Automatic Site Selection of Anaerobic Digestion Plants: A Sustainable Development Tool

Thesis in partial fulfilment of the degree of Master
of Science in Energy Systems and the Environment

By

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1 Copyright Declaration

2 Acknowledgments

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3 Abstract

Industrial developments over the past two hundred years have improved the quality of life for many people in various ways. But it has also caused escalating damage to the ecological and environmental factors on which our continued health and safety depends upon.

Sustainability is at the forefront of nearly all recent environmental legislation, which aims to mitigate and reverse this ecological damage. Two significant areas, where sustainability is essential, is energy production and waste management.

This project researches the sustainability issues surrounding anaerobic digestions as a method of waste management and as a source of heat and electricity. It will comprise of the following sections -

- Introduction and discussion of sustainability; in particular the two key areas which affect AD; energy and waste.
- Introduction of the AD process and drivers for such a method of waste management and energy production in central belt Scotland.
- Production and testing of a geographical analysis tool to allow for an automatic site selection, using central belt Scotland as a test location.

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6 Introduction

Industrial developments over the past two hundred years have improved the quality of life for many people in various ways. But it has also caused escalating damage to the ecological and environmental factors on which our continued health and safety depends upon.

The past 20 years have seen a growing recognition that the current developmental demands cannot be long-term. From the loss of biodiversity to the effect of carbon emissions, the current consumption patterns are having a detrimental effect on the environment and its inhabitants. This is placing an increasing burden on the planet which cannot be sustained.

It is clear that this method of development cannot continue indefinitely. What is needed is sustainable development, which allows all people to meet their basic needs and improve their quality of life, "without compromising the ability of future generations to meet their own needs." [1]

Sustainable development can be more simply defined as a better quality of life for everyone, now and for generations to come. It encompasses economic development, environmental protection as well as a social justice. The main objectives can be classed as:

- Balanced and equitable economic development
- High levels of employment, social cohesion and inclusiveness
- A high level of environmental protection and responsible use of natural resources
- Coherent policy making in an open, transparent and accountable political system
- Effective international co-operation to promote sustainable development globally

During the World Summit on Sustainable Development in Johannesburg (2002), it became clear that suitable mechanisms are required to provide these objectives. This huge challenge needs a concerted effort from governments and industries to achieve the overall goal of sustainable development.

Over the next decade, a major challenge for the EU will be to produce more welfare using fewer natural resources and more human resources. At the Gothenburg European Council in June 2001, EU leaders endorsed a strategy for sustainable development, stressing "the importance of decoupling economic growth from resource use." [2] This is needed as there has not been a reversal of trends in the state of the environment. In practice, most of the progress achieved at the level of environment policies has been cancelled out by economic growth.

The promotion of the sustainability agenda requires concepts, technologies and methodologies. But to assist in this goal, the issues must be fully understood.

7 Objectives

AD is a potential method of waste management and as a source of heat and electricity. With ever-tightening waste disposal regulations and an increased demand for sustainable process, this thesis will consider AD as a process to manage human sewage waste. It will focus on three main areas;

- Introduce and discuss sustainability; in particular the two key areas which affect AD; energy and waste.
- Introduce the AD process and cover the advantages and disadvantages which act as drivers for such a method of waste management and energy production in central belt Scotland.
- To maximise the benefits of AD, the process plants must be appropriately located. This thesis will also aim to produce and test a geographical analysis tool to allow for an automatic site selection. The location to test the feasibility of the site will be in central belt Scotland.

8 Introduction to Sustainability

8.1 Definition & Interpretation

The term ‘sustainable development’ (SD) first gained widespread recognition in 1987 when the World Commission on Environment and Development (the Brundtland Commission)[3] produced a report for the United Nations called ‘Our Common Future’. The Commission described sustainable development as "development which meets the needs of the present without compromising the ability of future generations to meet their own needs.”

This is often seen as the original definition of the sustainable development, and it is from this classification that most interpretations of are made.

There are three main goals of sustainable development – environment, society, and economy. These are more commonly known as ‘pillars’. Differences in interpretation mostly stem from how each of the ‘pillars’ are emphasised. Another point of contention is concerned with balancing the needs of present and future generations – the intergenerational dimension. There are some who consider it wrong to make assumptions about future human needs beyond basic biological ones.

Because of these differing interpretations there can be extremely different understandings of what is signified by sustainable development; from an almost radical ‘green’ call for a fundamental change in social, economic, and political life to a more ‘business as usual’ approach of economic growth in the name of social and environmental progress where market forces adapt to counter any unsustainable outcomes.

There will always be those who argue over the exact interpretation. However, most agree on enough common elements which are deemed as central to a sustainable development approach.

8.2 History of Sustainable Development

It is felt that the original concept of sustainable development was born out of the emerging environmental movement of the 1950s and 1960s. The movement was concerned that human activity was having severe and negative impacts on the planet, and that patterns of growth and development would be unsustainable if they continued unchecked.

8.2.1 Stockholm – 1972

The concept of sustainable development received its first major international recognition in 1972 at the UN Conference on the Human Environment[4] held in Stockholm. The term was not referred to explicitly, but nevertheless the international community agreed to the notion – now fundamental to sustainable development - that both development and the environment, hitherto addressed as separate issues, could be managed in a mutually beneficial way.

8.2.2 Rio de Janeiro – 1992

However, it was not until the 1992 United Nations Conference on Environment and Development in Rio de Janeiro that major world leaders recognised sustainable development as the major challenge it remains today. The Rio Summit marked the first international attempt to prepare action plans and strategies for moving towards a more sustainable pattern of development.

With over 100 Heads of State and 178 national governments attending, it was the largest gathering of national leaders that the world had seen at that time. It was also attended by representatives from a range of civil organisations, as it was realised that sustainable development would have an impact on all aspects of society.

The outcome of the Rio Summit was the signing of Agenda 21, a programme of the United Nations (UN) related to sustainable development. It is a comprehensive action plant to be taken internationally by organisations of the UN, governments, and major groups in every area in which human society impacts upon the environment. It covered four main areas –

1. **Social and Economic Dimensions –** It covers combating poverty, changing consumption patterns, population and demographic dynamics, promoting health, promoting sustainable settlement patterns and integrating environment and development into decision-making.
2. **Conservation and Management of Resources for Development –** This includes atmospheric protection, combating deforestation, protecting fragile environments, conservation of biological diversity (biodiversity), and control of pollution.
3. **Strengthening the Role of Major Groups –** including the roles of children and youth, women, NGOs, local authorities, business and workers.
4. **Means of Implementation –** including science, technology transfer, education, international institutions and mechanisms and financial mechanisms.

8.2.3 Johannesburg – 2002

In 2002, Johannesburg held the World Summit on Sustainable Development,[5] which was attended by 191 national governments, UN agencies, multilateral financial institutions and other major groups. The Johannesburg Summit delivered three key outcomes: a political declaration, the Johannesburg Plan of Implementation, and a range of partnership initiatives. Key commitments included those on sustainable consumption and production, water and sanitation, and energy.

During the World Summit on Sustainable Development in Johannesburg (2002), it became clear that suitable mechanisms are required to provide these objectives. This challenge requires intensive effort from governments and industries to achieve the overall goal of sustainable development.

8.3 Sustainability in the UK – post 1994

As a method of implementing the actions discussed in Stockholm and Rio, the UK published its first SD strategy in 1994: "Sustainable Development: The UK Strategy". In 1997 the Labour Government announced its intention to prepare a new strategy. A consultation document: "Opportunities for Change" was published in 1998. In 1999, the UK Government published "A Better Quality of Life: A Strategy for SD for the UK".

In producing this strategy, the Government introduced a new approach which emphasised the social dimension of sustainable development.

The Strategy had four main aims:

- Social progress which recognises the needs of everyone;
- Effective protection of the environment;
- Prudent use of natural resources; and
- Maintenance of high and stable levels of economic growth and employment.

The Government's policies also took into account of ten principles and approaches which reflect key themes of sustainable development, some of which are established legal principles, others more approaches to decision making:

- Putting people at the centre;
- Taking a long term perspective;
- Taking account of costs and benefits;
- Creating an open and supportive economic system;
- Combating poverty and social exclusion;
- Respecting environmental limits;
- The precautionary principle;
- Using scientific knowledge;
- Transparency, information participation and access to justice; and
- Making the polluter pay.

As proposed in the UK SD Strategy, the Government has established the Sustainable Development Commission.[6] It has 22 members, which are taken from a wide range of backgrounds and regions in the United Kingdom. Its role is to advocate sustainable development across all sectors in the UK, review progress towards it, and build consensus on the actions needed if further progress is to be achieved.

Sustainable Development issues must now be considered and reflected in the bids for funding of different Government departments. Each department in Government is must produce a report that explains the sustainable development aspect to their work.

The Commission's key objectives are:

- "To advocate a compelling vision of a sustainable economy and society;
- To review how far sustainable development is being achieved in the UK across all sectors;
- To identify the opportunities for, and obstacles to, step changes for sustainability by government, business and the media;

- To promote mechanisms which will deliver a sustainable society;
- To advance the innovative approaches to policy-making and encourage wider participation;
- To mainstream the principles and practices of sustainable development and to support and encourage leadership and best practice in all sectors of society."[7]

However, the main co-ordination role for all aspects of sustainable development policy lies with the DEFRA.[8] In June 2002 DEFRA published 'Foundations for Our Future – DEFRA's Sustainable Development Strategy'.[9] The strategy explains what sustainable development means in practice for DEFRA's policy development, decision-making and operations. In particular the strategy:

- "Sets out the principles and processes which DEFRA needs to adopt to ensure all its policies address economic, social and environmental objectives at the same time;
- Identifies DEFRA policy areas which pose the greatest challenges or can make the greatest contribution to the achievement of sustainable development;
- Looks at the scope to contribute to sustainable development through DEFRA's own operations (e.g. energy, waste, travel, and procurement);
- Establishes a way of monitoring and reporting on progress."[10]

8.4 Sustainable Development in Scotland

From the international summits, this concept of sustainable development has filtered down through to Scottish policy-making and decisions. A major influence on UK sustainable development policy is the decentralisation of power to the devolved administrations. This applies to the devolved administration in Scotland, which is now allowed to plan policies for sustainable development which reflects their particular circumstance.

In the UK, the UK Government and devolved administrations have stated their goal is to be "pursued in an integrated way through a sustainable, innovative and productive economy that delivers high levels of employment; and a just society that promotes social inclusion, sustainable communities and personal wellbeing. This will be done in ways that protect and enhance the physical and natural environment, and use resources and energy as efficiently as possible."[11]

To provide a clearer picture of what they mean in practice, such definitions are often underpinned by key principles that serve to guide policy-making and decisions. As such, the UK Government and the devolved administrations have agreed to a shared set of guiding principles for sustainable development which must be respected in order for a policy to be sustainable.

The Sustainable Development Commission Scotland is the Scottish Executive's independent advisory body on sustainable development. The Commission reports to the First Minister of Scotland on the following policy areas:

- Regeneration;
- Sustainable buildings;
- Local government;

- Energy;
- Food quality assurance.

The Scottish Commission assists in making sustainable development a key area for government departments, local authorities and businesses. It aims to:

- "Promote the work of the Commission and contribute towards the achievement of sustainable development in Scotland;
- Assist in the reporting and analysis of sustainable development at all levels of governance, and will provide effective liaison between the Commission, the Scottish Executive and the Scottish Sustainable Development Forum and other bodies engaged in sustainable development in Scotland;
- Raise awareness of sustainable development and actively seek speaking opportunities at conferences and other events and the use of the media;
- Support Commissioners in Scotland."[12]

As both the waste management and energy sectors are major areas in any sustainability drive, this political focus ensures that both areas become increasingly important.

9 Greenhouse gas emissions and sustainability

9.1 Global energy review

The majority of countries rely on abundant and readily available energy, primarily fossil fuels. Fossil fuels consist of crude oil, natural gas and coal and are unmatched as a source of energy. Unfortunately they are all non-renewable at the current rate of consumption.

However, long term forecasts show that world energy demand will dramatically rise due to population growth (from 6 billion to 9 billion people over the next 50 years) and increased standards of living. [13]

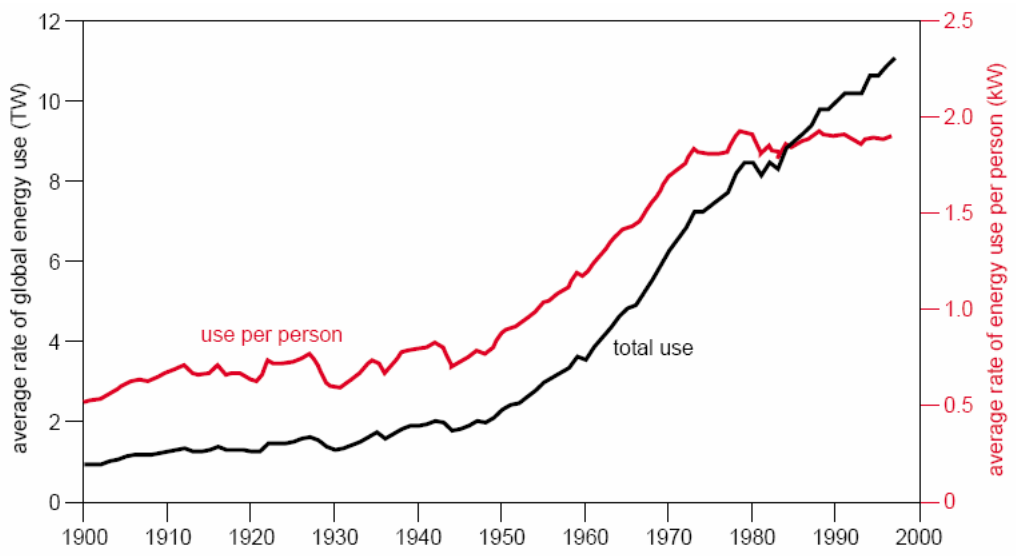

Figure 1 - Growth in global energy use [14]

Figure 1 - Growth in global energy use shows since 1900, the energy use per person has been increasing steadily until around 1980, where it began to slow down. However, the total energy use has seen a dramatic increase and continues to grow at a steady rate.

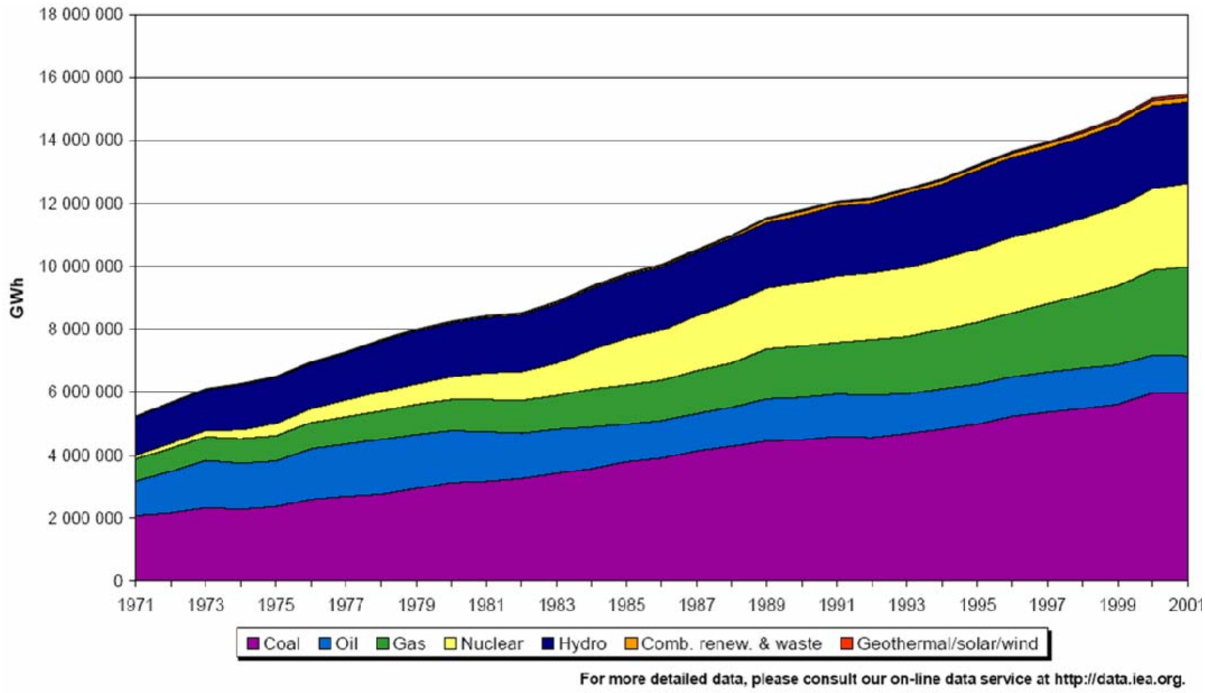

Figure 2 - Electricity generation by fuel from 1971 to 2001 [15]

Figure 2 - Electricity generation by fuel from 1971 to 2001 shows the global quantity of electricity generated from 1971 to 2001. Electricity generation has more than doubled since 1971 and this increased energy use, coupled with climate change concerns, is causing great concern. More that two thirds of the world greenhouse gas emissions (GHG) originate from the energy sector,[16] with scientific evidence backing the theory that increases in global temperatures, due to GHGs, can cause a rising sea level and changes in the amount and pattern of precipitation. These changes may "increase the frequency and intensity of extreme weather events, such as floods, droughts, heat waves, hurricanes, and tornados."[17]

This is leading to an increasing realisation that steps must be taken to mitigate and, if possible, reverse this trend.

9.2 Greenhouse Gas Emissions

Since large-scale industrialization began around 150 years ago, levels of several important greenhouse gases (GHGs) have increased by roughly 25%. During the past 20 years, almost three-quarters of human-made carbon dioxide emissions were from burning fossil fuels. [18]

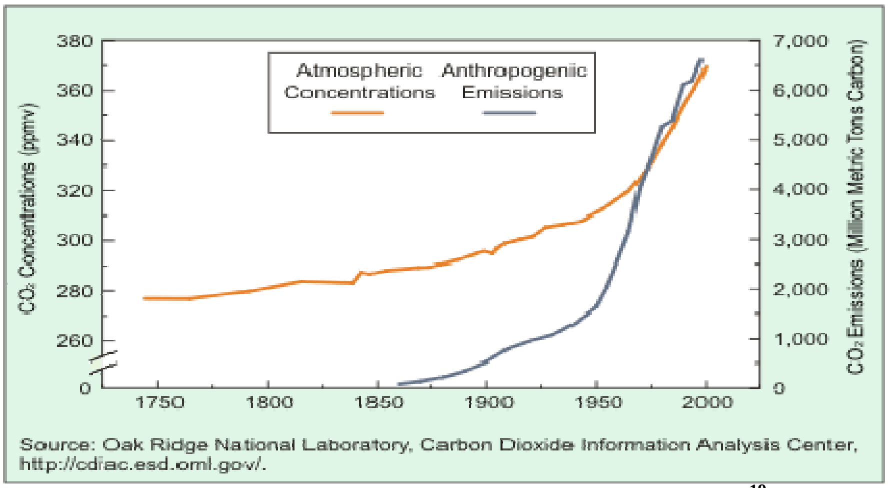

Figure 3 - Trends in CO_2 concentrations and emissions [19]

The CO_2 concentration in the atmosphere is naturally regulated by the carbon cycle. This is dominated by natural processes, such as plant photosynthesis and natural decomposition. While these natural processes can absorb some of the net 6.1 billion metric tons of anthropogenic carbon dioxide emissions produced each year (measured in carbon equivalent terms), an estimated 3.2 billion metric tons is added to the atmosphere annually. This positive imbalance between emissions and absorption results in increasing GHG gases in the atmosphere.

This environmental concern, coupled with the unsustainable use of fossil fuel use, creates serious concerns for the energy industry, and the world as a whole. Because of this, the UK government is committed to reducing the dependence on unsustainable, and GHG-emitting, fuels (e.g. oil, gas, coal, etc).

9.3 UK Energy

Since 1965 energy consumption by final users in the UK has increased by 16% and consumption of primary energy by 24%. Projections published by the Department of Trade and Industry (DTI) in March 2000 show energy use will continue to grow steadily.

Accord to DTI figure, primary energy is being used in the UK at an average rate of about 300 GW and almost 90% of it comes from fossil fuels. In 1998 the UK was also exporting fossil fuels at a net rate of 53 GW. The other main source of primary energy is nuclear power using imported uranium. The majority of the remainder comes from electricity imported from France (0.4%); and from direct flow hydro and wind power (0.2%). As of 2002, renewable energy did not account for a significant percentage of the energy supply.

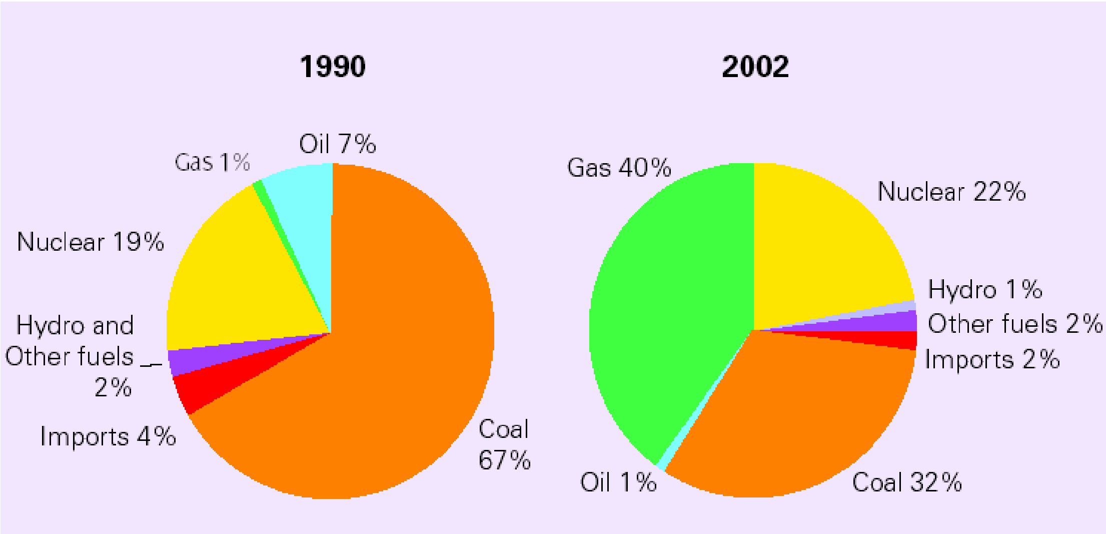

Figure 4 - UK electricity supply by Fuel Type [20]

Figure 4 - UK electricity supply by Fuel Type shows there has not been a significant reduction in fossil fuel use between 1990 and 2002. However, there has also been a dramatic change in other areas, with gas use increasing whilst coal use falls. Since 1990, gas has been the only fuel to increase in electricity generation, which rose from 1.6 to 148.7 TWh.

<table>
<tr><th rowspan="2">Fuel Type</th><th colspan="5">Electricity Produced (TWh)</th></tr>
<tr><th>1980</th><th>1990</th><th>2000</th><th>2001</th><th>2002</th></tr>
<tr><td>Coal</td><td>190.0</td><td>208.0</td><td>114.7</td><td>125.4</td><td>118.6</td></tr>
<tr><td>Oil</td><td>33.9</td><td>21.1</td><td>5.9</td><td>4.8</td><td>4.2</td></tr>
<tr><td>Gas</td><td>1.6</td><td>1.6</td><td>145.0</td><td>138.8</td><td>148.7</td></tr>
<tr><td>Nuclear</td><td>32.3</td><td>58.7</td><td>78.3</td><td>83.0</td><td>81.1</td></tr>
<tr><td>Hydro</td><td rowspan="2">7.3</td><td rowspan="2">7.9</td><td>4.2</td><td>3.2</td><td>3.9</td></tr>
<tr><td>Other Fuels</td><td>9.3</td><td>9.2</td><td>9.8</td></tr>
<tr><td>Net Imports</td><td>-</td><td>11.9</td><td>14.2</td><td>10.4</td><td>8.4</td></tr>
<tr><td>Total</td><td>265.1</td><td>309.4</td><td>371.6</td><td>374.8</td><td>374.7</td></tr>
</table>

Table 1 - Electricity production 1980 – 2002 [21]

Currently the UK relies heavily on gas, coal and nuclear to produce 94% of its energy requirements, but existing UK policy is adapting. The present push is on a more sustainable mix of electricity generation, with renewable energy and nuclear playing an important role in the development of this new mix.

In February 2003, the UK government released the Energy White Paper - Our Energy Future - Creating a Low Carbon Economy. The four objectives set out in this paper are as follows:

1. **Environmental stability –** This goal deals primarily with setting current energy policy, primarily to reduce carbon dioxide emissions by 60% by 2050. The reason given by the government for this stance is climate change. If the concentrations of greenhouse gases can be stabilised, the more serious consequences of climate change can be avoided. The two methods highlighted to meet this goal are reducing the amount of energy consumed, and by utilising more renewable electricity generation.

2. **Reliability of Britain's energy supplies –** The economics of a country rely on a constant and secure source of energy, and this must be met short term and long term to provide a secure economy.

3. **Raise the sustainable rate of economic growth and competitiveness –** This goal can be achieved through competitive markets which are reliable and affordable. The cost of energy should not "threaten the overall competitiveness of UK business or discourage inward investment." [22] It is equally important to all consumers, commercial and domestic, that energy is affordable. Liberalised and competitive markets are seen as a basis for achieving this goal. If the markets do not create the correct signals, the government "will take steps that encourage business to innovate and develop new opportunities to deliver the outcomes we are seeking." [23]

4. **Achieve social objectives and ensure that every home is adequately and affordably heated –** The impact of policies have to take be taken into account, and how it effects all segments of society. Detailed measures will be needed for particular groups. One example is how the policies effect fuel poverty and if it is exacerbating or alleviating the problem.

This White Paper is the main driving force for current and long term energy policy in the UK. It tries to address the challenges of climate change, sustainability and energy supply as well as market competitiveness. One method of helping overcome these challenges and achieving the above objectives is to utilise renewable energy. This could deliver a new mix of energy generation which is not dependent on any one fuel source.

9.4 Current energy supply in Scotland

In 90/91, the energy generation mix in Scotland was dominated by nuclear and coal, which made up 76.6% of the mix, with hydro and oil making up the rest. In 99/00, the nuclear, coal and hydro mix has not changed significantly, but oil has, in effect, been replaced by gas.

Source	90/91		99/00	
	GWh	%	GWh	%
Nuclear	12,143	37.5	18,933	44.3
Coal	12,666	39.1	12,562	29.4
Hydro	3,471	10.7	4,246	9.9
Gas	0	0	6,569	15.4
Oil	4,125	12.7	171	0.4
Other fossil fuels	0	0	0	0
Other renewables	-	-	227	0.5
Total Generated	32,404.6		42,481.5	
Total Consumed in Scotland	29,851		32,037.2	
Net Exported	3,129.9		10,568.4	

Table 2 - Scotland energy statistics [24]

What is also apparent from Table 2 - Scotland energy statistics is that the total amount of energy consumed in Scotland has increased since 90/91, which is in line with the global trend of energy consumption increase.

9.5 Renewable Energy Drivers

To assist in meeting the target of 10% of electricity from renewables by 2010, the UK government has introduced a range of new mechanisms for renewable energy. The focal point of the various mechanisms is the new Renewables Obligations. This is the successor to the Scottish Renewables Obligation (SRO) and the Non-Fossil Fuel Obligation (NFFO).

9.5.1 The New Renewables Obligations

The new Renewables Obligations provides a guaranteed market for renewables-generated electricity by creating suitable market conditions for a competitive renewables industry.

The Renewables Obligations in Scotland is called the Renewables Obligation Scotland (ROS). The ROS requires licensed electricity suppliers to meet a specified proportion of their customer demand from electricity generated from “eligible” renewable energy sources. Eligible technologies are landfill gas, sewage gas, hydro, onshore and offshore wind, biomass, geothermal, tidal and tidal stream, wave, photovoltaics and energy from waste (EFW) using gasification and pyrolysis. Normally, only renewable energy sources operational from 1990 onwards are eligible.

Tradable Renewable Obligation Certificates (ROCs) will ensure compliance with the Obligations. They can be sold separately to the electricity generated, raising the possibility of intermediary traders in ROCs. Suppliers have the option of meeting the obligation without contracting directly with renewables generators, while generators will be able to contract with different parties for electricity and ROCs. Because ROCs are tradable across the UK, electricity supplied under licence anywhere within the UK can redeem a ROC.

9.5.2 Capital Grants

In total, £89 million for capital grant support is being made available by the DTI and the New Opportunities Fund. [25] It is aimed at “longer-term technologies” which have not yet matured. This is predominantly offshore wind and biomass projects in England & Wales, but this may include marine power generation in Scotland.

9.5.3 The Climate Change Levy

Since April 2001, supplies of electricity, gas and some other fuels to business users and public bodies have been subject to the Climate Change Levy (CCL). The levy on electricity is collected from licensed electricity suppliers, who bill business customers accordingly. Electricity generated from renewable sources is exempt from the levy, which creates an advantage for renewable energy use.

In 2001/02, the full rate on electricity was 0.43 p/kWh. [26] Qualifying renewable energy generators are issued Levy Exemption Certificates (LECs) which must be sold with the electricity to which they refer. Generators and suppliers are free to negotiate the value of a LEC. The CCL has been a key factor in encouraging some businesses or public bodies to switch to renewable energy tariffs.

Part of the money raised from the CCL is used to assist energy efficiency projects and, to a lesser extent, renewable energy. Some of the money also goes to part fund the Carbon Trust, which helps promoting low carbon technologies to business.

9.5.4 Performance and Innovation Unit

A report from the Cabinet's Performance and Innovation Unit (PIU) recommended that an extra £100 million of funding should be split for a range of technologies and activities:

- £25 M for offshore wind
- £15.5 M for development of energy crops
- £18 M for demonstration of new energy crop technologies
- £10 M for community and household schemes
- £10 M for innovative PV schemes
- £10 M for research into "next generation" technologies
- £5 M for demonstration of wave and tidal technologies
- £4 M for grid-related advanced metering and control
- £2.5 M for facilitating best practice in planning [27]

9.5.5 Green Tariffs

Specialised green tariffs have proliferated since full supply-side electricity market opening. The Energy Saving Trust (EST) operates the "Future Energy" accreditation scheme for green tariffs in the UK.

One example is Scottish Power's current green tariff. If a customer signs up for the Green Energy tariff and takes gas and electricity, the annual £10.50 discount is donated to a Green Energy Fund. If the customer only takes electricity, a contribution to the Fund is made, which is equivalent to less than 3 pence a day. [28]

9.5.6 UK Carbon Trading Scheme

The UK government is providing up to £215 million over 5 years as incentive payments for companies participating in a voluntary carbon trading scheme. The scheme has been developed by the Emissions Trading Group set up by the CBI and Advisory Committee on Business and the Environment. Renewables projects will benefit indirectly in so far as targets are such that companies may opt to contract with renewable energy in addition, or in preference, to undertaking energy efficiency measures. Only those projects which have not benefited from the Renewables Obligations will be eligible.

10 Waste and sustainability

One major component of a sustainable future is environmentally sound management of waste. This is seen as a major issue in "maintaining the quality of the Earth's environment and especially in achieving environmentally sound and sustainable development in all countries." [29]

Out of the Rio Summit in 1992, came Agenda 21. Part of this focussed entirely on Environmentally Sound Management Of Solid Wastes And Sewage-Related Issues.

It was produced to elaborate upon "strategies and measures to halt and reverse the effects of environmental degradation in the context of increased national and international efforts to promote sustainable and environmentally sound development in all countries," in which "the Assembly affirmed that environmentally sound management of wastes was among the environmental issues of major concern in maintaining the quality of the Earth's environment and especially in achieving environmentally sound and sustainable development in all countries."[30]

In Agenda 21, it stated that "environmentally sound waste management must go beyond the mere safe disposal or recovery of wastes that are generated and seek to address the root cause of the problem by attempting to change unsustainable patterns of production and consumption." This suggested that, rather than just improving the management of waste, the full life cycle management concept should be used.

To look at the full life cycle, Agenda 21 document suggest that waste-related actions should be founded on a hierarchy of objectives and focused on the four major waste-related programme areas, as follows:

- Minimizing wastes;
- Maximizing environmentally sound waste reuse and recycling;
- Promoting environmentally sound waste disposal and treatment;
- Extending waste service coverage.

The four programme areas were deemed "interrelated and mutually supportive" and so must be integrated in order to provide a comprehensive and environmentally responsive framework for managing municipal solid wastes.

10.1 EU Policy

Each year in the European Union, 1.3 billion tonnes of waste is produced. This amounts to about 3.5 tonnes of solid waste per person. [31] Coupled with the 700 million tonnes of agricultural waste, it is clear that environmentally friendly treatment and disposal of this waste is a major issue.

The Organisation for Economic Cooperation and Development (OECD) calculated that the amount of waste generated in Europe increased by 10% between 1990 and 1995. Most of this waste is burnt in incinerators, or dumped into landfill sites (67%), both of which create environmental damage. Landfilling not only takes up more and more valuable land space, but it also causes air, water and soil pollution, discharging carbon dioxide (CO_2) and methane (CH_4) into the atmosphere and chemicals and pesticides into the earth and groundwater. This pollution affects the health of human as well as plants and animals.

The OECD estimates that by 2020 the EU could be generating 45% more waste than the 1995 levels. However, the EU's Sixth Environment Action Programme identified waste prevention and management as one of its priorities. Its primary objective is to decouple waste generation from economic activity, enabling growth within the EU without leading to increased waste.

The approach by the EU is based upon three principles:

- **Waste prevention**: If the EU can reduce the amount of waste generated in the first place and reduce its hazardousness by reducing the presence of dangerous substances in products, then disposing of it will automatically become simpler. Waste prevention is closely linked with improving manufacturing methods and influencing consumers to demand greener products and less packaging.

- **Recycling and reuse**: If waste cannot be prevented, as many of the materials as possible should be recovered, preferably by recycling. The European Commission has defined several specific 'waste streams' for priority attention, the aim being to reduce their overall environmental impact. EU directives now require Member States to introduce legislation on waste collection, reuse, recycling and disposal of these various waste streams.

- **Improving final disposal and monitoring**: Where possible, waste that cannot be recycled or reused should be incinerated, with landfill only used as a last resort. The EU has recently approved a directive setting strict guidelines for landfill management. It bans certain types of waste, such as used tyres, and sets targets for reducing quantities of biodegradable rubbish. Another recent directive lays down tough limits on emission levels from incinerators. The Union also wants to reduce emissions of dioxins and acid gases such as nitrogen oxides (NO_x), sulphur dioxides (SO_2), and hydrogen chlorides (HCL), which can be harmful to human health.

The EU is aiming for a significant cut in the amount of waste generated, through new waste prevention initiatives, better use of resources, and encouraging a shift to more sustainable consumption patterns. These objectives were set out in the EU Council Directive 1999/31/EC. [32] The main purposes of the Landfill Directive are:

- Landfill gas is to be reduced in order to reduce global warming;
- This is to be done by reducing the amount of biodegradable waste going to landfill, by encouraging the separate collection of biodegradable waste and in general by the prevention, recycling and recovery of waste in the first instance;
- The amount and hazardous nature of the waste going to landfills should be reduced;
- Landfills must be monitored to reduce or prevent harm to human health and the environment.

These objectives are to be achieved by various methods. Firstly, the landfills should be classified into three types:

- Hazardous waste;
- Non-hazardous waste;
- Inert waste.

The EU Member States are also made to produce a waste strategy to deal with the quantity of biodegradable waste going to landfills. It also sets targets for biodegradable waste.

The quantity of biodegradable waste going to landfill would have to be reduced to:

- 75% of the 1995 quantity by 2006;
- 50% of the 1995 quantity by 2009;
- 35% of the 1995 quantity by 2014.

10.2 Scottish Waste

Currently, over 3 million tonnes of waste is produced, per year, in Scotland. More than 90% of the municipal waste is sent landfill sites. Not only is this a huge misuse of resources, it also creates a source of greenhouse gases and other emissions to the environment.

Under the EU Landfill Directive, the amount of biodegradable municipal waste sent to landfill must dramatically reduce over the next 20 years.

The Scottish Environmental Protection Agency (SEPA) was required to prepare a national waste strategy for Scotland, which was published in December 1999. This strategy was adopted by the Scottish Executive. This National Waste Plan set the approach of the Scottish Executive's policies for sustainable waste management to 2020. It set out targets to bring about essential changes in the way Scotland's waste is managed.

The Executive aims to:

- Provide widespread source-separated kerbside waste collections across Scotland (to over 90% of households by 2020);
- Aim to stop growth in the amount of municipal waste produced by 2010;
- Achieve 25% recycling and composting of municipal waste by 2006, and 55% by 2020 (35% recycling and 20% composting);
- Recover energy from 14% of municipal waste;
- Reduce landfilling of municipal waste from around 90% to 30%;
- Provide widespread waste minimisation advice to businesses; and
- Develop markets for recycled material to help recycling become viable and reduce costs. [33]

1995 arisings of municipal waste	2.8 million tonnes (mt)
1995 arisings of biodegradable municipal waste	1.68 mt
Target for biodegradable municipal waste to landfill in 2010	1.26 mt
Target for biodegradable municipal waste to landfill in 2013	0.84 mt
Target for biodegradable municipal waste to landfill in 2020	0.59 mt

Figure 5 – Scottish landfill targets [34]

The above table shows clearly the targets for the biodegradable waste, in Scotland, up to 2020.

Currently the estimated operating costs of collecting, treating and disposing of municipal waste across Scotland are approximately £220 to £240 million a year. This equates to about £70 per tonne. [35] It is estimated that the operating cost of waste management is projected to increase to:

- £340 to 370 million in 2010 (£90 to £100 per tonne);
- £360 to 420 million in 2020 (£85 to £95 per tonne).

Over the same period capital expenditure of some £700 million will need to be invested in new infrastructure for municipal waste.

Because of the costly implications of these new regulations, local authorities have been searching for cheaper alternatives. One such method is anaerobic digestion, which has the potential to reduce organic material to landfill whilst also generating renewable energy.

10.3 Sewage in Scotland

10.3.1 Disposal Pre 1998

Before 1998, the sewage sludge produced within Glasgow and the surrounding areas were dumped at Garroch Head in the Firth of Clyde. Under the Urban Waste Water Treatment (Scotland) Regulations 1994, this method of disposal was prohibited.

As a new method of safe disposal was needed, SMW Ltd, a subsidiary of Scottish Power, started to examine various options for sludge utilisation and disposal.

10.3.2 Daldowie Sludge Treatment Facility

As a result of that study, SMW submitted a proposal to Scottish Water involving the re-use of dried sewage sludge pellets as a co-fuel with coal for combustion within a power station. The proposal involved the development of a sludge treatment centre at Daldowie, which would take sewage sludge from the nearby waste water treatment works and dry it to form pellets. These pellets would then be transported and used as a fuel source at a power station.

The Daldowie sludge treatment centre was constructed, costing around £65m, and began operation in 2002. Each year it converts around 2.3 million cubic metres of sewage sludge into 55,000 tonnes of waste derived fuel (WDF), which is then co-fired with coal at Longannet.

10.3.3 SEPA Evaluation

In 2002 SEPA wrote to Scottish Power to inform it of a decision which SEPA had taken regarding Directive 2000/76/EC on the incineration of waste and its application to Longannet. This European Directive is in place to prevent and limit negative environmental effects by emissions into air, soil, surface and ground-water, and the resulting risks to human health, from the incineration and co-incineration of waste. SEPA was of the opinion that the directive, applied to the use of dried sewage sludge as a fuel at Longannet. The sewage sludge had been discarded by Scottish Water and was therefore waste, not WDF. Since SEPA’s view was that the pellets were still waste until it was combusted, Directive 2000/76 applied and Longannet Power Station would have to meet the minimum requirements of this Directive.

In July 2003 SEPA stated that, since the incineration of dried sewage sludge at Longannet involved the incineration of waste at an existing waste incineration installation, the Waste Incineration (Scotland) Regulations 2003 and the Waste Incineration Directive (Scotland) Direction 2003 applied. SEPA was therefore legally obliged to include a condition in the Longannet authorisation requiring Scottish Power to make an application for variation of the authorisation, under regulation 3 of the 2003 Regulations, by 31 March 2005.

On 19 November 2003 SEPA issued to Scottish Power a notice of variation of the Longannet authorisation, stating a new condition:

"By 31 March 2005, the Authorisation Holder shall make an application under Regulation 3(2) of the Waste Incineration (Scotland) Regulations 2003."[36]

This view was contested by SMW, Scottish Water and Scottish Power, and a legal challenge was mounted, as it would require significant cost to bring Longannet Power Station up to the minimum emissions standards set out the in Waste Incineration (Scotland) Regulations 2003.

10.3.4 Court of Session Ruling

In December 2004, Lord Reed published his opinion on the challenge brought by the operators –

“It follows that the court must refuse to grant the declarator sought by Scottish Power that the WDF is not waste as defined by Article 1(a) of Directive 75/442 (as amended).”

Lord Reed agreed that the sewage pellets from Daldowie were still classed as waste and therefore Longannet Power Station must comply with the Waste Incineration (Scotland) Regulations 2003.

10.3.5 Future Disposal Route

Currently Scottish Power is exploring the possibility of a purpose-built biomass plant that would be compliant with the Waste Incineration (Scotland) Regulations 2003 to handle the sewage sludge pellets produced at Daldowie Treatment Centre.

However, one alternative to process the sludge is by implementing the process of anaerobic digestion (AD), which could have significant environmental, financial and social impacts.

11 Anaerobic Digestion (AD)

11.1 Introduction

AD is a naturally occurring process by which organic matter is decomposed by bacteria, in the absence of oxygen. The decomposition process produces a gaseous by-product, often called "biogas", primarily composed of methane (CH_4), carbon dioxide (CO_2), and trace amounts of hydrogen sulphide (H_2S). This process takes place in a variety of natural anaerobic environments, including water sediment, water-logged soils, natural hot springs, ocean thermal vents and the stomach of various animals (e.g. cows).

Anaerobic digestion provides an effective method for converting organic residues into three main products:

- **Biogas –** A methane/carbon dioxide mix (with trace amounts of hydrogen sulphide) which can be burnt to generate heat and/or electricity;
- **Fibre -** Can be used as a nutrient-rich soil conditioner, and
- **Liquor** - Can be used as liquid fertiliser.

Small scale AD and production of biogas is a widely used process and has been known for many years. Historically the reason behind developing the biogas technology was the search for an alternative energy source. However, more recently other environmental aspects have gained further importance.

AD is one of the few technologies that can create a wide variety of positive impacts. Recent interest in AD technologies is due to its potential to stabilise organic matter, reduce odours & pathogens, control physical & chemical contaminants, and provide recyclable end products. Its contribution towards solving environmental problems may assist in the further development of AD as well as ensuring its economic success.

One of the main trends of today’s waste management policies is to reduce the stream of organic waste going to landfills and to recycle the organic matter and the plant nutrients back to the soil. The way of achieving this is through the biological treatment of organic waste by AD.

Modern industrialised societies generate a tremendous amount of solid household waste. Not only is this a threat to the environment, but it also represents a hazard to human and animal health. To minimise and manage this, a range of different waste treatment and disposal methods can be used. The choice of method must always be based on maximum safety, minimum environmental impact and as far as possible, recyclable end products.

11.2 History

There is anecdotal evidence to suggest that biogas was used for heating hot bath water in Assyria during the 10th century BC and in Persia during the 16th century BC.[37]

Many prominent scientific researchers, including Benjamin Franklin and Joseph Priestly, were involved in the study of AD. Their experience with biogas from lake sediments was built upon further by Alexander Volta, who published his examination of the formation of inflammable gases from marshes and lakes in 1776. [38]

One of the first AD plant was built in Bombay (Mumbai), India in 1859 by Ulysse Gayon. The amount of biogas produced at this plant led Gayon (a pupil of Louis Pasteur) to conclude the gas may be suitable for heating and lighting if the plant operated at 35^{o}C. [39]

Between 1914 and 1921, Imfhoff and Blunk patented various technical advances, such as internal, double-walled heat exchangers and steaming of the digester, in an effort to increase the digester temperature. However, problems arose to prevent the complete application of their concepts.

In Essen, Germany, in 1926, a team using the first continuously heated digester discovered thermophilic digestion, which they classed as high temperature industrial digestion.

The first small-scale agricultural AD installation to run on solid waste was commissioned in 1938 in Algeria by Isman and Ducellier. However, the onset of World War II prevented further development of the system in Algeria. [40]

Although World War II prevented the development of AD in Algeria, it was soon used to produce an alternative fuel source in France, which operated over 40 small-scale digesters, increasing to over 800 in the 1950s. It was also used in war-time Germany, where the plants were of a larger size and designed to a high technical standard. [41]

During the 1970’s oil crisis, AD began to develop in a major way in Europe as an alternative fuel source. In the early years there were major technological issues, but during the past two decades, breakthroughs occurred which allowed the design and installation of feasible sites.

Today AD is a standard waste water treatment technology and technical developments over the past 20 years have enabled the production of inexpensive biogas to be utilised to generate heat and/or electricity. Today AD is included in many energy and environmental policy targets. On example is the aim set by China. The Chinese Ministry of Agriculture states that almost 15 million households in China were using biogas at the end of 2004. The Ministry aims to increase this to 27 million by 2010.[42]

11.3 AD Process

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. The digestion tank needs to be warmed and mixed thoroughly to create the ideal conditions for the bacteria to convert organic matter into biogas (a mixture of carbon dioxide, methane and small amounts of other gases).

During the anaerobic digestion process 30 - 60% of the digestible solids are converted into biogas.[43] This gas can then be burned, to generate heat, electricity or both. It can be burned in a conventional gas boiler and used as heat for nearby buildings as well as heating the digester. It can also be used to power associated machinery or vehicles. Alternatively, it can be burned in a gas engine to generate electricity. To increase efficiency, combined heat and power (CHP) systems can be used. The heat can be removed in the first instance to maintain the digester temperature, and any surplus energy can be used for other purposes. A larger scale CHP plant can supply larger housing or industrial developments, or supply electricity to the grid.

As fresh feedstock is added to the system, digestate (fibre and liquor by-products) is pumped from the digester to a storage tank. Biogas continues to be produced in the storage tank; collection and combustion may be an economic and safety requirement.

The residual digestate can be stored and then applied to the land at an appropriate time without further treatment, or it can be separated to produce fibre and liquor. The fibre can be used as a soil conditioner or composted prior to use or sale. The liquor contains a range of nutrients and can be used as a liquid fertiliser, which can be sold or used on-site as part of a crop nutrient management plan.

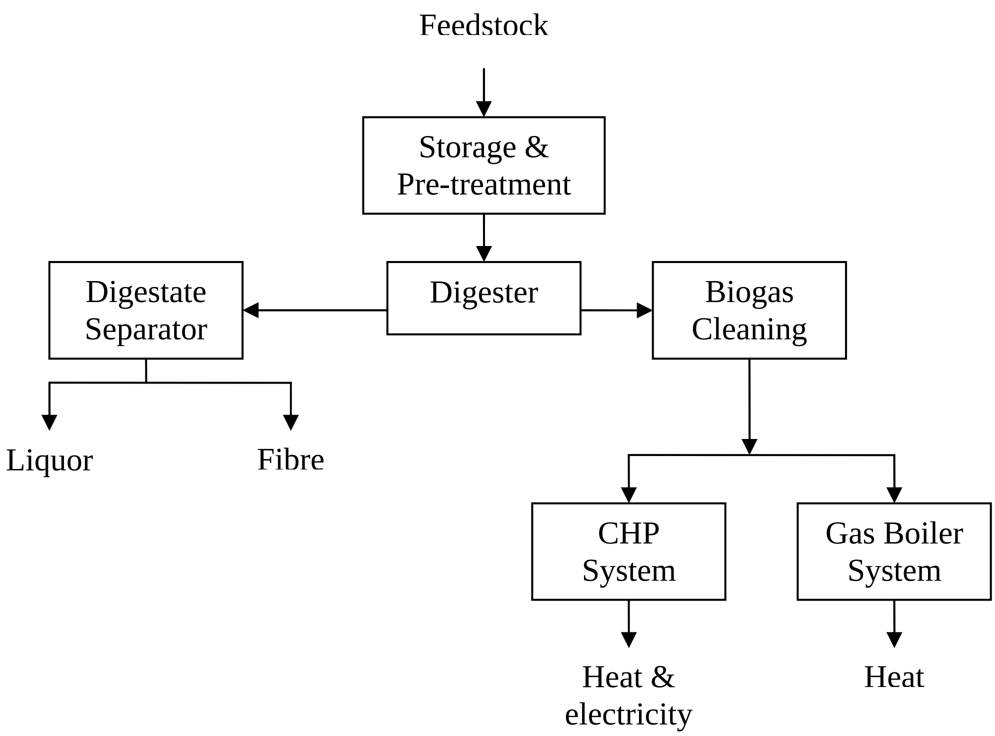

Figure 6 - Typical AD system

The above figure shows the main elements of a standard AD plant. As is shown, an AD plant requires more than just a sealed vessel for the process to take place. Typically it is made up of four main components:

- Production unit (including the sewage removal system, holding tank, sanitation system, and digester)
- Safety and gas upgrading equipment
- Gas storage facilities
- Utilisation equipment for gas, fibre and liquor

11.4 Microbial Process

There are four main microbiological steps in this process; hydrolysis, acidogenesis, acetogenesis and methanogenesis. [44]

These four stages coexist within the process and each stage is characterised 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.

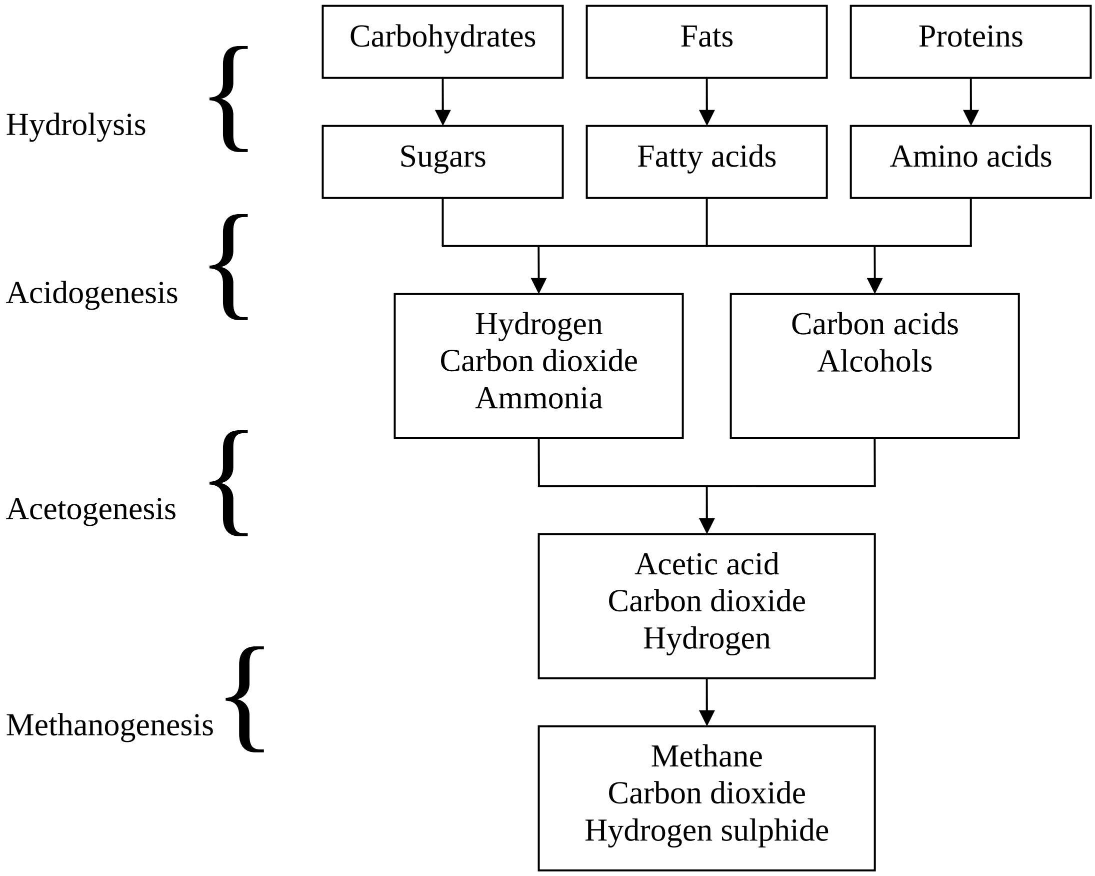

Figure 7 – AD conversion of organic material

The operating conditions of AD are relatively narrow, and the formation of methane is only maintained as long as the four above steps are working under optimal conditions. Some of the steps will not generate energy unless their products are removed by the next group of bacteria.

As a consequence, there are few parameters which can be altered to control the process; temperature, hydraulic retention time, organic loading rate and ammonia concentration.

11.4.1 Temperature

In industrial settings, there are three distinct temperature ranges:

- Psychrophilic – From 10^{o}C to 25^{o}C
- Mesophilic – From 25^{o}C to 35^{o}C
- Thermophilic - From 49^{o}C to 60^{o}C

So far, there have been no anaerobic psychrophilic bacteria found with a temperature maximum below 25^{o}C. However, there are many anaerobic bacteria that can operate at the two higher temperature ranges.

Mesophilic – This is the most commonly used anaerobic digestion process. The digester is heated to 25 - 35^{o}C and the feedstock remains in the digester typically for 15 - 30 days.

Mesophilic digestion tends to be more robust and tolerant than the thermophilic process, but less biogas is produced, larger digestion tanks are required and an extra sanitisation stage tends to be necessary. In total, around 40% of the volatile suspended solids (VSS) decompose.

Thermophilic – In this method of digestion, the digester is heated from 49^{o}C to 60^{o}C and the residence time is typically 12 - 14 days.

Thermophilic digestion systems offer higher methane production, faster throughput, better pathogen and virus ‘kill’, but it also requires more expensive technology, greater energy input and a higher degree of operation and monitoring.

11.4.2 Hydraulic Retention Time

The hydraulic retention time (HRT) is the average time the feedstock remains in the digester.

The minimal HRT is dependent on the type of feedstock to be digested. The lower the degradation rate is, the higher the HRT. The following basic feedstock classes degradation rate increase in this order:

- Cellulose;
- Hemicellulose;
- Proteins;
- Fat;
- Carbohydrates.

11.4.3 Organic Loading Rate

The organic loading rate (OLR) describes the amount of organic material which is fed daily per cubic metre of digester volume.

If heavy loads of feedstock are occasionally fed into the digester, AD plant operators tend to decrease the basic OLR to lower values than indicated to ensure proper degradation.

11.4.4 Ammonia Concentration

For many years it has been acknowledged that ammonia limits methanogenesis. More recently, it been found that ammonium is the true inhibitor. This means that pH and temperature have a major effect on the ammonium concentration by influencing the equilibrium in the system.

In AD plants, ammonia concentrations are of concern when protein-rich feedstock is used as the proteins may break down to form ammonia and ammonium, preventing methane production.

11.5 AD Impact

If AD process plants are to be considered for waste minimisation, then they must be assessed on a variety of areas. Typically, an environmental impact assessment for each site would be carried out which would cover the following activities:

- Gathering environmental information;
- Describing a development or other project;
- Predicting and describing the environmental effects of the project;
- Defining ways of avoiding, reducing or compensating for the adverse effects;
- Publicising the project and the Environmental Statement including a clear, non-technical prediction of the likely effects, so that the public can play an effective part in the decision making process;
- Consulting specific bodies with responsibilities for the environment;
- Taking all of this information into account before deciding whether to allow the project to proceed; and
- Ensuring that the measures prescribed to avoid, reduce or compensate for environmental effects are implemented.[45]

The following areas will play a major part in any public consultation, the suitability of the location and whether planning permission could be given by the local authority.

11.5.1 Environmental

Aside from being a source of biogas for energy production, anaerobic digestion of organic waste can provide many environmental benefits, direct and indirect:

- Increased recycling and resources saving;
- Sanitation of waste and ‘killing’ of pathogens and weed seeds, beneficial if agricultural disposal of the by-products takes place;
- Reduces demand load from traditional sources, with the opportunity to export heat and/or electricity;
- Potential to reduce odour, rather than spreading untreated waste on farmland;
- Reduce nitrate pollution of water courses.
- Run-off is reduced through more effective control of nutrient application to land;
- Control methane emissions more effectively than some other waste management methods;
- Minimise waste going to traditional landfill sites;
- Can help agricultural, water treatment sectors and others to respond to new regulations and public pressure by increasing the effectiveness of waste management.

However, as with all processes, there may be negative impacts and additional risks associated with anaerobic digestion:

- Risk of odours at the process plant and during transportation of waste;
- Risk of explosion;
- Increased traffic due to waste transport;
- Risk of spillages on-site or during transportation of waste.

11.5.2 Socio-political

Heightened concern about global warming, and climate change, has influenced UK Government and EU action plans over the past decade. Prior to the 1997 election the Labour Party's manifesto made a commitment to reduce UK carbon dioxide emissions by 20% of 1990 levels by 2010. Although the UK will not reach this target, it is still promoting heavily into carbon-neutral energy sources.

There are numerous advantages to the local communities and the wider area that may arise from the introduction of AD plants. Listed below are various reasons why AD may have non-environmental benefits:

- AD has the ability to offer a small increase in UK's renewable portfolio as per Government and EU policy and targets
- The energy industry is open to full competition, offering new and expanding markets for energy from alternative sources such as AD.
- Promotes local community initiatives such as partnerships between local authorities, waste producers, water treatment organisations and farmers;
- Potential for companies and local authorities to 'green' their waste disposal routes, providing beneficial marketing for the organisation;
- Public perceptions are changing, and consumers are increasingly demanding waste management practices are environmentally sensitive;
- There are increasing legislative and regulatory pressures with relation to local waste management and wider environmental concerns about farming practices;
- AD projects can directly boost the local rural and urban economies through creating jobs in AD developments, and indirectly through increasing disposable incomes, specifically in rural areas.

As with any industry, there are socio-political barriers and disadvantages to promoting or investing in AD:

- Shifts effort away from lower risk technologies (e.g., wind) or policies (energy efficiency);
- Negative view of waste derived fuel sources, primarily a throwback from old incineration technologies;
- Local authorities unwilling to invest in less traditional technologies;
- Intense lobbying from other energy sources (wind, nuclear, oil & gas) have a propensity to marginalise atypical energy sources such as AD;
- Requires major regulatory changes to promote AD over other waste/energy processes.

11.5.3 Economics

For AD plants to be implemented, a major factor will be the economics surrounding the technology. Currently, AD is used as a cost-effective method of treating sewage waste at water treatment facilities. However, for it to use extensively used, AD must maximise economic opportunities in the following areas;

- Generate income from sale of biogas (as electricity), liquor and fibre products;
- Attain Renewable Obligation Certificates (ROCs);
- Charge gate fees to receive feedstock from organic waste producers;
- Minimise gate fees for waste producers.

There are major economic barriers of the implementation of widespread AD plants

- High capital costs
- High operating costs (for thermophilic processes in particular);
- Not capable of competing against traditional waste disposal routes such as landfill or incineration;
- Not capable of competing against traditional electricity generation technologies
- No Government incentives for the promotion of selling heat
- Government incentives insufficient to allow attractive payback periods
- No relevant standards for the commercial selling of the by-products (fibre and liquor)

As is shown in this section, there are many impacts, advantages and disadvantages to AD. For it to be a beneficial tool to aid sustainability, all points require to be addressed. If not, it will not be fully utilised by public or private industry.

12 Automatic Site Selection Tool

As with any process plant, the location is a key aspect in the feasibility of a site. However, for an AD plant, the proximity to the feedstock is a major aspect as it can substantially affect the economics of the plant. As stated in the Objectives section, one aim of the thesis was to produce and test a GIS-based analysis tool to allow for an automatic site selection.

The primary reason for such a tool would be to ensure that any AD plant commissioned was in the most appropriate location. This would maximise the environmental and financial benefits of the plant.

A secondary advantage of this automatic method is to allow a rapid analysis of large areas without the need for extensive analysis by individuals. This provides the opportunity to save considerable man-hours when analysing regions for suitable sites.

12.1 AD Calculation Tool

The original AD calculator was designed by Jean Currie, Maureen Cloonan, Andrew Roscoe and Matthew Geraghty during a group project in 2004. The aim of the project was to investigate the "environmental and socio-economic viability of anaerobic digestion as a waste-to-energy process in rural and community-based situations." [46]

As part of this project, the team produced an Excel-based spreadsheet, which could carry out full energy and financial balances for a proposed plant. The calculator worked by inputting assorted variables for a given site. The inputs to the calculator include:

- The demographics of the area surrounding the plant
- Parameters defining the plant design
- Economic considerations

With these inputs, the size of the process plant was estimated. Next, the plant is sized appropriate to the waste stream magnitudes; the plant size affecting the digester sizes (and hence heat losses), capital cost, biogas engine size, and also the electrical process loads due to mixing and pumping. The input mixed waste stream is analysed for dry solids content, and also for C:N (carbon-nitrogen) ratio. The biogas yields are calculated simultaneously with the plant thermal operation characteristics. This is a complex iterative task as the digester temperatures influence the biogas yield, the biogas yield influences the biogas engine power available, and this in turn influences the plant thermal characteristics.

The outputs from the analysis include:

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

- Greenhouse gas contribution (relative to conventional procedures);
- Overall financial viability calculation, via net present value (NPV) and profitability index methods.

12.2 Modified Calculator

Although the existing calculator has the ability to analyse and determine the technical and economic details of a site, it is limited to analysing only one site at a time. This is a drawback as each individual area's demographics must manually input. If the site is not economically feasible, then a new site is chosen with new demographics, and the process is repeated. With thousands of potential sites throughout centre belt Scotland, it would not be feasible to carry out this method of analysis.

To prove that this concept has merit, the demographics section of the calculator was limited to only looking at sewage waste. Basing the site selection on sewage waste required the following;

- A modified Excel calculator
- Population data with spatial information

Detail on both can be found in the following sections.

12.2.1 Analysis Approach

With the population figures in grid format, a Visual Basic program was written which, in essence, looks through a grid and sums the resource within a user-defined radius. This is carried out for every 200m x 200m cell in the population grid and provides the grid reference for the cell which has the biggest population. It then inputs this totalled population into the original AD calculation tool, looks up the internal rate of return (IRR) for that value and if above a threshold limit, it publishes the x and y co-ordinates with the IRR. This is repeated until the IRR drops below this threshold limit. IRR can be defined as "a method to analyse investments which reflects and accounts for the time value of money. IRR is the discount rate which makes the net present value of revenue flows equal to zero or the investment equal to the present value of revenue flows."[47]

IRR is used as the determining factor as the plants organisations will not invest in uneconomical process plants, regardless of the environmental or social benefits.

Below are the main steps in the Visual Basic (VB) script that allows the modified calculator to assess the population grids. The full script can be found in the Full Script section of the appendix.

Step 1 – ClearCoords
Purpose – This VB routine ensures that the results (co-ordinates and IRR) of the previous analysis are cleared before undertaking a new grid search.
Reason – This prevents any sites being input into the GIS system more than once.

Step 2 – PopulateWorking
Purpose – Copies the original grid of population data into a new working sheet.
Reason – Provides Microsoft Excel with a new sheet of population data which can be modified without changing the original population grid.

Step 3 – GetSum
Purpose – Sums the area around every cell for a given radius. There are various stages in this step:

- Using the radius defined by the user, it changes this into the number of cells in the grid. For example, a 4km radius is converted to 20 x 200 metre cells in Excel.
- For each cell, it uses the equation of a circle to find the neighbouring cells within the radius. The equation used is in the form –
  $(x - h)^2 + (y - k)^2 = r^2$,
  where h and k are the x- and y-coordinates of the centre of the circle and r is the radius.
- It then sums the population in that radius and places the total value into a results sheet, which retains all the summed values.

Reason – This is a key step of the analysis as it allows the AD calculator to evaluate every grid reference for a given catchment area (e.g., 4km radius from a potential plant). The results sheet is then used in Step 4.

Step 4 – FindMax
Purpose – After finding the sum for every cell in the grid, it then finds the largest value. It then uses this population value in economic and heat balances of the original calculator and if this provides an IRR greater than the minimum, the x- and y-coordinates are recorded, with its corresponding IRR.
Reason – It is assumed that the most appropriate location of an AD plant is where there is the highest possible population.

Step 5 – MakeNullZone
Purpose – Once the best location has been chosen (Step 4), the calculator then converts every population value in the radius to zero.
Reason – This means when it analyses the population grid for the next AD plant, it prevents population values being used twice.

Step 6 – Repeat
Purpose – Steps 2 to 6 are then repeated until the minimum IRR threshold is reached.
Reason – In many of the population grids there will be more than one suitable site for an AD plant.

Population Data

The sewage waste of the original calculator is based on population figures in the catchment area of the AD plant, where the average person produces. To automate the analysis of large geographical areas, the population data requires have a geographical portion. This type of spatial data is usually used with GIS systems, but with modification, the analysis can be undertaken in Microsoft Excel.

The population figures used in the analysis tool were obtained from Surpop.[48] Surpop provides access to a set of population estimates for 200m cells derived from the 1981 Census of Population in England, Wales and Scotland, and the 1991 Census in England, Wales, Scotland and Northern Ireland.

The format available writes a file suitable for input to the GRID module of ArcView 3.2 and writes one record for each cell value, starting in the northwest corner, but with the addition of a 5-line header as follows:

Header contains	**Explanation**
NCOL 100	100 columns of data
NROW 100	100 rows of data
XLLCORNER 455000	X reference of SW corner of data (metres)
YLLCORNER 105000	Y reference of SW corner of data (metres)
CELLSIZE 200	cell size (metres)

This allows ArcView 3.2 to assign a population value to each grid reference based on a 200 metre grid. To cover central belt Scotland, 16 files were downloaded from the Surpop website

However the Example Population File, in the appendix, shows that the file is based on a header with one column. For Microsoft Excel to analyse this geographical data, this would have to be modified into a grid format. This option is available in ArcView 3.2, a GIS system.

Geographical information systems (GIS) are software packages for creating, storing, analysing and managing spatial data and associated attributes. In essence, it is a system capable of integrating, storing, analysing and displaying geographically-referenced information.

Geographic information systems technology can be used for scientific investigations, resource management, asset management, environmental impact assessment (EIA) development planning, cartography, and route planning. The GIS software used is ArcView 3.2, a package produced by ESRI.[49]

The population files were downloaded from Surpop and then imported into ArcView 3.2. From there, they can be exported as an .asc file, which can be read as a grid in Microsoft Excel.

12.3 Central Belt Scotland Analysis

To assess whether the modified calculator analysis was successful, the population grids of central belt Scotland were downloaded from the Surpop website. 16 grids were necessary to cover the relevant region. To visualise these areas, a screenshot from ArcView3.2 was taken, which can be found at Figure 8 - Population data. The darker the colour in the figure, the more densely populated the area. It is apparent that the majority of the population lie in Glasgow and Edinburgh, with concentrations following the coastlines and rivers.

A map covering the same area is also available at Figure 9 - Central Scotland to allow the reader to visualise where the population lies.

When analysing each area, the minimum IRR used was 8%, which was deemed a reasonable rate for investment.

A catchment area was necessary for the calculations and an arbitrary radius of 4km was used. This ensured any AD plants in the analysis would only be able to utilise sewage waste that was produced close to the plant location.

The following are the major assumption for this method of analysis:

- Sites can be built anywhere;
- The quality and quantity of sewage per person does not vary;
- All sewage produced is available to the AD plants;
- The AD plant only utilises the sewage from within the given radius.

12.3.1 Results

After running the 16 grids through the Excel-based Calculator, 114 sites in central belt Scotland were found to meet the minimum requirements of 8% IRR. For each grid, the minimum time took to analyse was 40 minutes, with some taking over 4 hours due to the number of calculation undertaken.

The site grid references, with their corresponding IRR can be found in Figure 13 - Site grid reference & IRR.

To ensure that the analysis tool was successful, the plant locations were then placed upon the population values in ArcView 3.2 (Figure 12 - Population & plant locations). As is clearly shown, the AD plants clustered around the areas of larger population.

However, the capital cost to install 114 sites would be prohibitive, and so only the most profitable locations should be researched further.

Another point to raise is that some of the sites were located in water. This tended to occur between towns separated by a body of water. Although this would not be feasible, the analysis tool in its current form does distinguish what the geographical area is made up of.

13 Conclusions

As stated earlier, this thesis considered AD as a process to manage human sewage waste, focussing on three main areas;

- Introduction to sustainability; in particular the two key areas which affect AD; energy and waste.
- Introduction of the AD process and the advantages and disadvantages which act as drivers for such a method of waste management and energy production in central belt Scotland.
- Production and testing of a geographical analysis tool to allow for an automatic site selection.

1. Clearly, there are many reasons to support the concept that AD has the potential to play an important part in future sustainable energy and waste processes. Its use of waste material to produce energy and valuable by-products fits well with all sustainability plans, including Agenda 21.
2. The process of AD is well-known and relatively simple. However, there are primarily economical and political reasons that hinder the widespread uptake of AD, regardless of the environmental and social benefits.
3. The concept of automatic site selection has been proven, using central belt Scotland as a test location. However, the analysis tool could not take into account that some locations could not be built upon, which include:
    - Sites with existing buildings;
    - Greenfield sites;
    - Sites on water.

   Aside from these issues, it was a successful proof of concept. To increase the validity of the site selection, further refining is recommended:
    - Inclusion of brownfield sites as the only locations available for AD plants
    - Exclusion of greenfield sites
    - Exclusion of water locations (e.g., rivers, sea, canals, etc)
    - Introduction of additional available feedstocks (e.g., municipal waste, agricultural waste, etc)

14 Appendix

14.1 Example Population File

NCOL 182
NROW 113
XLLCORNER 195000.00
YLLCORNER 635000.00
CELLSIZE 200
0
0
0
0
0
0
0
0
0
0
0
2
15
0
0
0
35
13
0
0
67
123
0
0
0
0
0
0
45
78
89
67
456
45
0
0
0
0
0

14.2 Visual Basic

14.2.1 Full Script

```
Sub Main()

'### initial run forced
ClearCoords

'### copy across the original population data to work on
PopulateWorking
GetSum
FindMax
MakeNullZone


'### checks there are still profitable projects
While Sheet23.Cells(16, 1).Value > Sheet23.Cells(17, 1).Value
   GetSum
   FindMax
   MakeNullZone
Wend

End Sub

Sub ClearCoords()
'### clears the returned coords for a new simulation

RowNo = 3
Sheet23.Cells(1, 13).Value = 3

While Sheet23.Cells(RowNo, 11).Value <> ""
'### clear the data
Sheet23.Cells(RowNo, 11).Value = ""
Sheet23.Cells(RowNo, 12).Value = ""
Sheet23.Cells(RowNo, 13).Value = ""
RowNo = RowNo + 1
Wend

End Sub



Sub GetSum()
'
' GetSum Macro
' Macro recorded 18/9/2004 by Administrator
'

'
```

```
radius = Sheet23.Cells(12, 1).Value  '### get radius in cells

'### get the centre
For XCentre = 1 To Sheet23.Cells(11, 1).Value
For YCentre = 1 To Sheet23.Cells(10, 1).Value

'##################################################################

Sum = 0
'### work out the cells in a surrounding square
'## calc the upper LH corner
Xulh = XCentre - radius
Yulh = YCentre - radius

'## now scan through using double the radius in each direction
For XCoord = Xulh To Xulh + (radius * 2)
   For YCoord = Yulh To Yulh + (radius * 2)
      '## if <1 in either row or column ignore
      If YCoord > 0 And XCoord > 0 And XCoord < 257 Then
         '### check that cell is within circle
         CheckRadius = ((XCoord - XCentre) ^ 2 + (YCoord - YCentre) ^ 2) ^ 0.5
         If CheckRadius <= radius Then
            '### calculate the sum
            Sum = Sum + Sheet24.Cells(YCoord, XCoord).Value
         End If
      End If
   Next YCoord
Next XCoord

'### output the sum to the sum sheet
Sheet26.Cells(YCentre, XCentre).Value = Sum

'##################################################################

Next YCentre
Next XCentre


End Sub


Sub FindMax()

MaxValue = 0

'### get the centre
For XCentre = 1 To Sheet23.Cells(11, 1).Value
   For YCentre = 1 To Sheet23.Cells(10, 1).Value
      If Sheet26.Cells(YCentre, XCentre).Value > MaxValue Then
```

```
            MaxXCentre = XCentre
            MaxYCentre = YCentre
            MaxValue = Sheet26.Cells(YCentre, XCentre).Value
        End If
    Next YCentre
Next XCentre

'### return the parameters to the required place
Sheet23.Cells(13, 1).Value = MaxXCentre
Sheet23.Cells(14, 1).Value = MaxYCentre
Sheet23.Cells(15, 1).Value = MaxValue

'### return the result to the results store
'If Sheet2.Cells(16, 1).Value >= Sheet2.Cells(17, 1).Value Then

    RowNo = Sheet23.Cells(1, 13).Value

    Sheet23.Cells(RowNo, 11).Value = Sheet23.Cells(13, 1).Value
    Sheet23.Cells(RowNo, 12).Value = Sheet23.Cells(14, 1).Value
    Sheet23.Cells(RowNo, 13).Value = Sheet23.Cells(16, 1).Value

    Sheet23.Cells(1, 13).Value = Sheet23.Cells(1, 13).Value + 1

'End If


End Sub


Sub MakeNullZone()
'### nullify all chosen cells

radius = Sheet23.Cells(12, 1).Value  '### get radius in cells

XCentre = Sheet23.Cells(13, 1).Value
YCentre = Sheet23.Cells(14, 1).Value

'##############################################################

'### work out the cells in a surrounding square
'## calc the upper LH corner
Xulh = XCentre - radius
Yulh = YCentre - radius

'## now scan through using double the radius in each direction
For XCoord = Xulh To Xulh + (radius * 2)
    For YCoord = Yulh To Yulh + (radius * 2)
        '## if <1 in either row or column ignore
        If YCoord > 0 And XCoord > 0 Then
            '### check that cell is within circle
```

```
            CheckRadius = ((XCoord - XCentre) ^ 2 + (YCoord - YCentre) ^ 2) ^ 0.5
            If CheckRadius <= radius Then
                '### zero the resource cells
                Sheet24.Cells(YCoord, XCoord).Value = 0
            End If
        End If
    Next YCoord
Next XCoord

'#############################################################

End Sub


Sub PopulateWorking()
For XCentre = 1 To Sheet23.Cells(11, 1).Value
For YCentre = 1 To Sheet23.Cells(10, 1).Value

Sheet24.Cells(YCentre, XCentre).Value = Sheet25.Cells(YCentre, XCentre).Value

Next YCentre
Next XCentre



End Sub
```

14.2.2 Additional Visual Basic Info

Sheet
1 – Read
2 – Demographics
3 – ResulstSummary
4 – EnergyBalance
5 – ParametersPlant
6 – ParametersEconomy
7 – FeedStockProperties
8 – DigestionCharacteristics
9 – InputFeedMix
10 – DigesterSizingAndHeat
11 – CarbonNitrogen
12 – BiogasYields
13 – ParametersEngine
14 – EngineSize
15 – ThermalBalance
16 – ElectricalLoads
17 – FeedTransportCosts
18 – DigestateTransportCosts
19 – ParametersCosting
20 – DetailedCosts
21 – FinancialBalance
22 – Greenhouse
23 – Control
24 – WorkingPopData
25 – OriginalPopDat
26 – SummedPop

14.3 GIS Mapping

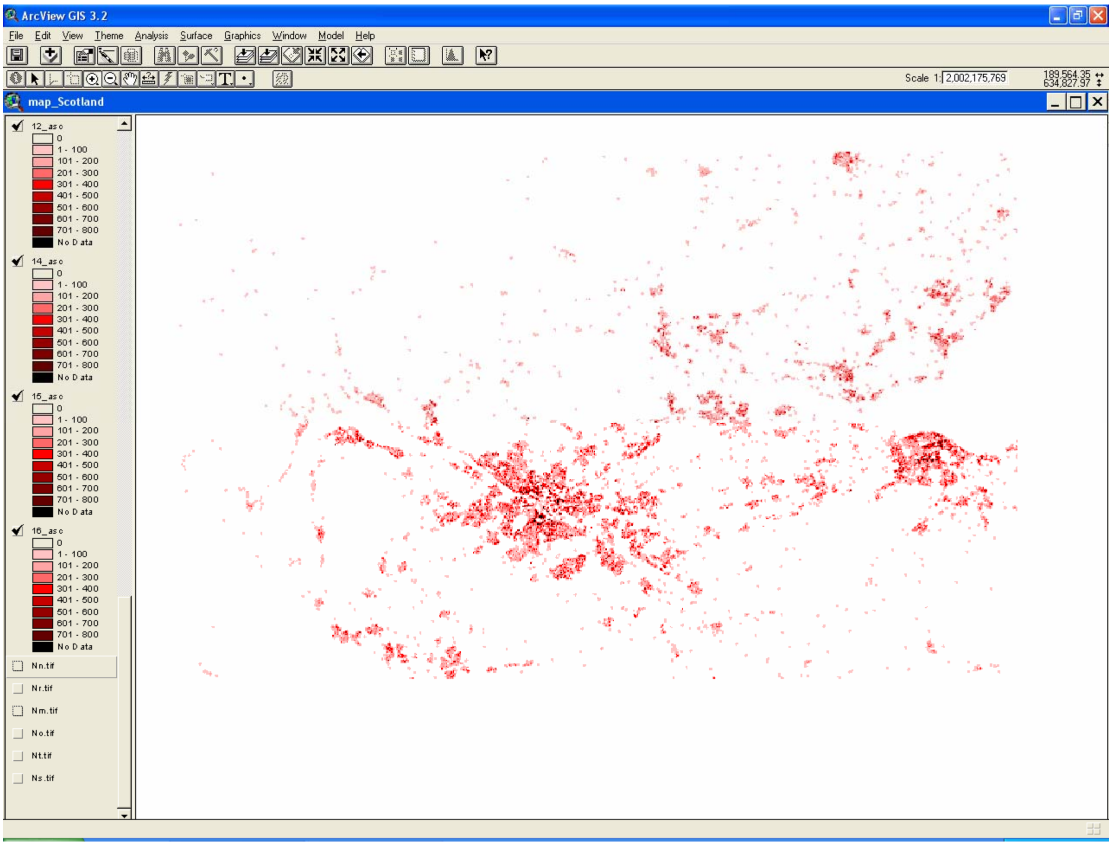

Figure 8 - Population data

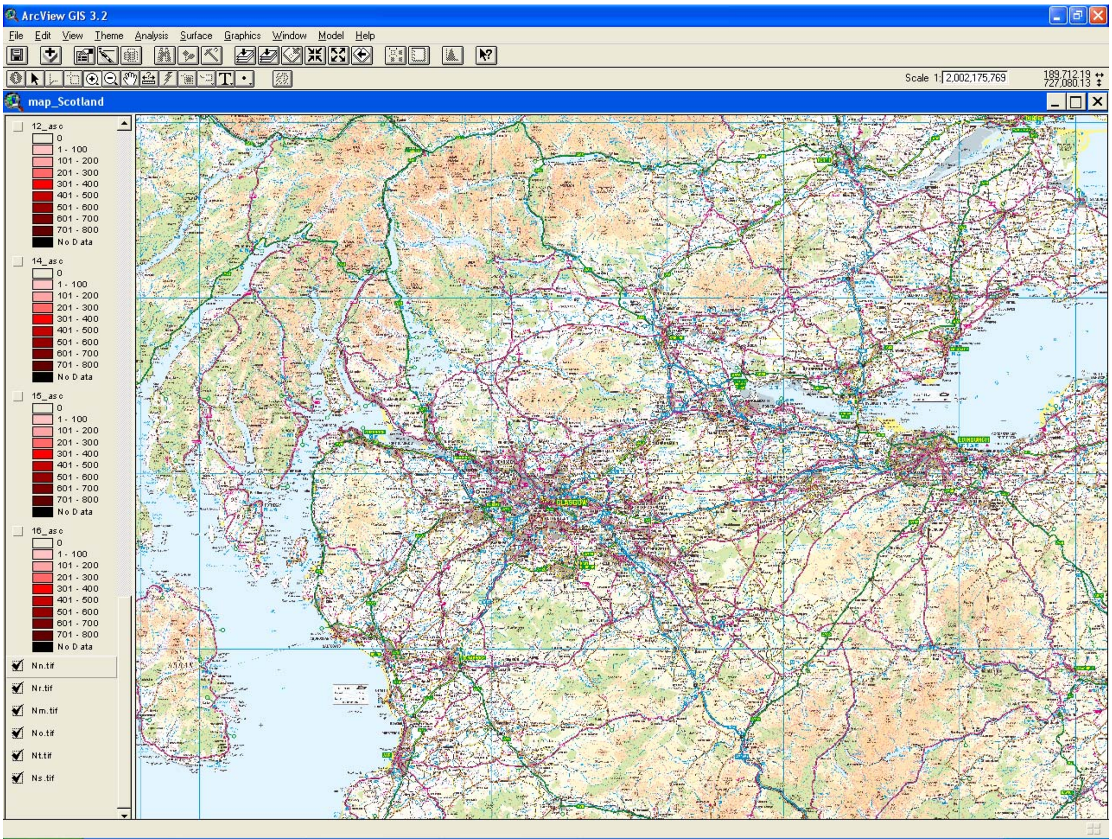

Figure 9 - Central Scotland

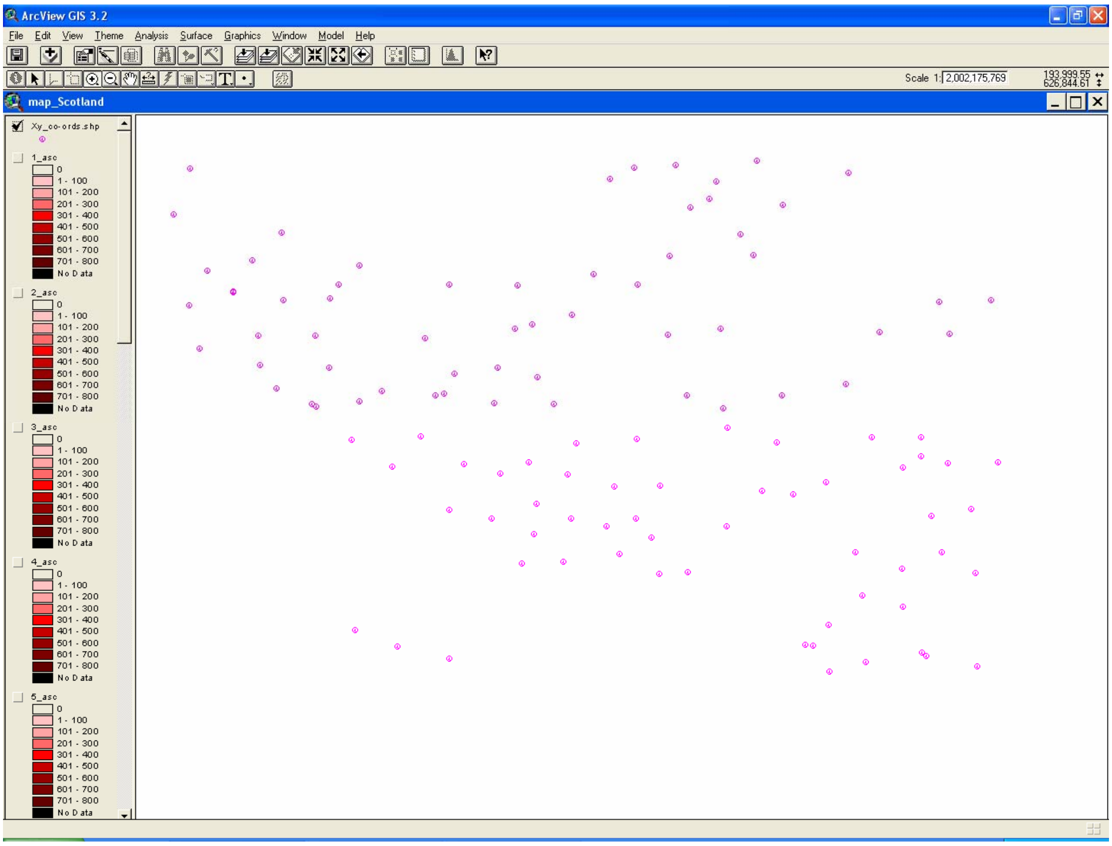

Figure 10 - Plant locations

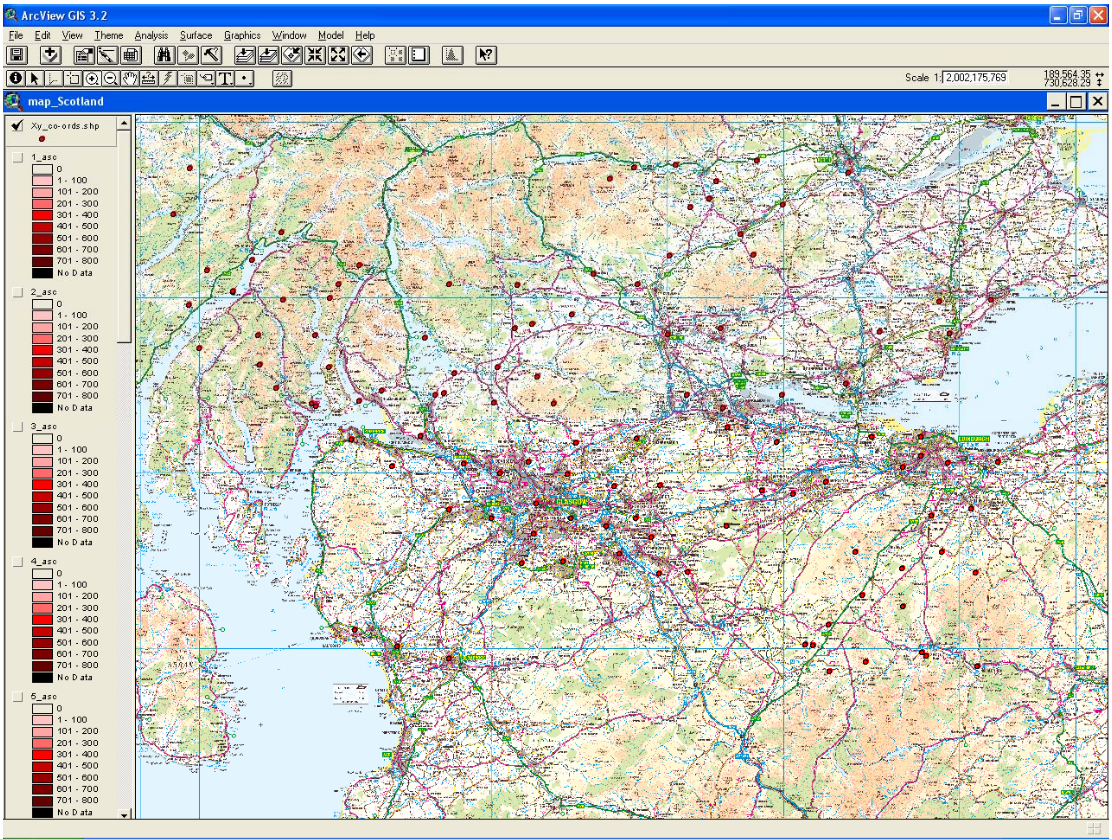

Figure 11 - Plant locations on map

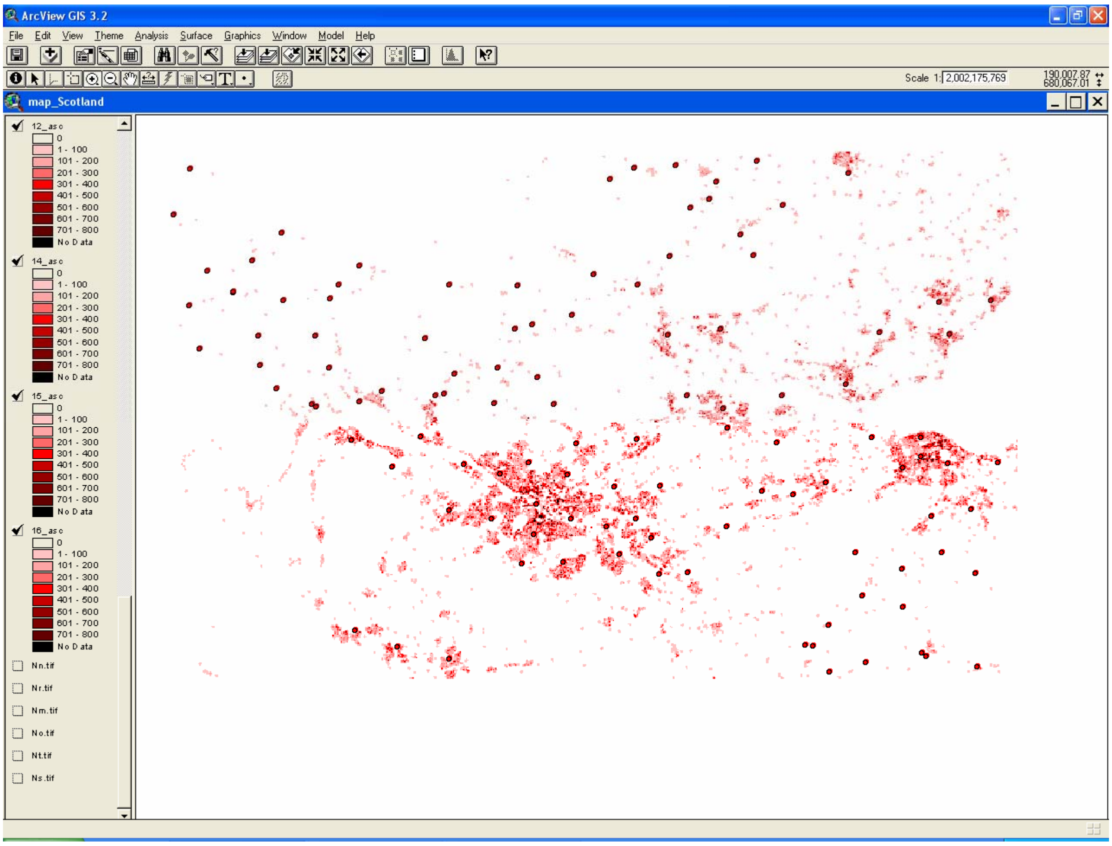

Figure 12 - Population & plant locations

14.4 Results

X	Y	IRR
323800	639400	80.82%
288600	720000	78.78%
292800	711000	37.51%
251200	688200	37.01%
333200	637000	34.86%
219400	682000	33.90%
222400	688200	32.90%
305200	640600	32.87%
313600	649200	31.98%
231400	684200	31.86%
264000	697200	31.83%
274600	722400	31.52%
300000	716000	31.44%
254200	694800	31.31%
280600	707200	30.98%
209200	706600	30.95%
227600	705600	30.93%
258000	686600	30.88%
254600	702200	30.65%
243800	687200	30.50%
206000	701000	30.40%
213400	684600	30.32%
320400	653800	30.31%
195800	714400	30.26%
295600	723600	30.25%
198600	722200	30.17%
214200	711200	30.17%
308000	636200	30.16%
222600	700000	30.13%
250600	682200	30.12%
307800	644200	30.07%
320600	647200	30.06%
275200	702400	30.04%
201600	704800	30.04%
198400	698800	30.01%
238800	693200	29.97%
333000	653000	29.93%
220000	693600	29.88%
257200	695600	29.88%
295000	707400	29.87%
270400	720400	29.87%
243000	702400	29.87%
312400	656600	29.86%
284200	715600	29.85%
200200	691400	29.85%
220200	681600	29.85%
210200	693600	29.84%
224000	702400	29.78%
281600	722800	29.77%
324600	638800	29.76%
314200	637800	29.76%
260800	682000	29.74%
206000	701200	29.72%
267600	704200	29.72%
214600	699800	29.68%
210600	688600	29.68%
287400	717000	29.67%

X	Y	IRR
303800	640800	29.66%
242000	683800	29.66%
327200	656600	29.66%
257800	664800	22.65%
323600	673000	22.61%
263800	662400	22.33%
251600	670000	22.33%
250200	662400	22.22%
274800	662400	21.98%
328200	671800	21.87%
257400	659600	21.80%
263200	669800	21.75%
272000	656200	21.53%
262400	655000	21.47%
310800	685400	21.15%
226200	675800	21.04%
320600	671000	20.98%
243000	663800	20.97%
275000	676000	20.95%
278800	652800	20.91%
307400	668600	20.87%
328600	694000	20.85%
243000	638400	20.84%
289800	681200	20.77%
332200	664000	20.65%
226800	643200	20.65%
280400	693800	20.49%
256600	672000	20.48%
326800	699400	20.43%
269800	661000	20.40%
234000	640400	20.29%
296400	667000	20.27%
289400	694800	20.25%
238000	676400	19.96%
311200	721400	19.93%
255400	654600	19.91%
290600	677800	19.78%
335600	699800	19.43%
336800	672000	19.24%
316600	694200	19.19%
271200	667800	18.98%
245400	671600	18.50%
264600	675200	18.39%
325400	662800	18.14%
283600	683400	17.95%
233200	671200	17.69%
279000	668000	17.02%
277600	659000	16.34%
227600	682400	15.24%
283800	653200	14.75%
299800	683400	14.60%
290400	661000	14.41%
315200	676200	14.34%
301800	666400	12.32%
240600	683400	11.83%
323600	676200	10.47%
299000	675400	9.28%

Figure 13 - Site grid reference & IRR

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