Department of Mechanical and Aerospace Engineering

Opportunities for Community Anaerobic Digestion to Produce Electricity and Heating from Organic Waste in Scotland

Author: Laura Clegg

Supervisor: Dr Paul Tuohy

A thesis submitted in partial fulfilment for the requirement of the degree
Master of Science
Sustainable Engineering: Renewable Energy Systems and the Environment
2017

Copyright Declaration

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

The copyright of this thesis belongs to the author under the terms of the United Kingdom Copyright Acts as qualified by University of Strathclyde Regulation 3.50. Due acknowledgement must always be made of the use of any material contained in, or derived from, this thesis.

Signed: Date: 25/08/2017

"Over 2 million tonnes of food waste are produced every year from all sectors in Scotland. If just half of this food waste was captured and treated through anaerobic digestion, the electricity generated could power a city the size of Dundee for six months, provide heat for local homes and businesses, and produce enough fertiliser for ten percent of Scotland's arable crop needs" – Scotland's Zero Waste Plan

Abstract

Scotland is aiming to lead action on climate and the development of renewable technologies. In the future, there will be a need to focus on improving the flexible use of the electric grid and addressing the need for decarbonising heating. Anaerobic digestion (AD) has the potential to contribute to both, though the production of biogas from organic waste. Many also see the future of sustainable energy provision lying in smaller, localised energy systems owned by communities, rather than the large, centralised power plants that represent the current structure of our energy systems.

This project aims to investigate the opportunities for community anaerobic digestion plants in Scotland, particularly for the recycling of local organic and sewage waste. The approach taken involves the development of an anaerobic digestion calculator to model a community plant for the town of Auchterarder and examine potential opportunities through a range of investigations. The investigations in this project are designed to examine the effect of community size, feedstock availability, transport requirements and end use on the feasibility of community anaerobic digestion. This is carried out through the analysis of plant profitability, energy output, greenhouse gas emissions and energy return on investment to determine where the opportunities are for community AD to be successfully developed in the future.

The outcome of this study shows that a community AD scheme using local organic and sewage waste would only meet around 5% of local energy demand. However, AD was highlighted as a more sustainable method of waste disposal than composting or landfill, releasing several times less carbon emissions. Additionally, community AD can make profit from product sales and incentives, provided it is implemented in a community with several thousand residents and has a payback period over 4 years. The results demonstrate that opportunities for community AD are currently in providing sustainable waste recycling and suppling energy to individual buildings or businesses rather than whole communities. Research needs to be focused on improving energy yields in the future. The results also show that grid injection technology is currently under incentivised and needs to become more financially competitive to be a practicable end use in the future.

Acknowledgements

I would firstly like to thank Paul Tuohy, the course director and my supervisor for this project, for his helpful advice and input throughout the process.

Secondly, I would like to thank Andrew Clegg and Bruce Reekie from Perth and Kinross Council for providing useful data and extensive sources of information and contacts on community anaerobic digestion.

I would also like to extend my thanks and acknowledgment to Andrew Roscoe, Maureen Cloonan, Matthew Geraghty and Jean Currie for allowing me use of the AD calculator they designed.

I would also like to thank the ScottishPower Foundation for funding this course and providing fantastic mentoring and insight into the energy industry throughout the year.

Finally, a huge thank you to my family and friends for all their brilliant support throughout my years at University.

Table of Contents

List of figures

List of tables

1 Introduction

1.1 Background

Scotland is aiming to increase the uptake of renewable energy to meet the equivalent of half of transport, heating and electricity needs by 2050 (2). To meet these targets sustainably there will be many challenges to overcome, including the need for improved flexibility in the use of electrical grid and increased focus on the decarbonisation of heating which currently accounts for over half of Scotland's energy demand (3).

Anaerobic digestion (AD) is a technology which breaks down organic waste to produce biogas. The production of 'green gas' is rapidly becoming an attractive solution to the provision of low-carbon heating, as it has the major benefit of being able to integrate easily with the current infrastructure. Scotland has one of the most developed gas grids in the world and four out of five households are reliant on gas to meet their heating needs (3). Developing the current infrastructure to accommodate renewable electric heating would require vast expenditure and add significant pressure to the electric grid. Additionally, biogas can be used to produce dispatchable electricity to fit with demand requirements which adds essential flexibility to the grid.

Anaerobic digestion uptake has grown in Scotland in recent years, however most organic municipal waste plants are large, centralised systems located close to cities. Distributed energy systems are steadily becoming viewed as a more efficient and flexible method of delivering renewable energy, offering both owners and consumers opportunities to reduce costs, ensure reliability and secure additional revenue through on-site generation and dynamic load management.

Using community AD systems to recycle organic waste in Scotland appears to be an ideal way to solve two societal problems, by producing renewable energy whilst recycling waste. Therefore, an understanding of what opportunities exist for AD as part of a community energy scheme would indicate the extent to which this technology could contribute to addressing renewable heating and electricity challenges in Scotland.

1.2 Problem Statement

With the energy infrastructure in Scotland being transformed into a more sustainable model based largely on renewables, there is a need to address the problem of grid flexibility and the provision of low carbon heating. Community anaerobic digestion schemes could produce energy from local organic waste, providing both renewable heat and dispatchable electricity as part of a flexible, distributed energy system. To understand if such schemes can be applied successfully within a community, there is a need to analyse the opportunities that exist and their outcomes, including potential energy returns, financial viability and greenhouse gas emissions.

1.3 Aim and Objectives

This project aims to investigate the opportunities for community anaerobic digestion systems to produce electricity and heating from local organic waste.

This aim will be met by the completion of the following objectives:

1. To perform a literature review on the use of anaerobic digestion to produce energy from organic waste and the current situation in Scotland.

2. To determine which factors affect the feasibility of small-scale AD systems.

3. To develop a model of a community AD plant for carrying out analysis of a range of investigative scenarios.

4. To analyse the potential opportunities for waste-fed community anaerobic digestion and make recommendations for the future development of community anaerobic digestion in Scotland.

1.4 Approach

This project begins with a literature review on the topic of anaerobic digestion, including an overview of AD technology (chapter 2), a background to the current AD landscape within Scotland (chapter 3) and a study of the factors which can affect the feasibility of an AD plant (chapter 4).

The literature review is then followed by the research methodology (chapter 5). This gives an outline of the method used to carry out the technical research in this project. A brief description of the research methodology is as follows:

1. Select and adapt an AD calculator tool to model a plant for a case study community.

2. Validate the tool with existing AD plant.

3. Model the community plant using local organic waste as feedstock and determine the feasibility by calculating:
    a. The plant energy balance.
    b. The percentage of community energy demand (heating & electricity) that can be met.
    c. The energy return on investment (EROI).
    d. The profitability of the plant.
    e. The carbon emissions released in comparison to other methods of waste disposal.

4. Carry out three further investigative scenarios to determine the best application of community AD:
    a. Investigation 1. Community Size – To determine the size of community that is required for an AD plant to be profitable and produce sufficient power output.

b. Investigation 2. Transport Requirements – To determine the effect of increasing transportation distance for collecting additional local agricultural waste on cost and power output.

c. Investigation 3. End Use – To analyse the profitability of two different methods for delivering heat and electricity: combined heat and power (CHP) and biomethane grid injection.

The process of selecting, adapting and validating an AD calculator to model the community AD plant is detailed in the model selection and adaption section (chapter 6), followed by the analysis section which describes the process of data collection and the model inputs for each investigation (chapter 7). The main calculations and results are then presented in the results section (chapter 8).

The main outcomes are discussed against the stated aims and the wider implications, after which the final recommendations are made along with a consideration of limitations and further work (chapter 9) and the project is concluded (chapter 10).

2 Literature Review 1: Anaerobic Digestion Technology

This section reviews the principles of anaerobic digestion to give a background to the technology, an understanding of the chemistry behind the digestion process, the factors that affect system design, justification as to why it should be used over other waste management systems and finally, a consideration of the barriers to uptake.

2.1 The Development of AD

Anaerobic digestion is not a recent technology; the use of biological treatment for waste goes back several centuries. However, it is only recently that AD has been valued as a source of energy production. The first notable implementation of the technology in the UK was in 1895, when biogas was recovered from a sewage treatment facility and used to power street lamps in Exeter (4). Throughout the years, anaerobic digestion has primarily been used in the UK for sewage treatment and agricultural waste disposal, whilst energy generation was a secondary interest. In some plants, the energy which could not be used for heating the waste treatment process was even flared off uselessly (5). In the 1970s, the oil crisis increased focus on the development of renewable energy sources and the use of AD for sustainable energy rather than only as a means of waste treatment. Today, there are many diverse designs of anaerobic digester. Most micro systems exist in developing countries, whilst developed countries tend toward large-scale industrial plants. Current research focuses on different combinations of feedstock and improving the design efficiency of the plant for energy production.

Figure 2.1. Small-scale digester in Uganda (Source: Community by Design)

Figure 2.2. 1480m^3 AD plant on a UK farm processing slurry, maize and glycerol (Source: Community by Design)

2.2 The Bio-Chemical Process

Before digestion, the feedstock must undergo a pre-treatment stage to improve the quality of the digestate by mixing different feedstocks, adding water or removing unwanted solids or particulates (6). Animal by-products must be sterilised or pasteurised at 70°C for at least 60 minutes to kill harmful pathogens such as salmonella and E.Coli, in accordance with EU legislation (7). The pre-treatment stage often varies, depending of the composition of the feedstock.

The digestion process itself involves the breakdown of organic material by microorganisms in an oxygen-free environment. This is a both a biological and chemical process, accomplished by four steps:

Step 1. Hydrolysis

Complex, organic polymers such as carbohydrates, lipids and proteins are broken down into monomeric products by enzyme activity.

Lipid → Fatty Acids
Polysaccharide → Monosaccharide
Protein → Amino Acids

Step 2. Acidogenesis

Acidogenic bacteria convert the simple monomers via fermentation into volatile fatty acids (VFA) and alcohols, along with by-products of ammonia, CO_2 and H_2.

Step 3. Acetogenesis

The acetic acid, CO_2 and H_2 can go directly to the final stage to produce biogas. However, the other products require acetogens to further ferment them into acetate, CO_2 and H_2 so that they can be used by the methanogens for methane production.

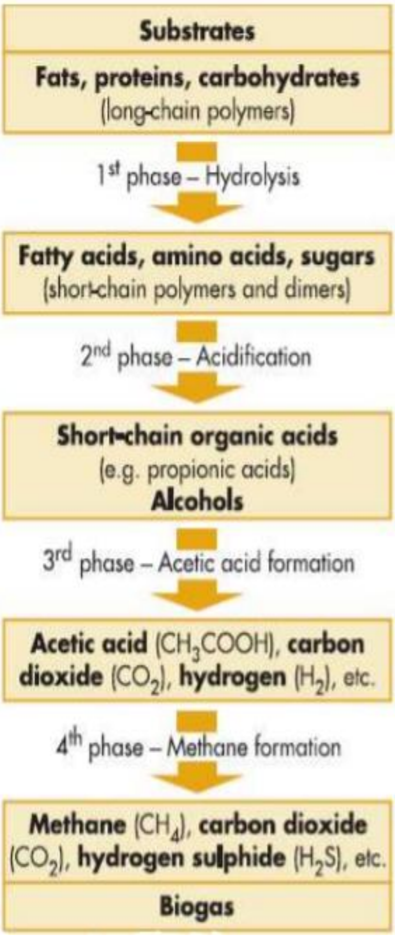


Figure 2.3. The digestion process

(Source: S.E.I)

Step 4. Methanogenesis

Two groups of co-enzymes convert the acetate and the H_2/CO_2 into methane gas, in the following reactions:

$$CH_3COOH \text{ (acetate)} \rightarrow CH_4 + CO_2$$

$$CO_2 \text{ (carbon dioxide)} + 4H_2 \text{ (hydrogen)} \rightarrow CH_4 + 2H_2O$$

After digestion, impurities such as hydrogen sulphide and water vapour must be removed before use in boilers or CHP units, as they can cause damage to mechanical parts. Carbon dioxide must be further removed to increase the methane content to a level that is suitable for the gas to be used for grid injection or as a transport fuel (6).

2.3 Feedstocks

Biogas can be produced from a wide range of feedstocks including:

- Organic municipal waste e.g. food scraps, garden waste such as grass cuttings, and sewage sludge
- Organic industry waste e.g. slaughterhouse waste, food and drink factory waste, distillery/brewery by-products
- Agricultural waste e.g. animal or crop by-products
- Energy crops e.g. plants grown specifically for producing energy. These can be controversial due to competition with land for food growth.

This project will be focused on organic municipal waste as a feedstock. Anaerobic digestion is highly effective with organic waste, but cannot breakdown non-organic or woody materials, as most anaerobes are unable to degrade lignin (8). Unlike combustion, anaerobic digestion is particularly suited to feedstocks with high moisture content (7). Every feedstock produces a different methane yield depending on individual properties such as the percentage of dry matter content (DM) and volatile solids content (VS). Some typical yields found in literature are shown in Table 2.1 (9) (10) (11).

Table 2.1. Feedstock properties

Feedstock	**DM (%)**	**VS of DM (%)**	**Methane Yield ($m^3kg^{-1}VS$)**
Pig Manure	5-8	80	0.2 - 0.4
Energy Maize	35-39	96	0.2 - 0.5
Food Waste	10	80	0.5 - 0.6
Garden Plant Waste	10	80	0.2 - 0.5
Sewage Sludge	5	65	0.1 - 0.3

Though the methane yield is similar for feedstocks such as energy maize and plant waste, as energy maize is specifically grown for the purpose of AD, it has a high percentage dry matter and volatile solids and therefore will produce more methane per tonne of wet feedstock.

2.4 Products

Several useful products are created by AD which can be used for generating revenue. The main outputs are as follows:

- Electricity or heating only (30-50% efficient)
- Combined heat and power (CHP) (up to 85% efficient)
- Injection into the gas grid
- Liquid or compressed gas transport fuel
- Digestate/fertiliser

Biogas is composed primarily of methane (55-80%) and carbon dioxide (20-45%). It is methane that is used for energy generation and the yields are highly dependent on the quality and type of feedstock, time spent in the digester and digestion conditions (12). Biogas has a range of end uses and can be used to provide heat through a biogas boiler, electricity through generator or both through a CHP scheme. Excess heat can be used as a source for the AD process itself, or to provide heat to nearby dwellings, potentially in a district heating scheme.

Alternatively, biogas can be upgraded to biomethane by removal of CO_2 and injected into the gas grid or compressed into transport fuel. Biomethane has the exact same composition as natural gas (> 95% methane), which allows it to be used in the current gas infrastructure (13). However, upgrading and injecting into the gas grid is expensive and as it is currently developing in the UK, there are few incentives or standards currently in place. With continued growth in the technology, this will be likely change in the future (14). This project is focused on the production of heat and electricity, therefore will investigate CHP and biomethane injection as end uses.

In addition to energy, a nutrient-rich digestate is produced by AD. This can be used as a biofertiliser, or optionally separated into a soil conditioner and liquid fertiliser. The use of the digestate to grow more food and plant-based matter can evolve the system into a closed-loop process, as demonstrated in Figure 2.4.

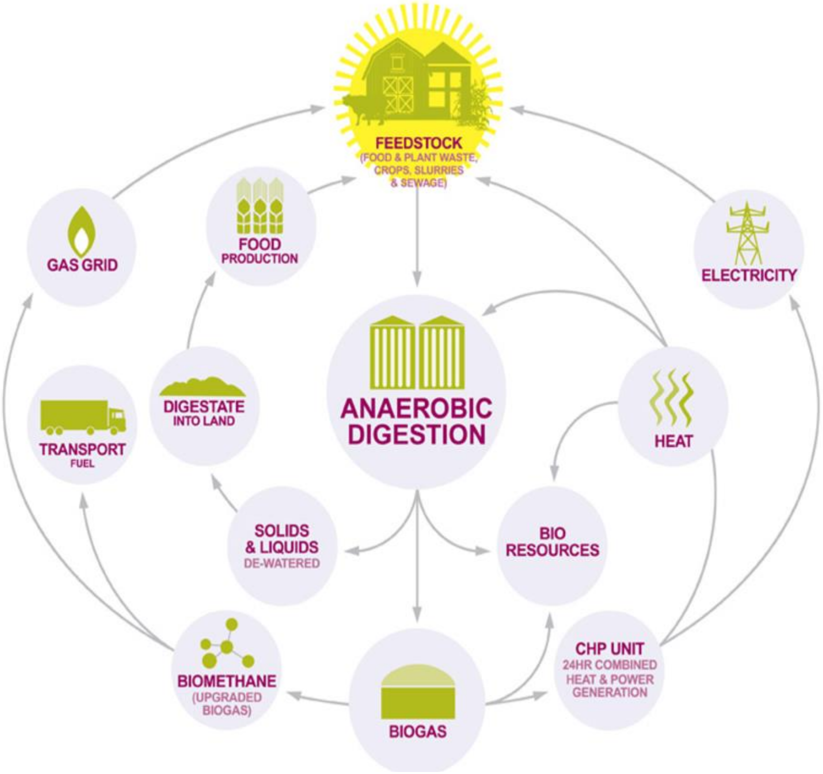


Figure 2.4. Diagram of closed loop AD process

(Source: ABDA)

2.5 System Design

An anaerobic digestion system can be as simple as an individual vessel with a boiler, into which all the feedstocks are input and the biogas is drawn off through a pipe into gas storage. There are many potential ways to improve the efficiency of design, such as the use of pre-treatment stages or multiple digesters (multi-stage digestion). The main components of an AD system include:

- Pre-treatment (sorting, screening, pasteurising etc.)
- Digestion tank
- Mixer/agitator
- Pumps
- Feeding systems for solid biomass
- CHP system or bio-methane converter

A process flow diagram of a simple anaerobic digestion system can be seen in Figure 2.5.

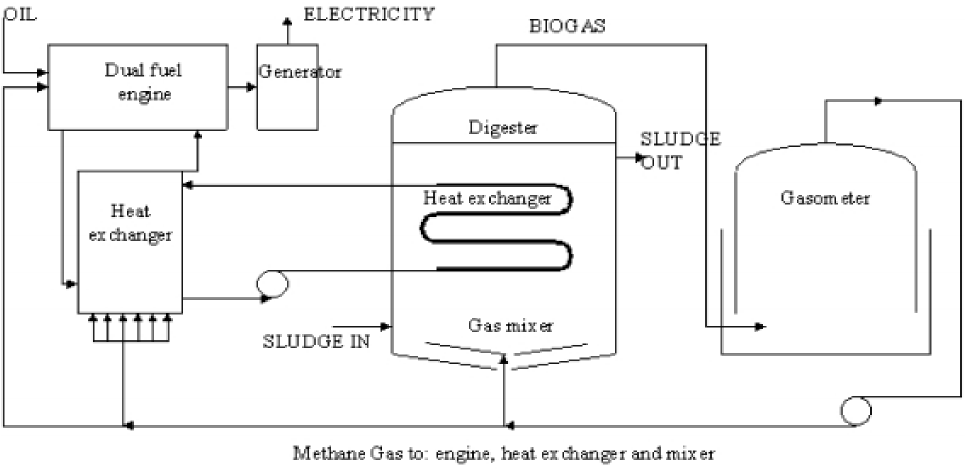


Figure 2.5. Flow diagram of low solids AD

(Source: soton.ac.uk)

This project will be focused on small-scale systems. Micro AD systems have a capacity <250 kW and are entitled to the highest level of government incentives. It is estimated that AD facilities with a 250 kW capacity would be suitable for treating up to 15 tonnes per day of organic municipal waste (around 5,500 tonnes per annum) and to be operationally viable must handle at least 130-180 tonnes per annum (15). Small units are currently available on the market from around £80,000 (15).

2.5.1 Digester Type

The digester type can be batch or continuous. Batch digesters are loaded once for the material to digest, whereas in a continuous-flow digester new substrate is constantly fed through. Smaller systems tend to be batch, whilst larger systems are often continuous. Continuous systems have higher capital costs as they involve mixing and pumping the substrate, however batch systems involve the challenging task of restarting the system from scratch which increases operating costs (16). The vessel itself can be either vertical or horizontal plug flow, with the horizontal tank being more expensive but allowing the feedstock to reside for an optimum time.

2.5.2 Temperature

There are two predominant temperature ranges which are preferred for anaerobic digestion: mesophilic systems which operate at 25-40°C and thermophilic systems which operate at 50-60°C (16). Mesophilic systems are more stable, cost less and require less energy, but thermophilic systems have the advantage of faster biogas production, as performance increases with temperature (17). Overall, it is generally accepted that 35-37°C is suitable for methane production (18).

2.5.3 pH

The pH can affect the reactions occurring within an anaerobic digestion system. The optimum pH to attain the maximum biogas yield varies among literature sources, however most are within the range of 6.5-7.5 (18). During the acidogenesis stage, acids are formed which results in the pH falling. If the pH drops too low, it can inhibit acidogenesis and be toxic for methanogenesis (6).

2.5.4 Total Solids Content

Anaerobic digestion can be a wet process or dry process. One advantage to AD is that it is successful with feedstocks of high moisture content. Total solids (TS) consist of volatile solids (VS) and suspended solids (SS). Volatile solids are the organic matter present in water which can be ignited or burned when exposed to high temperatures. This directly corresponds to the biogas yield; the greater the VS, the more biogas can be produced. The solids content is a critical factor in digester design: lower solids concentrations require larger reactors and higher heating requirements (19).

2.5.5 C/N Ratio

The carbon to nitrogen ratio in the organic material is important to provide an appropriate nutrient balance for the anaerobic bacteria growth, as well as for maintaining a stable environment (17). Literature suggests that a C/N ratio of 20-30 provides sufficient nitrogen for the process (18).

2.5.6 Retention Time & Mixing

The retention time is the length of time required for complete degradation of the organic matter. The exact retention time can vary depending on temperature and the composition of the waste, however tends to range from 30-60 days for a mesophilic digester and 12-14 days for a thermophilic digester (6). Slow mixing can improve the process efficiency as it prevents build-up of material and a temperature gradient and improves contact time between the micro-organisms and the substrate.

$$Digester\ Volume = \\ Organic\ dry\ matter\ added\ daily\ \times\ Retention\ time\ (days)$$

2.5.7 Organic Loading Rate (OLR)

Organic loading rate is the ‘feeding rate’ of substrate into the system and is measured in volatile solids per m^3 of the digester. The OLR is a measure of the biological conversion capacity of the system; if the system is being ‘fed’ above it’s OLR, there will be a low biogas yield due to an accumulation of inhibiting substances in the digester (e.g. fatty acids) (6). A typical OLR should be less than 4.5 kg/m^3/day (13).

$$OLR = \frac{Organic\ dry\ matter\ added\ daily\ (\frac{kg}{day})}{Net\ volume\ of\ digester\ (m^3)}$$

2.6 Benefits of AD

Anaerobic digestion is one of three main options for dealing with organic waste:

- Landfill (burying the waste)
- Incineration, gasification or pyrolysis (burning the waste)
- Anaerobic digestion or composting (bio-digesting the waste)

Anaerobic digestion is the only option which recovers maximum energy and is a completely closed system. The other methods are open systems and therefore release emissions more readily into the atmosphere. Global warming potential (GWP) is a mass-based measure of how much heat the gas traps in the atmosphere, relative to carbon dioxide and is published by the Intergovernmental Panel on Climate Change (IPCC). Methane has a global warming potential 25 times greater than CO_2 over a 100-year period (1).

Composting digests aerobically (with oxygen present), theoretically producing carbon dioxide and water vapour. This is demonstrated in an example using glucose:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$$

Anaerobic digestion and landfill digest anaerobically (no oxygen present), theoretically producing carbon dioxide and methane:

$$C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4$$

However, in AD all the methane is combusted to produce water vapour and less overall CO_2 than composting. Landfill, incineration, pyrolysis and gasification can also perform energy recovery, but as the reactions do not take place inside a sealed vessel they are around 25% less efficient than AD (1).

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

As can be seen in the equations above, although AD plants produce CO_2 emissions, they reduce overall emissions and therefore adhere to Scotland's climate change targets (20). Through combustion, anaerobic digestion prevents the release of methane which is twenty-five times more potent than carbon dioxide. Biogas production also reduces the need for fossil fuels and biomass combustion, which helps to reduce deforestation and prevents considerable quantities of air pollutants being released.

Additionally, landfill waste takes 20-25 years to decompose as it is not designed for efficient decomposition. Composting and AD are more efficient and produce a useful fertiliser product, as vessels are specially designed and monitored. Composting takes approximately 20 weeks for digestion and AD approximately 3 weeks (1).

2.7 Barriers to Uptake

Small biogas plants can often face greater challenges than their large-scale counterparts. Figure 2.6 shows a summary of some of the main barriers to the uptake of AD technology from a presentation delivered by the Renewable Energy Association (REA).

Technical challenges involve designing the plant to produce maximum biogas yield and so that it is cost effective on a small scale. This is often a case of optimisation, weighing up cost factors with plant efficiency. There are also technical decisions to be made on whether the addition of biogas to biomethane upgrading units would provide sufficient revenue to be a worthwhile investment.

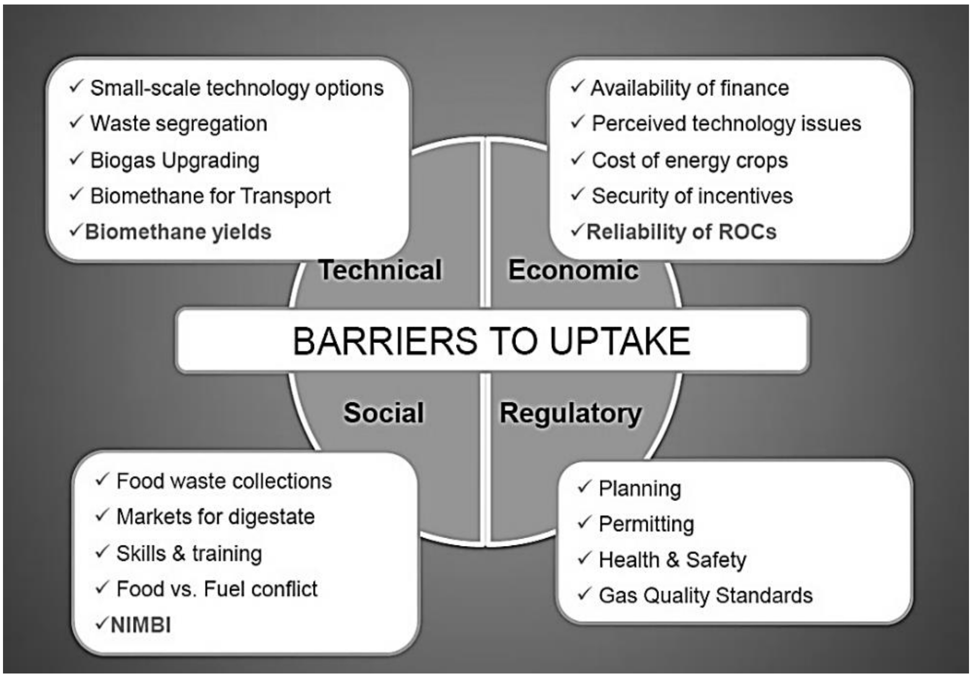


Figure 2.6. Barriers to uptake

(Source: REA)

Economic challenges can include the availability of loans or financing schemes to cover the high capital costs and the security of incentives for energy production. AD is highly reliant on renewable energy incentives for revenue, however they are unreliable in the long term depending on government policies. Not having the capital to start-up or not producing enough revenue are often the biggest financial barriers to AD projects.

In addition to these challenges, there can be several regulatory hurdles to overcome. AD has the potential to harm health and the environment if mismanaged, as it holds waste material and powerful greenhouse gases. In Scotland, the Scottish Environment Protection Agency (SEPA) manage waste regulatory controls. AD plants must have Pollution Prevention Controls and Waste Management Licensing in place if the feedstock input exceeds 10 tonnes a day (21).

Finally, several social challenges exist, particularly when developing AD locally. They can include the provision of organic waste collection, the availability of a competitive digestate market, the specialist skills required to build and operate the AD system and resistance from residents who would disapprove of a plant being built near the community (NIMBY-ism).

2.8 Summary

In summary, anaerobic digestion is a mature technology for organic waste treatment which has more recently been developed as a source of renewable energy production. Anaerobic digestion works flexibly with most organic feedstocks and produces digestate and biogas, which can then be used for a range of purposes including CHP, grid injection and transport fuel. Micro-AD includes systems with a capacity of <250kW. They can often face more barriers to implementation than their large-scale counterparts, including funding, planning, reliability of incentives and availability of feedstock.

The process of anaerobic digestion is influenced by complex bio-chemical factors which results in the need for specific design parameters, including temperature and pH among others. System designs can vary, but primarily depend on feedstock type and financial constraints. Improving the effectiveness of the AD is a process of optimisation between efficiency and cost.

AD produces less greenhouse gas emissions than other systems that deal with organic waste. This is because AD takes place within a closed system and the methane is combusted efficiently to produce water and less carbon dioxide than is produced in composting. Landfill is the most polluting method of organic waste disposal, as methane is produced and is often released into the atmosphere. AD provides a range of uses for organic waste, including energy and fertiliser, and has more benefits than simply burning or composting the waste.

3 Literature Review 2: Anaerobic Digestion in Scotland

This section reviews the energy and AD landscape in Scotland to give an understanding of the current situation for community anaerobic digestion. The present system for disposing of organic waste in Scotland is also reviewed and the energy generation potential from recycling organic waste using anaerobic digestion is calculated.

3.1 Energy in Scotland

The Government in Scotland is highly committed to renewable energy and climate change targets, aiming for 100% of electricity and 11% of heat to be produced from renewable sources by 2020. The latest Scottish Draft Energy Strategy, released in January 2017, aims to continue the advancement of renewable technologies by committing to meet the equivalent of half of Scotland's electricity, heating and transport needs by renewables by 2030 (2).

In recent years, development of renewable electricity generation has seen significant growth within Scotland. By 2015, the Government had surpassed their interim electricity targets with 59.4% of gross electricity consumption being produced from renewable sources (3). A major portion of this generation can be attributed to the growth of wind power, which accounted for 64% of 2015 renewable electricity production (3). However, wind power, as with many forms of renewable generation, comes with the challenge of flexible use. With the closure of the last coal-powered station in 2016 and a commitment not to replace nuclear plants after the current generation are exhausted, Scotland will be continuing to focus largely on renewable sources in the future, which means the need for flexibility will be vital.

The provision of low-carbon thermal energy is another significant challenge facing the Scottish energy sector, as heat is responsible for 55% of energy use and is the largest source of carbon emissions (22). Targets in this area have always been lower than renewable electricity and only 3.8% of heat was generated from renewable sources in 2014 (3). Thermal energy production and management is an area likely to gain significant attention in the future, with a commitment from the Government in the 2015

Heat Policy Statement to largely decarbonise heating systems by 2050 (22) and a lot to do before then to achieve that target.

Anaerobic digestion could contribute to overcoming the energy challenges in Scotland, as it can provide both low-carbon heating and dispatchable renewable electricity which will improve the flexibility of the electric grid. Biogas has an advantage over other forms of renewable heating, such as heat pumps, as four out of five households in Scotland already use gas for heating, which means it is simpler and cheaper to integrate into the current infrastructure (3). The Scottish Government is set to support the key development of bioenergy up to 2050, with a Bioenergy Action Plan due to be released in conjunction with the new Scottish Energy Strategy in the coming years (2).

3.2 Review of Scottish AD Industry

Anaerobic digestion is a technology which has developed significantly in Scotland in the last few years. Figures published by the Anaerobic Digestion and Bioresources Association (ADBA) show that in 2015 the AD industry grew by two-thirds, from sixteen to twenty-seven installed projects and the number of AD plants in Scotland has risen to almost fifty in the past two years (23). It is the Scottish Government's preference that when not being used for transport fuel, biogas should be used in heat-only or high quality combined heat and power (CHP) schemes, as it is believed that this is where they can provide most effective use (22).

According to the Renewable Energy Association (REA), there are two categories of AD developing in the UK. These are farm-fed systems and waste-fed systems (24). Farm-fed systems process material generated on farm only, including manure, energy crops and crop waste. The scale is typically 100 kW to 1 MW and planning is straightforward as there are less regulations involved. The energy and digestate produced can be used on farm or locally. Waste-fed systems process external wastes including domestic and commercial food waste, sewage sludge and garden waste. These plants tend to be on the larger scale, typically 1 MW to 2.5 MW and require more stringent planning, waste and environmental regulations. These plants use CHP or direct gas grid injection to utilise the biogas and sell digestate off-site.

As with the rest of the UK (and most developed countries), the current waste-fed AD landscape in Scotland leans towards development of large-scale, centralised plants (25). Whilst these are often more cost-effective, they do not benefit the disperse, rural communities which make up the majority of Scotland, as shown in Figure3.1. They also increase the transportation distance of feedstock required, elevating both costs and carbon emissions. The commercial viability of community AD systems in Scotland is a topical and as-yet inconclusive area of research. The Scottish Biofuels Programme was supported by Zero Waste Scotland until 2017 to provide impartial advice to biofuel businesses. They recognised the effective deployment of decentralised AD systems as a potential solution for local energy generation and waste management for rural communities in Scotland and conducted a small number of case studies, however limited results were published as an outcome (25).

At present, there is no official list of AD sites in Scotland and the independent lists are constantly being updated. One of the most recent is from the NNFCC in 2017 (see Appendix I). It estimates that there are currently forty-two anaerobic digestion plants in Scotland, the majority dealing with farm waste. Of the forty-two plants, twenty-seven are farm-based, seven process distillery/brewery waste and seven recycle municipal organic waste. Six of the seven municipal waste plants are located in the central belt region, near the cities of Edinburgh and Glasgow. The exception is the Western Isles Integrated Waste Management Facility installed in Stornoway in 2006.

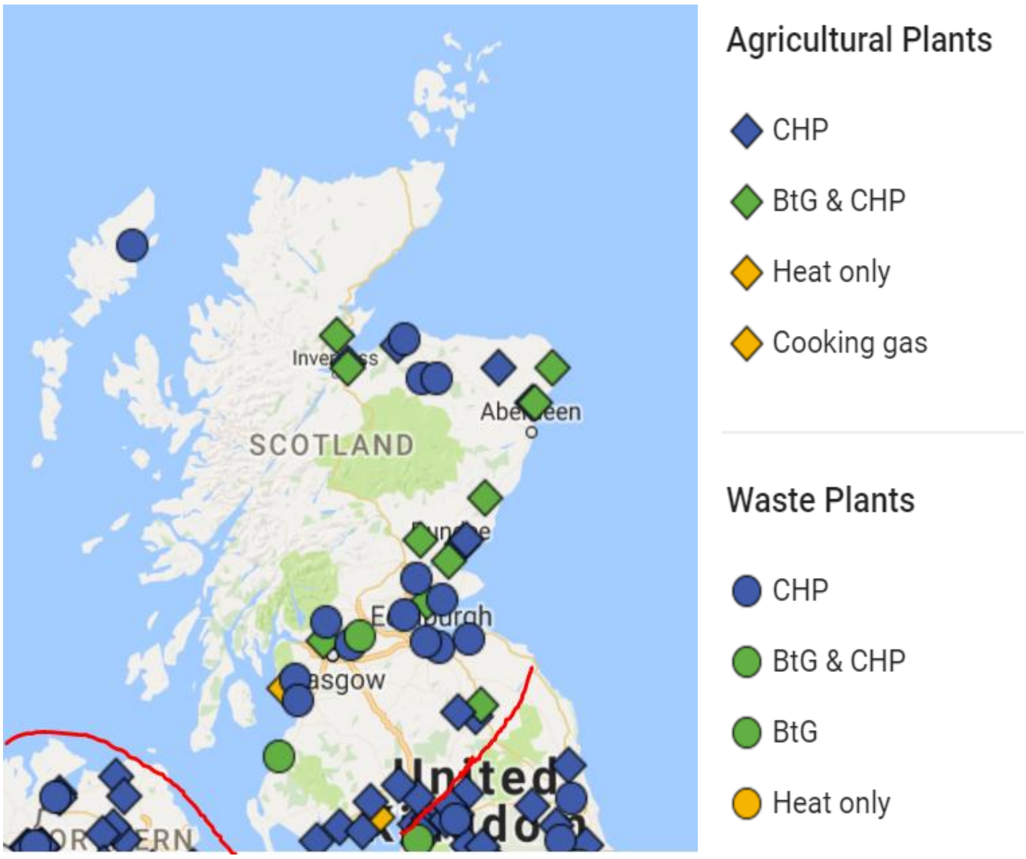


Figure 3.1. Map of AD plants in Scotland (source: NNFCC)

There is clearly a gap where small-scale community AD is concerned in Scotland, particularly as a means of organic waste recycling. There is currently a lack of waste-fed projects being installed in rural Scotland out with private farms or the central belt, which means there are opportunities for renewable heat and electricity generation from local organic waste going unfulfilled. In 2015, biomass produced 89% of renewable heat in Scotland and energy from waste (including combustion) produced only 5% (26). The increased uptake of anaerobic digestion facilities would reduce pressure on forests and sensitive peat land areas in Scotland, reduce the need for biomass imports and provide a cleaner source of fuel than the combustion of biomass, which causes significant air pollution. Locally produced biogas can also reduce the transport costs involved in moving waste down to large, centralised plants, encourage the growth of local employment and give an improved sense of community energy ownership.

However, whilst small-scale anaerobic digestion can provide a range of environmental, societal and economic benefits, a major barrier to development is economic viability. In addition, government incentives have been in a period of flux over the past few years, which has reduced the willingness of funders to invest in local AD in the long term (27). Therefore, to see an increase in the uptake of community biogas to help meet Scotland's renewable energy targets, there is a need to understand where small-scale AD systems can be effectively installed and their applicability within the context of Scottish communities.

3.3 Organic Waste Disposal in Scotland

A joint benefit of AD is the potential for organic waste disposal. This fits in well with Scottish aspirations to become a 'zero waste' society, with a major push in recycling resulting from the Scottish Zero Waste Plan. Developed in 2010, this is a high-level document which sets out a strategy to change the way Scotland views waste, to see it as a resource rather than a problem to be disposed of. The ZW Plan sets an ambitious target for 70% of Scotland's waste to be recycled or composted by 2025 and seeks to eventually ban biodegradable waste from entering landfill (28). This outlook is echoed by the Scottish Circular Economy Strategy, which aims for increased production of renewable fuels, heat and fertilizer products from biological waste and for Scotland to become a leader in anaerobic digestion (29).

However, it is important to understand that 'energy from waste' is part of a hierarchy of waste management, to avoid putting a value on waste that competes with reduction, reuse or recycling. The Scottish Circular Economy Strategy underlines the importance of the waste hierarchy, stressing that waste should be used for energy recovery only when the material cannot be retained for higher value use (29).

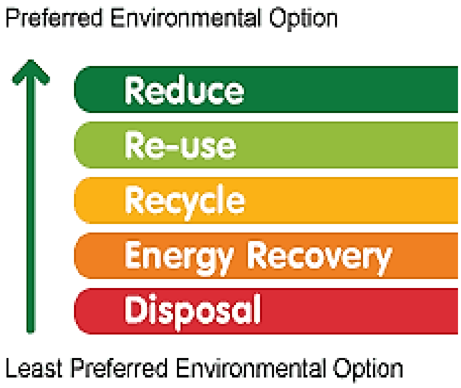


Figure 3.2. The waste hierarchy
(Source: South London Waste Partnership)

In the past, there have been difficulties with ascertaining the amount of organic waste material in Scotland that could be used for AD. In many areas, green waste collection is a recent endeavour- in Glasgow, for example, green waste collection only began in 2016 (30). Additionally, the monitoring of organic commercial wastes has not been part of the remit of local councils in the past, which has resulted in a lack of available data on the quantity of waste and disposal methods. However, recently the Scottish Government and the Scottish Environment Protection Agency (SEPA) have identified the need to collect more robust data on household, commercial and industrial waste to improve waste management the future (28). Arising from this, SEPA have created an interactive tool where annual data on waste produced and managed in Scotland can be viewed (31). This will likely improve the ability to strategically install AD projects in the future.

According to the SEPA Waste Tool, in 2015 there was 2,469,485 tonnes of household waste produced in Scotland, of which 393,904 tonnes were mixed garden and food waste (16%). There were also 3,599,063 tonnes of commercial and industrial waste produced, of which 803,343 tonnes were mixed garden and food waste (22%). This gives a total of 1.2 million tonnes of mixed food and green waste that could potentially be used in anaerobic digestion. Additionally, there was 16,487 tonnes of sewage sludge produced in Scottish waste treatment facilities in 2015.

Using Figure 3.3, 65% methane content and the energy density of methane, the energy potential for a year of biogas production could be calculated.

$$Energy\ potential = 1.216\ \times 10^{6}\ tonnes\ \times \frac{175\ m^{3}}{wet\ tonne} \times\ 65\%\ \ \times \frac{36\ MJ}{m^{3}}\ \times\ \frac{1\ MWh}{3600\ MJ}$$

$$= 1383\ GWh$$

In 2010, the total energy output from waste treatment (including energy from waste, landfill gas and anaerobic digestion) was 74 GWh , therefore there is a huge opportunity for growth in biogas production in Scotland (32).

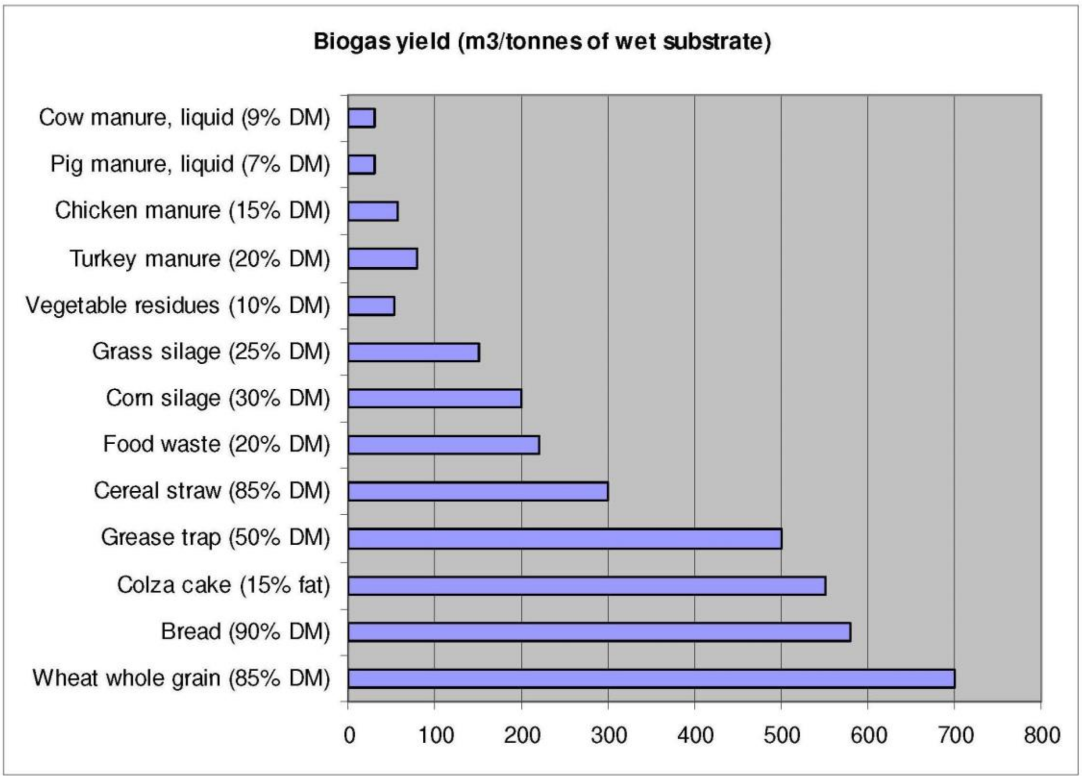


Figure 3.3. Biogas yield of various substances (source: BC Bioproducts Association)

For comparison, the total energy demand of Scotland (heat and electricity) in 2014 was 111,000 GWh (26), therefore anaerobic digestion has the potential to provide 1% of this. Individually electricity demand was 32,000 GWh and heat demand was 79,000 GWh, therefore biogas can produce 4% and 2% of this respectively.

Consequently, it must be appreciated that while the production of energy from organic waste can contribute to renewable energy in Scotland, it cannot produce nearly enough to be the only solution and must be considered as part of a mix of different technologies.

3.4 Summary

In summary, the view for the future in Scotland is to grow renewable energy capacity and maximise the usefulness of waste whilst reducing landfill. Scotland needs energy solutions that can improve the flexible use of a grid that is becoming increasingly dependent on non-dispatchable renewable energy sources. There is also a need for solutions that contribute to the provision of low-carbon heating, which currently accounts for only 3.8% of heat generation.

Anaerobic digestion is uniquely placed to help meet these aspirations as part of a future energy mix. It is simpler to integrate into current heating infrastructure than other forms of renewable heating and can also be used to generate dispatchable electricity. However, AD cannot produce nearly enough energy overall to meet demand, therefore can only be considered as a small part of the energy mix.

Whilst the uptake of anaerobic digestion has increased in the past few years, the focus in Scotland has been on farm-fed or large decentralised waste-fed systems which do not benefit the rural communities representing most of the country. There is currently a gap in understanding of where waste recycling schemes incorporating small-scale biogas digestion can most effectively fit into communities.

4 Literature Review 3: Factors Affecting Feasibility of AD

Major factors which influence the feasibility of small-scale AD plants have been identified as capital and operating expenditure (CAPEX/OPEX), income and feedstock selection (33). This project is focused on organic municipal waste recycling, which sets the feedstock influence. This section reviews the areas which influence the CAPEX, OPEX and plant income to give an understanding of the factors which affect the feasibility of an AD plant.

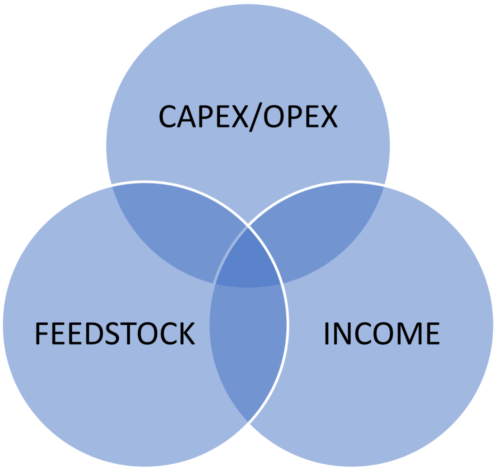


Figure 4.1. Factors which influence viability of AD plants

4.1 Capital Costs

Any AD operation will involve a high capital set-up. These include equipment costs; pre-treatment, heat exchangers, pipes, mixers, digesters, storage, transport vehicles and CHP, dependent on plant requirements (33). Another aspect to capital cost is the feasibility study and project development costs. These include planning, professional fees, expert advice, and training. The longer the capital investment can remain operational, the greater the potential profitability of the project will be (14). Capital costs are dependent on limiting factors such as feedstock supply, the capacity of the electric or gas grid and sight-specific issues such as height restrictions and space (34).

According to the UK Waste Resources Action Programme (WRAP), AD plants can be generalised into three main economic categories (34):

- At the lowest end of the scale are facilities designed to treat agricultural waste or energy crops, as these have less regulations on pre-treatment and air quality.
- Costlier are the plants dealing with biodegradable municipal waste and sewage, as these incur more stringent regulations on air quality and product quality, thereby requiring more treatment stages.
- The highest cost AD systems are usually plants which are part of a mechanical biological treatment (MBT) facility, as these come with all the costs of a waste plant, in addition to a more complex pre-treatment stage due to a high level of mixed waste and dry matter content. MBT is a mechanical sorting system to process residual mixed municipal waste. It removes any recyclables (e.g. glass, metal, plastics) before digesting the organic material.

As capital costs are usually high, there are several methods of procurement. This can include buying outright, taking out a loan which can be paid back over a period of time with interest, or using a leasing model whereby equipment is hired at a fixed annual rate (15). Given the expensive nature of start-up costs for AD, leases or loans are often the more attractive option for project developers.

4.2 Operating Costs

Operating costs encompass the ongoing expense of running the AD plant once it has been constructed. This includes labour, maintenance, waste permitting and energy use, dependent on the plant requirements. The energy required for use within the plant itself is called ‘parasitic energy’ and typically accounts for 5-10% of output electricity (15). Operating costs are directly related to the size and type of plant: for example, a small farm digester may only need one or two people to operate it, whereas a large plant which involves waste sorting will require many more people.

4.3 Economies of Scale

Economies of scale can benefit the capital and operating costs of AD plants, which are highly dependent on both tonnage and type of feedstock used (34). Research shows clearly that as the size of the plant increases, the cost per tonne of feedstock digested decreases. Reasons behind this occurrence can include limitations on the CHP units. For example, if the digester only generates enough biogas to service the smallest available CHP unit for 50% of the time, it leaves the unit idle for the remaining time (15). Furthermore, it limits the use of electricity and heat from the CHP engine as they are only available for half the time the unit is operational. An optimum AD unit would be scaled to produce biogas matched to an available small-scale CHP engine running 100% of the time. Figure 4.2 illustrates economies of scale trend by comparing the capital cost per tonne of organic waste digested against the tonnage throughput of feedstock, using data from suppliers obtained by WRAP (15).

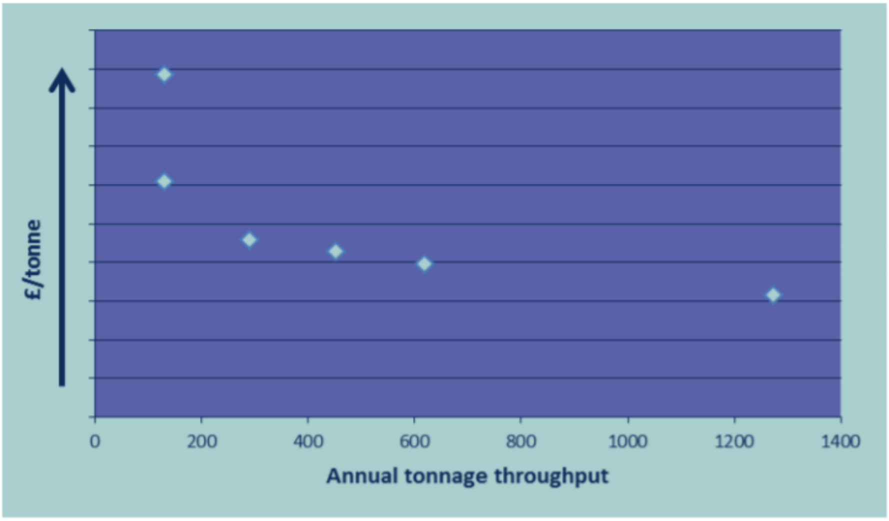


Figure 4.2. Economies of scale for AD plants

(Source: WRAP)

4.4 Energy Return on Investment

The Energy Return on Investment (EROI) is the ratio of energy returned to energy invested in that energy source, along its entire life-cycle. This demonstrates whether an energy source is sufficient to power society.

$$EROI = \frac{Quantity\ of\ Energy\ Supplied}{Quantity\ of\ Energy\ Used\ in\ Supply\ Process}$$

The units are usually given in units available to both energy supplied and used, for example kWh. The ‘quantity of energy supplied’ includes the electricity, useable heat or power for useful work produced by the source. The ‘quantity of energy used in the supply process’ includes construction, installation, operations, maintenance, decommissioning, transportation, roads and manufacture of equipment (35).

When the EROI is large, the energy from that source is easy and cheap to acquire. When the number is small, the energy from that source is difficult and expensive to acquire. When the number is one, there is no return on the energy invested. The break-even number for sustaining modern society is 7, however energy used directly at source is the exception to this (35).

Some EROI values from a recent study by Weißbach (2013) are summarized in the Figure 4.3 (36). For societal needs, the value with energy storage is more representative of the EROI. Only in situations where the energy produced is used directly and the demand can vary with the supply, is the value without energy storage comparable (35).

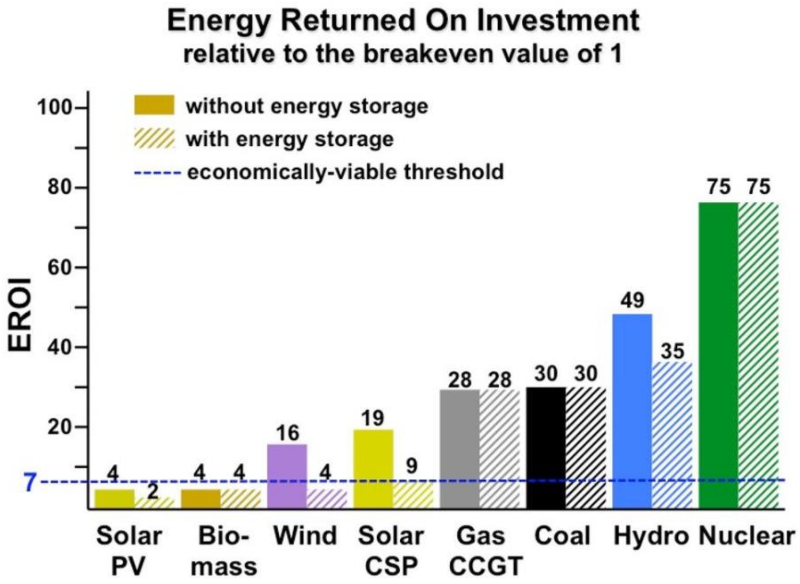


Figure 4.3. EROI for various technologies

4.5 Transportation Distance

If the feedstock supply and the removal of digestate necessitate vehicular movements the costs will very rapidly escalate (14). While digestate is a valuable soil conditioner and fertiliser, its low dry matter content makes it very expensive to move. Transport requirements can also increase the overall CO_2 emissions of the plant, negating the positive contribution to CH_4 emissions reduction. Transport costs directly oppose the benefits of economies of scale: larger plants are more likely to be decentralised; therefore, will require greater transportation of feedstocks and products. It is a question of optimisation to determine the balance between plant scale and transport distance.

4.6 End Use

The end use of products can significantly affect both cost and income generated by an AD plant. Using biogas for CHP allows the biogas to be used once the H_2S and H_2O have been removed, without the need for upgrading to biomethane. Using the biogas for transport fuel or grid injection requires upgrading which can be expensive due to the additional equipment required. Furthermore, the grid connection is a prohibitively expensive part of gas injection, due to the high level of gas quality monitoring involved. However, as the technology develops in the future it is predicted that the costs of grid connection will decrease (34).

Biomethane injection is an emerging technology in the UK, but has been implemented throughout Europe. From data on European facilities collated by WRAP, it can be seen in Figure 4.4. that the capital cost of upgrading decreases with the quantity of biomethane produced (34). Below 300 m^3/h of biomethane production, there is stronger dependency on high incentives and therefore a greater chance that the plant will not be viable (34).

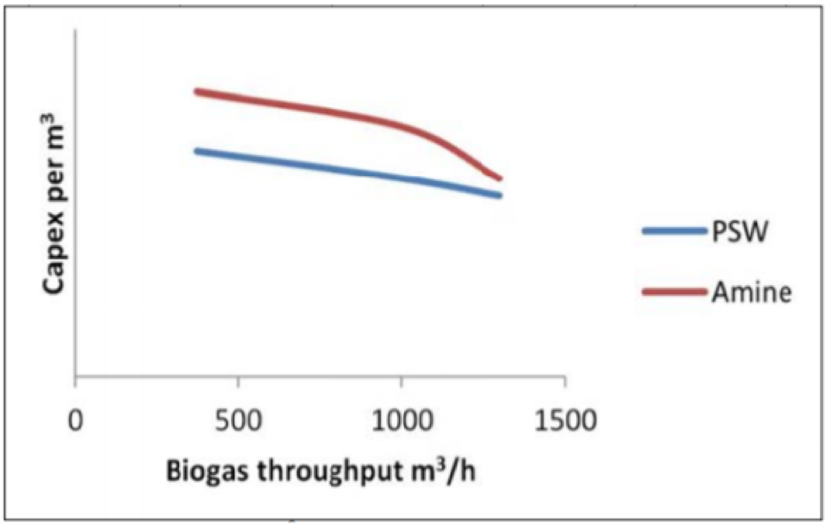


Figure 4.4. Typical CAPEX per m^3 of biogas processed by PSA and amine scrubbing (Source: WRAP)

Shown in Figure 4.5, WRAP have published a comparison conducted by the Carbon Trust, showing the cost and revenue for each end use. This shows that at the time of study, net returns were similar for each technology, with transport gaining the highest net revenue. It should be noted that the report was published in 2010 and therefore gate fees, incentives and product prices will have been subject to change over the years.

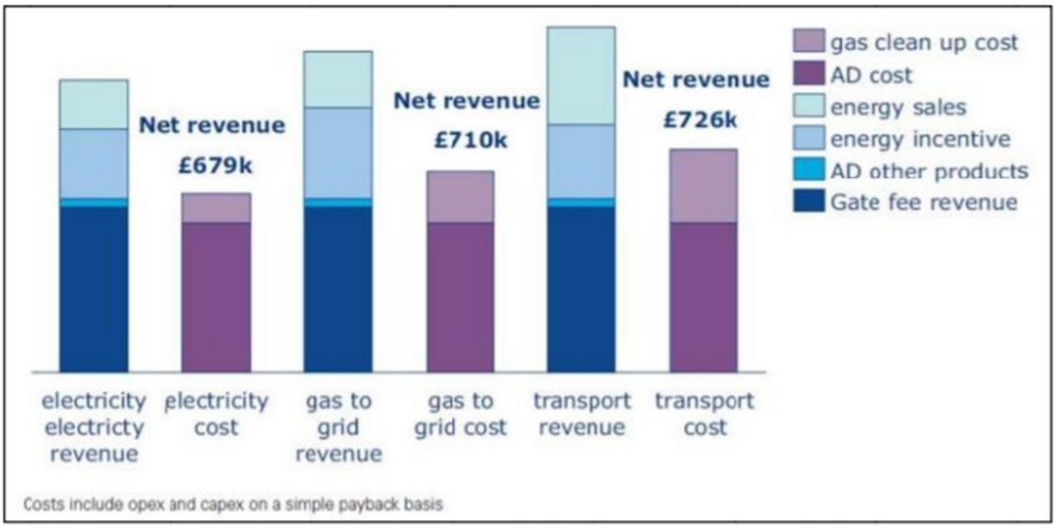


Figure 4.5. Revenue and costs for a 25,000 tpa food waste plant (Source: WRAP, Carbon Trust)

4.7 Incentives

Government incentives play a key role in providing income to a plant, however can be unreliable in the long-term due to changing government policies. The two main incentives currently available for heat and electricity production are:

- The Renewable Heat Incentive (RHI)
- The Feed in Tariff (FIT)

The RHI provides financial support in quarterly instalments for 20 years. This is eligible for heat generated from renewable sources and includes biomethane injection and combustion of biogas (37).

The FIT scheme is a government programme designed to promote the uptake of small-scale renewable and low-carbon electricity generation technologies. These are only available for AD facilities with less than 5MW capacity and each tariff runs for 20 years. The FIT scheme requires participating licensed electricity suppliers to make payments on both generation and export from installations (38).

4.8 Additional Sources of Income

Additional income can be sourced from gate fees and digestate. The gate fee is the fee paid by waste disposal to deposit waste at the AD site and can vary depending on competition. Recently gate fees have been decreasing for AD due to the rapidly increasing development of AD facilities in the UK.

The digestate market in Scotland is young, and digestate is predominantly used on agricultural land as a biofertiliser or as waste cover in landfills (39). In the future it is anticipated that agriculture will remain as the principal use of digestate, but the market could develop to include uses in soil creation, brownfield remediation, horticulture, sports grounds, golf courses and retail outlets (39). In the UK, digestate is encouraged to be to PAS110 quality standard which means there are limits on the level of contaminants and the type of feedstocks used.

4.9 Summary

In summary, there are a complex variety of interlinked factors which affect the feasibility of an AD plant. These primarily concern the economic balance between cost and revenue, however feedstock type and energy production are also important aspects to consider.

Table 4.1. Factors affecting the feasibility of a biogas plant

Factor	CAPEX/OPEX	Income	Feedstock
Determined by	• Capital cost • Operating cost • Economies of scale • EROI • Transport costs • Product end use	• EROI • Product end use • Financial incentives • Digestate price • Gate fees	• Plant location/ feedstock availability

5 Research Methodology

This section describes the technical research carried out in this project. This follows a structured research methodology, illustrated by Figure 5.1.

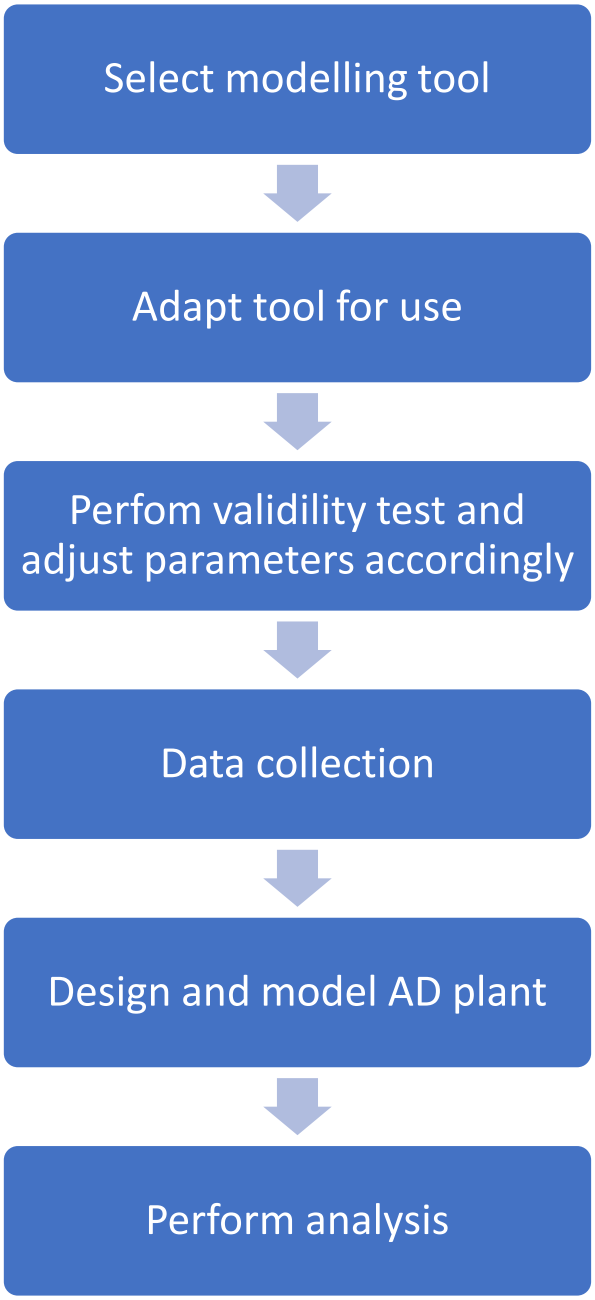


Figure 5.1. Diagram showing the methodology process

The aim of this project is to investigate the opportunities for community AD to produce heat and electricity from local organic waste. To achieve this, a plant was modelled to produce heat and power for the community of Auchterarder. This allowed the determination of the feasibility of a community AD system through calculating:

- The plant energy balance.
- The percentage of community energy demand (heating & electricity) that can be met.
- The energy return on investment (EROI).
- The carbon emissions saved in comparison to other methods of waste disposal.
- The profitability of the plant.

Due to the timescale, this project only covered one community, however analysing AD potential for further communities could be a useful study in the future.

Analysis was then carried out for three investigations, designed to determine the best application of community AD:

Investigation 1. Community Size – To determine the size of community that is required for an AD plant to be profitable and produce sufficient power output.

Investigation 2. Transport Requirements – To determine the effect of increasing transportation distance for collecting additional local agricultural waste on cost and power output.

Investigation 3. End Use – To analyse the profitability of two different methods for delivering heat and electricity: combined heat and power (CHP) and biomethane grid injection.

These investigations allow analysis to be carried out on whether community AD is a feasible venture and if so, where the best opportunities are. This can then be translated into recommendations for wider Scotland.

The case study community of Auchterarder is a typical Scottish community located in Perth and Kinross and has a population of 4,141 residents (40). A field trip determined that there is one main commercial street with local shops, including two small supermarkets, two butchers, a green grocer and approximately 20 food-related businesses including take-aways, cafes and restaurants. The inputs to the plant will include organic waste streams from the commercial outlets, household waste from domestic ‘brown bins’ and local sewage sludge from the Auchterarder sewage works. For the purposes of this study, the waste streams are transported in trucks and processed at a plant located on the edge of town. The AD plant can then provide heat and power directly to the community.

Figure 5.2. Auchterarder area

6 Model Selection and Adaption

6.1 Model Selection

To carry out the analysis of the proposed investigations for this study, a software-based modelling tool was required which had the following properties:

a) Can model a community AD system
b) Allows alteration of feedstock input and transport distance
c) Analyses different product end uses
d) Can calculate energy outputs and financial viability

A range of modelling tools were reviewed with regards to their suitability for this project from both Universities and independent organisations. None examined the above factors in the detail required for this project. Some were too simple and could not be adjusted, such as Biogas World's online calculator (41). Many were found to have been developed for an agricultural-related purpose and therefore were too specific or narrow in their scope, such as the economic evaluation model by Georgakakis et al. to assess cost-effectiveness of biogas production systems fed with pig manure (42).

There is also a distinct lack of available anaerobic digestion software which had the ability to calculate technical parameters such as biogas yield and energy output in addition to conducting an economic analysis. For example, the Biogas Calculator Template designed by Waterford City Council, encompasses only the calculation of biogas yield. There appears to be few models looking at biogas production from municipal organic waste.

Therefore, an AD sizing calculator developed by Geraghty, Roscoe, Cloonan and Currie for the Energy Systems Research Unit at the University of Strathclyde was selected to provide a base model which could be adapted for purpose (43). This AD calculator was selected as it is designed to investigate waste to energy processes in rural community-based situations, which is highly suitable for this study and is an Excel-based spreadsheet which is simple to adapt. The calculator provides full design and energy balances for a single or a two-stage mesophilic plant depending on the waste stream type entering. The calculator input data includes:

- The demographics of the local area
- The size of the local area, determining waste collection distance
- The waste digestion characteristics including wet mass per person/animal per day and dry solids content/volatile solids content of feedstock.
- The plant design specifications; including retention time, digestion temperature, component efficiencies and energy requirements

The plant is sized according to the magnitude of the waste streams, derived from the local population. The size of the plant affects the digester volume, engine size and the electrical process loads required for pumping and mixing. The dry solids content and volatile solids content of the input waste stream are then used to estimate the biogas yield.

From the biogas yield, the model can use the methane content of biogas and the calorific value of methane to size a CHP engine. Gross heat and electrical energy available can then be calculated, considering the efficiency of each component. The heat and electrical energy requirements of the plant itself are used to gain a final output of net electrical and heat energy available.

The calculator output data includes:

- Plant sizing including digester and biogas engine size
- Biogas yield
- Electrical and CHP heat surplus available for export
- Process electrical and heat loads
- Overall energy balance

The results are displayed in low, medium and high estimates, which allows for variation in feedstock properties. A model validation exercise was not required at this stage in the project, as the model had already gone through extensive validation by the original developers. The results of the previous validation exercise showed that ‘medium’ estimates were most realistic and the ‘low’ estimates slightly pessimistic (43). Therefore, the medium estimates will be used for the main result in this project.

6.2 Model Adaptation

Whilst the selected AD calculator provides a suitable base for calculating the biogas and energy yields from organic waste for a community plant, it does not carry out an economic analysis which is an important aspect of this study.

Therefore, the model had to be adapted. This was achieved by the addition of an ‘economics parameters’ sheet, which allows the sources of cost and revenue for an AD project to be entered. This can then be used to find the initial estimation of cost, profit and ultimately the financial viability of a potential AD plant.

In addition to this, as the original model was only concerned with CHP as an end use, parameters for biogas injection had to be added in, such as conversion factors, additional equipment costs for upgrading biogas, costs of grid injection and the income from biomethane.

Finally, the model was provided for use in the University by the original developers and therefore has been altered and adapted in the past. The version used for this project was not set out in the clearest and most logical manner and had input pages missing or extra pages which were not required. Therefore, as part of this project the model inputs and calculation mechanisms were reviewed and adjusted for improved use in the future. This is particularly useful considering the lack of comprehensive AD models currently available.

6.3 Cost Parameterisation and Assumptions

To create the 'economic parameters' sheet, the factors which influence the cost of an AD plant had to be identified. From the detailed literature review carried out in chapter 4, the main parameters which contribute to sources of cost were identified as: capital cost, maintenance and operational cost and transport cost.

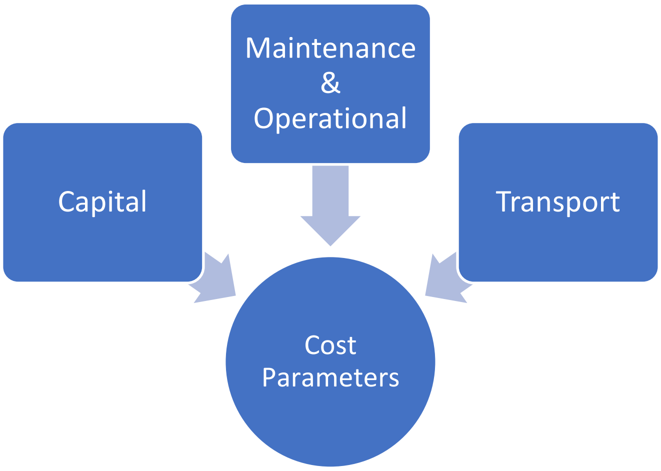


Figure 6.1. Cost parameters

6.3.1 Capital Costs

To estimate capital costs, some typical prices for AD plant equipment were deduced from the current market prices and reports on the economics of anaerobic digestion. These include the Remade Scotland Report: An Introduction to the Digestion of Organic Wastes (44), Redman's Detailed Economic Review (14) and multiple reports by WRAP (34) (15).

In reality, equipment prices differ depending on the vendors for each individual plant. This means exact costs are impossible to obtain, however the sources reviewed in this study gave a typical range per kW or per m^3 of capacity, which can be scaled to a specific plant. Another aspect to be taken into consideration is that capital costs vary according to economies of scale, i.e. a larger AD facility will have a lower capital cost per tonne of waste than a smaller equivalent technology, provided it is operating at optimum capacity (15). Therefore, a range of costs for various sizes of plant (small, medium and large) were provided in the model to reflect this. Truck prices for transport were also added to capital costs and prices were sourced from manufacturers. To increase reliability, costs were compared across literature sources so that the final capital cost generated by the model provided a reliable estimate.

Finally, as this project investigates the different end uses of biogas, the costs of upgrading to biomethane and injecting into the grid were required as part of the capital costs. These prices were estimated from data on European facilities collated by Redman and WRAP (14) (34). A summary of the final capital costs parameters used in the model are given in Table 6.1.

Table 6.1. Capital costs

AD Capital Costs	
Anaerobic digestion plant and CHP unit price per m^3 digestion capacity	£400-750/m^3
Storage price per m^3 storage capacity	£100/m^3
Biomethane upgrading price	£480,000 for up to 80 m^3/hr biogas production
Grid connection	£400,000-750,000
Vehicle cost	£25,000-30,000

6.3.2 Maintenance & Operational Costs

Maintenance and operational costs also depend on the scale of the plant. Redman (2010) estimates that operation and maintenance can be taken as 1-2% of the capital cost of a plant (14), whilst other sources were more specific but spanned a wide range of values, from £6,500/annum for a small plant to £900,000/annum for a large scale waste management plant (15) (44). As this model cannot be highly specific in nature and is aiming to provide an estimate of potential costs, it was deemed most appropriate to take maintenance and operational costs to be 1-2% of the capital cost of the plant.

$$Maintenance\ and\ operational\ costs = (1-2\%) \times capital\ cost$$

6.3.3 Transport Costs

Finally, transport costs were estimated from current diesel prices and HGV truck specifications. The number of HGV vehicles per plant can be calculated from the size of the selected truck and the mass of feedstock required to be transported.

The vehicle cost is a capital investment and the driver costs are covered by operational costs; therefore, transport costs only encompass the price of fuel per annum. This was calculated from the current cost of fuel (1.14£/l), the kilometres per litre achieved by HGV vehicles and the overall distance driven.

$$Transport\ costs\ per\ annum = \frac{km}{year} \times \frac{litre\ fuel}{km} \times \frac{£}{litre\ fuel}$$

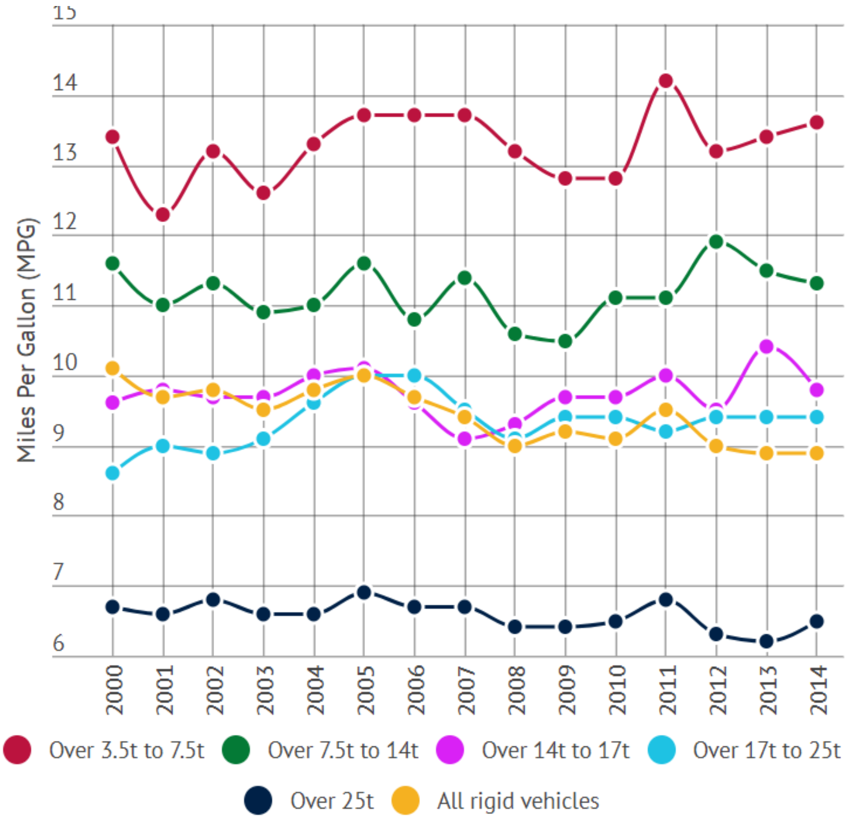


Figure 6.2. Miles per gallon achieved by HGVs

(Source: infograph)

6.4 Revenue Parameterisation and Assumptions

To complete the ‘economic parameters sheet’ for the model, parameters which could present a source of income to an AD facility also had to be identified. From the detailed literature review carried out in chapter 4, the parameters which contribute to plant revenue were identified as: gate fees, digestate sales and government incentives.

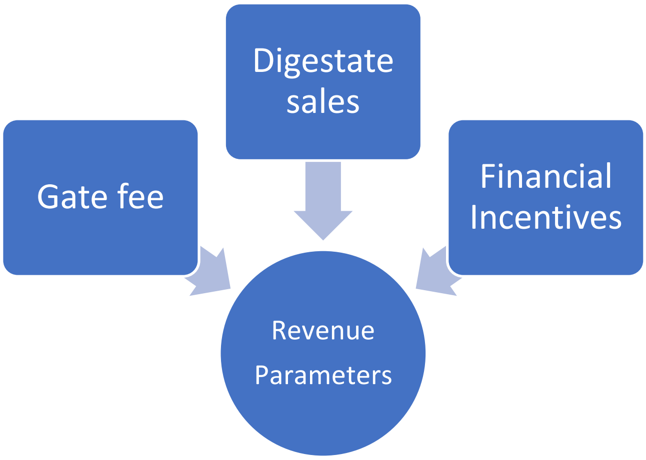


Figure 6.3. Revenue parameters

6.4.1 Gate Fees

Gate fees can vary and are reported annually in WRAP’s Gate Fee Report, as shown in Figure 6.2. The latest, released in 2016, states that the average gate fee for anaerobic digestion currently sits at £40/tonne (34) (45). In reality, a rate of £18-£40 per tonne is more likely due to organic recyclers reducing their fees as competition from councils and businesses becomes more intense (46). For comparison, the landfill tax is £102/tonne, making landfill a significantly more expensive option for waste treatment.

Table 6.2. Summary of UK gate fees 2015/16 (source: WRAP)

Treatment	**Materials / Type of facility / Grade**	**Median**	**Mode[2]**	**Range[3]**
MRF	*All contracts (4 materials or more)*	*£25*	*£0 to £5*	*-£62 to £89*
	Contracts started in 2015 (4 materials or more)	*£38*	*£20 to £25*	*£3 to £89*
Organics	*Open Air Windrow (OAW)[4]*	*£24*	*£20 to £25*	*£9 to £57*
	In-Vessel Composting (IVC)[5]	*£47*	*£55 to £60*	*£22 to £61*
	Anaerobic Digestion (AD)	*£40*	*£40 to £45*	*£0 to £75*
MBT	*Household residual waste*	*£85*	*£95 to £100*	*£67 to £111*
EfW[6]	*All*	*£86*	*£85 to £90*	*£22 to £131*
	Pre-2000 facilities	*£58*	*£40 to £45*	*£22 to £90*
	Post-2000 facilities	*£95*	*£85 to £90*	*£65 to £131*
Wood Waste	*All Grades /tonne collected from Household Waste Recycling Centres (HWRCs)[7]*	*£35*	*£45 to £50*	*-£5 to £82*
Landfill	*Non-hazardous waste including landfill tax[8]*	*£102*	*£90 to £95*	*£91 to £145*
	Non-hazardous waste excluding landfill tax	*£19*	*£10 to £15*	*£8 to £62*

6.4.2 Digestate Price

The current digestate market sale price is estimated at £5/tonne in a recent report on the digestate market by Zero Waste Scotland (39).

6.4.3 Financial Incentives

AD can be supported by several incentive schemes, depending on how the biogas is used– the Feed in Tariff (FIT) for electricity generation and the Renewable Heat Incentive (RHI) for supplying heat or injecting biomethane to the gas grid (47). The price for each incentive could be found from Ofgem. It should be noted that the Renewables Obligation (RO) was not considered in this study as it was closed to all new generating capacity on the 17th March 2017.

The FIT provides a guaranteed price for a fixed period to small-scale electricity generators in Scotland to encourage the provision of small-scale low carbon electricity. There are two elements to the scheme; the generation tariff for every kWh of electricity generated, and the export tariff for every kWh of electricity exported to the national transmission network (48). The current tariffs for AD are as follows (38):

Table 6.3. Feed-In Tariff Rates

Feed in Tariffs (2017)		
FIT – Generation Tariff	0-250 kW	5.57 p/kWh
	250-500 kW	5.27 p/kWh
	500-5000 kW	1.99 p/kWh
FIT – Export Tariff	-	5.03 p/kWh

The RHI provides a fixed income per kWh to generators of renewable heat. The lifetime of the tariff is 20 years (48). Injecting biomethane into the grid is also supported under the RHI for 20 years at all levels (47). The current RHI tariffs are as follows (37):

Table 6.4. RHI Tariff Rates

Renewable Heat Incentive Tariffs (2017)		
RHI	Biomethane injection (<40,000 MWh)	3.2 p/kWh
	Biomethane injection (40-80,000 MWh)	1.89 p/kWh
	Biomethane injection (>80,000 MWh)	1.45 p/kWh
	Combustion - small (<200 kWth)	2.88 p/kWh
	Combustion - medium (200-600 kWth)	2.46 p/kWh
	Combustion - large (>600kWth)	0.86 p/kWh

6.5 Economic Parameters Sheet

With cost and revenue parameters for an AD plant identified and valued, the economic parameters calculation sheet could be added to the AD model. The outputs from the economic sheet include:

- Capital cost/loan required
- Annual costs
- Annual revenue
- Annual loan repayment
- Annual profit

The final economics sheet produced for the model is shown in Figure 6.4. The capital cost/loan requirement is calculated from adding the cost of the anaerobic digestion unit based on economy of scale (with the option to add biomethane upgrade and grid injection if required), the cost of a storage unit to add flexibility and the cost of vehicles for transportation.

The capital costs equal the amount that initially needs to be invested in start-up costs. This can be paid up front, but the option of a loan can often be attractive due to the expensive nature of AD projects. The annual loan repayment can be calculated from the following formula:

$$Annual\ loan\ repayment = \frac{Cr(1+r)^n}{(1+r)^n - 1}$$

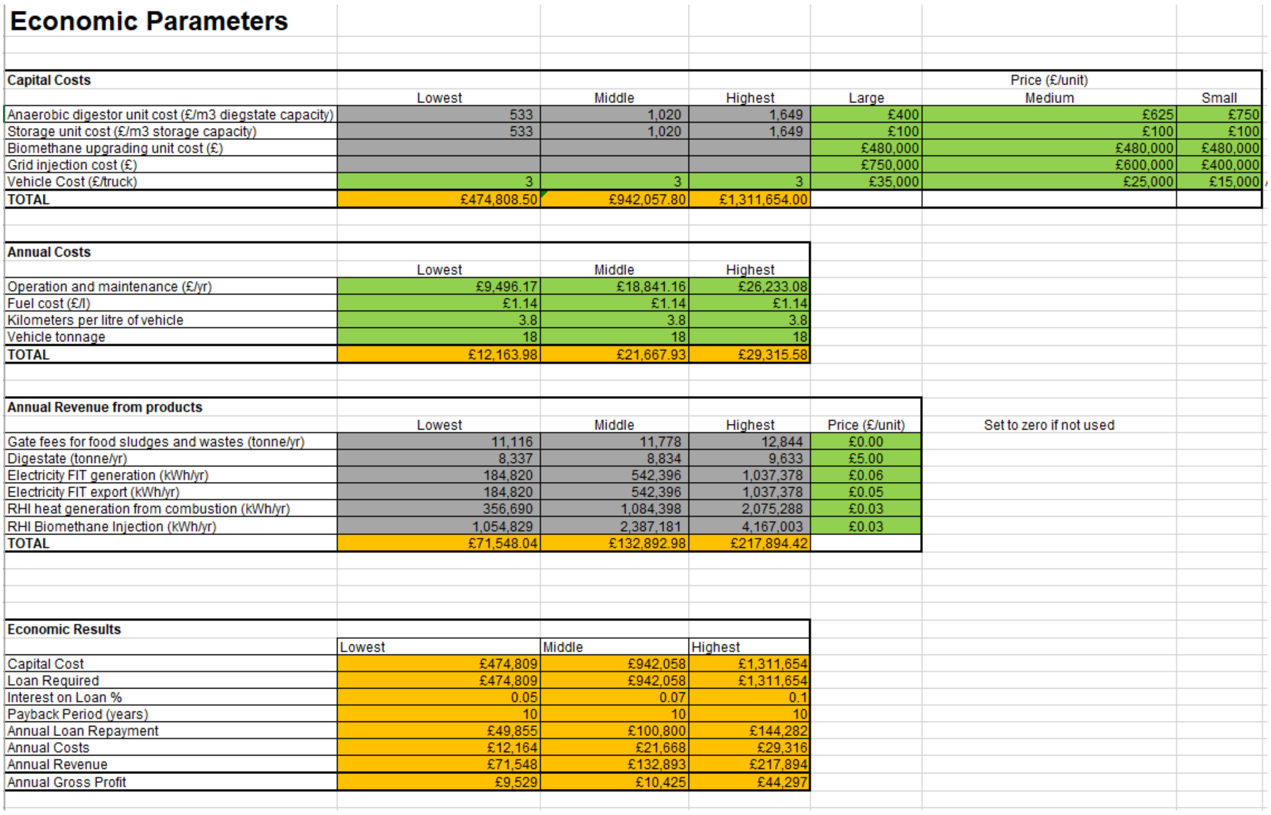
Where:
C = value of investment (£)
r = interest rate on loan (%)
n = payback period (years)

In addition to loan repayment, the annual running costs of the plant were calculated from the operation and maintenance costs and the price of fuel per km of transportation distance. Together, the annual loan repayment and the annual running costs make up the total annual cost of the plant.

The total annual revenue could be calculated from the annual product revenues and incentives that would be received. From this, the annual gross profit could then be calculated:

$$Annual\ gross\ profit = Annual\ revenue - Annual\ costs$$

The annual gross profit gives the indication of if the plant is ultimately profitable or not. If profits are negative, it means the plant is not financially viable and needs to either decrease plant costs or produce more revenue.



Economic Parameters

Capital Costs	Lowest	Middle	Highest	Large	Medium	Small
				Price (£/unit)		
Anaerobic digestor unit cost (£/m3 diegstate capacity)	533	1,020	1,649	£400	£625	£750
Storage unit cost (£/m3 storage capacity)	533	1,020	1,649	£100	£100	£100
Biomethane upgrading unit cost (£)				£480,000	£480,000	£480,000
Grid injection cost (£)				£750,000	£600,000	£400,000
Vehicle Cost (£/truck)	3	3	3	£35,000	£25,000	£15,000
TOTAL	£474,808.50	£942,057.80	£1,311,654.00			

Annual Costs	Lowest	Middle	Highest
Operation and maintenance (£/yr)	£9,496.17	£18,841.16	£26,233.08
Fuel cost (£/l)	£1.14	£1.14	£1.14
Kilometers per litre of vehicle	3.8	3.8	3.8
Vehicle tonnage	18	18	18
TOTAL	£12,163.98	£21,667.93	£29,315.58

Annual Revenue from products	Lowest	Middle	Highest	Price (£/unit)	Set to zero if not used
Gate fees for food sludges and wastes (tonne/yr)	11,116	11,778	12,844	£0.00	
Digestate (tonne/yr)	8,337	8,834	9,633	£5.00	
Electricity FIT generation (kWh/yr)	184,820	542,396	1,037,378	£0.06	
Electricity FIT export (kWh/yr)	184,820	542,396	1,037,378	£0.05	
RHI heat generation from combustion (kWh/yr)	356,690	1,084,398	2,075,288	£0.03	
RHI Biomethane Injection (kWh/yr)	1,054,829	2,387,181	4,167,003	£0.03	
TOTAL	£71,548.04	£132,892.98	£217,894.42		

Economic Results	Lowest	Middle	Highest
Capital Cost	£474,809	£942,058	£1,311,654
Loan Required	£474,809	£942,058	£1,311,654
Interest on Loan %	0.05	0.07	0.1
Payback Period (years)	10	10	10
Annual Loan Repayment	£49,855	£100,800	£144,282
Annual Costs	£12,164	£21,668	£29,316
Annual Revenue	£71,548	£132,893	£217,894
Annual Gross Profit	£9,529	£10,425	£44,297

Figure 6.4. Final economic parameters sheet created for the model

6.6 Additional Modifications

Although the addition of the ‘economic parameters sheet’ was the most important modification to the AD calculator, some additional changes were made for this study.

The original calculator did not consider multiple end uses for biogas and only had the capacity to model CHP. As this study aims to make a comparison as to the viability of different methods for providing heat and electricity, the model had to be adjusted to include biomethane injection into the gas grid. This was achieved by using the percentage of methane in the biogas (~ 60%) to calculate the volume of methane production followed by the energy content of methane to calculate the energy output.

6.7 Economics Sheet Validation

To confirm that the adapted model produces reliable results, a validation exercise was carried out on an existing case study.

6.7.1 Case Study

The case study used was McDonnell Farms Biogas Ltd, located in County Limerick in the Republic of Ireland. All information regarding this plant was taken from the Sustainable Energy Authority of Ireland (SEAI) (49).

Figure 6.5. Primary digester (source: Biogas plant McDonnell Farms Limited)

The McDonnell farm houses 300 dairy cows and a medium-sized poultry farm (5,000-10,000 hens). The input to the anaerobic digester is primarily composed of manure produced on-farm, but is supplemented with food waste and glycerine from a nearby biodiesel plant. The output gas is used to produce electricity via CHP and the digestate provides a higher quality fertiliser which is used on the farm.

The plant is single-stage and mesophilic. It includes one primary digester with a volume of 980 m^3, two storage tanks located before and after the digestion stage with respective volumes of 200 m^3 and 2,500 m^3, an external heat exchanger, biological gas cleaner and a 250 kW CHP unit. There are also several pre-treatment stages present, including a disinfection unit and separator.

The biogas plant produces electricity and heat constantly for 8,000 hours per annum, equating to approximately 2 GWh of electricity and 2.1 GWh of heat.

Feedstock:

- Cattle slurry: 5000 tpa
- Food waste: 2,800 tpa
- Poultry litter: 900 tpa
- Dairy sludge: 900 tpa
- Glycerine: 360 tpa

Total: 10,760 tpa

Operating parameters:

- Temperature: 40°C heated by hot water from the CHP unit
- Organic Loading Rate: ~4 kg/m^3d
- Retention Time: 40 days primary digester

Outputs:

- Availability CHP unit: 85%, 8,000 full load hours per annum
- Biogas production: 950,000 m^3/annum (55% CH_4 content)
- Electricity production: 2 GWh/annum, exported to the national grid
- Heat production: 2.1 GWh/annum, heat exported for heating the plant, for pasteurisation and for heating the poultry sheds
- Total capital cost: £1.3 million, payback time of 10 years

The feedstocks for the McDonnell plant were input into the model, minus the glycerine for which there is not an option. This was made up for by adding an extra 360 tpa of food waste, which has comparable properties. The plant design was adjusted for the correct operating parameters, such as temperature and retention time.

6.7.2 Results

The results produced by the model are shown in Table 6.5.

Table 6.5. Model validation results

Parameter	**Value Low**	**Value Med**	**Value High**	**Real Value**
Biogas production (m^3/annum)	237,020	605,900	1,105,950	930,000
Electricity production (kWh/annum)	578,656	1,481,316	3,006,849	2,000,000
Heat production (kWh/annum)	624,339	1,598,276	3,422,112	2,100,000
Capital cost (£)	635,800	1,411,000	2,575,500	1,300,000

6.7.3 Conclusion on Model Accuracy

From the estimates produced by the AD calculator, it can be concluded that it provides a reasonable level of accuracy in terms of biogas production, electricity production and heat production. For all three parameters, the real value fell between the model's 'medium' and 'high' estimates, whilst the low estimate was pessimistic.

The model calculates the biogas output based on the percentage of dry solids and biogas yield and then uses the energy content of methane to calculate energy outputs. Therefore, it is unlikely that the estimates are 100% accurate, as yields and energy content can vary depending on the exact feedstock composition. The CHP generator was taken to be 85% efficient, however there could be additional losses which are unaccounted for. Nevertheless, the model estimates are close enough to be deemed an acceptable level.

With regards to the economic parameters sheet, the model estimates for capital cost were within an acceptable range and the medium estimate matched the actual cost within a 10% margin. Therefore, the estimations of capital cost from literature are concluded to be reasonably accurate.

As the product revenue is calculated from real gate fees, digestate market prices and incentive tariffs, the plant profitability is highly likely to be a reasonable estimate. However, no information could be found regarding the financial performance and annual profit of the McDonnell plant, therefore this could not be validated directly. For the purpose of this project, reasonable revenue values have been found in literature and all values can be edited and updated in the future.

In conclusion, the AD calculator and the new economic parameters sheet have shown that they can estimate values to an acceptable degree of accuracy for use in this project.

7 Analysis

7.1 Plant Design

With the AD calculator selected and adapted for use, the Auchterarder plant could be modelled for analysis. The plant design for the analysis was kept simple as the effect of additional components is out with the scope of this study. Due to it being an established technology, the same single-stage mesophilic digester used by the original model creators was used in this study (43).

This design comprised of the following stages:

1. Shredders to reduce the particles in the feedstock to 12mm.
2. An input buffer tank to control flow to the pasteuriser and store excess feedstock.
3. A pasteuriser where the feedstock resides at 70°C for 1 hour to destroy unwanted pathogens and comply with EU legislation.
4. A single-stage, mesophilic digestion tank at 38°C with a retention time of 40 days.
5. Gas storage to control the biogas flow into the CHP engine.
6. Digestate storage to allow the fibres and liquor to separate, if desired.

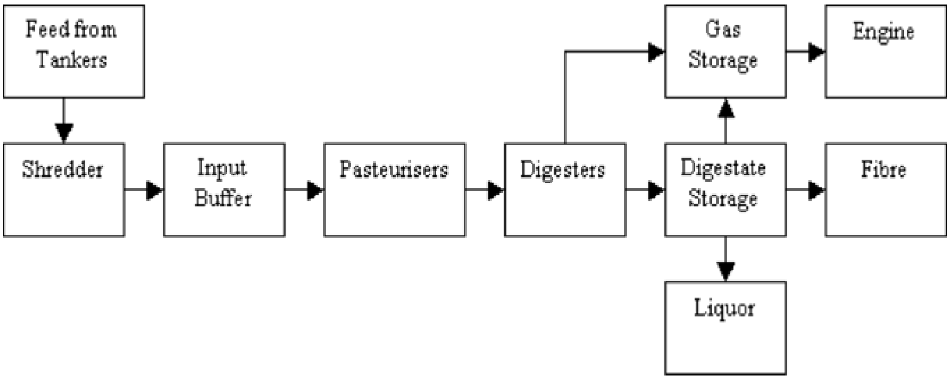


Figure 7.1. Flow diagram of mesophilic process (43)

For the analysis on end use, biogas requires additional treatment for grid injection. This typically includes the removal of carbon dioxide, hydrogen sulphide and oxygen to increase the calorific content and align the physical properties of biomethane with natural gas (34). Forms of treatment include scrubbing with water or amine solutions, pressure swing adsorption (PSA), membrane separation or cryogenic separation.

For this study, pressure swing adsorption was selected due to its low investment and operating costs compared to the other methods, which is important for a small-scale system. Scrubbing and membrane separation have very high parasitic energy loads compared to PSA. The main disadvantage to PSA are the higher rates of fugitive methane emissions (<0.5%) compared to the other methods (34).

Pressure swing adsorption separates methane and carbon dioxide using their differences in size and physical properties. PSA works in columns over four stages. In the first stage, carbon dioxide is adsorbed onto zeolites or activated carbon materials under increased pressure. The pressure is then lowered in the following two stages to regenerate the adsorption material. In the last phase, pressure is built up again.

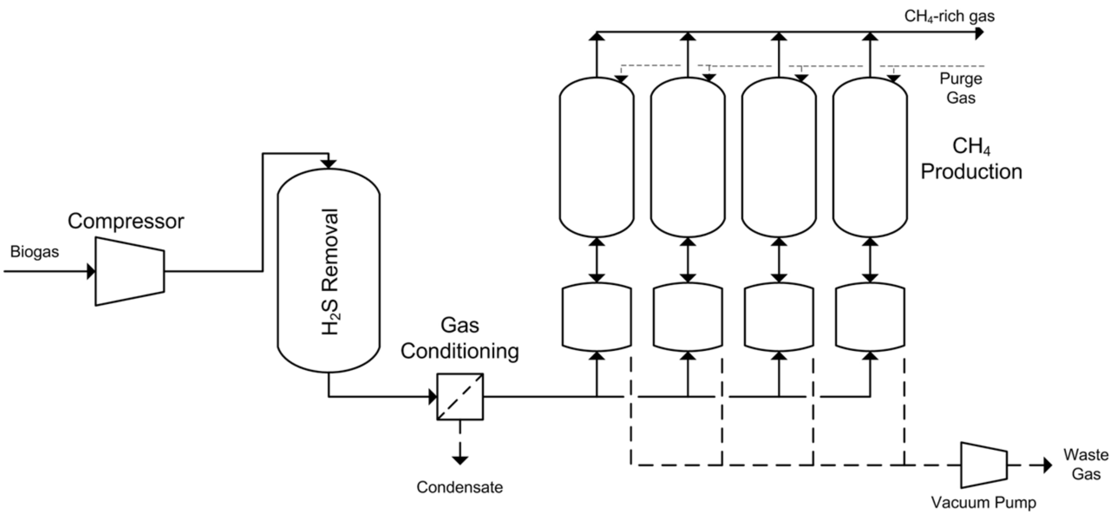


Figure 7.2. Flow diagram of PSA process (50)

7.2 Data Collection

To make the results as useful and as realistic as possible, Perth and Kinross Council were contacted and waste data was obtained.

The data collected from Perth and Kinross Council shows the average mass of food and garden waste collected per household in 'brown bins' from 2008 to 2017, assuming four residents per household on average. This data was input into the model to give a realistic analysis of the biogas potential for a typical community in Scotland.

Table 7.1. Food and Garden Waste collected in the last 8 years (kg/household/week)

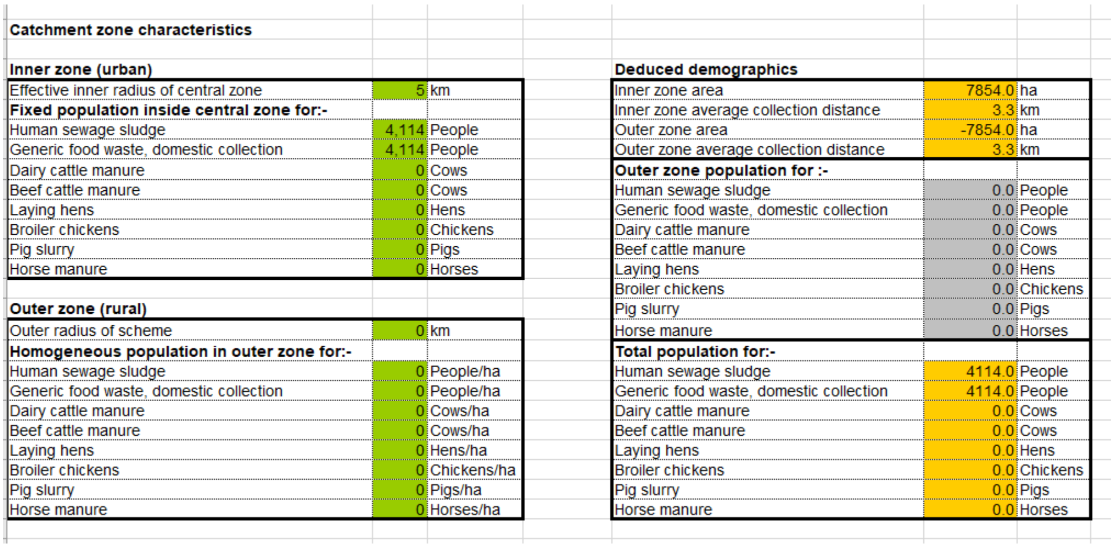
Average	**2008/09**	**2009/10**	**2010/11**	**2011/12**	**2012/13**	**2013/14**	**2014/15**	**2016/17**
Food Waste	3.4	1.71	1.56	1.06	1.00	1.32	1.60	2.31
Garden Waste	9.2	9.31	8.54	5.96	8.21	7.28	6.78	7.79
Contamination	0.16	0.09	0.17	0.11	0.15	0.11	0.12	0.14
Totals	12.7	11.13	10.27	7.13	9.56	8.71	8.5	10.23

Interestingly, this data shows that the amount of the food waste collected per household per week last year increased by 44% and is the highest amount of food waste collected since 2008/09. This shows that the mass of organic waste collected may in fact increase in the next few years, as more people are starting to recycle due to the green waste recycling bin distribution.

7.3 Model Inputs

7.3.1 Modelling the Auchterarder Plant

The first step was modelling an AD plant for Auchterarder to find the feasibility of a community AD plant, looking at the energy balance, percentage energy demand that could be met, the energy return on investment, the carbon dioxide equivalent (CO_{2e}) emissions and the profitability. To do this, the following demographics were input to the model, shown in Figure 7.3.



Catchment zone characteristics

Inner zone (urban)		
Effective inner radius of central zone	5	km
Fixed population inside central zone for:-		
Human sewage sludge	4,114	People
Generic food waste, domestic collection	4,114	People
Dairy cattle manure	0	Cows
Beef cattle manure	0	Cows
Laying hens	0	Hens
Broiler chickens	0	Chickens
Pig slurry	0	Pigs
Horse manure	0	Horses

Outer zone (rural)		
Outer radius of scheme	0	km
Homogeneous population in outer zone for:-		
Human sewage sludge	0	People/ha
Generic food waste, domestic collection	0	People/ha
Dairy cattle manure	0	Cows/ha
Beef cattle manure	0	Cows/ha
Laying hens	0	Hens/ha
Broiler chickens	0	Chickens/ha
Pig slurry	0	Pigs/ha
Horse manure	0	Horses/ha

Deduced demographics		
Inner zone area	7854.0	ha
Inner zone average collection distance	3.3	km
Outer zone area	-7854.0	ha
Outer zone average collection distance	3.3	km
Outer zone population for :-		
Human sewage sludge	0.0	People
Generic food waste, domestic collection	0.0	People
Dairy cattle manure	0.0	Cows
Beef cattle manure	0.0	Cows
Laying hens	0.0	Hens
Broiler chickens	0.0	Chickens
Pig slurry	0.0	Pigs
Horse manure	0.0	Horses
Total population for:-		
Human sewage sludge	4114.0	People
Generic food waste, domestic collection	4114.0	People
Dairy cattle manure	0.0	Cows
Beef cattle manure	0.0	Cows
Laying hens	0.0	Hens
Broiler chickens	0.0	Chickens
Pig slurry	0.0	Pigs
Horse manure	0.0	Horses

Figure 7.3. Demographic inputs

Using the data from Perth and Kinross Council, it was estimated that each person would produce 0.36 kg/day of organic municipal waste. In addition, 2 tonnes per day of food and green waste were estimated from commercial outlets in the community. Sewage sludge output from the Auchterarder sewage works was estimated to be 0.6 kg/person/day.

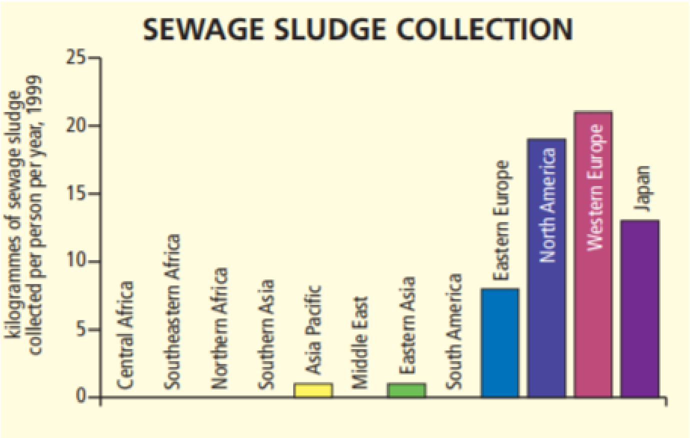


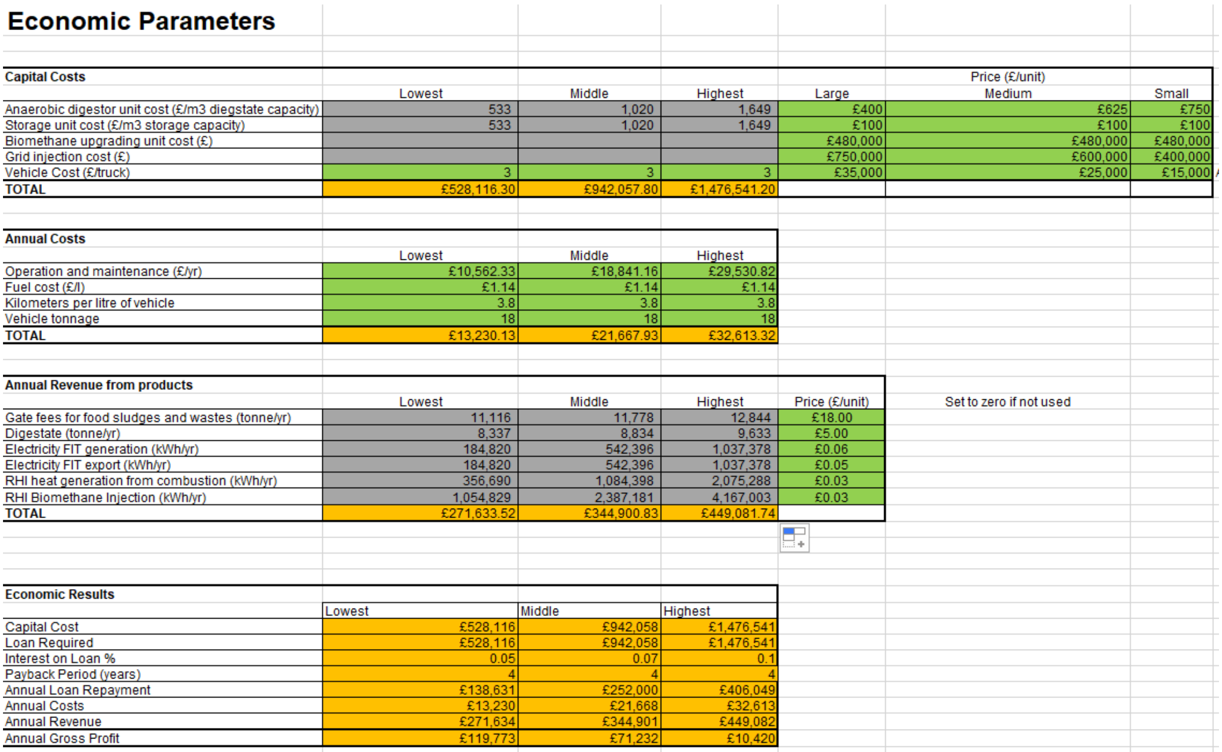
Figure 7.4. Sewage sludge collection collected per person per year (1999)

Source: SASI Group

The biogas yield in m^3/tonne of dry volatile solids was found in literature (see Table 2.1) and the energy output per day was calculated using the percentage methane content and the energy content of methane at 11.04 kWh/m^3 (51). This could then be used to find the average power by dividing by the number of hours in a day. The model then sized the engine as a percentage of the methane input power from the biogas production using the linear equation $y = 0.0185\ln(x) + 0.2063$, where x is methane input power.

The economic inputs included a digester and CHP system at £750 per m^3 of biogas production and a storage unit at further £100 per m^3 of biogas storage capacity. It was estimated that three 18-tonne trucks would be required to transport feedstock and digestate at a capital cost of £25,000 each. The trucks would be travelling 5km per journey on average with an estimated fuel consumption of 3.8 km/litre. The cost of fuel was taken at the market price of £1.14/litre.

Digestate prices were set at £5/tonne and gate fees were set at £18/tonne to account for competition. It was assumed that the plant would receive both the FIT electricity generation and export tariff and the RHI heat generation tariff for the CHP production. A loan was introduced to pay off the capital costs on an annual basis, with a 7% interest rate. Payback time was adjusted to find the minimum possible time over which a profit could be made.



Economic Parameters

Capital Costs				Price (£/unit)		
	Lowest	Middle	Highest	Large	Medium	Small
Anaerobic digestor unit cost (£/m3 diegstate capacity)	533	1,020	1,649	£400	£625	£750
Storage unit cost (£/m3 storage capacity)	533	1,020	1,649	£100	£100	£100
Biomethane upgrading unit cost (£)				£480,000	£480,000	£480,000
Grid injection cost (£)				£750,000	£600,000	£400,000
Vehicle Cost (£/truck)	3	3	3	£35,000	£25,000	£15,000
TOTAL	£528,116.30	£942,057.80	£1,476,541.20			

Annual Costs			
	Lowest	Middle	Highest
Operation and maintenance (£/yr)	£10,562.33	£18,841.16	£29,530.82
Fuel cost (£/l)	£1.14	£1.14	£1.14
Kilometers per litre of vehicle	3.8	3.8	3.8
Vehicle tonnage	18	18	18
TOTAL	£13,230.13	£21,667.93	£32,613.32

Annual Revenue from products					
	Lowest	Middle	Highest	Price (£/unit)	Set to zero if not used
Gate fees for food sludges and wastes (tonne/yr)	11,116	11,778	12,844	£18.00	
Digestate (tonne/yr)	8,337	8,834	9,633	£5.00	
Electricity FIT generation (kWh/yr)	184,820	542,396	1,037,378	£0.06	
Electricity FIT export (kWh/yr)	184,820	542,396	1,037,378	£0.05	
RHI heat generation from combustion (kWh/yr)	356,690	1,084,398	2,075,288	£0.03	
RHI Biomethane Injection (kWh/yr)	1,054,829	2,387,181	4,167,003	£0.03	
TOTAL	£271,633.52	£344,900.83	£449,081.74		

Economic Results			
	Lowest	Middle	Highest
Capital Cost	£528,116	£942,058	£1,476,541
Loan Required	£528,116	£942,058	£1,476,541
Interest on Loan %	0.05	0.07	0.1
Payback Period (years)	4	4	4
Annual Loan Repayment	£138,631	£252,000	£406,049
Annual Costs	£13,230	£21,668	£32,613
Annual Revenue	£271,634	£344,901	£449,082
Annual Gross Profit	£119,773	£71,232	£10,420

Figure 7.5. Economic inputs

7.3.2 Investigation 1: Community Size

This investigation was designed to find the minimum population size required for a plant to be viable. Using the Auchterarder AD plant model and a long 20-year payback period, the community population size was altered for the generic food waste and sewage sludge inputs at small increments from 50 to 5,000 residents. The change in population resulted in the digester being resized by the model. All other inputs were kept the same.

7.3.3 Investigation 2: Transport Requirements

This investigation was designed to determine whether transportation costs outweigh economies of scale when increasing the transportation distance of feedstock. Feedstock from local agriculture within a 15km radius was added to the Auchterarder plant to estimate the additional energy demand that could be met, as shown in Table 7.2.

Table 7.2. Additional agricultural feedstock

Feedstock	**Units**
Dairy Cattle Manure	300 cows
Beef Cattle Manure	500 cows
Laying hens	10,000 hens
Pig slurry	50 pigs
Horses	100 horses

Once the effect on the energy demand met was established, a second AD plant was modelled using the agricultural feedstock with additional parameters altered, as outlined in Table 7.3.

Table 7.3. Altered Parameters

Parameter	**Original value**	**New Value**	**Reason**
Transportation distance	5km	15 km	Greater area of feedstock collection
AD plant cost	£750/m^3	£400/m^3	Economies of scale
Truck size	18 tonnes	26 tonnes	Increased mass of feedstock
Fuel usage	3.8 km/l	2.6 km/l	Increased truck size
Vehicle cost	£15,000	£35,000	Increased truck size

Vehicle drivers are accounted for in the operational costs which are 1-2% of capital costs.

This model and the original Auchterarder model were then compared for differences in transportation cost and capital cost resulting from the increased feedstock intake and transportation distance.

7.3.4 Investigation 3: Product End Use

The final investigation was designed to determine which end use is most effective for producing heat and power from a community AD plant: combined heat and power or gas injection. The result was achieved by modelling the Auchterarder plant with two different end uses (a) and (b) and calculating the profit vs. end use.

a) CHP- The original Auchterarder model was used, as it was already designed for CHP production.

b) Gas Injection- Here, the original model was used, but altered slightly. A biogas upgrading unit was added for £480,000 and a grid injection cost of £400,000 was assumed. Revenue was earned from gate fees, digestate sales and the Renewable Heat Incentive for biomethane injection (based on 100% biomethane produced being sent to the grid). All other parameters were kept the same.

8 Results

8.1 Auchterarder AD Plant

Shown below is an overview the main outputs calculated for the Auchterarder community AD plant. The full results sheet shown in Appendix II.

Table 8.1. Overview of plant properties

Parameter	**Output**
Feedstock input (tonnes/day)	29.9
Biogas production (m^3/day)	1020.1
Energy production @ 11.04 kWh/m^3 inc. parasitic loads (kWh/day)	6820.5
Average power inc. parasitic loads (kW)	284.2
Plant Capital Cost	£942,058
Annual Costs (loan payment + transport costs + maintenance and operational costs)	£122,157
Annual Revenue (Gate fees + digestate sales + incentives)	£318,250
Annual Profit (AR-AC)	£196,093
Minimum payback period	4 years

The plant capacity at 284.2 kW is slightly greater than 250 kW, therefore the plant is marginally bigger than micro scale AD. The feedstock input totalled from residential waste, commercial waste and sewage is 29.9 tonnes per day or 10,914 tonnes per annum.

The plant capital costs are calculated from plant equipment, storage and vehicles and total close to £1 million. Comparing with similar sized plants (see Appendix I), this value is reasonable. The minimum payback period is 4 years and the plant makes a profit of £196,093. This is from gate fees, digestate sales and incentives including FIT and RHI.

8.1.1 Energy Balance

The first aspect to analyse is if the system can produce enough energy to operate the plant and provide excess energy for heating and electricity within the community. The process heating required by the pasteuriser, digester and heat exchangers was calculated using the following equation:

$$Q = mC_p\Delta T$$

Q = energy required to heat substrate (kWh/year)
m = mass of substrate input to the system (kg/year)
C_p = specific heat capacity of substrate (kJ/kg°C)
ΔT = change in temperature (°C)

The process heat is provided by the CHP unit, assuming 85% efficiency, and the remainder goes to community district heating. Heat losses were accounted for in the generator and engine using efficiencies and through the walls using the component areas and heat transfer coefficients. An insulation thickness of 100mm was assumed for pasteurisers and digester walls, with a k value of 0.04 W/mK. The process electricity required was estimated using the electrical loads for each component (see Appendix III). The results show that the parasitic energy loads account for 34% of the energy usage, leaving 66% to be used for community heating and electricity.

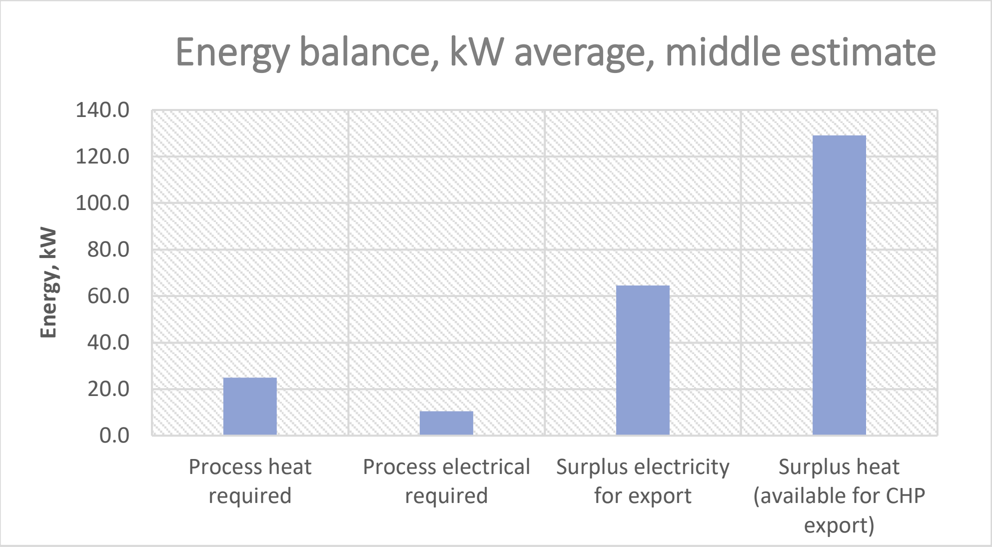


Figure 8.1. Plant energy balance

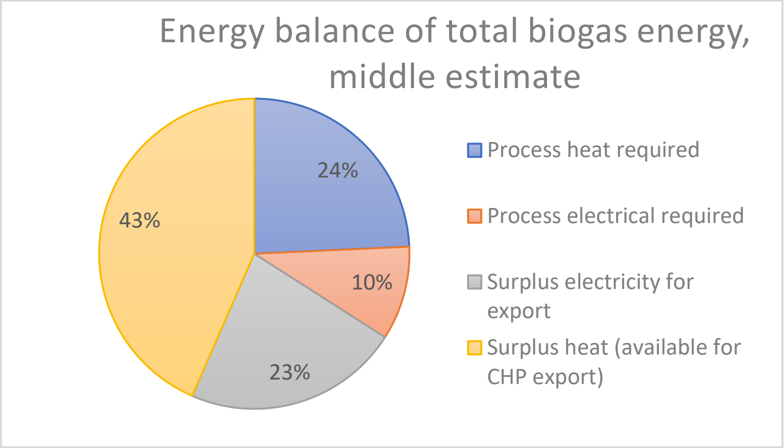


Figure 8.2. Energy balance breakdown

The process heat and electrical loads are small as the plant is of a simple single stage, mesophilic design. This means that there is only heating required to have one digester at 38°C and one pasteuriser at 70°C. Electricity is required for the running of the shredder, mixers fans and pumps. The CHP engine is small with a mechanical output power of 90 kW. Therefore, this system can produce a net positive energy balance.

8.1.2 Energy Demand Met

The total surplus energy produced from the plant in the medium estimate equated to 1.6 GWh per annum. To analyse how much of the local energy demand this would meet, the percentage energy demand met was calculated. The annual energy demand per capita in Scotland is approximately 11,000 kWh (26). Therefore, the energy demand met by the AD plant in Auchterarder can be calculated by:

$$\%\ energy\ demand\ met = \frac{1{,}696{,}812\ kWh/annum}{(11{,}000 \times 4{,}114)kWh/annum} \times 100\%$$

This calculation was repeated for the low and high estimates and, as shown in Figure 8.3, the energy production from the plant would meet 1-7% of energy demand in Auchterarder. Organic municipal waste such as food, garden waste and sewage have low percentage of dry matter, which accounts for the low energy production. As shown in the earlier scoping stage, the digestion of organic waste alone does not produce enough energy to meet demand.

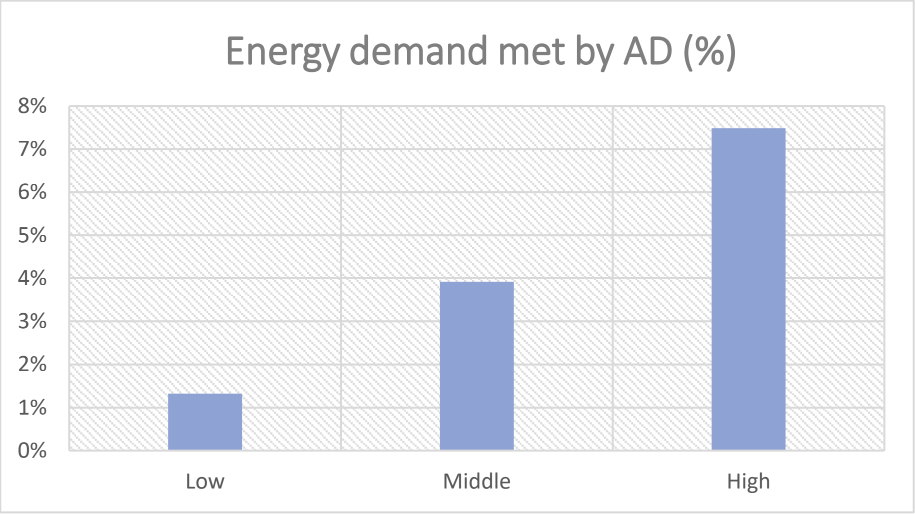


Figure 8.3. % energy demand met by AD

8.1.3 Energy Return on Investment

The energy return on investment (EROI) is a mechanism to show how efficient the AD system is. The energy return on investment is as follows:

$$EROI = \frac{Quantity\ of\ Energy\ Supplied}{Quantity\ of\ Energy\ Used\ in\ Supply\ Process}$$

The energy supplied by the plant, excluding the parasitic loads, is 4,648.8 kWh/day. The quantity of energy used in the supply process is very hard to quantify without monitoring a real plant. However, a very rough estimate was conducted:

- 852 kWh/day in parasitic energy used to operate the plant.
- Assuming 150 kWh/day to account for the energy used to produce the plant equipment, construction and maintenance, spread out over a lifetime of the plant.
- 1 litre of diesel equates to approximately 9 kWh (52). Therefore, to transport 33.4 tonnes of feedstock per day a 5km distance in an 18-tonne tuck with 3.8 km/l would account for approximately 50kWh/day.

In this rough estimate, the EROI would be approximately 4. Therefore, the AD plant is an energy positive process but due to the low energy output, is not able to provide renewable heating or electricity to meet the needs of modern society, as an EROI of 7 or above is required.

8.1.4 Profitability

The plant profit was calculated by adding all the sources of revenue and subtracting the annual loan repayments, transport costs and the operation and maintenance costs. With a minimum payback period of 4 years, the plant produced an annual profit of £196,093 (middle estimate) or 7-20 p/kWh of energy produced, based on low, middle and high estimates.

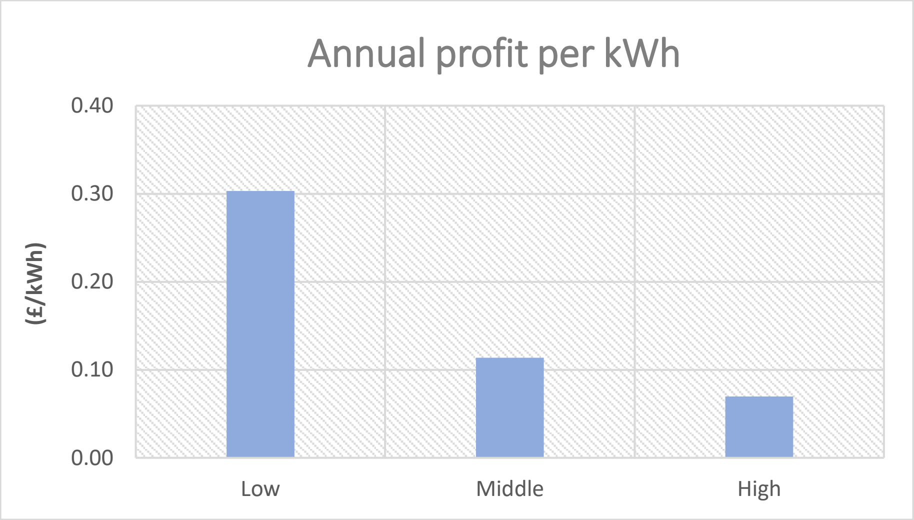


Figure 8.4. Annual profit per kWh

Looking at the revenue breakdown in Figure 8.5 shows that gate fees have a substantial impact on the profitability of the plant. Energy incentives (particularly the FIT generation tariff) also play a major role. This poses some level of risk to the investment. Incentives have been cut in recent years but are still highest for small-scale AD plants. Gate fees for waste can vary with competition and may not be charged at all if the waste has value in other uses. These sources of income are enough to offset the high capital cost, if paid back over at least 4 years with an interest rate of 7%. If the gate fees or FIT were to be cut, the payback time would increase to at least 10 years, if not more.

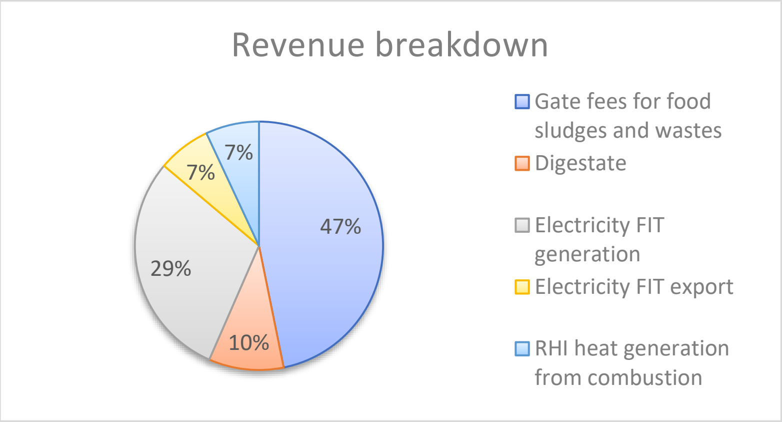


Figure 8.5. Revenue breakdown

8.1.5 Greenhouse Gas Emissions

Finally, the carbon dioxide equivalent emissions (CO_{2eq}) balance was calculated for the plant. It is most reliable to compare emissions per mass of organic volatile solids (VS) rather than per mass of organic matter, as waste disposal methods process organic matter in different forms, for example with varying moisture contents (1).

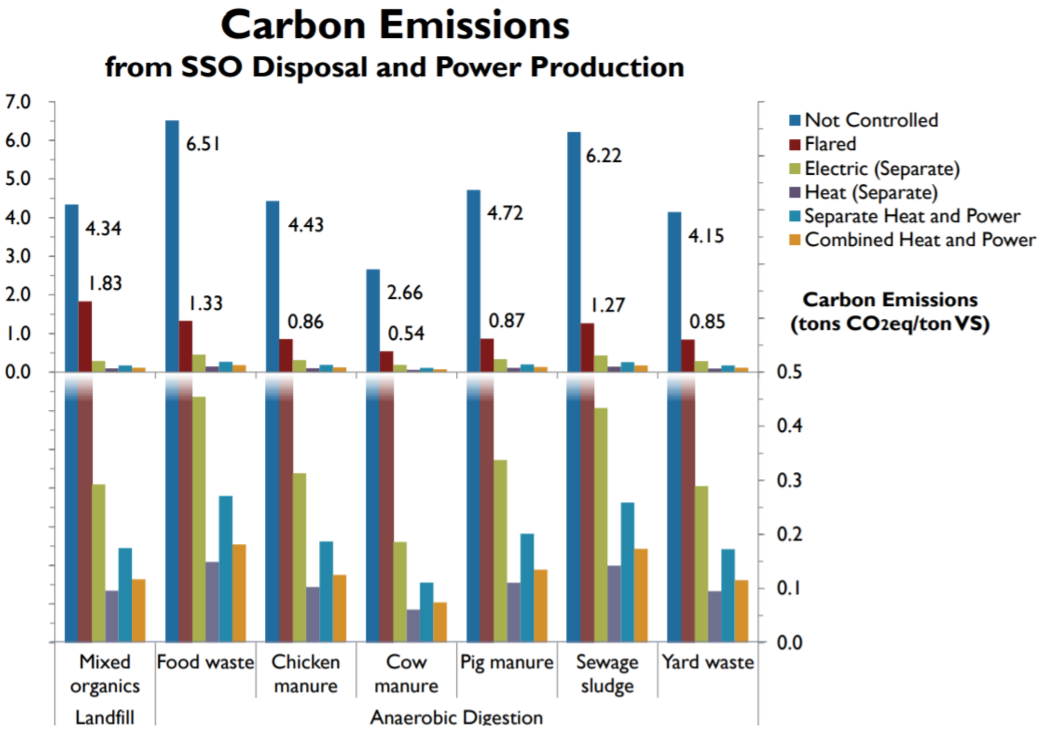


Figure 8.6. CO_{2eq} emissions comparison landfill and AD (1)

Figure 8.6 shows a comparison of the CO_{2eq} emissions per ton of volatile solids produced from uncontrolled landfill (4.34 tons CO_{2eq}/ton VS) and CHP anaerobic digestion (0.17 tons CO_{2eq}/ton VS). The Auchterarder plant deals with an estimated 730 tons of VS per annum. Therefore, the combined heat and power generation would produce:

$$0.17\ \frac{tons\ CO_{2eq}}{tons\ VS} \times 730\,\frac{tons\ VS}{annum} = 124.1\ tons\ CO_{2eq}$$

In comparison, for the same quantity of organic waste, uncontrolled landfill would produce:

$$4.34\ \frac{tons\ CO_{2eq}}{tons\ VS} \times 730\ \frac{tons\ VS}{annum} = 3168.2\ tons\ CO_{2eq}$$

It was not possible to find emissions in terms of tons CO_{2eq}/ton VS for composting, however literature gives a value of 0.045 tons of CO_{2eq} per wet ton of food waste decomposed (53). The Auchterarder plant uses 10,913 wet tons of food waste per annum, therefore the CO_{2e} emissions would be:

$$0.045\ \frac{tons\ CO_{2eq}}{wet\ tons} \times 10{,}913\,\frac{wet\ tons}{annum} = 491.1\ tons\ CO_{2eq}$$

Therefore, it can be concluded that the Auchterarder AD plant would save greenhouse gas emissions compared to other methods of organic waste disposal. This is because landfill and composting release methane and carbon dioxide respectively into the atmosphere via digestion processes. In AD, the methane is combusted for CHP, therefore only carbon dioxide is released. Here four times less CO_{2eq} is released than would be released by composting.

8.2 Investigation 1: Community Size

This analysis measured the profit and average power output from the Auchterarder plant against a gradual increase in population to determine what size of community is required for a plant to be viable. Beginning at 50, the population was increased by small increments and the plant resized by the model for each population. It was decided to set the gate fees to zero to be able to analyse the profit made from only energy and digestate production. With the gate fees included, all plants would appear to make a profit as the gate fees make up such a sizeable proportion of the revenue. However, gate fees are not guaranteed and if using an AD plant for waste disposal only and not for energy production, composting would be a cheaper option.

At a 20-year payback period, the results show that a community AD digester begins to make a profit from energy and digestate sales when the population is around 1500 people. However, only 5kW of power would be output on average, which would not be worthwhile for a town of 1,000 residents. In reality, a community would have to have a population of several thousand to produce any significant quantities of energy. Small-scale AD plants are highly dependent on incentives for income. Without these the plant would not get money for renewable electricity and heat generation, only for exporting electricity to utility companies- and would likely make losses as a result.

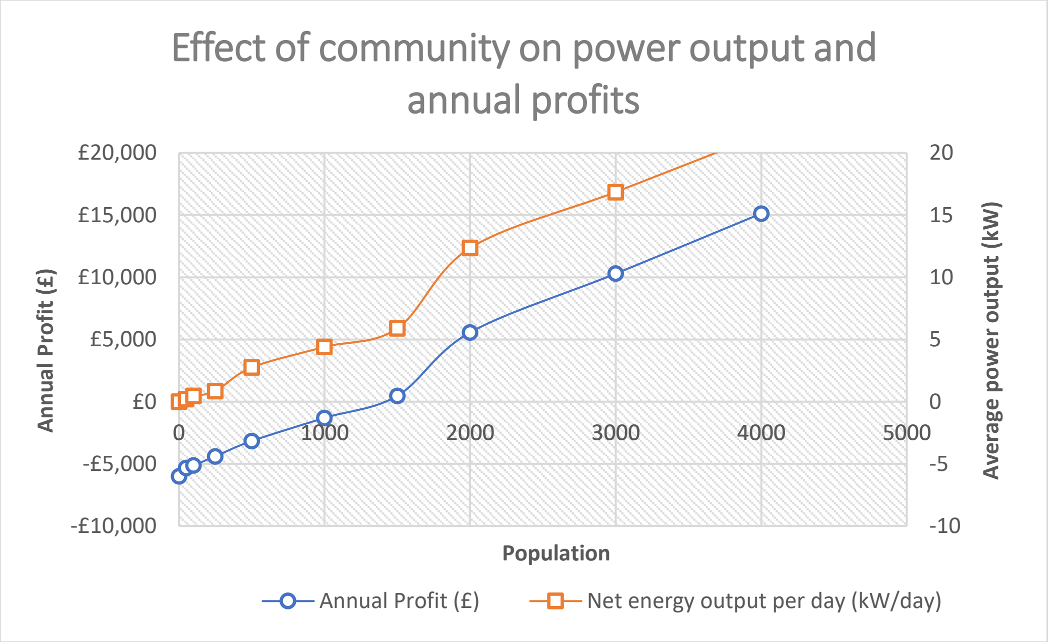


Figure 8.7. Community size vs profit and power output

8.3 Investigation 2: Transport Requirements

The addition of local agricultural waste was found to increase the energy demand met by over double, to 15%. This is a result of not only a higher volume of feedstock being input to the digester, but an increase in the percentage of volatile solids due to having a mixed feedstock.

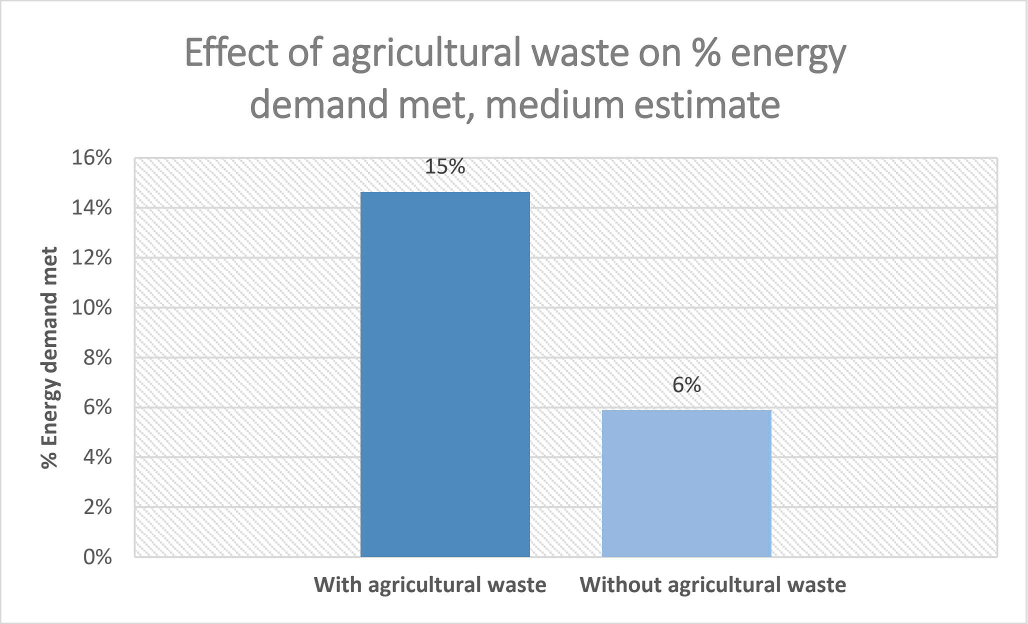


Figure 8.8. Effect of additional agricultural waste on % energy demand met

Collecting more feedstock from a larger area would result in a larger plant. Therefore, capital costs per tonne of feedstock input would decrease due to economies of scale. Conversely, transport costs would increase due to the increased feedstock collection distance.

The transport costs for delivering the extra feedstock were found to be very small compared to capital costs, as can be seen in Figures 8.9 and 8.10. This is because capital costs include the cost of the plant, storage, CHP unit and trucks whereas transport costs only encompass fuel costs. This indicates that minimising capital costs will have a greater effect on the profitability of a plant than the transport costs.

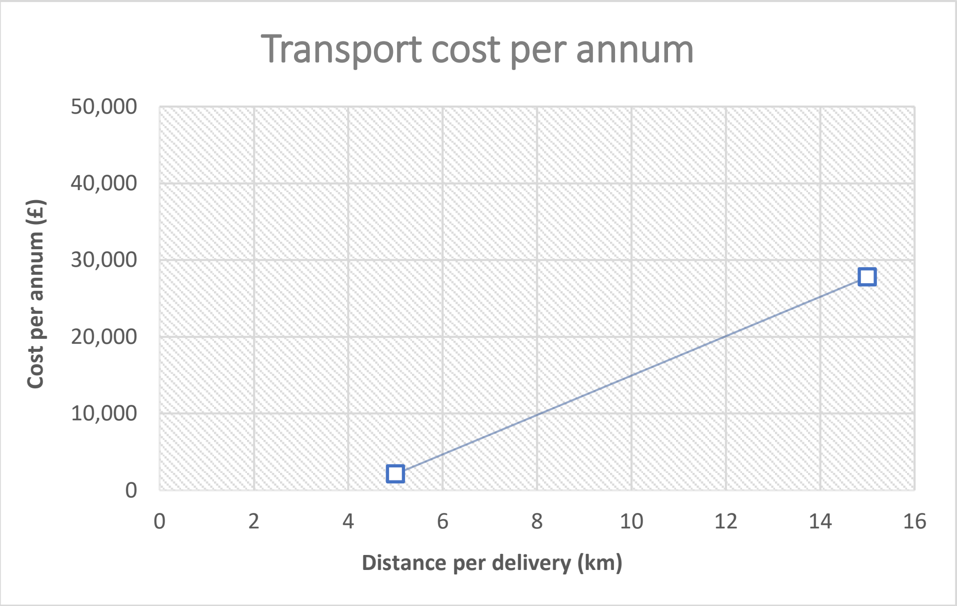


Figure 8.9. Transport cost per annum vs transport distance

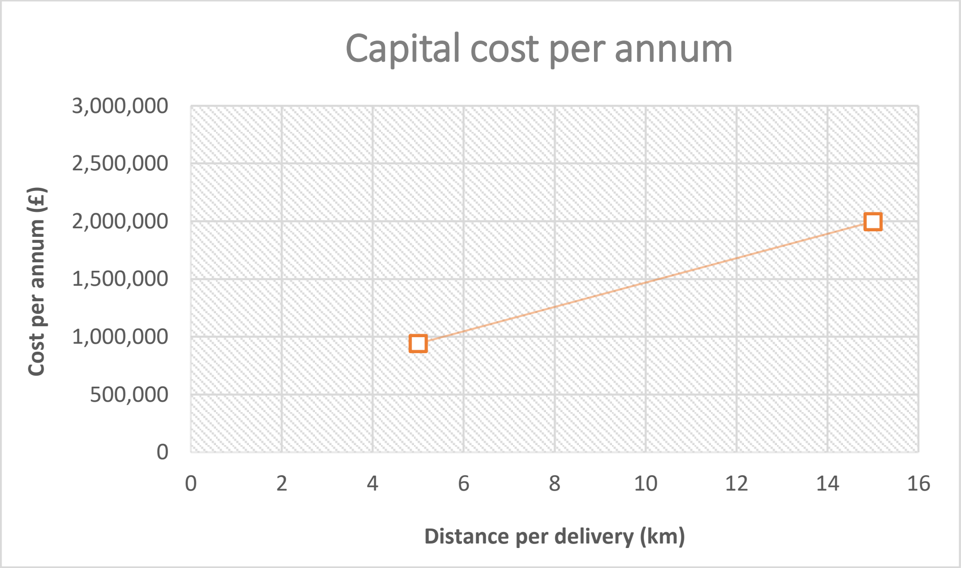


Figure 8.10. Capital cost per annum vs transport distance

The savings made on capital costs vs the additional cost for transport were calculated and compared in Table 8.2. Increasing the feedstock quantity and transportation distance by a kilometre creates a saving on capital cost of 1.5 p/kWh and increases transport costs by 0.0185 p/kWh.

Table 8.2. Additional costs and savings

Distance per delivery (km)	5	15	**Total cost/saving per km**
Capital cost per kWh	36 p/kWh	20 p/kWh	- 1.5 p/kWh
Transport cost per kWh	0.089 p/kWh	0.274 p/kWh	+ 0.0185 p/kWh

8.4 Investigation 3: Product End Use

Over a 10-year payback period, combined heat and power (CHP) was found to be the most profitable end use for producing heat and electricity from a small scale anaerobic digestion plant. Grid injection made significant losses and therefore is not suitable for a community scale plant.

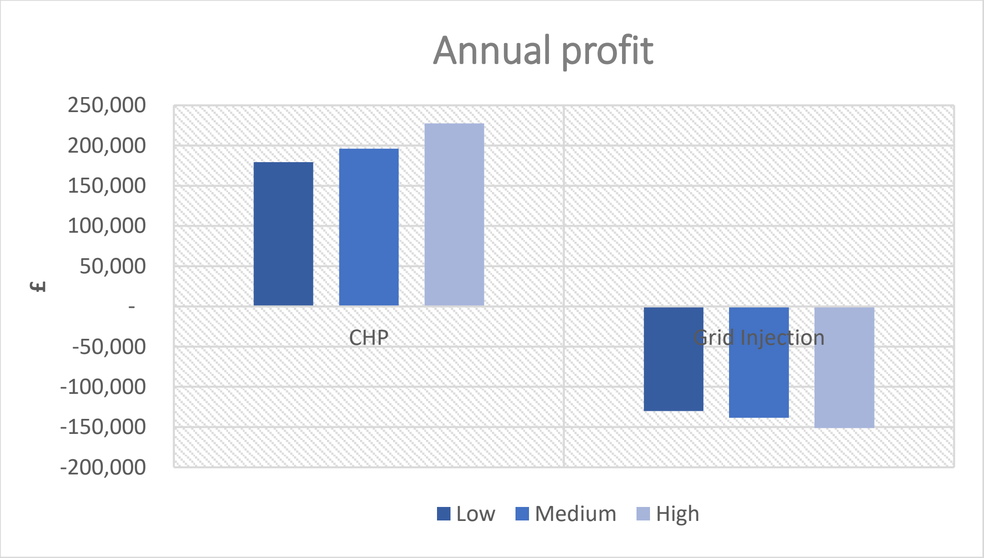


Figure 8.11. Annual profit vs product end use

It could be thought that the lack of profit for grid injection is due to the large capital investment required, including biogas upgrading and costs of grid connection. Whilst capital costs for biomethane and grid injection are expensive, it can be seen in Figure 8.12 that the product revenue also decreases significantly for grid injection.

This suggests that increased subsidies are required for this application to be suitable on a small-scale. Grid injection currently only receives RHI for biomethane injection and does not receive FIT as there is no electricity generation. In comparison, CHP can receive FIT for generation and export as well as the RHI for renewable heat generation, hence the higher revenue. The incentives for grid injection need to be competitive with CHP or significantly more gas needs to be produced to offset the additional capital investment required for grid injection.

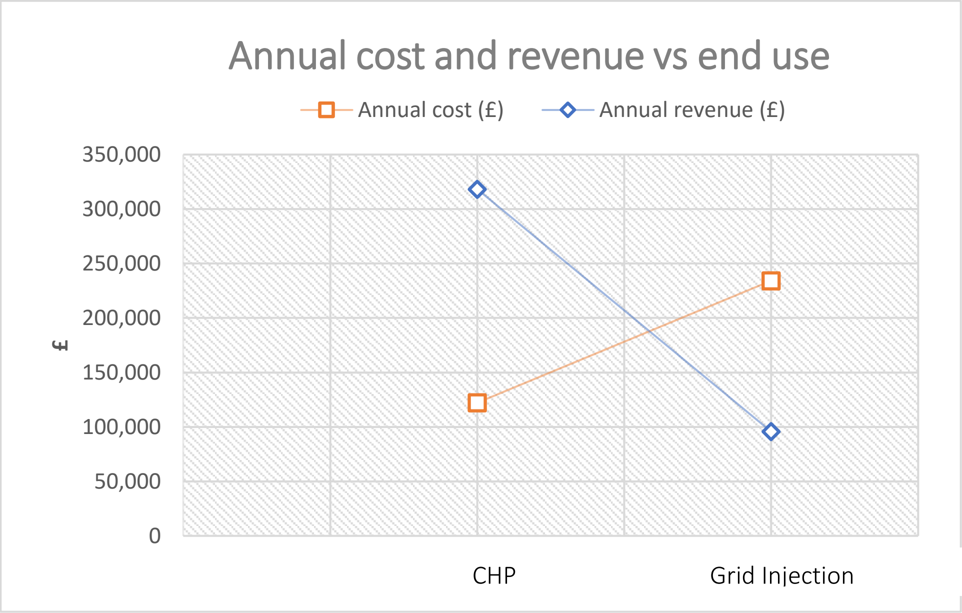


Figure 8.12. Annual cost/revenue vs product end use

8.5 Summary of Results

An overview of the main findings from the results section:

- As the Auchterarder plant was of a simple, mesophilic single-stage design, it did not require excessive parasitic energy loads and produced a net positive energy balance.

- Based on the demand for Auchterarder, the plant could only meet 1-7% of the local energy demand. This is due to the low solids content of the feedstock resulting in low energy content.

- A very rough estimate of energy return on investment showed the plant had potential to give a small positive return around 4. However, due to the low energy production in comparison to the current energy demand of society, it would not meet the EROI of 7 required for it to be a sustainable energy solution alone.

- The Auchterarder plant showed reasonable profitability of 7-30 p/kWh of energy produced, based on low, middle and high estimates and a minimum payback period of 4 years. This shows that the current incentives for small plants are high enough to offset capital costs, provided they are paid back in the form of a loan with around 7% interest. A breakdown of revenue showed that gate fees also had a substantial impact on profits, providing almost 50% of the revenue.

- The plant would save approximately 25 times the CO_{2e} that would be released for the same mass of waste in landfill and 4 times the CO_{2e} released in composting due to the combustion reaction taking place in the gas CHP engine.

- In ‘Investigation 1’ it was found that an AD plant of the same feedstock and design as the Auchterarder plant could make profit from energy and digestate production at a minimum community size of 1,500 people and a payback period of 20-years. However, to produce power of any significance, feedstock would have to be collected from several thousand people.

- In ‘Investigation 2’ it was found that the collection of local organic waste could increase the percentage of energy demand met by the plant by over double. This is due to the additional feedstocks providing a greater mass of volatile solids. It was also found that when increasing the collection distance of feedstocks, the decrease in capital costs due to economies of scale outweighed the increase in transportation costs per km by a factor of 100. This is because capital costs include the cost of the plant, storage, CHP unit and vehicles whereas transport costs only encompass fuel.

- In ‘Investigation 3’ CHP was found to be a significantly more profitable method of producing electricity and heat whereas grid injection produced significant losses. This was not only due to the additional capital costs for upgrading and injecting, but was also due to the lack of incentives for grid injection. Grid injection currently only receives RHI for biomethane injection and does not receive FIT as there is not electricity generation. In comparison, CHP can receive FIT for generation and export as well as the RHI for renewable heat generation, hence the higher profit.

9 Discussion and Recommendations

9.1 Discussion of Results

This project aimed to investigate the opportunities for using community anaerobic digestion to produce heating and electricity from local organic waste.

The overall outcomes demonstrate that that whilst a community AD plant can operate successfully, the energy production using organic waste and sewage alone is too small to meet energy demand and will produce a low energy return on investment. For the community of Auchterarder, an AD plant using organic waste and sewage could meet around 5% of total demand. For this reason, community scale anaerobic digestion of local organic waste is not an effective method of proving low carbon heating and electricity in Scotland. Some potential routes for improving energy generating potential would be drying the feedstock (with additional cost) or extending the feedstock type to the collection of agricultural waste and industrial waste. The results from 'Investigation 2' recognised that additional transportation of feedstocks from further afield would not majorly increase costs, however would have to be considered along with the environmental impact.

Despite the low energy output, AD remains an environmentally friendly method of organic waste disposal, producing less emissions than either composting or landfill. Additionally, the use of AD would reduce reliance on fossil fuels and biomass resulting in further indirect emission reductions. This demonstrates that AD is a sustainable method of waste disposal, and whilst it may not be able to produce a vast quantity energy on a community scale (and will not solve Scotland's energy challenges), there is still a very strong case to use it as a means of waste treatment. The small energy output could be suitably used to power a few public buildings, for example the town hall or library.

Due to income from incentives and gate fees AD can be a profitable venture for communities of a few thousand residents and above, with a loan to cover the high capital costs. The minimum payback period would be around 4 years, however as the community is paying it back, there could be time available to make it a longer-term investment and extend the payback period up to 20 years. The capital cost of the Auchterarder AD plant would be around £1 million, which is considered reasonable when compared with similar plants, such as Kemble Farms digester in Cirencester which has a 300 kW CHP unit and cost £1.2 million (54). The study suggested a strong dependency on gate fees for income, therefore the waste would have to be bought from the local council or other suppliers willing to sell their waste. Without the gate fees, for example if the plant was being supplied directly, the AD plant could still make a profit from incentives and digestate sales, but the payback time would be longer and the financial risks would be a lot higher.

Whilst biomethane injection to the grid is a developing technology in the biogas sector, the incentives are not high enough to support it on a community level. For this application, CHP is a much more profitable venture. Heat delivery by CHP requires the plant to be located close to the point of use. This is possible for a small community, whereas for heating buildings that are a greater distance away, gas injection is more effective. Due to higher capital costs, the RHI for biomethane injection must become competitive with the FIT for biogas owners to be encouraged to go down the biomethane route. Grid injection technology is currently receiving plenty of interest from both the gas and renewables sector and therefore is likely to develop significantly in the future.

Finally, when placing an AD plant within a local area, it is important to consider the social implications as the area will be sensitive to change. Jobs could be created locally for the operation of the plant, but may also be taken away depending on where the waste was treated before the installation of an AD plant. In addition, technical training may be required for members of the community involved in the plant set up and design. As well, the assumption was made in this study that all products of the AD plant could be sold for profit, however in reality, these markets would have to be established locally.

9.2 Recommendations

The AD industry in Scotland has developed very quickly in the past few years, resulting in many opportunities to improve the effectiveness of its application for waste disposal and renewable energy production. As a result of the main outcomes from this project, the following recommendations can be made:

- AD should be used as a highly sustainable method of recycling local waste if the town population has several thousand residents or more. The plant could be used primarily as a form of sustainable waste recycling and the small energy output could be used to provide energy to local community buildings such as a town hall. AD cannot provide sufficient energy to produce renewable heating and electricity for the whole community, unless biogas yield is significantly improved.
- Profitability can be good if waste is sourced from local councils and businesses willing to pay gate fees. This reduces reliance on changeable incentives.
- The feedstock intake can be sourced from a wider area to produce a greater energy output, making the plant more centralised. Increasing the transport distance does not have a significant detrimental economic impact, but from an environmental point of view shorter distances should be prioritised.
- CHP should be the primary end use for community AD where demand is located close to source. Financial support should be increased for grid injection in the future, as it is a highly promising method of transporting biomethane further distances. The incentives for grid injection need to become competitive with CHP.

9.3 Limitations

As mentioned previously, the methodology and approach taken in this project has allowed for reasonable estimates to be deduced with regards to the feasibility of a community AD plant in a range of scenarios. However, there were several limitations to this study which will have prevented results of a higher accuracy.

Given more time, real data on energy demand, the exact mass of organic waste produced by businesses in the community and the exact sewage output per person could have been recorded. An attempt to mitigate this was contacting Perth and Kinross Council for brown bin waste data which provided a stronger basis for calculations. However, some reasonable estimations still had to be made in place of real data.

In addition, accurate equipment costs for an AD plant were difficult to find and vary depending on plant design and manufacturers. This limited the accuracy of the capital cost calculations to a range of typical costs for the whole AD plant rather than breaking it down into individual component costs. A validation test was carried out to ensure a reasonable accuracy could be achieved using the cost ranges from literature.

The estimations of dry solids, volatile solids and energy content of the different feedstocks could have been analysed in greater detail and with greater accuracy, through lab-based research. This would improve the accuracy of the energy potential estimations of a plant enormously.

The EROI was calculated very roughly in this study, as the exact energy consumption involved in construction, installation, operations, maintenance, decommissioning, transportation, roads and manufacture of equipment was very difficult to quantify. Again, real data from an AD plant could have hugely improved the accuracy of this estimation.

Finally, it was assumed in this project when calculating revenue that 100% of the products from AD could be sold. This may not be the case and further research into markets for digestate and energy could have improved the accuracy.

9.4 Further Study

This project and the model developed can be used in future studies to determine the applicability of AD systems in a range of situations and locations. During the course of this project, several further areas of study which could provide useful insights into the use of AD for renewable energy were highlighted.

The literature review emphasised a lack of comprehensive and available software-based tools that could be used to model anaerobic digestion plants. There is potential for the AD calculator used in this project to be developed further. Some examples would be to add more feedstock options such as energy crops or micro-algae, evaluate feedstock properties in greater depth or model plants with different designs to evaluate the effect on efficiency. This would provide a highly useful tool to the anaerobic digestion industry.

It was acknowledged that the biogas yield of feedstocks is a huge limiting factor on the energy potential of a community AD plant. Further research on methods for improving biogas yield such as drying, pre-treatment, temperature control and feedstock mixing could provide an invaluable understanding of how to improve energy production at minimum additional cost.

This study looked at the potential to provide heating and electricity locally. For heating to be delivered by CHP there must be a constant thermal demand at the location of the plant. Further study into the integration of AD into district heating schemes or the gas grid could prove useful to understanding where the technology could potentially fit into low carbon heating networks. In addition, gas injection is a promising technology but is currently financially infeasible on a small scale. Further research into how grid injection can be made more profitable will help this technology develop.

Finally, this study did not carry out full social and environmental impact analysis as this was out with the scope of the project. The introduction of any new technology within a small community can have significant social and environmental implications, therefore a more in-depth social and environmental impact analysis on small-scale AD would be highly beneficial to the implementation of such schemes.

10 Conclusion

The aim of this project was to determine the opportunities for community anaerobic digestion to produce heating and electricity from local organic waste.

A literature review was carried out to evaluate the current AD landscape in Scotland and established a gap in the development of waste-fed plants in the majority of rural areas, out with private farms. A review was then carried out to determine the best software-based tool to model a small-scale AD plant. An AD calculator was selected and adapted so that it could be used to determine both the technical and financial feasibility of community AD. Once adapted for use, an AD plant for the community of Auchterarder in Perthshire was modelled and the energy balance, the percentage of energy demand met, the EROI, profitability and greenhouse gas emissions were calculated. From this model, three further investigations were completed analysing the effect of community population size, transport distance and end use.

The outcomes from this project demonstrate that anaerobic digestion cannot produce enough energy to be a single solution in providing renewable heating and electricity to a community. Due to low dry solids content, organic municipal waste will only meet around 5% of local energy demand. However, AD is a profitable venture when using gate fees and CHP incentives as sources of revenue, and can make up to 30 p/kWh of energy produced depending on the payback period. In addition, AD produces less greenhouse gas emissions than both composting and landfill due to the efficient combustion of methane gas. CHP was found to be a financially feasible method of providing renewable heat and electricity, provided that the AD plant is located close to the community, whilst grid injection was found to incur significant losses due to additional equipment costs and low incentives.

Based on the results, recommendations can be made for anaerobic digestion to be used as a sustainable method of waste recycling, with the energy produced being supplied to individual buildings rather than the whole community. Further research into routes for yield improvement must be investigated for the technology to make a bigger impact on energy demand. Additionally, biomethane injection needs to be made more financially attractive through technology cost reductions or increased incentives to encourage uptake on smaller-scales.

Finally, the AD calculator developed in this project can be accessed for use as an invaluable tool to model AD plants in any location and assess their technical and financial feasibility. This will encourage the more strategic development of the AD sector in the future.

Appendices

Appendix I: List of AD digesters in Scotland 2017

Green highlight = organic municipal waste plant

CHP = combined heat and power

BtG = biomethane to grid

Name	**Location**	**Waste type**	**Capacity (kWe)**	**Feedstock (tpa)**	**Output**	**Year**
Broadwigg Farm	Dumfries & Galloway	Farm	500	28,000	CHP	2015
Rainton Farm	Dumfries & Galloway	Farm	25	2,500	CHP	2012
Balmangan Farm	Dumfries & Galloway	Farm	124	5,500	CHP	2016
Corsock Farm	Dumfries & Galloway	Farm		80	Heat	2004
Crofthead farm	Dumfries & Galloway	Farm	124	3,000	CHP	2016
West Roucan Farm	Dumfries & Galloway	Farm	1,200	20,000	CHP	2016
Charlesfield Farm	Dumfries & Galloway	Farm	500	11,200	CHP	2016
Carterhaugh Farm	Galashiels	Farm	160	2,000	CHP	2016
Charlesfield Industrial Estate	Galashiels	Farm	500	24,995	BtG & CHP	2015
Standhill Farm	Galashiels	Farm	200	11,000	CHP	2014
Pure Malt Products	Edinburgh	Brewery & food production	500	25,000	CHP	2016
Millerhill AD	Edinburgh	Food Waste	1,400	30,000	CHP	2017
North British Distillery	Edinburgh	Brewery	3,400	9855	CHP	2010
Girvan Distillery	Ayrshire	Brewery	7,200	300,000	BtG & CHP	2009
GSK Irvine	Ayrshire	Factory waste	1,000	10,000	CHP	2015
Miekle Laught Farm	Ayrshire	Farm		190	Heat	2005
Barkip AD	Ayrshire	Food Waste	2,200	75000	CHP	2011
Tambowie Farm	Glasgow	Farm	250	24,000	BtG & CHP	2016
Deerdykes Composting and Organics Recycling Facility	Glasgow	Food Waste	1,000	30,000	CHP	2010
Cumbernauld AD	Glasgow	Food Waste	3,600	100,000	BtG & CHP	2011
Claylands Farm	Glasgow	Farm	500	30,000	CHP	2014
Lochhead Landfill (Dry-AD)	Fife	Food Waste	1,400	45,000	CHP	2014
Inchdairnie Farm	Fife	Farm	2,000	40,000	BtG & CHP	2016
Cameron Bridge Distillery	Fife	Distillery	5,500	90,000	CHP	2013
Binn Farm	Perthshire	Food and Farm	700	15,000	CHP	2012
Keithick Farm	Perthshire	Farm	500	36,000	BtG & CHP	2014

Peacehill Farm	Dundee	Farm	500	30,450	BtG & CHP	2015
Kirkton Farm	Dundee	Farm	250	2,000	CHP	2016
East Denside Farm	Dundee	Farm	250	5,000	CHP	2014
Brae of Pert Farm	Montrose	Farm	250	35,000	BtG & CHP	2016
Savock Farm	Aberdeenshire	Farm	250	40,000	BtG & CHP	2016
Kinknockie Farm	Aberdeenshire	Farm	250	9,500	CHP	2015
Downiehills Farm	Aberdeenshire	Farm	500	55,000	BtG & CHP	2016
Gask Farm	Aberdeenshire	Farm	460	15,000	CHP	2006
Glenfiddich Distillery	Aberdeenshire	Distillery	3,500	80000	CHP	2015
Dailuaine Distillery	Aberdeenshire	Distillery	500	15000	CHP	2013
Roseisle Speyside Whisky Distillery	Elgin	Distillery	500		CHP	2010
Woodside Farm	Elgin	Farm	200	5,228	CHP	2015
Morayhill AD	Inverness	Farm	250	40,000	BtG & CHP	2016
Wester Kerrowgair Farm	Inverness	Farm	1,000	20,650	CHP	2015
Rosskeen Farm	Highlands (Invergordon)	Farm	250	36,000	BtG & CHP	2016
Western Isles Integrated Waste Management Facility	Highlands (Stornoway)	Food Waste	305	7,000	CHP	2007

Appendix II: Full results sheet for Auchterarder AD plant

Results summary

Input feed properties

		Estimates		
	Lowest	Middle	Highest	(Biomass)
Total tonnes per day	28.5	29.9	33.0	tonnes
Dry solids content range of feed	6.6%	8.2%	9.6%	%
Total dry solids per day	1.9	2.5	3.2	tonnes
VS content of dry solids	82.0%	82.0%	81.7%	%
Total volatile solids per day	1.5	2.0	2.6	tonnes
Carbon:Nitrogen ratio	33.34	31.34	28.83	

HRT and SRT

Two stage process?		yes/no
HRT,1st phase	40	days
HRT, 2nd phase	0	days

Digester properties

Input buffer diameter	4.71	4.79	4.95	m
Input buffer height	4.71	4.79	4.95	m
Pasteuriser diameter	1.41	1.43	1.48	m
Pasteuriser height	1.41	1.43	1.48	m
1st stage diameter	11.17	11.36	11.73	m
1st stage height	11.17	11.36	11.73	m
2nd stage diameter	0.00	0.00	0.00	m
2nd stage height	0.00	0.00	0.00	m
Digestate buffer diameter	8.92	9.08	9.37	m
Digestate buffer height	8.92	9.08	9.37	m

Temperatures

Pasteuriser	70.9	70.9	70.9	C
1st stage digester	38.0	38.0	38.0	C
2nd stage digester	38.0	38.0	38.0	C

Biogas/methane power outputs

		Estimates		
	Lowest	Middle	Highest	
Total biogas per day	533.1	1020.1	1648.9	m^3
Methane content range of biogas	51.2%	60.6%	65.4%	%
Total methane per day	273.0	617.8	1078.4	m^3
kWh per day @ 11.04 kWh/m^3	3013.8	6820.5	11905.7	kWh
kW average power (methane)	125.6	284.2	496.1	kW

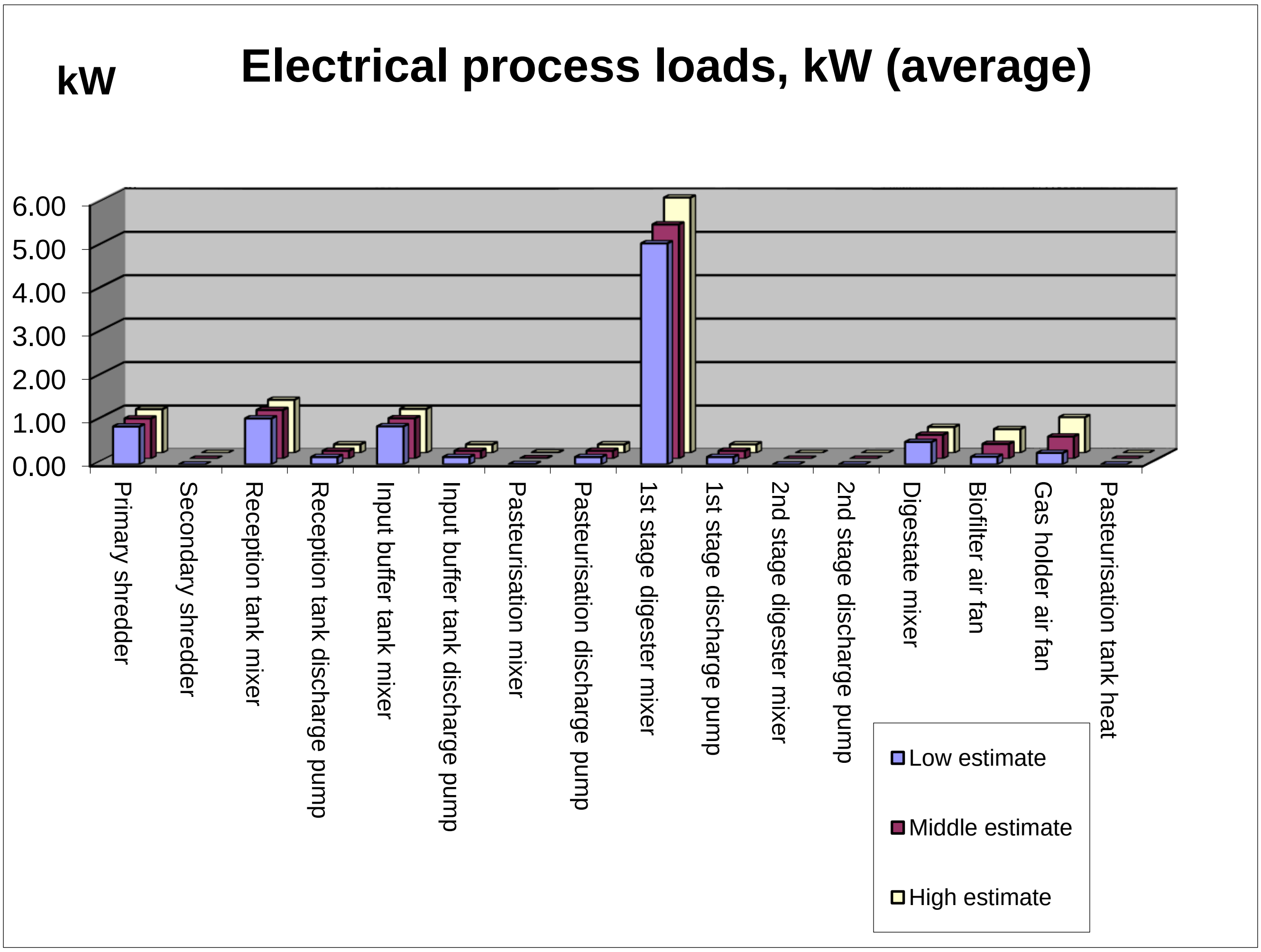
Energy

Total energy yielded, of which	125.6	284.2	496.1	kW
Engine heat lost	22.2	41.8	62.7	kW
Generator heat lost	5.6	13.2	23.9	kW
Process heat required	21.6	22.5	24.6	kW
Process electrical required	8.6	9.4	10.8	kW
Surplus electricity for export	22.9	65.6	124.6	kW
Surplus heat (available for CHP export)	44.6	131.5	249.5	kW
Check energy sum	97.8	229.2	409.4	kW
Surplus CHP water temperature	58.9	73.3	77.8	C
Surplus CHP water at mass flow rate	0.20	0.46	0.82	kg/s

Economic Analysis

	Lowest	Middle	Highest	
Capital Cost	£528,116	£942,058	£1,476,541	£
Loan Required	£528,116	£942,058	£1,476,541	£
Interest on Loan %	5%	7%	10%	%
Payback Period (years)	10	10	10	years
Annual Loan Repayment	£55,452	£100,800	£162,420	£
Annual Costs	£12,954	£21,357	£32,302	£
Annual Revenue	£247,946	£318,250	£422,426	£
Annual Gross Profit	£179,540	£196,093	£227,704	£

Appendix III: Electrical process loads for Auchterarder AD plant



References

1. Brockway A. Comparing Greenhouse Gas Emissions from Organic Waste Disposal Methods. American Biogas Council; 2012.

2. Government S. Scottish Energy Strategy: The future of energy in Scotland. Edinburgh: Scottish Government; 2017.

3. Government S. Energy in Scotland Overview. Edinburgh: Scottish Government; 2017.

4. McCabe J, Eckenfelder W. Biological Treatment of Sewage and Industrial Wastes. New York: Reinbold Publishing; 1957.

5. Richards DK. Anaerobic Digestion- A Credible Source of Energy. Oxon: Energy Technology Support Unit; 1984.

6. Monnet F. An Introduction to Anaerobic Digestion of Organic Wastes. Scotland: Remade Scotland; 2003.

7. Association RE. Biogas- Renewable Technologies. Renewable Energy Association; 2017.

8. Bhatia SC. Advanced Renewable Energy Systems, (Part 1 and 2). New Delhi: CRC Press; 2014. p. 430.

9. Gebrezgabher SA, Meuwissen MPM, Prins BAM, Lansink AGJMO. Economic Analysis of Anaerobic Digestion - A Case of Green Powered Biogas Plant in the Netherlands. NJAS - Wageningen Journal of Life Sciences. 2010;57(2):109-15.

10. Steffen R, Szolar O, Braun R. Feedstocks for Anaerobic Diegstion. Vienna: University of Agricultural Sciences Vienna; 1998. p. 17.

11. Plan BRA. Quantification of Feedstocks for Anaerobic Digestion Group Report. Northern Ireland: Biogas Research Action Plan; 2014. p.17.

12. Korres N, O'Kiely P, Benzie JAH, West J. Bioenergy Production by Anaerobic Digestion. New York: Taylor and Francis; 2013.

13. Knitter T. Fundamentals in Anaerobic Digestion: First Steps in Developing a Project Cork: Sustainble Energy Ireland

14. Redman G. A Detailed Economic Assessment of Anaerobic Digestion Technology and its Suitability to UK Farming and Waste Systems. In: Centre TA, DECC, NNFCC, editors.: The Andersons Center; 2010.

15. WRAP. Guidance for the on-site treatment of organic waste from public and hospitality sectors. In: Management SEaFR, editor.: WRAP; 2013.

16. biogas-info. Anaerobic Digestion 2017 [Available from: http://www.biogas-info.co.uk/about/ad/.] Cited: 06/07/2017

17. Zhang C, Su H, Baeyens J, Tan T. Reviewing the anaerobic digestion of food waste for biogas production. Renewable and Sustainable Energy Reviews. 2014;38:383–92.

18. Khalid A, Arshad M, Anjum M, Mahmood T, Dawson L. The anaerobic digestion of solid organic waste. Waste Management. 2011;31:1737–44

19. Jerger DE, Tsao GT. Feed Composition. Anaerobic Digestion of Biomass. Barking, Essex: Elsevier Applied Science; 1987.

20. Government S. DRAFT CLIMATE CHANGE PLAN: The draft third report on policies and proposals 2017-2032. Edinburgh: Scottish Government; 2017.

21. SEPA. Licensing of Anaerobic Digestion Plants: SEPA; 2014 [Available from: https://www.sepa.org.uk/media/145269/position_anaerobic_digestion_plants.pdf.] Cited: 12/07/2017

22. Government S. The Heat Policy Statement: Towards Decarbonising Heat: Maximising the Opportunities for Scotland. Edinburgh: Scottish Government; 2015.

23. Abda Launches First Conference for Scottish AD Industry: ABDA; 2017. [Available from: http://adbioresources.org/news/press-release-adba-launches-first-conference-for-scottish-ad-industry.] Cited: 10/07/2017

24. Association RE. Biogas and Energy Production from Waste: A UK Perspective. In: Waldron K, editor.: Renewable Energy Association 2012.

25. Programme SB. Micro AD: Scottish Biofuels Programme; 2017 [Available from: http://biofuels-scotland.co.uk/micro-ad-scotland.] Cited: 08/07/2017

26. Government S. Energy in Scotland 2017 Publication Edinburgh: Scottish Government 2017 [Available from: http://www.gov.scot/Topics/Statistics/Browse/Business/Energy/EIS/EIS2017data.] Cited: 10/07/2017

27. Association RE. Anaerobic Digestion in Scotland- Opportunities and Challenges. In: Grant J, editor.: Renewable Energy Association; 2013.

28. Government S. Zero Waste Scotland Plan. Edinburgh: Scottish Government; 2010.

29. Government S. Making Things Last: A circular economy strategy for Scotland. Edinburgh: Scottish Government; 2016.

30. Council GC. Food for thought as Glasgow launches major recycling drive. Glasgow City Council; 2016.

31. Agency SEP. Scotland's Environment Waste Data Discover Tool. Stirling: Scottish Environmental Protection Agency; 2017.

32. Government S. Energy in Scotland: A Compendium of Scottish Energy Statistics and Information. Edinburgh: Scottish Government; 2012.

33. Methanogen. Micro Scale Anaerobic Digestion. Biofuels Scotland; 2014.

34. Bright A, Bulson H, Henderson A, Sharpe N, Dorstewitz H, Pickering J. An Introduction to the Production of Biomethane Gas and Injection into the National Grid. WRAP; Advantage West Midlands; 2011.

35. Conca J. EROI- A tool to predict the best energy mix. Forbes; 2015.

36. Weißbacha D, Ruprechta G, Hukea A, Czerskia K, Gottlieba S, Husseina A. Energy intensities, EROIs, and energy payback times of electricity generating power plants. Energy. 2013;52:210-21.

37. Ofgem. Tariffs and Payments: Non-domestic RHI. Ofgem; 2017.

38. Ofgem. Feed-In Tariff (FIT) Rates. Ofgem; 2017.

39. Scotland Z. Digestate Market Development in Scotland. Scotland: Zero Waste Scotland; 2010.

40. Scotland NRo. Perth and Kinross Council Area- Demographics Factsheet. Scotland; 2015.

41. Greece DaUoaEEMtAEoLCRBPi. Biogas Calculations. 2017.

42. Georgakakis D, Christopoulou N, Chatziathanassiou A, Venetis T. Development and Use of an Economic Evaluation Model to Assess Establishment of Local Centralized Rural Biogas Plants in Greece. Appl. Biochem. Biotechnol.; 2003. p. 275 - 84.

43. Cloonan M, Roscoe A, Geraghty M, Currie J. Biomass- Using Anaerobic Digestion. University of Strathclyde: University of Strathclyde; 2004.

44. Monnet F. Remade Scotland Report: An Introduction to the Digestion of Organic Wastes. 2003.

45. WRAP. New Gate Fees Revealed by WRAP Show Changes in the Market: WRAP; 2016 [Available from: http://www.wrap.org.uk/content/new-gate-fees-revealed-wrap-show-changes-market.] Cited: 18/07/2017

46. Waste G. Food Waste Gate Fees are Dropping as UK AD Capacity Increases. GPT Waste; 2015.

47. ABDA. Financial Incentives. ABDA; 2017.

48. NNFCC. Incentives. NNFCC; 2015.

49. Ireland SEAo. Anaerobic Digestion, A Case Study: McDonnell Farms Biogas Limited, Shanagolden, Co. Limerick. Sustainable Energy Authority of Ireland; 2010.

50. Flow diagram of PSA. [Available from: http://1.bp.blogspot.com/-WLjDCih16Xs/Tz05o_v4rgI/AAAAAAAAADU/U50c3n9UjE0/s1600/Picture5.png] Cited: 22/07/2017

51. Bank C. Optimising Anaerobic Digestion. University of Reading: University of Reading; University of Southampton; Forestry Commission 2009.

52. GreenNav. How much energy in cars? 2015. [Available from: http://www.nottenergy.com/energy_cost_comparison] Cited: 12/07/2017

53. Earth Fot. Briefing: Food Waste Collection. London: Friends of the Earth; 2007. p. 3.

54. Bilsborrow DP. Anaerobic Digestion In the UK- An Overview. Newcastle University: DEFRA.