Department of Mechanical Engineering

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Alternative Use of Waste Project:

A Feasibility Study of an Anaerobic Digestion Plant for Solway Veg Limited

By

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This thesis is dedicated to my loving parents; Mr & Mrs A.S Martyns-Yellowe – for all they have been and still are to me.

ABSTRACT

This work is a feasibility study of an anaerobic digester plant for Solway Veg Limited, Gretna. It aims at identifying an alternative use of waste technology option, which is most viable; technically, environmentally and economically for the company. Several Energy from waste technologies were reviewed to find the most suitable for the company's waste stream.

Anaerobic digestion technology and the processes involved were investigated and evaluated.

Policy and legislation relating to sustainable waste management and energy were investigated; focusing on the key areas of legislation specific to the installation, design and operation of this technology.

The design parameters of the proposed plant were defined and biogas yield and energy yield calculations were made from the waste information provided.

Project costs, potential income sources and funding sources were also identified; with a sensitivity analysis carried out to identify the effect of certain variables on the plant. The Net Present Value (NPV) of the project was also estimated.

Results obtained from the analyses of the proposed plant design using an average weekly waste output of 50 tonnes, show an annual methane yield of 1517.910MWhrs which will produce electricity and heat to meet the process's heat and electricity requirements with surplus electricity and heat of 409.830MWhrs and 379.477MWhrs annually respectively, that can be sold off to generate an annual income of £35,947.11.

The initial cost of the project is £208,800. The Net Present Value of the project defined by a 10year lifespan and annual depreciation rate of 5.75% is £242,792.54. A positive NPV shows that the project is feasible with a return on investment. Further analysis on the variables shows that the NPV remains positive even with significant changes on the variables.

This study concludes that incorporating anaerobic digestion will provide a more sustainable waste management option for the company and the construction and operation of a biogas plant by Solway Veg Limited is feasible and economically sound.

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1 INTRODUCTION

The term waste has been defined in different ways. There are however two main definitions of waste; one is from the perspective of the individual or organisation producing the waste and the other is from the view of Government and is set out in transformed acts of waste legislation. The two definitions have to join to ensure the safe and legal disposal of the waste.

The European Union (EU) defines the term waste as an object the holder discards, intends to discard or is required to discard (Waste Framework Directive – European Directive 75/442/EC as amended)[11].

In the United Kingdom, the Environmental Protection Act 1990 indicated that waste includes any substance which constitutes a scrap material; an effluent often arising from the application of any process or any substance or article which requires to be disposed of or which has been broken worn out, contaminated or otherwise spoiled; supplemented with anything which is discarded otherwise dealt with as if it were waste shall be presumed as waste unless the contrary is proved[14]. This was later amended by the Waste Management Licensing Regulations 1994 which defined waste as “any substance or objects the holder discards, intends to discard or is required to discard but with exception of anything excluded from the scope of the Waste Directive”.

Waste is classified legally by the premises from which it is produced. They include household waste, commercial, industrial, agricultural, radioactive and clinical wastes. These wastes, depending on the source, can pose serious hazard to people and the environment if handled wrongly. It is therefore important that waste management plans consider sources as well as volume of waste in other to minimise the risks their effect have on the society as a whole.

The management of waste is one of the key themes of ‘sustainable development’. This concept originated from the 1992 United Nations Rio conference on Environment and Development, its working definition is “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”[34].

Sustainable waste management concepts vary with countries and regions, the most commonly accepted and adopted is the three R’s principle (reduction, re-use and recovery), otherwise known as the waste hierarchy. Its main aim is to extract the maximum practical benefits from products and generate the minimum amount of waste. In the UK, it has been widely adopted, it is often used in conjunction with the 'proximity principle' (in which the waste is disposed of as close to its source as possible) to achieve the Best Practise Environmental Option (BPEO).

The Landfill Tax escalator encourages diversion of waste from landfills as the cost of sending waste to landfill has increased. The climate change levy is another way in which the UK government tries to ensure that polluters pay for the waste they generate. In a world of finite resources with increased demand of higher environmental standards globally, it is important that individuals, businesses and societies change the way in which they consume energy and materials and dispose of waste; finding a safe and cost effective disposal of waste has become necessary. Industries around the world are intensifying their efforts to be more sustainable in their activities i.e. processes and waste management as part of their commitment to sustainable production and consumption; this is also important as it plays a vital part in the battle against climate change. Food processing industries are not left out of this, as they account for a substantial amount of the bio-degradable component of UK's annual industrial waste. The need for food processors to consider more sustainable ways of handling their wastes as well as general material flow has become paramount. This report will consider the options available to Solway Veg Limited in particular as they seek to effectively manage wastes generated in their business.

1.1 Project Aim

This project aims at identifying an alternative use of vegetable waste option, which will be technically, environmentally and economically viable for Solway Veg Limited.

1.2 Project Objectives

- To review the different energy from waste technologies available and choose the one that is most suited for Solway Veg Limited.
- To undertake a detailed study of the chosen technology.
- To deliver recommendations to Solway Veg Limited based on the findings as regards managing their waste.

1.3 Report Outline

The structure for this report is outlined as follows. Chapter 2 presents an overview on waste management in the UK, with particular interest in the food processing industry. It presents sustainable options of managing these wastes; the different technologies available for energy recovery from wastes as well as some case studies of Energy from Waste projects in the UK.

Chapter 3 gives a general background on the case study of this project – Solway Veg Limited in relation to its waste generation, current waste management practice and the case for Anaerobic Digestion.

Chapter 4 presents a detailed analysis of the AD technology, the process, planning, legislation; environmental issues involved as well as the benefits of utilizing this technology.

Chapter 5 presents the details of the proposed biogas plant for the case study. It will give biogas calculations in the proposed plant.

Chapter 6 presents an economic analysis of the project; it will consider the markets involved in the process as a possible source of income, the project costs and finally, funding sources could be used to help an AD project for Solway Veg Limited. This is followed by conclusions and recommendations.

2 ALTERNATIVE USE OF WASTE

2.1 Introduction

This chapter presents an overview on waste management with particular interest in the food processing industry. It will also present sustainable options of managing these wastes (considering alternative uses for these wastes).

Further to this, the different technologies available for energy recovery from wastes are considered.

2.2 Waste Management

Waste management refers to the collection, transport, processing, recycling or disposal of waste materials in an effort to reduce their effect on human health, local aesthetics and local amenities[35]. The wastes are often produced as a result of human activities.

The UK produces around 330 million tonnes of waste annually[13], a quarter of which is from households and businesses; while construction/demolition, sewage sludge, spoils from mines, farms and dredging of rivers account for the rest. The National Waste Strategy was set out as a framework within which the Government can reduce the amount of wastes it produces and deal with the waste in a way that has no detrimental effect on future generations. The strategy covers all household, industrial and commercial waste.

The Food Processing industry in the UK prides itself as being efficient in the delivery of a wide-ranging supply of fresh and processed foods of high quality to consumers; nonetheless, every step in the system process is characterized by by-products and wastes with possible impact on the environment[26]. The management of resources, recycling and reuse of materials, exploitation of by-products and bioconversion of waste materials, collectively with the reduction of environmental loadings may all contribute to the sustainability of the environment. Legislative restrictions on landfill disposal will increasingly force the industry to consider new ways to reduce waste and alternative handling approaches for wastes generated. Food processing wastes have the potential for energy recovery; efforts to utilize existing technologies for energy recovery are being made; creating the opportunity of reducing the effects of having to landfill wastes. Land filled waste from food production has been estimated at 2.7 million tonnes per annum, [29] much of which is organic matter. It is a potential source of energy, and may also be the source of useful materials for other applications. Most of this value is currently written off as unrecoverable, and paying landfill disposal charges compounds the write-off.

2.3 Sustainable Waste Management Options for Food Processing Industries

Food processing industries, like every other industry, are made to pay for the environmental cost of the wastes they produce. There is a need for them to reduce the amount of waste they produce; alternatively recycle and recovery where possible before considering the option of disposal of the waste. This system of options is known as the waste management hierarchy[4]. The waste hierarchy provides an order of preference for waste management policy – reduction, reuse, recovery and disposal framework to consider in the management of any kind of waste[25]. The main aim of the hierarchy is to extract the maximum practical benefits from products and to generate the minimum amount of waste.

Waste minimisation is aimed at reducing the production of waste through education, adopting better operational practises, improved production process; seek innovative process technologies rather than aiming to increase technology to improve the treatment of waste. Waste minimisation is the most important element of the waste hierarchy; it has a potential to reduce costs or increase profits by maximising the use of resources and reducing the amount of waste to be disposed, which invariably reduces the cost of waste management[20]. It is, however, unlikely that waste streams will be eliminated completely; the need for other options therefore remains. Re-use of the waste generated can have significant financial and environmental benefits. The food processing industry produces a large volume of mainly organic wastes which could be reused within the industry or sold as raw materials for other purposes.

A number of well established outlets for the reuse of these wastes are in existence. Some examples of these include the use of bread, flour and yeast waste from bakery industries used as feed for animals; diary wastes such as cheese whey are now recovered and also used in food and animal feed; waste molasses from sugar producing industries are now used to grow yeast and vegetable and fruit waste such as the peels and pulps are used as feed for animals[27]. A number of ways in which these wastes can be turned into valuable resources have been recognised; an EU project investigating ways of turning onion produced in Europe into valuable food ingredients such as onion oil for flavouring, fructooligo saccharides and low-lignin dietary fibre for use in texturally sensitive foods is presently underway[29]. Recycling involves additional processing of a material to change it into a product of more value. It can reduce the amount of processing waste and packaging materials sent to landfill. In food processing industries, raw material packaging and containers represents a major source of solid wastes. Businesses can identify ways of reusing packaging materials on site and send the remaining materials for recycling. The major packaging wastes suitable for recycling are plastics, paper, glass, steel and aluminium. Department of Food and Rural Affairs (DEFRA) provides information on producer responsibility for packaging waste; Valpak Limited operates the UK's main scheme for helping companies meet the requirements for waste packaging recovery and recycling under the packaging waste regulations[32]. Energy recovery from organic waste is a another option for managing these wastes; technologies exist today to achieve energy recovery from food processing wastes, some with the potential to provide valuable co-products and closed-loop resource recovery. The following section discusses the concept of energy from waste as a sustainable waste management option.

2.4 Energy from Waste

Energy from Waste (EfW) is a process by which energy stored in the waste is extracted for use as a power source for various applications. The recovered electricity can be fed into the national grid and recovered steam exported to adjacent industrial premises or townships for space heating, hot water supply, and other duties. Plants that recover both heat and electricity are called Combined Heat and Power (CHP) plants.

The recovery of energy from wastes (municipal and industrial sources) provides an opportunity for generating income from heat and power sales while providing a safe and cost effective means of waste disposal.

In countries such as Sweden and Denmark some 40% of the community and domestic requirement comes from district heating schemes linked to EfW/CHP plants. However, this type of application has yet to find widespread use in the UK[30].

The growth of EfW will play a vital role in helping the UK to meet its international obligations to reduce the emission of greenhouse gases, in particular carbon dioxide, by replacing fossil fuels as a source of energy. As a result of this, EfW generated heat and electricity is exempt from the Climate Change levy.

The Scottish Environmental Protection Agency (SEPA) has undertaken research into the acceptability of Energy from Waste technology in Scotland[19]. Public, industry and local government opinions were investigated on Energy from Waste options. The study concluded that Energy from Waste was viewed by all sectors as a necessary technology for sustainable waste management when combined with recycling and recovery systems, and that the Best Practise Environmental Option (BPEO) principle should be employed when assessing Energy from Waste facility proposals[7].

Presently, 210 MW of electricity is generated in 15 EfW plants in the UK incinerating 3.3 million tonnes of municipal waste. In 2002, 3% of electricity generated in the UK was sourced from renewables, of which 23% was derived from EfW[30].

2.5 Energy from Waste Technologies

A number of well established technologies are available for generating heat or power from wastes. The choice of technology utilized for energy recovery should be dependent on the nature and composition of wastes generated. It should also reflect local circumstances, which will vary. In the UK, the government expects greenhouse gas emissions to be a key consideration of those developing waste to energy plants[10].

These technologies are further divided into thermal and non-thermal. The thermal technologies include direct combustion (incineration), gasification, pyrolysis, while anaerobic digestion and mechanical biological treatment are available non-thermal technologies. Brief descriptions of these technologies are presented in the following sections.

2.5.1 Direct Combustion with Energy Recovery

Incineration is the controlled burning of waste at high temperatures. This practice decreases both the amount of solid waste that communities must deal with and reliance on non-renewable energy sources[26]. The heat recovered from the plants is may be used to generate electricity or for other industrial heat applications. It however, faces criticism regarding the pollution that it creates, particularly the pollution resulting from exhaust gases that are by-products of the process. New waste to energy plants in Organisation for Economic Co-operation and Development (OECD) countries must meet strict emission standards.

The basic principle behind generating energy via incineration is by utilizing the steam raised in the combustion process to drive a steam turbine to generate electricity, in a similar manner to a conventional coal fired power station. This process of heat generation is called "Combined Heat and Power" (CHP) or "co-generation"[26]. Co-generation is a method of ensuring maximal energy efficiency in the incineration process.

Combustion is best suited to bio fuels with low moisture content, as it uses a portion of the energy to evaporate the water.

Table 2.1 Pros and Cons of Direct Combustion as an EfW Technology

Pros	Cons
Handle MSW waste with no pre-treatment required	High capital costs. Since fixed costs are high the need for consistently high utilisation is paramount.
Energy recovery including Combined Heat and Power (CHP) plants and opportunity for district heating programmes	Residue quality and disposal, although bottom ash can be reused
State-of-the-art technology in global use including pollution control technology	Negative public perception - NIMBY (stack emissions and lack of understanding of technology)
No long term liability	Debate over measurement and long term health effects of dioxin emissions, it should be noted that controls issued throughout the 1990s and more recently with the Waste Incineration Directive have reduced dioxin emissions to well below that of other combustion processes.
Proven and commercially available technology	Minimum materials recovery, except for ferrous materials
Reduces volume of waste by ~90%	Minimum or guaranteed tonnage may be required by the operator to cover costs

Source: *http://www.waste-technology.co.uk/EfW/efw.php*

2.5.2 Gasification and Pyrolysis

Gasification and pyrolysis, like incineration, are advanced thermal technology options for the recovery of energy from waste. They involve the indirect combustion of the waste under controlled conditions[24].

Pyrolysis is a thermal process where organic materials in the waste are broken down under pressure and in the absence of oxygen. The process works best when the input waste is carbon-rich, preferably sorted or pre-sorted.

Gasification is a thermo-chemical process in which biomass is heated in the absence of air, to produce a low-energy gas containing hydrogen, carbon dioxide and methane. The gas, often called synthetic or syngas, can be used as a fuel in a turbine or combustion engine to generate electricity.

Gasification and pyrolysis systems are now becoming more commercially viable for use in waste management systems. Compact Power is a UK based environmental management company that uses pyrolysis, gasification and high temperature oxidation to "convert waste to fuel and other usable products e.g. carbon". It runs the first commercial plant to have received an Intergovernmental Panel on Climate Change (IPCC) licence from the Environment Agency, at Avonmouth near Bristol. The plant consists of two pyrolysis tubes which can process 8,000 tonnes of waste, primarily clinical waste a year. The company also has planning permission for a 64,000 tonnes per annum plant in Dumfries[16]. This plant will take a mixture of non-recyclable municipal, light industrial and commercial wastes including organic, timber and textiles, rubber tyre shreds and sewage sludge screenings and will generate up to 7.8 MW of electricity[8]. It will qualify as renewable energy under the ROS scheme, thus creating an attractive revenue stream from the energy generated from waste.

Table 2.2: Pros and Cons using Pyrolysis and Gasification as an EfW Technology

Pros	Cons
Potential to recycle a large proportion of residues depending on the process	Many processes will still have residues to be disposed of, some of which (from flue gas treatment) will be hazardous in nature
Qualifies for the Renewables Obligation for a substantial proportion of the feedstock processed	Requires extensive pre-treatment to be able to handle MSW
High temperatures may make the system more flexible for other waste streams such as clinical	More sensitive system than moving grate incineration technology
Smaller units more acceptable and part of an integrated system	More expensive (in terms of gate fee) than other EfW technologies

Source: http://www.waste-technology.co.uk/EfW/efw.php

2.5.3 Landfill Gas

This is the gas generated by decomposition of organic material at landfill disposal sites. The average composition of landfill gas is approximately 50 percent methane and 50 percent carbon dioxide and water vapour by volume. The methane in landfill gas may be vented, flared, combusted to generate electricity or useful thermal energy on-site, or injected into a pipeline for combustion off-site. The gas may also be used in fuel cell technologies, which use chemical reactions to create electricity, and are much more efficient than combustion turbines. The potential of direct use schemes is limited by the need for an adjacent user of the gas since schemes become uneconomical if gas has to be piped any appreciable distance.

The use of landfill gas for energy generation is now an established technology and, since its inclusion under UK renewable energy support schemes, has resulted in an ever-increasing uptake rate[7]. Approximately 110MW of electricity are currently being produced from landfill gas in the UK at more than 75 landfill sites.

The Greengairs landfill site in Scotland is an example of energy generation from landfill gas. At this plant approximately 6000 m3 of gas/hour are abstracted from over 160 operational gas collection wells drilled into the waste contained in completed areas of the landfill generating almost 12MW of energy from the site[7]. The electricity generated is passed into the national power grid.

2.5.4 Anaerobic Digestion

Anaerobic digestion is the degradation of organic matter in an oxygen free environment. The decomposition is by bacterial processes. It is characterized by the release of an energy rich biogas and the production of a nutrient rich digestate, which is composed of a liquid portion known as liquor and a solid fibrous material. The gas produced is 60% methane, with the remainder as carbon dioxide (CO_2) and smaller amounts of hydrogen sulphide (H_2S) and ammonia (NH_3). The methane can be used to fuel a Combined Heat and Power (CHP) system for the generation of electricity and heat, which would have otherwise been released to the atmosphere, under natural decomposition. AD helps to reduce natural greenhouse gas emissions; it also provides an opportunity to displace conventional generation.

AD is increasingly used as a technology that can deal with mixed organic waste streams (e.g. animal slurry, sewage, BMW, food processing wastes) and countries such as France, Denmark and Germany are now leading the way in organic waste treatment by AD[5].

Table 2.3: Pros and Cons using AD as an EfW Technology

Pros	Cons
Suitable for wet waste	AD is more capital intensive than composting
Reduced greenhouse gas emissions compared to other waste management options.	Land filling digestate produced can count as BMW and will be subject to active landfill tax.
AD process complies with Animal By-Products legislation.	The contamination of final product may be difficult to avoid; this present marketing problems.
It is an enclosed system; emissions are avoided; reducing environmental impacts.	Materials handling problems with front end processing can be costly.
It has energy recovery potentials (methane generation) as well as the possible sale of surplus.	There may be odour emissions during material handling.
Excess energy is eligible for Renewable Obligation Certificates (ROC's)	Gas handling, storage and cleanup facilities are required; this will add additional costs to treatment process.
It contributes to national recycling and recovery objectives.	It treats only the organic fraction of municipal solid waste (MSW), there may be used on residual municipal waste stream with contaminants rejected as part of the process
It reduces organic wastes from landfill which reduces the production of landfill gas and leachates; a key of the landfill directive	AD is more capital intensive than composting

Source: http://www.waste-technology.co.uk/AD/ad.html

2.5.5 Mechanical Biological Treatment (MBT)

Mechanical Biological Treatment is energy from waste system that enables the recovery of materials contained within, as well as the stabilization of the biodegradable component of the material[21]. MBT plants combine individual mechanical and biological processes in different ways depending on the output required; that is the mechanical process can be used to separate the dry recyclables like glass and metals, while the biological processes are employed to remove moisture and stabilize the organic fraction of the incoming waste. MBT systems are separated into two different categories[15]:

- Mechanical, then biological treatment: Dry processes are used for the mechanical extraction, maximising the diversion of recyclable materials, leaving a mainly organic fraction for the biological decomposition (which is the next stage). The aim of this stage is to reduce the waste and to stabilise any biologically active materials. Some MBT systems may propose AD for the biological treatment, capturing the methane produced to provide energy for the plant[15].

- Biological, then mechanical treatment: In type of MBT process, the residual waste is shredded and dried in drums or autoclaves. It is then sorted using various equipment, such as magnets or a separation drum to remove metals, glass, stones for recycling.

This method of energy recovery from waste is already being put to use extensively in some European countries like Germany and Austria[9]. The technology is currently being promoted for handling of residual waste municipal waste in the UK.

Table 2.4: Pros and Cons using MBT as an EfW Technology

Pros	Cons
Potential hazardous waste contaminants In the waste stream, such as batteries, solvents, paints etc will not reach landfill sites due to sorting of the waste prior to treatment.	Some local authorities see the MBT as a means to meet recycling rates without the need for separate collection of recyclables.
The biodegradability of the waste is reduced; thus reducing the methane and leachates production once the waste is land filled.	Though the biodegradability of the waste has been reduced, the residue may not be classed as inert and therefore ay not help local authorities to meet the EU landfill directive targets
The stabilisation of the waste reduces its side-effects at landfill sites such as odour, dust, windblown paper and plastics.	Large MBT plants draw in waste from a wider area, contradicting the proximity principle.

Source:http://www.foe.co.uk/resource/briefings/mchnical_biolo_treatmnt

2.6 Case Study of EfW schemes in the UK

2.6.1 South Shropshire Biowaste Digester

This plant was constructed under DEFRA's New Technologies Demonstrator Programme. It was designed and installed by Greenfinch in partnership with the South Shropshire district with a capacity of 5000 tonnes each year at a cost of between £40 and £50 per tonne[18]. The biogas is converted into electricity and 800,000 kilowatts per hour is used to supply heat to the plant. The pasteurised bio-fertiliser is offered to local farmers. The plant could produce around 4,320 tonnes of bio fertiliser and 880 tonnes of biogas each year. In the future, biogas may be used in a local district heating system. It began full operation in the first quarter of 2006, processing source separated kitchen and garden waste collected from households. Presently the plant now focuses on food waste alone as high mix of garden waste inhibits biogas production.

2.6.2 Teesside Energy from Waste Plant

This is the only EfW plant operating in the North East of England. It is run by SITA Tees Valley Ltd, a joint venture between SITA UK and the four Teesside local authorities of Stockton, Middlesborough, Redcar & Cleveland and Hartlepool.
The plant has been fully operational since May 1998; operating 24hours a day, 7 days a week processing up to 4000tonnes of municipal and non-hazardous industrial and commercial waste every week. The plant produces an average of 20MW of electricity per hr; enough to supply 40,000 homes with power[12].

2.6.3 Biogen Plant, Milton Ernest, Bedfordshire

BIOGEN UK runs an AD plant at Milton Ernest in Bedfordshire which processes pig slurry and food manufacturers' waste. The plant also receives about twelve tonnes of food waste each week from Bedford County Council, Luton Borough Council and Milton Keynes Council. These councils are trialling weekly food waste collection schemes with support from the Waste & Resources Action Programme.

The plant is capable of accepting up to 30,000 tonnes of food waste and 12,000 tonnes of slurry and can produce over 1MW of electricity (enough for 1,000 homes) and over 1.5MW of heat. The bio-fertiliser produced is used on the adjacent arable farmland[6].

2.6.4 Dundee Energy from Waste Plant, Scotland

The plant is the first in the UK to use bubbling fluidised bed technology for waste treatment; it utilizes the heat released during combustion to produce steam that drives the turbines. The plant came on-line in autumn 1999; it is operated by Dundee Energy Recycling Ltd (DERL) - a joint venture between Dundee City Council and three private sector partners. The plant processes 120,000tonnes/year of municipal and commercial waste, and small amounts of non-hazardous clinical waste and liquid wastes. About 10.5MW of electricity is generated from the plant, 8.3MW of which is enough to meet the needs of 14,000 households is sold to the grid under a Scottish Renewables Obligation (SRO) contract.

3 BACKGROUND ON CASE STUDY

3.1 Introduction

This chapter gives a general background on the case study of this project – Solway Veg Limited. It considers their major activities, their processes, waste generation and current waste management practise. It concludes by considering the case for Anaerobic Digestion for Solway Veg Limited.

3.2 Solway Veg Limited, Gretna

Solway Veg is one of UK's leading quality processors and suppliers of vegetables and fruits, processing over 300,000kg of raw material every week. With a reputation that spans over twenty years, their major customers are mainly food manufacturing companies that require a regular supply of raw vegetables for use in chilled meals, sandwiches and other foods.

The ready to use vegetables are produced and delivered daily within a three hours radius of Gretna, where they are located. One of the largest customers is Marks and Spencer.

The fruits and vegetables range from carrots, onions, peppers, lemongrass, Portobello mushrooms and pink garlic to a range of organic vegetables and fruits. All produce that are bought are UK assured or its European equivalent, offering a wide-ranging selection of machine and hand-cuts; standard cuts as well as some more intricate once; i.e. diced, minced, wedges, rustic, segments, grated, juices, ribbons etc.

Fig 3.1: Range of products

At Solway Veg Limited, they pride themselves in providing a first class and reliable service with full traceability of all products with regards to a dedicated range of growers.

3.3 Site Details

The main processes involve peeling, preparation, packaging and distribution of fresh chilled vegetable and fruit products. For a normal production of 24hours/day (plus 9hours on Sunday) for onions; 9 hours/ 7day for carrots (or potatoes) and hand preparation, typical weekly output is about 120 tonnes onions, 40 tonnes carrots, 20 tonnes potatoes and hand prepared specialist products.

There are separate buildings on the site[17];

- Main building which comprises four sections – the goods in, onion peeling and process, carrot/potato peeling and process, puree making and the dispatch sections.
- The bean room, hand preparation, potato store.
- The blast chill
- Engineering Workshop
- Offices

3.4 Waste Generation

Waste is generated from most of the production process, with some processes generating more waste than others. Essentially, this occurs in the slicing and dicing room as well as in most of the peeling processes. Approximately 300kg a day of waste is generated in the dicing and slicing room. The types of waste range from vegetable waste, cardboard to miscellaneous waste i.e. gloves, paper towel etc.

- **Hand Preparation:** Here vegetables are cut and processed by hand depending on the order specification. Typical vegetables that are processed here are peppers, butternuts and baby potatoes. Lemon juice is also made in this unit, once the zests have been taken off. A large percentage of the wastes in this unit are cardboard boxes which the farm products are delivered in.

Fig 3.2: Waste vegetables from hand preparation

- **Onion Line:** This is where the largest volume of waste is generated in the factory. In this process, onions are fed into the machine in an upright position to ensure that the top, bottom and skins are removed as it goes through the machine. At the final stage, leftover skins are removed by hand before it goes though final washing and then into containers. Waste on this line is generated at every stage of this process; onion heads, skins and also onions that are too small just fall through without the skins being taken off.

Figure 3.3: Onion waste

- **Potato & Carrot line:** Here the vegetables are fed into machines where their skins are taken off; they are then washed and ready for further processing. The waste generated here are mostly the skins and a few that are defective.
- **Slicing and Dicing room:** Already cleaned vegetables are processed (sliced or diced) to different sizes depending on the order specifications. Waste is also generated in this process.

Fig 3.4: Waste carrots and potatoes

- **Miscellaneous waste:** This covers inorganic waste such as gloves, cardboard boxes, paper towels, etc. This study will not focus on these kinds of wastes.

3.5 Current Waste Management Practice

Waste management practises in Solway Veg Limited have changed over the years with industries trying to be more environmentally responsible in all their operations and processes. This section will focus on waste management practises for vegetable waste as it accounts for majority of the waste generated during production and its utilization is the main focus of this study. Waste management practises are dependent on the type of the vegetable waste. This is divided into;

- Hand preparation and onion line
- Carrot and potatoes line

3.5.1 Hand Preparation and Onion line

Currently two options are available for handling the wastes generated here. They are using the waste as stock feed or composting.

- Stock feed: Vegetable wastes are taken away by farmers at no charge to serve as feed for their animals. This accounts for two-thirds of the waste generated during production, it varies considerably with the seasons and the animals. Less waste is taken for stock feed in summer because volume sales are generally less in summer than winter (summer meals are lighter than winter meals).
- Composting: This accounts for the rest of the waste generated (one-third). The waste is taken away to a composting facility, where it is composted to produce a soil conditioner. This costs £23/tonne.

3.5.2 Carrot and Potatoes line

This is waste produced essentially from peeling the vegetables. The waste produced here is a sludge, which is allowed to settle in a pit to allow settling of the solids. The waste water flows into a canal where further sedimentation is allowed to take place before it is discharged into a sewer. The sediments are pumped out from the pit after settling and spread on agricultural land at a cost (£7/tonne). The challenge with this is getting land to spread on; wheat farmers are most likely to allow spreading. Sediments can also be spread on silage land after cutting grass.

The purchase of a machine that can compact the waste, removing as much water as is possible is being considered. This would serve two purposes; the production of a dry finished product that can be sold off to pig farmers, as feed for their pigs, and waste water that is clearer with lower solids content. The machine will cost approximately £30,000.

3.5.3 Solway Veg Ltd and the case for Anaerobic Digestion

We are concerned with the organic waste produced by the business in this study; which is vegetable waste. The main options for dealing with organic wastes are landfill, incineration, gasification or pyrolysis; or bio-digesting the waste by means of anaerobic digestion or composting. The table below presents a compares these methods.

Table 3.1: Comparism of the different technologies

Technology	Sustainable	Impact on the environment	Energy recovery	Fertiliser output	Water recovery	Heavy metal recovery
Landfill	✗ Unsustainable waste of resources	✗ Some CH_4 to atmosphere, leachates problems	✓ Partial if landfill gas extracted	✗ No fertiliser outputs	✗ Lost in leachates	✗ Not possible
Composting	✗ Energy required	✗ Damage to ozone layer, also leachates problems	✗ None	✓ Incomplete pathogen kill	✗ Lost to atmosphere	✗ Not possible
Incineration	✗ Fertiliser loss negates any energy gain	✗ Toxic ash	✓ Some but Energy wasted	✓ Some P&K output, but N destroyed	✗ Burnt off	✗ Secondary waste
Pyrolysis	✗ Fertiliser loss negates any energy gain	✗ Toxic ash, emissions regulated	✓ Some but Energy wasted	✓ Some P&K output, but N destroyed	✗ Burnt off	✗ Secondary waste
Gasification	✗ Fertiliser loss reduces energy gain	✓ Pollutants locked in slag	✓ Some but Energy wasted	✓ Some P&K output, but N destroyed	✗ Burnt off	✗ Controlled not recovered
Anaerobic digestion	✓ Carbon neutral	✓ Total recovery of energy as CH_4 CO_2 & fertiliser	✓ Maximum overall energy	✓ Clean NPK fertiliser and trace elements	✓ 100%	✓ Heavy metals can be recovered from digestate

Source: Organic Power Limited

AD is the only sustainable option with the potential to recover the maximum energy from organic waste. It operates as a closed system with no emissions to air or land; retaining the fertiliser and moisture content of the waste. It will provide a first choice option as an alternative use of waste produced by Solway Veg Ltd. Other factors that can act as incentives for the adoption of the technology are listed below:

- Electricity derived from the energy recovered from AD is eligible for Renewable Energy Obligation Certificates (ROC's). These are currently worth £44/MWh and as such can encourage greater use of AD.
- AD is also a potential source of renewable heat. Government has shown its commitment through the Climate Change and Sustainable Energy Act[16], to promote the use of renewable heat. Ernst and Young have been commissioned to analyse the case of long term support for the renewable heat sector.
- The demand for new sustainable technologies investment opportunities increasingly manifested in actions and investments by large companies and big investors. Big supermarkets in the UK are now using renewable energy technologies in their businesses, including Anaerobic Digestion. Marks and Spencer is one of the first companies to implement the use of renewables in its business activities; being Solway Veg's largest customer, incorporating AD in their operation shows a consistency in their commitment to be more sustainable in their activities.

4 ANAEROBIC DIGESTION TECHNOLOGY

4.1 Introduction

This chapter presents an overview of the AD technology. It also provides a description of the different processes involved, process parameters, regulations relating to plant design and operation.

4.2 Anaerobic Digestion

Anaerobic digestion is a biological process in which microbes, particularly bacteria, digest organic waste material in an oxygen-free environment.

The digestion process takes place in a warmed, sealed airless container (the digester) which creates the ideal conditions for the bacteria to ferment the organic material in oxygen-free conditions. There are two main types of AD process, the mesophillic digestion and thermophillic digestion.

The process generates three main products:

- Biogas – a mixture of carbon dioxide (CO_2) and methane (CH_4), which can be used to generate heat and or electricity.
- Digestate (Fibre) – can be used as a nutrient-rich soil conditioner
- Liquor – can be used as a liquid fertilizer.

AD with biogas utilization can be a source of income and may partially increase the income of the company.

4.3 AD Process Descriptions

The AD process takes place in three main phases: hydrolysis, acid and methane, with each phase characterized by the main activity of a certain group of bacteria. During the AD process, the bacteria decompose the organic matter in order to produce the energy necessary to their metabolism, of which methane is a by-product.

- **Phase 1: Hydrolysis**

This is the first phase of the process. Here, complex molecules of proteins, cellulose, lipids and other complex organics in the vegetable waste are solubulized into glucose and amino acids and fatty acids. This stage is also known the polymer breakdown stage[2].

- **Phase 2: Acid phase**

In this phase, facultative acid-forming bacteria convert the solubulized organic matter to organic acids. The principal acids produced are acetic acid, propionic acid, butyric acid and ethanol. The optimum temperature range for this phase is 30ºC[7].

- **Phase 3: Methane Phase**

The third phase results in the production of methane by methanogenic bacteria. They convert the acids produced in the second phase into methane and carbon dioxide.
The AD process is controlled effectively by this group of bacteria; they are very sensitive to pH, substrate composition and temperature. If the pH level in the digester drops below 6.0, methane formation ceases and there is more acid accumulation bringing the digestion process to a halt[28].

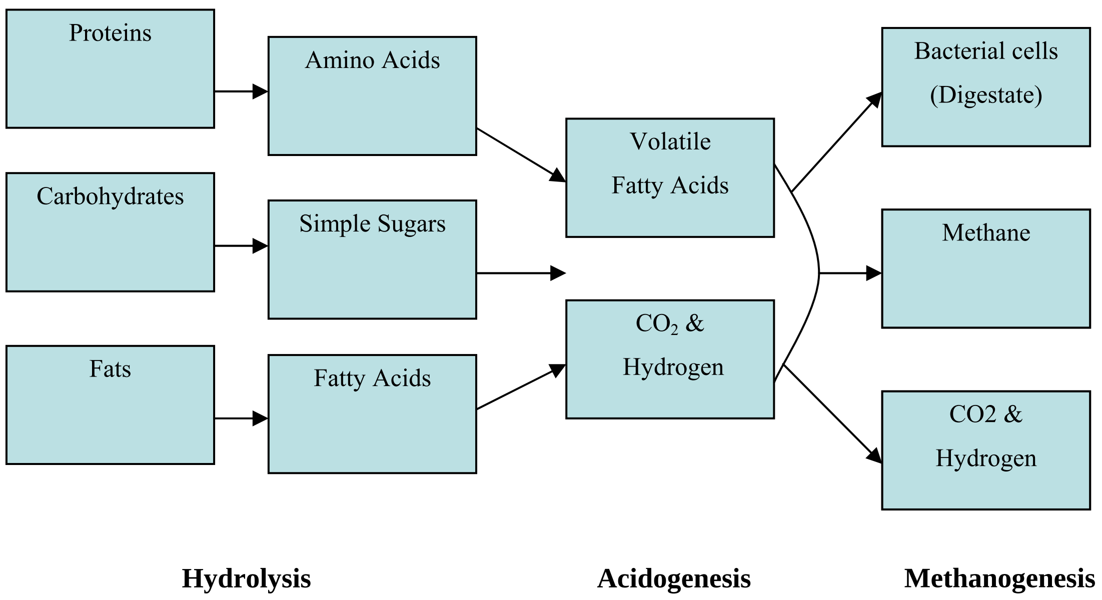

Fig 4.1: Simplified diagram of the AD process

4.4 Required Process Parameters

AD is a complex biological process dependent on many physical and chemical factors. The most important factors are temperature and pH; other factors to be considered in the successful digestion of the organic wastes are discussed in the following sections.

4.4.1 Temperature

There are essentially two temperature ranges for anaerobic digestion. The mesophillic range; this takes place optimally between 37^{o}-$41^{o}C$. It can also take place at ambient temperatures of 20^{o}-$45^{o}C$[3]. Thermophilic bacteria breakdown organic matter in the waste at higher temperatures of about $55^{o}C$. Temperatures can get up to $70^{o}C$ in some situations.

Thermophilic digester systems are less stable; however, the increased temperatures enable faster rates of reaction, thus faster gas yields. Higher temperatures provide a more sterile digestate. For the Solway Veg case, the only wastes digested are vegetable waste so there are no major causes of concern in terms of the sterility of the waste.

It is very important to maintain constant temperatures in the digester. This is because the methanogenes, which are the methane-forming bacteria, are inactive in extreme temperatures. They are unable to achieve a stable population for waste stabilization and methane formation, if temperature varies too fast[2].

4.4.2 pH

The different bacteria involved in the digestion process have different pH requirements for stabilization of the waste and methane formation. There is, however, an optimal pH value of input mixture in the digester. This is between 6 and 7.2. The pH concentration in the digester is also a function of the retention time. pH values below this range often show high concentration of volatile fatty acids and can be toxic to the bacterial populations especially the methanogenic bacteria. Higher pH ranges than 7.2 also slow down methane production.

4.4.3 Carbon Nitrogen (C: N) Ratio

The C: N ratio is the amount of carbon to nitrogen in the feedstock material. Carbon and nitrogen constitute nutrient elements required by the microbes in the digester; they however consume carbon at a faster rate than they utilize nitrogen. The optimum ratio of carbon nitrogen should assure conversion of all the available carbon to methane and carbon dioxide with the least amount of loss of available nitrogen. This will range from 20:1 to 30:1. Where the ratio is higher, the nitrogen will be exhausted while there is still a supply of carbon left, causing some bacteria to die, releasing the nitrogen in their cells. This affects the methane production as digestion takes place slowly as a result of this. On the other hand, if there is too much nitrogen, i.e. where the C: N is lower; the carbon is utilized at a fast rate, causing ammonia accumulation and its associated pH rise. This can have adverse effect on the methanogenic bacteria inhibiting methane formation. Mixed waste or co-digestion is more favourable in that waste of differing nutrient content, when digested together, balances the carbon to nitrogen ratio.

4.4.4 Dry solids content

There are two different operational parameters associated with the solids content of the digester feedstock.

High solids digesters can process thick slurries; they however require more energy input to move and process the feedstock. Low solids digesters will require less energy for processing the feedstock, the benefit of this is that the liquid environment enables a more thorough circulation of materials and contact between the bacteria and their food.

4.4.5 Loading rate

The loading rate often refers to the amount of raw materials fed per unit volume of digester capacity per day. It is expressed in volatile solids (VS)/m^3 of digester volume or Chemical Oxygen Demand (COD)/m^3 of digester volume.

Overfeeding of the plant will cause the acids to accumulate, inhibiting methane production. Underfeeding on the other hand, will cause lower gas production rate in the plant.

4.4.6 Mixing

Some means of mixing the slurry in a digester is always desirable, though not absolutely essential. If left alone, the slurry tends to settle out in layers and its surface may be covered with a hard scum which hinders the release of gas.

This is a greater problem with vegetable matter than with manure, since the animal waste has a somewhat greater tendency to remain suspended in water and, thus, in intimate contact with the gas-releasing bacteria. Continuous feeding also helps, since fresh material entering the tank always induces some movement in the slurry.

4.4.7 Retention time

The retention time refers to the average amount of time that a given quantity of input remains in the digester to be acted upon by the methanogenic bacteria. It ensures sufficient digestion of the organics.

The retention time varies with the type of digestion. The mesophillic process usually requires a longer time for complete stabilization, while the thermophillic digestion operates in a shorter period of time.

4.5 Types of Anaerobic Digesters

Anaerobic digesters—also known as bio digesters—are made out of concrete, steel, brick, or plastic. They are shaped like silos, troughs, basins or ponds, and may be placed underground or on the surface. There are two basic types of digesters[31]:

- **Batch:** Batch-type digesters are the simplest to build. Their operation consists of loading the digester with organic materials and allowing it to digest. The retention time depends on temperature and other factors. Once the digestion is complete, the effluent is removed and the process is repeated.
- **Continuous**: In a continuous digester, organic material is constantly or regularly fed into the digester. The material moves through the digester either mechanically or by the force of the new feed pushing out digested material. Unlike batch-type digesters, continuous digesters produce biogas without the interruption of loading material and unloading effluent. There are three types of continuous digesters: vertical tank systems, horizontal tank or plug-flow systems, and multiple tank systems. Proper design, operation, and maintenance of continuous digesters produce a steady and predictable supply of usable biogas. They may be better suited for large-scale operations.

4.6 Factors affecting the development of an AD plant project

The development of an AD plant project is dependent on a number of factors. The figure below shows the main areas to be considered before incorporating an AD plant system as an onsite or centralized method of waste management.

The following sections will consider these factors with respect to the case study of this project; Solway Veg Ltd.

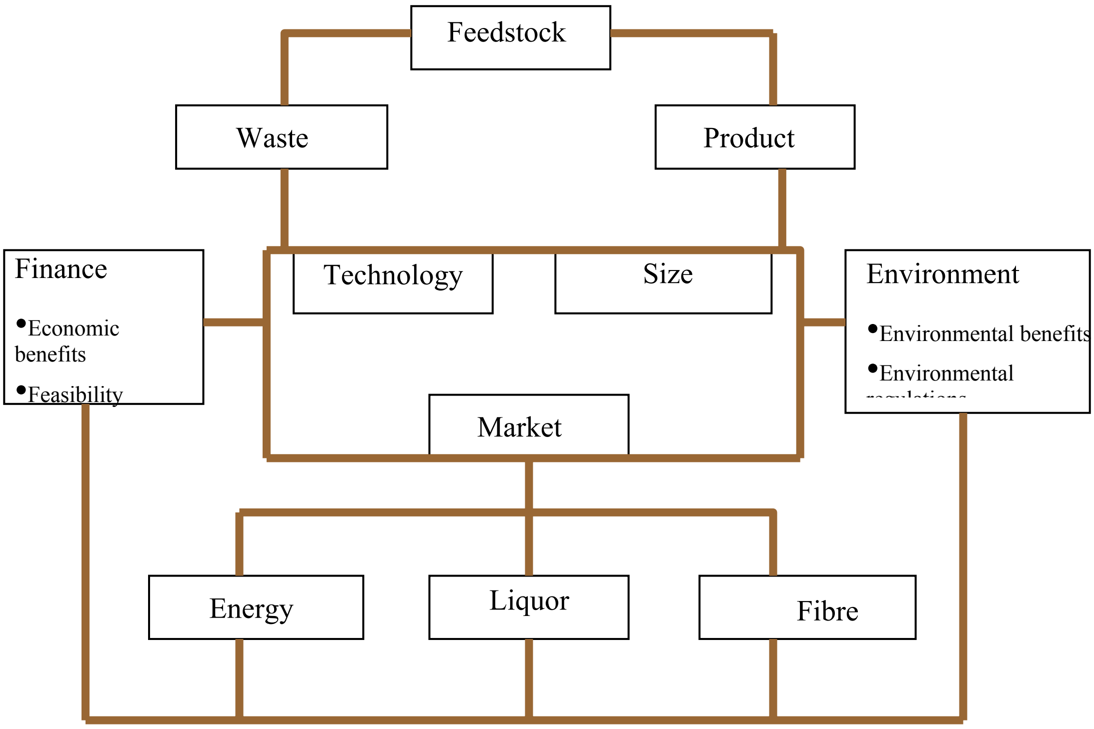

Fig 4.2: Factors affecting the development of an AD plant

Source: Anaerobic Digestion of farm and food processing residues Good practise guidelines.

4.7 Feedstock

The main feedstock in this project is vegetable processing wastes. The vegetable waste in this case consists mainly of onion skins, carrots, peppers and other vegetables processed onsite.

It is wet, and this together with intrinsic properties produces a total water content of c85%, with a corresponding dry solids content of 15%. Approximately 3500 tonnes of waste are available per annum.

The quantity and quality of feedstock is dependent on the priority for output of the plant. In this case, the priority is maximising gas yields; the key factors here will organic matter content and the percentage of dry matter (5-12.5% maximum of feedstock should be dry/solid waste). For food processing waste, with a dry matter content of 15, will give a biogas yield of 46m^3/tonne of feedstock. This has an energy value of 21-25MJ/m^3 biogas[3].

The quality of the feedstock in terms of its gas yield is partly dependent on the freshness of the supply i.e. the fresher it is, the higher the gas yield will be and the less chance of it becoming acidic.

The loading system required for the digester is dependent on the consistency of the feedstock.

4.8 Products of AD

The AD process creates biogas, fibre and liquor. In order for a scheme to be financially viable, uses for all the products need to be developed and balanced.
The balance of thee different products from AD is shown in the figure below.

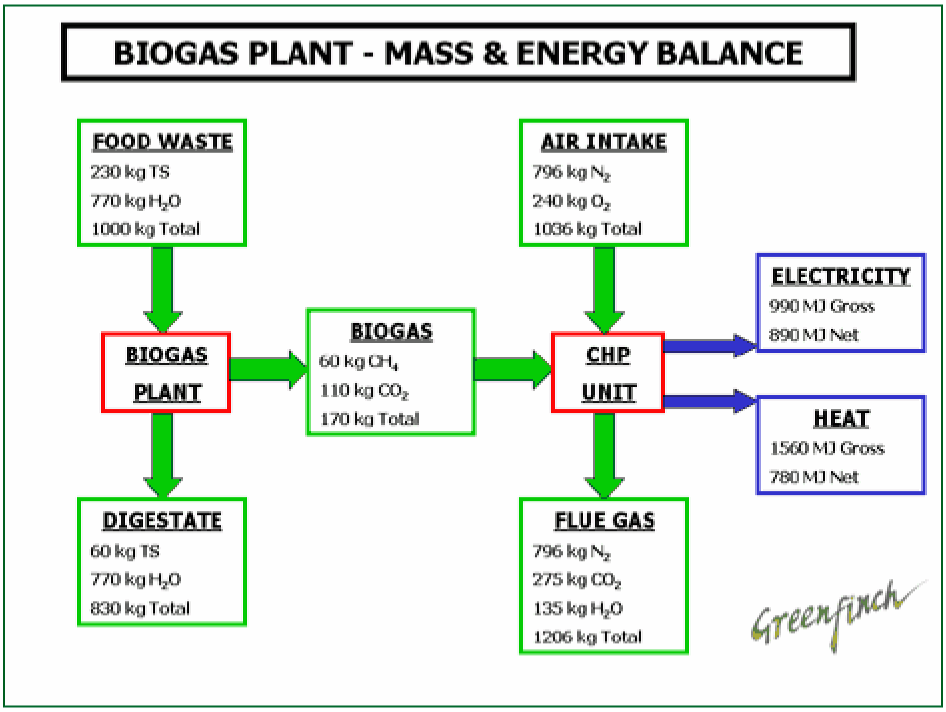

Fig 4.3: Mass balance of Anaerobic Digestion Process

Source: http://www.greenfinch.co.uk/mass.html

4.8.1 Biogas

This is made of mostly methane (approximately 60%) and carbon dioxide with traces of other gases such as ammonia and hydrogen sulphide. The gas is considered to be an environmentally friendly energy source for a number of reasons. The first is that the carbon dioxide is from an organic source with a short carbon cycle. It does not contribute to increasing carbon dioxide concentrations. The amount of gas produced is dependent on the quality of the feedstock.
The biogas produced through the AD process needs to be cleaned as soon as possible after generation for two main reasons; hydrogen sulphide produced is foul smelling and corrosive as it reacts with moisture in the biogas to form sulphurous acid during combustion; this could damage the engines for power generation. Carbon dioxide, on

the other hand, occupies space without providing any extra benefit, though the removal of hydrogen sulphide is a greater concern. Methods of removing the gases are outlined below;

Dry based process: This is a dry-based chemical method that is simple and cost effective for H_2S removal. It involves passing the biogas through a bed of steel wool or iron oxide in a glass container. Examples of dry-based chemical methods are the iron sponge and the potassium hydroxide impregnated activated carbon method.

Biological Removal Techniques: This is more capital intensive than the dry based process, it however offers the advantage of lower labour costs and improved environmental impact. Biomethane is one the companies that specialize in this technology.

Carbon dioxide is removed by passing the gas through a water spray tower. This is a simple scrubbing operation where the CO_2 is scrubbed by water falling down the tower which is collected at the bottom of the tower and then sprayed down a second column to release the CO_2 from the water before it is vented out.

4.8.2 Digestate

The digestate produced can be further separated into the liquor and fibre, the quality of which is dependent on the quality of the feedstock.

Fibre: This is an organic material composed largely of lignin. It is bulky and contains a small amount of plant nutrients. It can be used as a soil conditioner.

Liquor: This is often used as a fertiliser. It is rich in nutrients and as a result of its high water content; it has additional irrigation benefits. The level of potentially toxic waste is low for the feedstock as it essentially vegetable waste. The digestate would pose little or no problems in terms of handling and utilizing them.

4.9 Legislative Framework for incorporating AD

There are many legislative requirements to be fulfilled when an AD plant uses the Biodegradable Municipal Waste (BMW). Presently, the proposed biogas plant (which uses vegetable waste) will be subjected to key UK and EU legislation. The following sections will consider these legislations generally, and with respect to the plant.

4.9.1 EU Landfill Directive 1999/31/EC

The EU Landfill Directive was adopted in April 1999. It includes statutory targets for the reduction of the land filling of municipal waste of organic nature (kitchen waste, garden waste, paper, card, textiles and wood). The justification is that the uncontrolled decomposition in a landfill causes: the emission of methane (a very potent greenhouse gas) and of carbon dioxide; the production of leachates; and the attraction of vermin. Food and vegetable wastes are by far the fraction of biodegradable waste that has the greatest environmental impacts. A biogas plant use a similar process to that taking place in a landfill site, the key differences being that the former is contained & controlled, and takes only one month compared with many years in a landfill. An AD is a suitable technology for meeting the biological waste diversion targets.

Different countries have set criteria using 1995 waste data figures. In the UK, set targets are shown below:

Year	**% BMW to landfill**
2010	75% of 1995 levels
2013	50% of 1995 levels
2020	35% of 1995 levels

4.9.2 Scottish and DEFRA Animal By-Products Regulations

Enacted Oct 2003 – National Regulations in compliance with EU Animal By-Products Regulation. These follow the same guidelines as set forth in the EU document, with a few additional definitions and requirements.

Premises Requirements: In relation to Biogas and AD plants, there is further definition on the cleaning and reception areas within a plant. There shall be a clean area in which treated compost of digested residues are stored, reception area; a vehicles and containers cleaning area.

- The clean area shall be adequately separated from the reception area and the area in which vehicle cleaning area so as to prevent contamination of the treated material. This will be that liquid cannot seep into the clean area from the other areas.

- The reception area shall have an enclosed and lockable place or container to receive and store the untreated animal by-products.
- Containers, receptacles and vehicles used for transporting untreated animal by-products shall be cleaned in the dedicated area before they leave the premises and before any treated material is loaded. In the case of vehicles transporting only untreated catering waste and not subsequently transporting treated material, only the wheels of the vehicle need be cleaned.

4.9.3 Process Requirements

Pasteurisation of material is defined as either;

- 1 hour @ 70^{o}C minimum particle size 6cm
- 5 hours @ 57^{o}C minimum particle size of 5cm
- In addition to pasteurisation of material, a barrier of average 18 days storage of digestate is required-during or after process.

Implications for the proposed plant: Additional capital and operational costs that accrue as a result of compliance with the detailed requirements of the animal by-products regulation, will not apply here as the proposed plant is designed to handle vegetable waste which will not require pasteurisation.

4.9.4 Pollution Prevention and Control (Scotland) Regulations 2000 (PPC Regulations)

The following biological treatment processes are subject to regulatory control under the PPC regime:
S5.3A(c) - Disposal of non-hazardous waste in plant with a capacity >50 tonnes per day by biological treatment specified in paragraph D8 of Annex IIA to Council Directive 75/442/EEC on waste. Where the capacity of a biological treatment process is less than the respective thresholds identified above, it will fall under the WML Regulations.

4.9.5 The Control of Pollution (Scotland) Regulations 2001

Slurry, including manure, urine, bedding and dirty water from farming activities, is highly polluting to watercourses. It should never be allowed to enter a watercourse or land/ surface water drain. If farm effluent is to be discharged to the foul sewer, a written trade effluent consent from the statutory sewerage undertaker, Scottish Water is required.

These regulations will require the farmers to provide notification of any new slurry/digestate holding tanks built on their farms as part of the Biogas project. The farmers are currently operating under these regulations.

4.9.6 Control of Pollution Act 1974

The Control of Pollution Act 1974 (COPA 1974) controls discharges of poisonous, noxious or polluting substances to controlled waters in Scotland. Prior to the 1990 EPA, The Control of Pollution Act made wide ranging provisions with respect to waste disposal, water pollution, noise, atmospheric pollution and public health. Most of COPA has been superseded; however, COPA 1974 still has importance in Scotland for control of pollution from liquids and protection of groundwater.

Businesses intending to discharge such substances, or those discharging trade or sewage effluent directly to controlled waters, must have an authorization from SEPA. Authorizations contain conditions on both the quality and quantity of effluent permitted.

Under COPA it is an offence to discharge noxious substances to the environment, either to land or sea. COPA could be used to prosecute farmers causing pollution through ill-advised slurry spreading but the proposed plant is not using any noxious material so COPA is not applicable to the proposed plant.

4.10 Benefits of the AD technology

AD projects have several benefits, depending on the priorities of the plant management. The main reasons for developing an AD project are summarized below:

4.10.1 Environmental Benefits

- AD is an integrated waste management technique that can be used to reduce pollution considerably.
- AD offers the opportunity to capture methane from manures and effluents leading to reduction in emissions to the atmosphere because the methane is converted into carbon dioxide (CO_2), a less potent greenhouse gas.
- AD can reduce the risks of the spread of disease and contamination by destroying bacteria, viruses and weed seeds.

- Improved air and water quality is achieved when an AD plant is operated properly and the digestate is applied correctly to land.

4.10.2 Commercial Benefits

- AD can generate income by charging gate fees, selling biogas (as electricity or heat) liquor and fibre products.
- AD can produce savings by avoiding the costs of synthetic fertilisers, soil conditioners and energy from other sources.

5 DESIGN OF PROPOSED PLANT FOR CASE STUDY

5.1 Introduction

This chapter presents the details of the proposed biogas plant for the case study. It gives biogas calculations in the proposed plant.

5.2 Design Criteria

Key factors to consider in the design of an AD plant:

- Cost
- Size
- Availability and type of organic feedstock material.
- Design should cater to the needs of the business.
- Design of the plant must promote safe working conditions for the operator.
- Environment threats must be eliminated.

This design provides a simple robust solution to AD design better suited to the needs of Solway Veg Ltd. The parameters for the digester design are;

- Batch Process
- Mesophillic Digestion @ 39^{o}C

5.3 Plant Process Layout

All anaerobic digestion system designs incorporate the same basic components; a basic layout for the process plant is shown below, with a brief description of the key components.

- A reception pit/tank used for short duration storage where its contents are homogenised by a chopper pump which reduces the particle size and pumped to the digester on a regular basis to maintain the set residence time in the digester.
- The feed to the digester is pumped using a progressive cavity pumps which enables the metering of the input and output. The feed pump is usually protected from coarse materials by an in-line macerator.

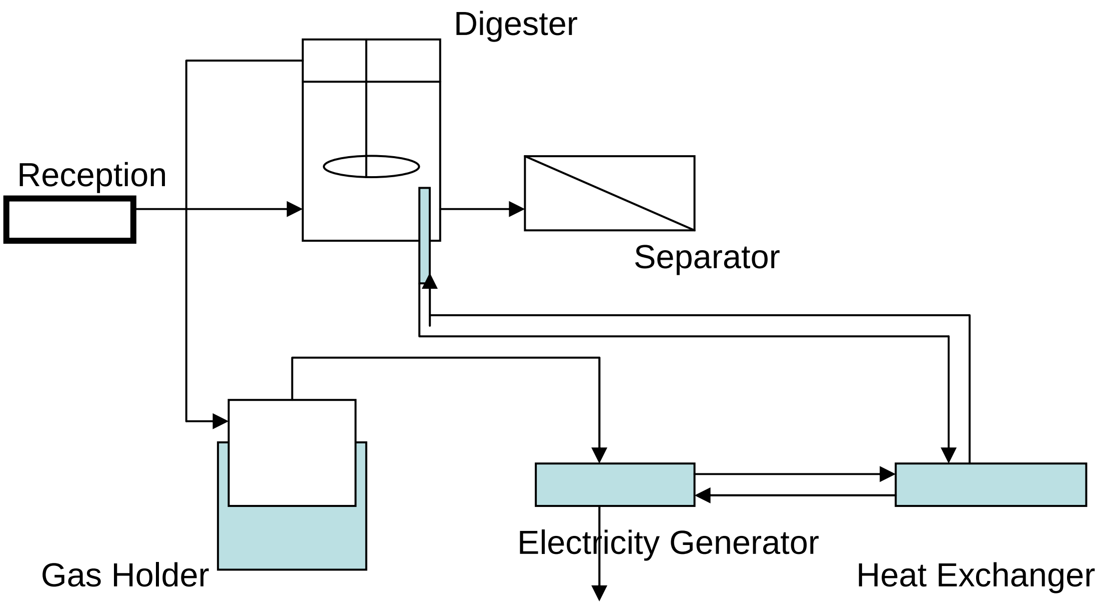

Fig 5.1: AD plant layout

- The digester is a gas tight tank usually thermally insulated, and constructed with the aim of preventing sedimentation of the waste particles. It is equipped with a mechanical or gas mixing system which keeps the wastes in a homogenous state, thus optimising the digestion process and minimising any gradients of temperature, solids, substrate, and gas concentrations in the digested mass. Furthermore, the digester will also have a system (a heat exchanger) for maintaining the process temperature at either around 37°C or 41°C. The only disadvantage of having moving parts in the digester is that they require maintenance and the process of emptying a digester for maintenance is prohibitively expensive.
- The biogas produced from the digester is directed to a small bell-over-water gas holder which also acts as pressure regulator. Biogas is normally de-sulphurised, to remove hydrogen sulphide before it is passed to a compressor and then to a boiler. The use of compressor eliminates any condensate formed and thus increases the equipment life. The boiler is installed according to the heating requirements of the plant.
- Digested vegetable waste is stored in an above-ground tank capable of holding the digestate until it is utilized. The digestate is made up of liquid and fibrous materials and which can be separated usually by a centrifuge, to produce compostable solids and liquor rich in plant nutrients.

- All the above-ground tanks are fabricated in glass-coated steel panels and the digester has a stainless roof. The installation is kept relatively simple. The operation of the digester is fully automated with the exception of filling the reception tank and the unloading of the digestate tank. The levels in the reception tank, digester, digestate tank and gas holder and the temperature in the digester and in the heating circuits are monitored.

5.4 Waste Stream Characteristics

The proposed plant is designed to handle predominantly vegetable waste. It is wet, and consists mainly of onion skins as well as potatoes, carrots and other hand prepared vegetables.

This analysis will assume an average weekly output of 50 tonnes

Moisture Content = 85%

Dry Solids content = 15%

Volatile Solids content = 77%[1]

5.5 Operating Parameters Calculation

These parameters were obtained using the biogas conversion primer[22]

5.5.1 Batch Size and System Volume

Weight of vegetable waste = 50tonnes/week = 50000kg/week

In 1day = 7142.85kg ≈ 7150kg

TS in waste = %TS * weight of waste = 7150 * 15%

= 1072.50kg

Batch Size = TS in the waste/%TS

= 1072.5/0.15

= 7150kg

Assuming a HRT is 20days;

The required system volume = 7150 * 20

= 143000litres

$= 143m^3$

Design volume of tank = 143 m^3

5.5.2 Organic Loading Rate

Organic Loading Rate, OLR = VS/System Volume

VS in vegetable waste = VS% of TS

= 77% * 1072.5

= 825.825kg

Therefore OLR = 825.825/143

= 5.775kg VS/m^3/day

5.6 Energy Calculations

5.6.1 Methane Yield

Assuming a digestion efficiency (DE) of 80%

VS converted to biogas = VS in the waste * DE

= 825.825 * 80%

= 660.66kg

Assuming biogas density = 1.14kg/m^3

Total gas produced = 660.66/1.14 = 579.526m^3

Assuming CH_4 content of 65%

Total CH_4 = 65% * 579.526m^3

= 376.69m^3

Therefore Methane Yield = Volume of methane/VS in the waste

= 376.69/825.825

= 0.456 m^3 CH_4/kg VS added

5.6.2 Methane Production Rate

This is determined using the Total Methane and System Volume:

Methane Production Rate = Total Methane/ Digester Volume

= 376.69/145 m^3/m^3-day

≈ 2.60 m^3/m^3-day

5.6.3 Energy Yield

This is estimated at 11.04kWhr/m^3 methane[7]

Recall that vol. of methane produced = 376.69m^3 per day

Energy Yield = 11.04kWhr/m^3 * 376.69m^3

= 4158.6576kWhrs per day

5.6.4 CHP Production

Assuming efficiency of 80% CHP conversion; with 30% electricity and 50% heating

- **Electricity generation**: 30% of 4158.6576Whrs = 1247.60kWhrs per day = 4491.36MJ per day

Therefore, in 1 year, electricity produced ≡ 1639346.4MJ = 455.374MWhrs.

Process Electricity requirements: 124.76kWhrs per day. This is taken as approximately 10% of electricity generated[24]. This is equivalent to 45.54MWhrs per year.

Surplus Electricity available: 409.83MWhrs per year

- **Heat generation**: 50% of 4158.6576kWhrs = 2079.329kWhrs per day = 7485.584MJ per day.

In 1 year, heat produced by CHP ≡ 2732238.043MJ = 758.955MWhrs

Process Heat requirements: This is taken as 50% of heat generated[18]. 1039.665kWhrs per day which is equivalent to 379.478MWhrs per year.

Heat surplus available: 379.477MWhrs per year

6 ECONOMIC ANALYSIS OF THE PROJECT

6.1 Introduction

The economic analysis is carried out to establish the in detail the economics of an AD process. It will consider the markets involved in the process as a possible source of income, the costs involved as well as funding sources available to Solway Veg Limited.

6.2 Energy Market

The AD plant provides biogas which is used to generate two forms of energy, electricity and heat, in combined heat and power (CHP) units of gas engines. Excess electricity generated in the process can be sold under the Renewable Obligation Certificates (ROCs), Carbon Credits and Climate Change Levy Exemption Certificates (LECs). If a plant were to sell electricity to supply companies a Power Purchase Agreement contract would be enacted. Normally this guarantees the purchase of electricity at a set price for a fixed period of time, and locks both the buyer and generator into a contract with some security. It could be expected that, due to the different schemes like Non-Fossil Fuel Obligation, the electricity could be sold for approximately £0.45 to 0.06/kWh.

The sale of heat for heating large complexes such as hospitals and factories, or providing heat for district heating brings further revenue to the AD plant operator.

Income may also be generated from the generation of gate fees from the waste streams imported to the plant (similar waste streams). Landfill tax and additional costs are now major cost component for many businesses, and if AD were to offer an alternative to landfill at a similar or slightly lower cost then this can greatly increase the financial viability of a plant.

6.2.1 Energy Income for Solway Veg Limited

Electricity: Surplus electricity generated = 409.830MWhrs per year

If sold at 6p/kWhr = £24,589.80

Heat: Surplus heat generated = 379.477MWhrs per year

Sold at 3p/kWhr = £11384.31

The cost of digestate is not known yet; the proposed system can be expected to generate an annual income of £35947.11

6.3 Market for Digestate

The digestate from anaerobic digestion contains useful nutrients and can be used as a fertiliser and soil conditioner. The sale of this digestate is a potential source of income for the business. DEFRA is working to establish full potential of the market for digestate. WRAP is charged with developing this market along with its work to establish markets for waste-derived compost. Nearby farms present a potential market for digestate produced in our case study; the regulations applying to use of AD products from animal waste sources do not apply here because of the type of waste involved.

6.4 The Cost of the AD Plant

Anaerobic digestion is a proven technology but it is not a simple process. It requires storage space for the raw and treated material, dosing pumps, a gas tight reactor with heat exchanger and mixing facilities, a bio-gas reservoir, boiler and/or internal combustion engine with an electrical energy generator.

To make the process economical, with a minimal payback period, a high percentage of biogas has to be utilised. This target is where electrical energy/heat co-generation is the incorporated in the design.

The cost of the AD plant is separated into the capital costs, annual running costs and revenue streams. The capital and running costs are dependent on the size of the unit, quality of materials used and management skills.

6.4.1 Capital Costs

This is also known as the Total Capital Investment (TCI); it includes all costs required to purchase the necessary equipment; the costs of the materials and labour needed to install that equipment and the cost of permit applications (the direct installation costs); the costs for site preparation and buildings; and the cost for engineering, contractor fee, contingencies, and other indirect installation costs. The costs for land, working capital, and offsite facilities are also included in the TCI**.**

The capital costs associated with the anaerobic digester are:

- ***Digester***. Biogas is generated by the digester according to the amount of feedstock added.
- ***CHP***. The cost of the CHP is the additional capital cost of installing a CHP unit that utilises the biogas to generate electricity and heat. With an expected efficiency of 80% (30% electrical and 50% heat efficiency). Surplus CHP units can be sold to energy companies.
- ***Separator (if this option is considered)***. The second output of the digester is the liquid digestate. Whilst the digestate can be applied directly to the fields as a fertiliser, it can also be separated into its solid and liquid components. The solid component is similar to compost and can be sold (if there is a market for compost). It is assumed that 10% of the digestate can be recovered as solid material when a separator has been added to the digester.
- ***Start up***. The start up costs cover the initial cost of the fuel required to heat the digester up to its optimum temperature. Once the digester temperature has been raised sufficiently, the biogas generated can be combusted to maintain the digester temperature. This model assumes that the digester only has to be started once and does not need to be restarted during its operational lifetime.
- ***Grid connection***. The cost of grid connection is only applied when a CHP is included with the AD plant. This cost includes the capital cost of connecting the generating engine to the local electricity supply network safely. We have assumed that all necessary network re-enforcements are undertaken by the grid operator and that costs are applied to the business according to the OFGEM guidance.
- ***Storage tanks.*** In addition to the tanks available on the farm, it would be necessary to install another tank to accommodate the increased plant capacity due to addition of energy crop to the feedstock.
- ***Compressor/pumps.*** The feedstock from the vegetable tank will be fed into the digester using a chopper pump. This is necessary to prevent clogging of the pump by solid particles in the waste. The compressor is required to remove the moisture content of the biogas.

The British Biogen estimates the Capital Cost of an AD plant to be between £3000 - £7000 per kW_e (what is the meaning of kW_e) produced[6].

Taking the mean of these values and calculating electricity produced for this case study, the Capital Cost of the plant can be computed as follows:

1year = 8760hrs

Annual electricity generated is 455.374MWhrs = 455374kWhrs = 51.9kW ≈ 52kW per year

Therefore plant cost ≡ £4000 * 52 = £208,800

- Annual operating costs: This is taken as 5%[7] of the capital costs Capital Cost = £10440
- Revenue streams: This is estimated from the cost of selling surplus electricity and heat. For this case study, the annual income is £35947.11

This leaves an annual profit of £25,507.11 Solway Veg Limited.

The final figures that represent the profitability of the plant are the Net Present Value (NPV).The **Net Present Value** of the plant indicates how much money the plant will generate over its 10-year life cycle, related back to present day values. This figure should be positive and larger than the cost of the initial investment to represent an investment that will be able to pay of the initial costs and generate a return on investment. For this case study, the NPV @ 5.75% interest rate and project lifespan of 10years is £242,792.54

The resulting positive NPV of the above project is £242792.54. This indicates that pursuing the above project is optimal.

6.5 Sensitivity Analysis

This analysis was carried out to assess the financial sensitivity of the proposed plant. The analysis takes into account, variations in electricity and heat sale prices as well as variations in methane production.

Recall that for Base Case;

7.15 tonnes of vegetable waste yields = 376.69m^3 of methane/day

1 tonne of the waste = 52.68m^3 of methane/day

Electricity sale price: 6p/kWhr

Heat sale price: 3p/kWhr

Annual Income: £25,507.11

Interest rate: 5.75%

Life cycle: 10yrs

NPV: £242792.54

Case 1: Assumes a 20% reduction in the volume of methane produced.

1 tonne of vegetable waste = 42.14m^3 of methane/day

Electrical sale price 6p/kWhr

Heat sale price 3p/kWhr

Interest rate: 5.75%

Annual Income: £18327.85

Life cycle: 10yrs

NPV: £226131.30

Case 2: Assumes the cost of power and heat are 4p and 2p respectively

1 tonne of the waste = 52.68m3 of methane/day

Electrical sale price 4p/kWhr

Heat sale price 2p/kWhr

Interest rate: 5.75%

Annual Income: £13542.74

Life cycle: 10yrs

NPV: £221606.37

6.5.1 Conclusion of Analysis

These calculations indicate that the proposed plant is profitable; variations in energy sale prices and yield have indicated a positive NPV. This profitability can be guaranteed by selling all of the surplus electricity to the grid under a renewables agreement and either selling all of the heat.

It should be noted that the possibility of obtaining grant (up to 50%) and other possible streams of income earlier identified would make the construction and operation of a biogas plant financially viable.

It was necessary to perform the sensitivity analysis to see how expected cash flow would fluctuate with various changes in cost variables. The results show that we can comfortably conclude that design is very elastic and robust with a worst case NPV of £221606.37

6.6 Funding Sources

High capital costs involved in the installation of an AD plant could prove a barrier to the project for Solway Veg. Sustainable waste management and renewable energy projects such as this eligible to receive funding from a wide range of sources. Grants from UK and European sources are potentially available for the project. Some of the possible sources are presented below:

6.6.1 Lottery Funded Programmes

A range of funding programmes is available from National Lottery Sources. These include the "Renewable Energy Programme", the "Green Spaces and Sustainable Communities Programme" and the "Green Spaces Scottish Land Fund Scheme".
The Big Lottery Fund is calling on organisations working within the small-scale biomass heat sector to help channel the final £2 million in lottery good cause funding from the Fund's Renewable Energy programme.

The Bio-Energy Capital Grants Scheme (BECGS) is welcoming new applications, of between £50,000 and £500,000**,** from projects working with small-scale biomass fuelled heat installations or biomass fuelled CHP installations.

The scheme aims to promote the efficient use of biomass for energy, in particular the use of energy crops, by stimulating the early deployment of biomass fuelled heat and electricity generation projects[33].

6.6.2 The Renewables Obligation Scotland (ROS)

The Renewables Obligation came into force in April 2002, and requires licensed electricity suppliers to source at least part of their electricity from renewable generation. The amount of the Renewables Obligation starts at 3% of total electricity supplied to customers in Great Britain in 2002/2003 and reaches 10.4% in 2010/2011.

A licensed supplier can meet its Renewables Obligation by producing ROC/ROS to Office of Gas and Electricity Markets (OFGEM) or making a buy-out payment or a combination of both. The Government has reinforced its commitment to the scheme by announcing in December 2003 an intention to consult on an increase in the level of the Renewables Obligation for the years between 2010/2011 and 2015/2016. This has increased the demand for renewable generation quite considerably in recent years. It is envisaged that a biogas plant if installed would qualify for ROS certification and therefore the electricity generated would be sold to an electricity supplier at an attractive price.

6.6.3 Intelligent Energy – Europe

Intelligent Energy Europe (IEE) is the Community's support programme for non-technological actions in the field of energy, specifically in the field of energy efficiency and renewable energy sources. Eligible applicants could receive grant up to 75% of their project cost[34] the programme is structured into four fields, one of which is relevant: -

ALTENER - promotion of new and renewable energy sources for centralised and decentralised production of electricity and heat and their integration into the local environment and the energy systems Under the ALTENER programme these are the programmes that are applicable to biogas applications:

- **Electricity from renewable energy sources (RES-e)**, to support EU policy by tackling barriers to market growth and helping to achieve future renewable energy targets.
- **Renewable energy heating/cooling (RES-H/C)**, to promote greater use of biomass, solar and geothermal heating and cooling, especially in buildings and industry.
- **Domestic and other small-scale RE applications**, to increase use of small-scale renewable energy systems in buildings, in line with the Energy Performance of Buildings Directive, and to promote use of small-scale stand-alone RE systems.

- **Biofuels**, to promote use of sustainable forms of biodiesel, alcohols, biogas and bioadditives to replace fossil fuels for transport applications and to contribute to achieving future EU targets.

7 CONCLUSION AND RECOMMENDATIONS

7.1 Introduction

This chapter outlines the key conclusions drawn and the recommendations made as a result of this research. It is useful to recap the initial objectives of this project;

- Review the different energy from waste technologies available and choose the one that is most suited for Solway Veg Limited.
- Undertake a detailed study of the chosen technology.
- Deliver recommendations to Solway Veg based on the findings as regards managing their waste.

7.2 Conclusions

The project has investigated the feasibility of integrating an Anaerobic Digester plant for Solway Veg Limited as a cost-effective, sustainable as environmentally responsible energy from waste technology option for managing their organic waste. This is in line with the company's interests in sustainability issues. The following conclusions have been drawn from this project.

- Anaerobic digestion is a net energy producing process. Surplus biogas can be used to generate electricity and thus defray the cost of the process. Also, the excess of heat can be sold off for district heating purposes.
- By producing energy from non-fossil derived fuel, it reduces the impact on global warming.
- That most anaerobic digestion plants and feed stream combinations provide beneficial energy balances. The energy produced in the CHP engine outweighs the energy required to transport the feed & digestate and to operate the plant.
- The anaerobic digestion of vegetable wastes produced by Solway Veg Limited is financially viable option, a resulting positive NPV of £242792.54, indicates that pursuing the above project is optimal.
- Funding and grants up to 50% of project cost should be available from a variety of UK and EU sources

- The plant is considered to be feasible and commercially sound.
- The project is environmentally friendly and therefore should not attract any resistance from the neighbouring community

7.3 Recommendations

The system that is proposed to Solway Veg Limited as a result of the foregoing analyses is based on a biogas plant that will process all the wastes produced; generate heat and electricity via a CHP engine whose main technical and financial details are presented in Appendix 1.

The following are recommended for further work:

- Cost impact of charging gate fees for vegetable wastes from other sources.
- Cost of utilising a continuous process as opposed to batch anaerobic digestion process.

APPENDIX 1: PLANT PROCESS REQUIREMENTS

Anaerobic Digester

Hydraulic Retention Time	-	20 days
Digester Volume	-	$143m^3$
Batch Size	-	7150kg
Organic loading rate	-	$5.775kgVS/m^3/day$
Volatile Solids Reduction	-	77%
Volatile Solids Destroyed	-	660.66kgVS/dayday
Biogas Production	-	$579.526m^3/day$
Methane Yield	-	$0.456\ m^3\ CH_4/kg\ VS$

Process Heat Requirement

Digester Temperature	-	39^oC
Ambient Temperature	-	5^oC
Total Digester Heat Requirement	-	3742.79MJ/day

Energy Production

Biogas Production	-	$579.526m^3/day$
Methane Production @ 65%	-	$376.69m^3$ per day
Energy @ 39.74MJ per m3 methane	-	14971.17MJ/day

Combined Heat & Power

Efficiency of Electricity generation	-	30 %
Electricity Production	-	1247.60kWhrs/day
Efficiency of heat generation	-	50 %
Heat Production	-	7485.58MJ/day
CHP availability	-	95 %
Annual electricity production	-	455.374MWhrs/year

Process Electricity Requirement

Process electricity requirement	-	124.76kWhrs/day

Value of Energy

Gross annual electricity output	-	455.374MWhrs/yr
Surplus Electricity Production	-	409.83MWhrs/yr
Unit Value of Renewable Electricity	-	£47.74/ MWhr
Value of Electricity	-	£18565.28 per year
Gross annual heat output	-	2.73million MJ
Surplus Heat Production	-	1.37million MJ/yr

Physical Characteristics

Diameter of digester tank	-	7m
Height of Digester Tank	-	5.5m
Thickness of Insulation	-	50 mm
Average Thermal Conductivity of Insulation	-	0.030 W/m°C

APPENDIX 2: LIST OF ABBREVIATIONS

AD:	Anaerobic Digestion
BECGS:	Bio-Energy Capital Grants Scheme
BPEO:	Best Practise Environmental Option
BMW:	Biodegradable Municipal Waste
C:	Carbon
CHP:	Combined Heat and Power
CH_4:	Methane
COD:	Chemical Oxygen Demand
DEFRA:	Department of Environment, Food and Rural Agriculture
DS:	Dissolved Solids
EfW:	Energy from Waste
EPA:	Environmental Protection Agency
EU:	European Union
IEE	Intelligent Energy Europe
IPCC:	Intergovernmental Panel on Climate Change
MBT:	Mechanical Biological Treatment
MJ:	Mega Joules
MSW:	Municipal Solid Waste
NIMBY:	Not In My Back Yard
OECD:	Organization for Economic Co-operation and Development
OFGEM:	Office of Gas and Electricity Markets
SEPA:	Scottish Environmental Protection Agency
UK:	United Kingdom
VS:	Volatile Solids

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