW$_e$: capital cost of a power generation plant expressed as a function of the power output in MW$_e$
Capex £/Nm^3: capital cost of biomethane plant expressed as a function of biomethane output in normal cubic metres per hour

Table 4: Capex Metrics.

Each metric is assessed and the result presented as a series of graphs, with both the linear and 'best fit' trend lines and associated R^2 values shown on each graph. The possible effect of the different types of feedstock on Capex and Opex are not considered in this paper and would need to be the subject of a separate paper.

Opex

Items that comprise an AD facility Opex can be configured in various ways when considering the overall viability of a potential facility. Thus, some investors include the development costs and professional fees, while others do not etc., depending on how the finance is raised. On this basis the Opex of apparently identical plants will differ by varying amounts.

Opex costs consist of fixed and variable components. Fixed costs typically comprise the following:

- labour (management and plant operators);
- machinery (e.g. CHP unit, mobile shovels, pumps etc.);
- purchased power (when parasitic power plant not operational);
- property costs (e.g. rent and rates);
- administration (including laboratory testing, accountants, permitting/licensing fees, additives etc.)

The variable component of the Opex usually comprises operations i.e. staffing and maintenance costs, feedstock purchase, waste disposal costs and loan repayments/interest etc. The Opex build-up used in this paper comprises the above elements. Four Opex metrics are considered as shown in Table 5.

Opex £k: Opex expressed as the total tonne per annum design feedstock capacity
Opex £/tpa: Opex cost expressed per tonne per annum processing capacity of the design feedstock capacity
Opex £/MW$_e$: Opex cost of a power generation plant expressed as a function of the power output MW$_e$
Opex £/Nm^3: Opex cost of biomethane plant expressed as a function of biomethane output in normal cubic metres per hour (Nm^3/h)

Table 5: Opex Metrics.

As with Capex, a series of graphs are presented to identify the effect of changes in the specific plant parameters described above. The same approach and limitations apply as with those for Capex i.e. linear trend line and trend line of best fit, as measured by the highest value of R^2.

Plant Capex

The first metric to be considered is the straightforward relationship between Capex and the plant design feedstock capacity i.e. [Capex £M], including all types of feedstock and both power and biomethane plants (Figure 1). Subsequently differentiation between the Capex for power and biomethane plants separately will be considered.

The two trend lines are shown in Figure 1, linear regression for reference the trend line with the highest R^2 value, a fourth order polynomial, with R^2= 0.576.

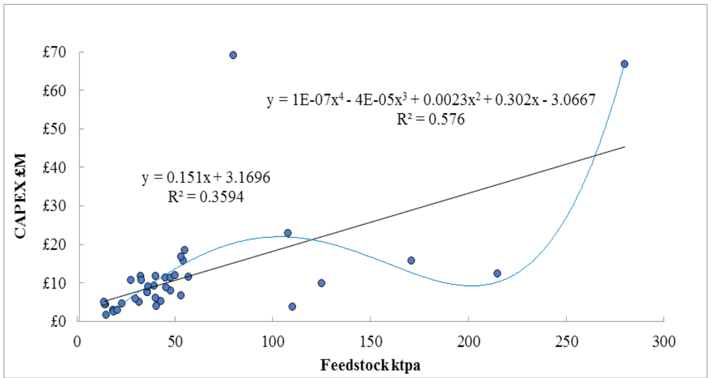

Figure 1: Capex £M and design feedstock capacity.

Figure 1 confirms the general trend of increasing Capex with increasing annual throughput, with the increased Capex due to the effect of site-specific constraints e.g. site access roads and grid connection and the possible impact of a more complex feedstock menu that requires additional pre-processing and handling stages, with the concomitant increased cost of additional equipment.

Two plants stand out as being different to the rest of the dataset; an 80ktpa plant that is primarily a biomethane plant but with a much larger power output than required for just the parasitic plant load and; a 280ktpa plant that is primarily a power plant but has also a modest biomethane output. Both the 80 and 280ktpa plants are in effect 'hybrid' plants and the result of these changes is a higher than usual Capex for either a power/biomethane only plant of the same capacity. Compared to the linear trend line the trend line of best fit i.e. highest R^2 value, is a fourth order polynomial curve, with R^2 0.576, compared to 0.3594 for linear regression. An alternative metric to [Capex £M], is [Capex £/tpa] as a function of the design feedstock capacity. Using the same data as Figure 1 the results are presented in Figure 2.

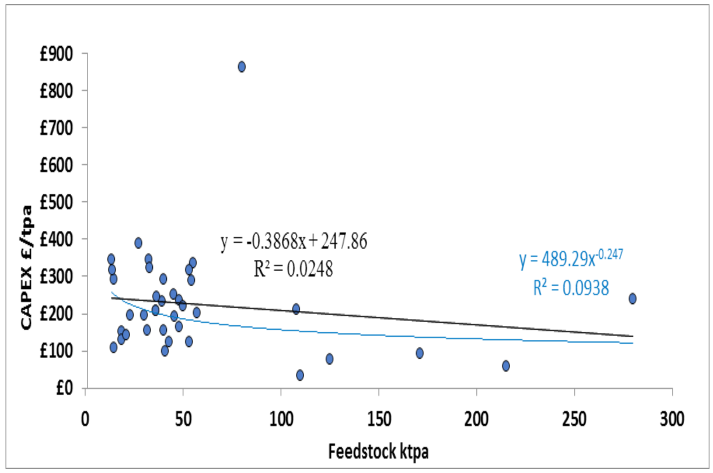

Figure 2: Capex £/tpa and design feedstock capacity.

The 'anomalous' point at c.80-ktpa is a hybrid biomethane power generation plant that reflects the difficulties of seeking to assess different types of AD facilities. Both curves show relatively poor correlation, with a significant degree of variation in Capex £/tpa in the <50ktpa capacity range. Linear regression gives a low R^2 value of 0.0248, while a power law regression gives the highest R^2 value at 0.0938. Comparison of the two metrics, [Capex £M] and [Capex £/tpa], with the design feedstock throughput, suggests that [Capex £] gives the more reliable means of estimating the Capex of an AD plant. In the following sections the metrics for power and biomethane plants are assessed and presented separately.

Power Plant Capex

AD plants producing electricity were initially the most common to be developed, due to the attractive fiscal incentives pertaining at the time and consequently, large numbers were built in the UK and EU. The current estimate of the number of AD plants generating electricity in the UK is 566 [20]. However, current tariffs applying in the UK were insufficient to be attractive to developers, as exemplified by the 13MWe capacity remaining available under the current 'Tarif Period 4' and with the scheme ending in March 2019 [21].

Figure 3 shows the variation in [Capex £M] with the design feedstock capacity for throughputs up to 215ktpa, or 5MWe power output, encompassing all types of feedstock i.e. energy crops, household and post production food wastes, manures etc. but without the 80ktpa biomethane 'hybrid' plant.

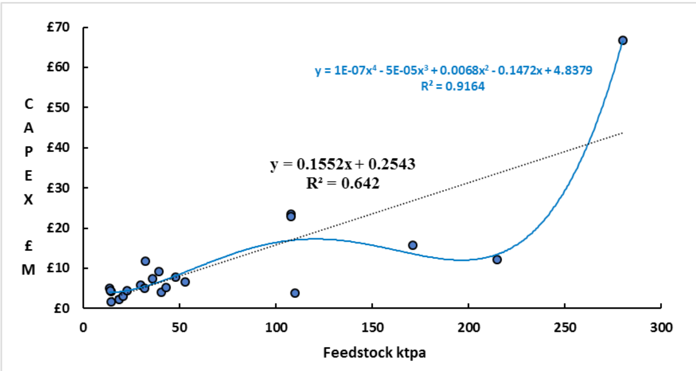

Figure 3: Capex £M and design feedstock capacity.

The overall trend is similar to that in Figure 1 i.e. increasing Capex with increasing tonnage throughput and the trend line with the best fit has R^2 of 0.9164, compared to a linear curve with R^2 0.642. The clustering of plant capacities around the range 20ktpa-50ktpa feedstock reflects the combined effects of grid connection capacity and feedstock availability within a given catchment, a key factor especially for food waste plants. In theory manure and energy crop plants do not have such a limitation, as they (usually) supply most/all of their feedstock from in house sources. These potential effects will be explored in a subsequent paper. Figure 4 shows the results for the metric [Capex £/tpa] and feedstock capacity]. The R^2 value for linear regression is 0.0794, while the highest R^2 value of 0.3366 is for a fourth order polynomial regression

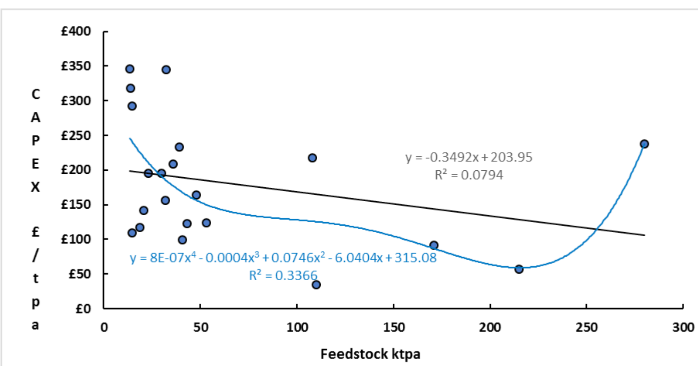

Figure 4: Capex £/tpa and design feedstock capacity.

Figure 5 presents the metric [Capex £/ MWe]. For a linear trend line R^2 is 0.1575 and the highest value at 0.27 for a second order polynomial trend line.

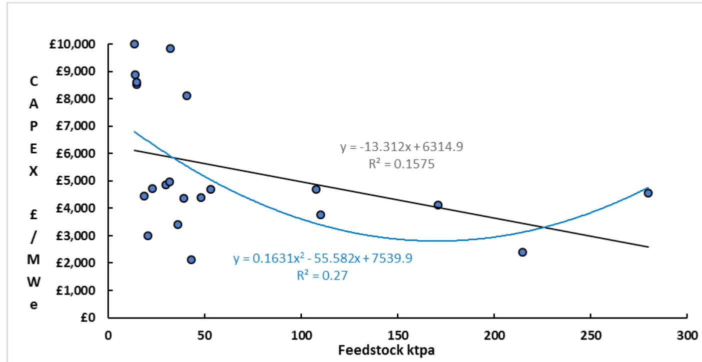

Figure 5: Capex £/MWe and design feedstock capacity.

The similarity of the R^2 values suggests that simple linear regression is a still likely to give a reasonable fit for the metric. The limitations imposed on a project by the availability of sufficient feedstock impact directly on the potential power output; hence the clustering of plants in the range 0.5MWe-2MWe output that reflects the ready availability of feedstock in most areas. The 'gap' in power output from 2MWe to 5MWe mirrors both the increased project Capex for a large plant and inability to secure sufficient feedstock for such a large plant.

The final metric [Capex £/MWe] versus MWe output is shown in Figure 6.

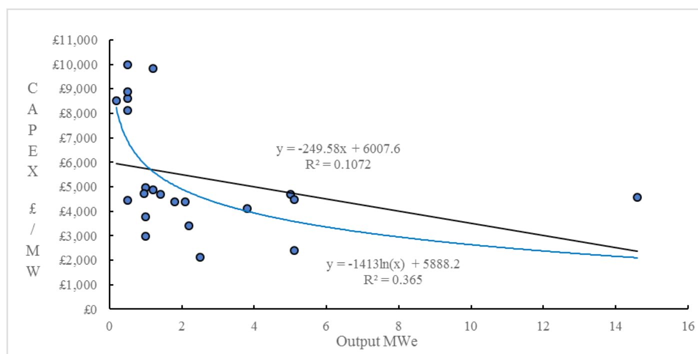

Figure 6: Capex £/MW_e and MW_e Output.

The line of best fit is a logarithmic curve, with R^2 0.365, compared to R^2 0.1072 for linear regression.

Table 6 summarises the maximum R^2 values for each metric assessed and includes those for all plants to allow comparison

METRIC	MAXIMUM R^2 VALUE	
	All plants	Power plants
Capex £M and design feedstock capacity	0.576	0.9164
Capex £/tpa and design feedstock capacity	0.0938	0.3366
Capex £M/MW_e and design feedstock capacity		0.27
Capex £/MW_e and MW_e Output		0.365

Table 6: Summary of Capex Metric R^2 values for power plants.

The Table shows a clear choice of the metric with the highest R^2 value, [Capex £M] at 0.9164, with the next highest R^2 values at 0.365 and 0.337 for [Capex £/MW_e and MW_e Output] and [Capex £/tpa]. The lowest R^2 value of 0.1575 was achieved for [Capex £M/MW_e]. The results in Table 6 suggest that the [Capex £M] provides a means of estimating the Capex of a power producing AD plant with a reasonable degree of accuracy. This finding fits with the data for all plant types where the same metric had the highest R^2 value, albeit lower than for power plants alone. Equally the metric [Capex £/tpa] for power plants only was higher than for all plant types, which supports the view that AD plants with different types of energy output need to be considered separately.

Biomethane Plant Capex

About 100 biomethane plants had been built in the UK by the end of 2018. Using a similar set of metrics for biomethane plants as used for power plants the results are presented in Figures 7-9. Figure 7 shows the plant Capex as a function of the annual feedstock tonnage processed. Each plant includes typically a power unit of sufficient capacity to provide the parasitic load of the AD facility, commonly of the order 0.25-0.5MW_e.

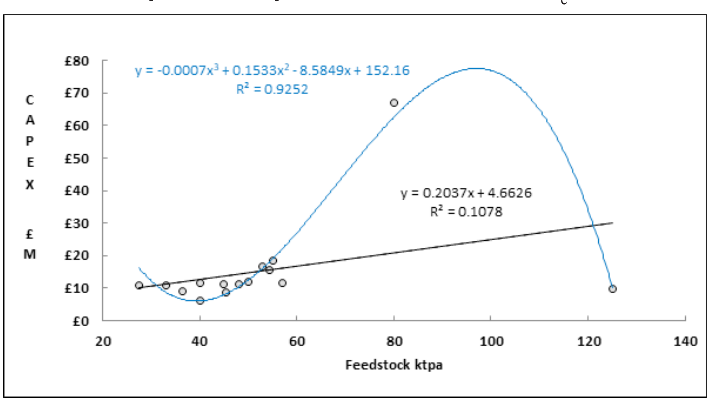

Figure 7: Capex £M and design feedstock capacity.

The data in Figure 7 reflects the increase in Capex with the increasing quantity of feedstock processed. The anomalous value at c.80ktpa is associated with the facility being a hybrid plant, having a larger power output than required for just the parasitic load, with the surplus power exported. Thus the relatively high Capex of the c.80ktpa plant reflects factors such as additional generator sets and the connection cost for power export. In contrast the relatively low Capex for the 125ktpa plant reflects the nature of the feedstock that is provided 'ready prepared' from an adjacent facility and does not need any processing before inputting into the digester. The polynomial curve with R^2 0.9252 provides the best correlation, compared to the linear curve with R^2 0.1078. Figure 8 shows the metric [Capex £/tpa] against the design feedstock capacity. The shape of the curve is similar to Figure 7 and the highest R^2 value of 0.907 is similar to that for [Capex £M] versus feedstock capacity but slightly lower than the 0.9252 achieved for [Capex £M] and feedstock capacity, suggesting the two metrics are broadly similar but [Capex £M] and feedstock capacity giving a slightly better fit.

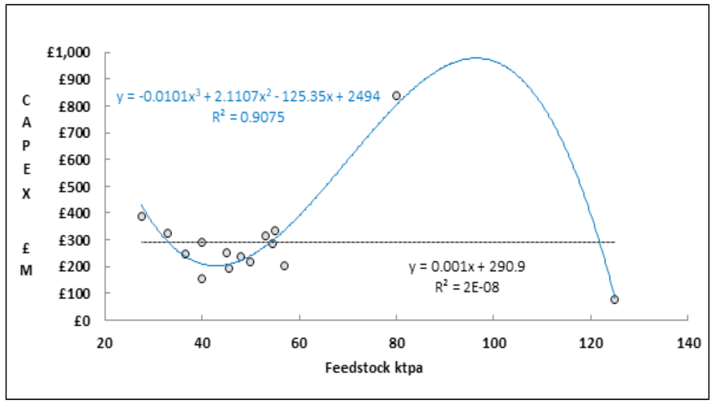

Figure 8: Capex £/tpa and design feedstock capacity.

The metric [Capex £M and Nm^3/h output] and feedstock capacity is presented in Figure 9, with the highest R^2 value 0.7869.

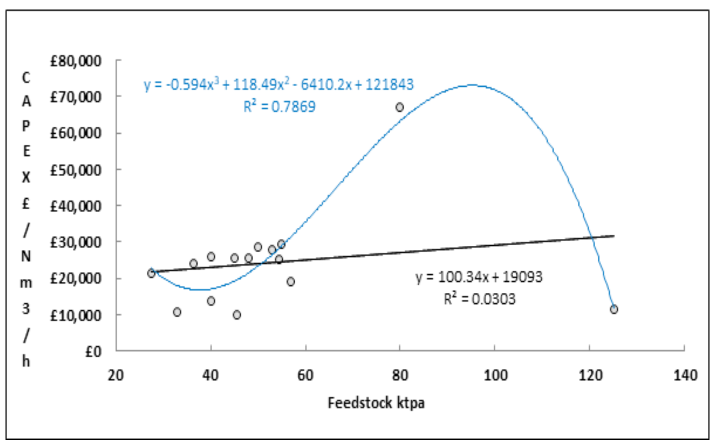

Figure 9: Capex £/Nm^3/h and design feedstock capacity.

The final metric assessed is [Capex £/Nm^3/h] against biomethane output (Figure 10).

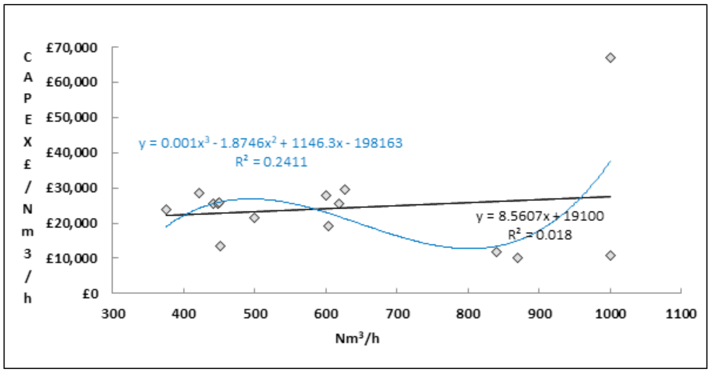

Figure 10: Capex £/Nm³/h and biomethane output.

The anomalous data point at c. 1,000Nm³/h is a hybrid biomethane/power plant, with the power output significantly greater than just the plant parasitic load. The higher R^2 value 0.2411 is less than the preceding metrics, with the data focussed mostly in the range c.£10,000-£30,000/Nm³/h and outputs ranging from c. 400 - c.900Nm³/h. The exception is the 'hybrid' plant at c.£60,000/Nm³/h, which has a larger power output than the other plants. Table 7 summaries the maximum R^2 values for each metric and includes those for 'all plants for comparison.

METRIC	MAXIMUM R^2 VALUE	
	All plants	Biomethane plants
Capex £M and design feedstock capacity	0.576	0.9252
Capex £/tpa and design feedstock capacity	0.0938	0.9075
Capex £/Nm³/h and design feedstock capacity		0.7869
Capex £/Nm³/h and biomethane output		0.2411

Table 7: Summary of Capex Metric R^2 Values for Biomethane Plants.

The Capex data for biomethane plants shows again that the metric [Capex £M] has the highest R^2 value at 0.925, slightly higher than the metric [Capex £/tpa] at 0.9075. The remaining two metrics are both lower but with the R^2 value for [Capex £/Nm³/h] higher at 0.7869 than the metric [Capex £/Nm³/h] against and Nm³/h output, which is the opposite ranking for power plants based on Capex £/output and 'feedstock capacity', as against 'output'.

Equally R^2 [Capex £/tpa] was significantly higher than the equivalent metric for power plants only. The reasons for this are attributed to the combination of plants with a more limited range of feedstock capacity and a more consistent feedstock that makes the plant process configurations similar. In terms of estimating the Capex of a potential AD biomethane plant, it is considered reasonable to use both the [Capex £M] and [Capex £/tpa] metrics. Strictly this applies only to UK based plants, due to the particular set of regulatory and fiscal drivers that apply, as described in the introductory sections.

Operating Costs

As referred to in Section 3 the Opex of an AD facility comprises fixed and variable costs, with the ratio depending on factors such as the plant output i.e. power or biomethane, feedstock types i.e. food wastes, manures, energy crops etc. and arrangements for the operation and maintenance of the plant. Typical costs for power and biomethane AD plants are discussed in the following sections. Figure 11 shows the [Opex expressed as [Opex £k].

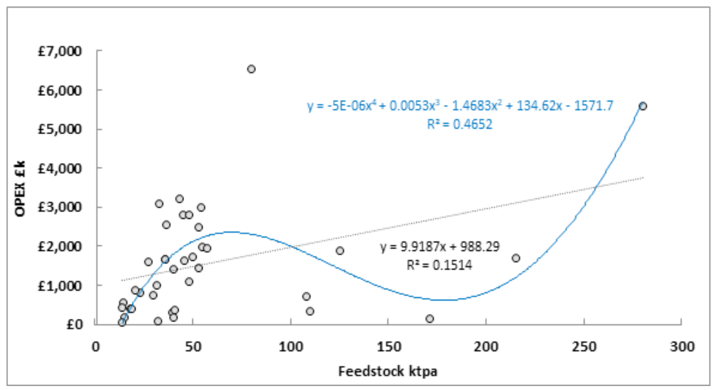

Figure 11: Opex £k and design feedstock capacity (all plants).

The Opex is generally <c.£3M but with exceptions in the range £6M-£7M. The higher Opex values are not all associated with a higher plant capacity, indicating that other technical matters are in play. Thus the high Opex for the c.80ktpa plant is associated with it being a hybrid plant, involving both biomethane production and a higher power output than just the plant parasitic load, while the high Opex for the c.280ktpa plant producing electricity involves both multiple numbers of medium capacity gas engine generator sets, rather than a few large capacity sets that leads to increased maintenance costs due to the number of generator sets involved, together with the plant also operating a biomethane unit. The R^2 value of 0.4652 compares to a linear trend line value of 0.1514.

Figure 12 shows the metric [Opex £/tpa] where the R^2 is lower than just the Opex £k, with R^2 0.1158 for an exponential curve.

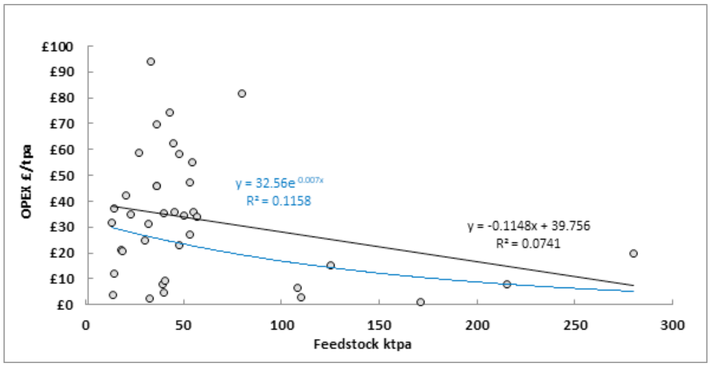

Figure 12: Opex £/tpa and design feedstock capacity (all plants).

The results suggest that the best correlation is achieved with the metric [Opex £k].

Power Plants

Considering only power plants, Figure 13 shows the graph of [Opex £k] against the design feedstock capacity.

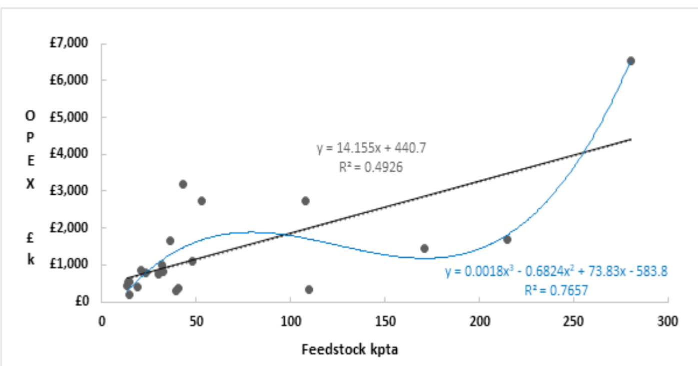

Figure 13: Opex £k and design feedstock capacity.

Many plants have an Opex <c.£1M, even for throughputs up to c.100ktpa. The Opex range increases up to +£3M for plants with a similar feedstock capacity, which reflects the more complex process configurations likely to be involved, including depackaging of food wastes and drying dewatered digestate etc. The highest value for R^2 is 0.7657 for a third order polynomial curve, compared to 0.4926 for linear regression. Changing the metric to [Opex £/tpa], Figure 14 shows the enhanced degree of scatter in the <50ktpa feedstock capacity range, with values ranging from a few £/tpa to over £70/tpa.

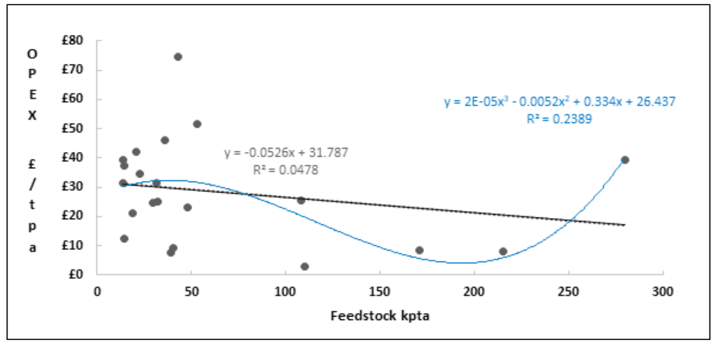

Figure 14: Opex £/tpa and design feedstock capacity.

At higher plant capacities, above c.50ktpa the [Opex £/tpa] reduces to a more consistent range and is generally <£30/tpa, with the exception being the highest throughput plant that has a c.£40/tpa Opex value. At this scale of power plant, multiple numbers of gas engine generators are utilised and the economies of scale gained with single, large units is not gained. The R^2 value at 0.2389 is not as high as the [Opex £k] R^2 value of 0.7657, suggesting that [Opex £k] is the more realistic metric. Nevertheless [Opex £/tpa] has the benefit of giving both an enhanced degree of detail and a practical parameter that is more easily understood at the operational level than an Opex expressed in £M. A further refinement is the metric [Opex £k/MW_e] against feedstock capacity, which gives an R^2 value of 0.2824, slightly higher than a linear regression and higher than the same metric for a power plant at 0.1925 (Figure 15).

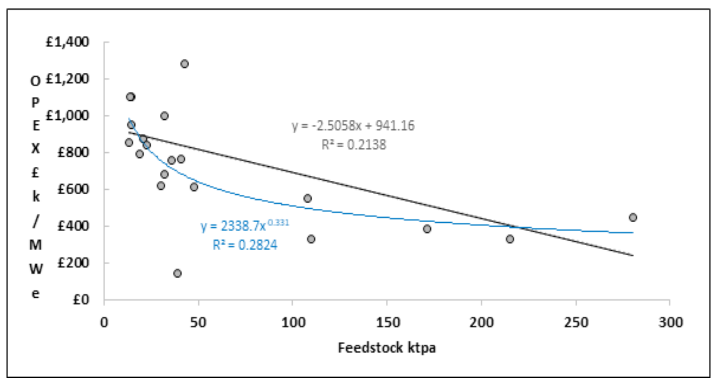

Figure 15: Opex £/MW_e and design feedstock capacity.

The final metric reviewed is [Opex £k/MW_e] against MW_e output (Figure 16), which gave an R^2 value of 0.2066 for a power law relationship, compared to 0.1176 for a linear relationship.

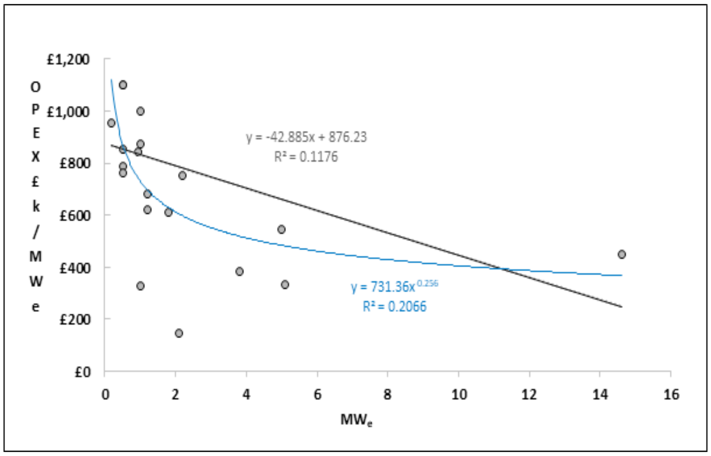

Figure 16: Opex £k/MW_e and MW_e output.

Table 8 summarizes the R^2 values for both 'all plants' and power plants only to allow comparison of the two metrics in common.

METRIC	MAXIMUM R^2 VALUE	
Opex £k and design feedstock capacity	0.4652	0.7657
Opex £/tpa and design feedstock capacity	0.1158	0.2389
Opex £/MW and design feedstock capacity	n/a	0.2824
Opex £/MW and MW Output	n/a	0.2066

Table 8: Summary of Opex Metrics R^2 Values for Power Plants.

The ranking of the first two metrics is the same for both 'all plants' and power plants only, albeit the R^2 values for 'all plants' are much lower, reflecting a lesser degree of correlation. The ranking of metrics for the power plants is clear cut, with [Opex £k] having the highest R^2 value, albeit statistically not particularly strong but better compared to the other metrics. This suggests that a number of the factors contributing to the Opex, such as feedstock cost, equipment maintenance and staffing costs, vary widely between the power plants. Based on examination of the individual plants involved, it is noted that the feedstock type and plant capacity appear to be major variants.

Biomethane Plants

Figure 17 shows the metric 'Annual Opex for biomethane plants and feedstock capacity'.

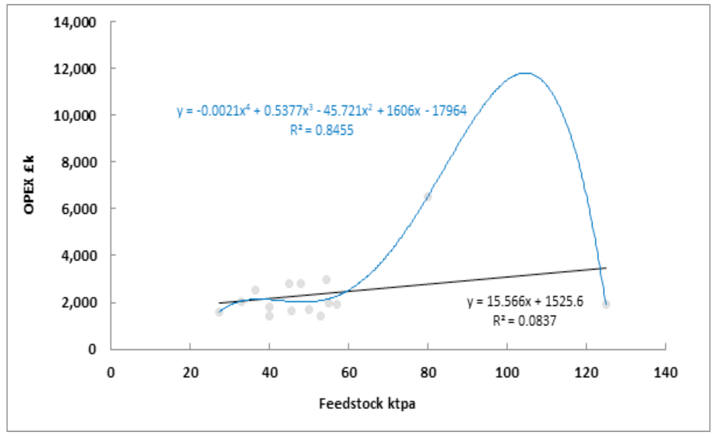

Figure 17: Opex £k and design feedstock capacity.

The degree of scatter is similar to [Opex £k] for power plants, with the R^2 value of a slightly higher value at 0.8455. The relationship for [Opex £/tpa] against feedstock capacity is shown in Figure 18.

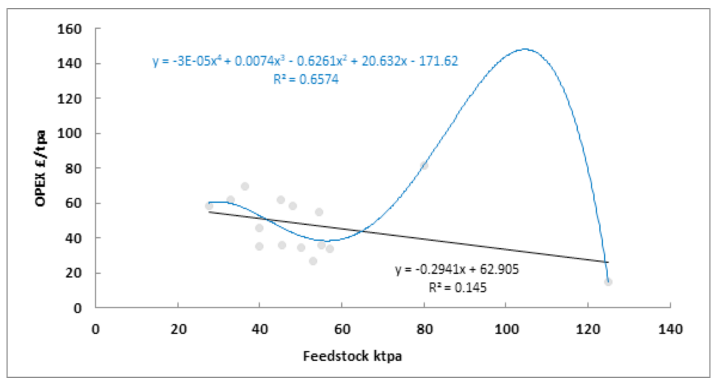

Figure 18: Opex £/tpa and design feedstock capacity.

Figure 19 presents the metric [Opex £/Nm^3/h] biomethane against design feedstock capacity. Similar to the metric 'Opex against output' for power plants the Opex generally decreases with increasing plant output and the R^2 value of 0.2848 is generally similar to that for power plants at 0.2393.

Citation: McKendry P (2019) Overview of Anaerobic Digestion and Power and Gas to Grid Plant CAPEX and OPEX Costs. Int J Bioprocess Biotech 02: 109. DOI:10.20911/IJBBT-109.100009

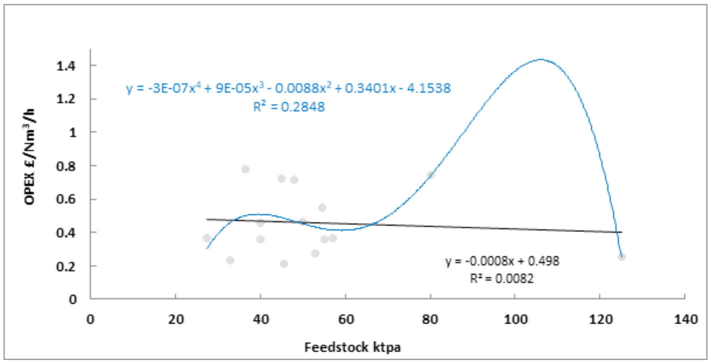

Figure 19: Opex £/Nm³/h biomethane and design feedstock capacity.

The final metric is *[Opex £/Nm³/h]* against output as Nm³/h (Figure 20).

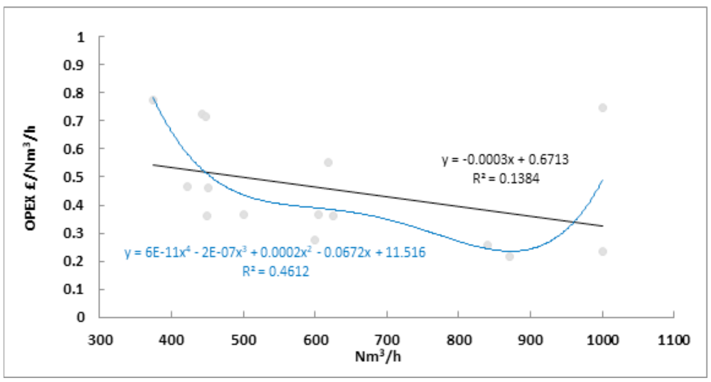

Figure 20: Opex £/Nm³/h and Nm³/h.

The highest R^2 value is 0.4612 compared to linear regression at 0.1384. As with other comparable metrics the variations are due to primarily to the type and quantity of feedstocks used.

Table 9 summarises the R^2 values of the Opex metrics for both biomethane plants and 'all plants'.

METRIC	MAXIMUM R² VALUE	
Opex £k and design feedstock capacity	0.4652	0.8455
Opex £/tpa and design feedstock capacity	0.1158	0.6574
Opex £/Nm³/h and design feedstock capacity	n/a	0.2848
Opex £/ Nm³/h and Nm³/h Output	n/a	0.4612

Table 9: Summary of Opex Metrics R2 Values for Biomethane Plants.

As with comparing 'all plants' and power plants only the first metric, [*Opex £k*], has the highest R^2 value but with the biomethane only plants having the higher R^2 value compared to 'all plants'. Of the other metrics, [*Opex £/tpa]* again has the highest R^2 value, suggesting that the other two metrics are limited/no use.

Discussion

AD is an established, commercially viable technology, able to produce renewable energy in the form of biogas, electricity or biomethane and utilising a diverse range of feedstocks, be they agricultural wastes e.g. cow, pig and chicken manures/slurries and wheat straw, purpose grown energy crops e.g. silage maize, whole crop rye and sugar beet, or a wide range of food wastes, from household and post-consumer to post-production wastes.

The introduction and background sections sought to establish what constructing and operating an AD plant encompasses and to establish its position within the EU 'energy' market place, in terms of waste management and recycling and the appropriate regulatory issues and fiscal incentives that determine what a plant must achieve and deliver.

The results presented in this overview are based on projects that have been proposed by a project developer and presented to potential investors/funders for funding, most of which were subsequently constructed. The project Capex is therefore based on the actual cost required to build the proposed plants in specific locations, taking account of site ground conditions, access requirements, grid connection costs for power/gas and the specific technology costs associated with processing the proposed feedstocks for digestion.

The key project parameters are based primarily on the type and quantity of feedstock to be processed that then determine the required process configuration needed to meet both the technical and regulatory requirements and to satisfy the financial demands of the project.

While the technical considerations are largely known, key aspects that have a significant impact on the financial viability of a project are related primarily to site location and access to a suitable export capacity power/gas grid connection. In the UK it is generally easier to find a suitable capacity biomethane to gas grid export connection local to a plant than a comparable 'biogas output' capacity power to grid connection. Recent changes in the UK fiscal incentives have also favoured biomethane production over power production i.e. lower power tariffs compared to biomethane tariffs.

While the overall plant database is of a reasonable size the range of plant feedstock capacities i.e. 14ktpa to 280ktpa, are biased toward the range c.20ktpa to 60ktpa, which tends to limit the accuracy of any assessment of higher capacity plants.

The variations in plant Capex and Opex costs were examined using a number of different metrics, in an attempt to identify a semi-quantitative method to enable a quick comparison of different types of AD plants producing power or biomethane, to assist project developers assess their proposed project against typical costs for a similar type of plant.

The Capex and Opex metrics are based on a number of parameters, such as annual feedstock capacity, unit cost per tonne of feedstock and the plant energy output, as power (MW_e) or biomethane (Nm^3/h), in an attempt to identify which metric has the strongest correlation and therefore would be most useful to both developers of potential projects and investors/funders alike.

It can be seen that comparison of AD projects is possible to a modest degree of accuracy but is dependent on a range of project specific factors, such as site location, feedstock quantity, process configuration required to treat the proposed feedstocks, site conditions impacting on construction costs, type of energy output and access to a suitable capacity power line or natural gas grid connection for export of the plant output.

To compare the various Capex metrics with the highest R^2 value, Table 10 summarises the metrics for 'all plants' and as power and biomethane plants.

METRIC	ALL PLANTS	POWER PLANTS	BI-OMETHANE PLANTS
Capex £M and design feedstock capacity	0.576	0.9164	0.9252
Capex £/tpa and design feedstock capacity	0.0938	0.3366	0.9075
Capex £/MW_e or Nm^3/h and design feedstock capacity		0.27	0.7869
Capex £/MW_e or Nm^3/h and MW_e or Nm^3/h output		0.365	0.2411

Table 10: Summary of Capex R^2 values.

The metric [*Capex £M]* applies to both 'all plants' and to power/biomethane plants and it is clear that while the 'all plants' R^2 value is modest and 0.576, power/biomethane plants have R^2 values significantly higher at c. 0.91-0.92.

The reason for the improved correlation is postulated to be due the difference in feedstock capacity i.e. power plants have a larger range, up to c.215ktpa, compared to biomethane plants at a maximum c.125ktpa. When separated into power/biomethane plants the Capex against feedstock capacity reflects the actual capital costs involved for the technology option, compared to taking all plants together, where the lower overall Capex of power plants also encompasses the larger feedstock capacity range than the more costly biomethane plants.

The R^2 values for [*Capex £/tpa]* for both 'all plants' and power plants are low i.e. 0.0938 and 0.3366 respectively, compared to biomethane plants that has an R^2 value of 0.9075, similar to the 0.9252 R^2 value for [*Capex £M]*. The relative insensitivity of biomethane plants is ascribed to the types of feedstocks typically used, which tend to have a relatively narrow but high range of energy content, making plants more likely to be of a similar design/type/configuration etc., whereas power plants use a wider range of feedstocks including lower energy content manures.

The metric [*Capex £/MW or* Nm^3/h*]* shows a low degree of correlation for power plants i.e. R^2 = 0.27, compared to the higher 0.7869 R^2 value for biomethane plants. The lower degree of correlation is considered due to the wide range of both feedstocks and treatment capacities, compared to biomethane plants that have closer output capacities.

The metric, [*Capex £/*MW_e*] or [Capex £/*MW_e *or* Nm^3/h*]* against output gives poor correlation for both power and biomethane plants, with R^2 values of 0.365 and 0.2411 respectively. The difference is again ascribed largely to a hybrid plant that is principally a power plant but also has a significant biomethane output. It is accepted that the presence of such 'anomalous' plants will bias the dataset but this initial assessment is intended to provide an overview rather that a rigorous statistical review.

In summary the metric [*Capex £M]* as a function of the design and feedstock capacity provides the best correlation for 'all plants' and for power and biomethane plants only. The other three metrics do not provide any strong correlations for power plants but the metric [*Capex £/tpa and Feedstock Capacity*] applied to biomethane plants also provides a similar level of correlation to the metric [*Capex £M and Feedstock Capacity]*.

As with the approach taken with examining Capex costs, Opex costs were assessed similarly, to identify potential metrics to be able to compare different types of potential AD projects. A summary of the results is presented in Table 11.

METRIC	ALL PLANTS	POWER PLANTS	BI-OMETHANE PLANTS
Opex £M and design feedstock capacity	0.4652	0.7657	0.8455
Opex £/tpa and design feedstock capacity	0.1158	0.2389	0.6574
Opex £/[MW/Nm^3/h] and design feedstock capacity		0.2824	0.2848
Opex [£/MW_e or Nm^3/h] and [MW_e or Nm^3/h] output		0.2066	0.4612

Table 11: Summary of Opex R^2 Values.

As mentioned in the introductory section, a key factor impacting the Opex results derived from the dataset is the presence of two hybrid plants that were left in. It was not possible to separate out the impact of the individual effects associated with the two plants, while leaving them out would have reduced the size of the already limited dataset; hence the decision to include the two plants under 'power' or 'biomethane' plants accordingly.

The first metric reviewed was [*Opex £M*] as a function of the design feedstock capacity, with the R^2 value for 'all plants' significantly lower than that for power and biomethane plants only. This is not an unexpected result, due to the intrinsic variances in the operating costs of equipment for power and biomethane plants, different feedstock types typically used e.g. manures and energy crops, compared to food wastes etc. and inclusion of the two hybrid plants.

The metric [*Opex £/tpa]* again gave a low R^2 value for 'all plants' and reduced values for both power plants and biomethane plants, although the biomethane R^2 value did not reduce as much from the [O*pex £M]* metric as the R^2 value for power plants. It is suggested that the difference in using *Opex £/tpa* is associated primarily with the types and cost of feedstocks and the different technology costs involved i.e. use of multiple gas engines against a single biomethane unit etc. i.e. use of multiple equipment (usually) incurs higher maintenance costs that a single large unit.

Comparing the power and biomethane plants using [*Opex £/[MW/Nm³/h]* and [*Opex [£/MW$_e$ or Nm³/h]* and as a function of MW_e or Nm^3/h output the correlation results were much lower compared to those based on [*Opex £]* and [*Opex £/tpa]*.

The metric [*Opex £/[MW/Nm³/h]* for both power and biomethane plants has near identical, poor R^2 values at 0.2824 and 0.2848 respectively. The metric [*Opex [£/MW$_e$ or Nm³/h] and [MW$_e$ or Nm³/h] o*utput gives a slightly higher R^2 value for biomethane plants at 0.4612 but a lower value for power plants at 0.2066.

The above results suggest that the simplest metric, [*Opex £M]*, provides the most accurate indicator when comparing all types of AD plants, with its accuracy increasing when power/biomethane plants are considered separately.

Conclusions

- Application of anaerobic digestion to treat a wide range of organic materials to produce a methane rich biogas, is used successfully and extensively around the world;
- Biogas can be used to provide heat, as a fuel in a gas engine or turbine to produce electricity, or upgraded to biomethane for use as a natural gas substitute;
- The residual solid material, post digestion, termed digestate, has valuable properties when spread to land, both as a soil improver and as a solid or liquid fertiliser;
- Recognition of biogas as a means of both processing organic wastes and providing renewable energy led to a significant increase in the number of AD plants in the EU and UK and increasingly North America and other parts of the world;
- A range of regulations specify national objectives and legally binding targets for renewable energy in EU Member States. In response to their obligations under EU legislation the UK implemented a series of regulations and fiscal incentives that impacted significantly on the viability of AD projects and promoted its use to reduce the environmental impacts of energy production;
- Key to a successful electricity/biomethane AD project is the combination of available types/quantities of feedstocks, process technology, proximity to suitable grid connection, government regulations, fiscal incentives and importantly, capital and operating costs;
- To assist project developers and investors/funders with assessing potential projects, potential metrics that could enable comparison of proposed projects with existing, operational AD projects based in the UK were proposed and evaluated;
- The evaluation included an overview of the capital and operating costs of the common form of AD, mesophilic digestion and plants producing electricity and biomethane using a range of soli/liquid feedstocks. The database was derived from 46, separate AD projects processing solid/liquid feedstocks comprising consumer/post-production food wastes, purpose grown energy crops and animal slurries/manures and mixtures of feedstocks;
- Types of feedstock and quantities processed are the principal design parameters determining the technical performance and financial success of a project, as they govern the biogas yield, suitability of the process technology, plant configuration and treatment capacity;
- The choice of process technology and process configuration is governed primarily by the need for either single stage digestion, requiring only a single digester i.e. animal manures, or two stage digestion, requiring two (or more) digesters i.e. energy crops and food wastes;
- Once the proposed feedstock mixture is specified process issues can be addressed but if a plant designed for specific feedstocks subsequently changes the feedstocks, both operational problems and poor plant performance are likely to arise, unless the impact of processing the new feedstocks is not assessed adequately;
- Connection to the electricity grid for exporting the electricity generated, or natural gas grid for injecting biomethane, are both key facets of an AD energy project. Securing a grid connection point able to accommodate the proposed plant output can be a problem, leading in some cases to relocation of a proposed plant to a more suitable connection point;
- Selection of metrics to identify the most useful for comparing potential project costs with actual costs was based around combinations of Capex and Opex costs, either as absolute values, cost/te waste processed, or cost/energy unit output as electricity of biomethane;

- An assessment of the statistical significance of each metric was undertaken using regression analysis and the 'best fit' trend line and coefficient R^2, initially for all plants and then separately as power and biomethane plants;
- Considering 'all plants', comparison of metrics *[Capex]* and *[Capex/tpa]* against the design feedstock capacity using linear, logarithmic, exponential, polynomial and power law trend lines, showed [*Capex £]* was the better metric with R^2 = 0.576;
- Using the same approach to assess power plants also gave the metric [*Capex £]* as a function of the design feedstock capacity the highest R^2 value (0.9164), based on a fourth order polynomial, compared to a linear trend line at 0.642;
- These results suggest [*Capex £M]* against the plant design feedstock capacity provides the best accuracy for estimating the Capex of a power producing AD plant, a finding that fits with the data for 'all plant' types, where the metric had the highest R^2 value, albeit lower than for power plants alone;
- Assessing biomethane plants using the same process also gave the metric [*Capex £]* as a function of the design tonnage the highest R^2 value (0.925), based on a third order polynomial trend line, compared to linear regression at 0.108. Closely behind was the metric *[Capex £/Nm³/h]* and plant design feedstock capacity with R^2 0.9075 (third order polynomial trend line) compared to a linear trend line with R^2 near zero;
- In terms of Opex for 'all plants' the metric *[Opex £k]* against the design feedstock capacity gave the higher R^2 value (0.465, fourth order trend line), compared to 0.151 for a linear trend line;
- For power plants the highest R^2 value was 0.766 (third order polynomial) for *[Opex £k]* against the plant design feedstock capacity, with R^2 for *[Opex £k/tpa]* lower at 0.657 (fourth order polynomial);
- For biomethane plants [*Opex £k]* against the design feedstock capacity is the metric with the highest R^2 value at 0.8455, with *[Opex £k/tpa]* lower at 0.657;
- The results suggest that the metric [*Opex £k]* is the most accurate indicator when comparing all types of AD plants, with the accuracy increasing when power/biomethane plants are considered separately;
- Reasons for the variations are postulated to involve plants with multiple outputs or hybrid plants i.e. both power and biomethane and the type of feedstock, which results in different process configurations and hence, different Capex/Opex costs. A review assessing the potential impact of different types of feedstock on the metrics would be needed to identify the possible effects of feedstock type on Capex/Opex;
- It should be noted that the all of the above findings apply strictly only to UK based plants, due to the particular regulatory and fiscal drivers that apply.

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