PYROLYSIS FOR WASTE TREATMENT: A LIFE CYCLE ASSESSMENT OF BIODEGRADABLE WASTE, BIOENERGY GENERATION, AND BIOCHAR PRODUCTION IN GLASGOW AND CLYDE VALLEY

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ACRONYMS

AD: Anaerobic digestion

BMW: Biodegradable municipal waste

BCHY: Biochar yield

CD: Construction and demolition

CHP: Combined heat and power

CI: Commercial and Industrial

CO_2-eq: Carbon dioxide equivalents

GCV: Glasgow and Clyde Valley

GHG: Green house gas

IBI: International Biochar Initiative

LCA: Life cycle assessment

MSW: Municipal solid waste

MWhe: Megawatt hour of electricity

PPM: Parts per million

RO: Renewables Obligation

ROC: Renewables Obligations Certificates

Contents

CHAPTER 1: INTRODUCTION 1
CHAPTER 2: GENERAL CONTEXT 4
  Bioenergy crops or biodegradable waste: current biomass debate context 4
  Biodegradable waste and bioenergy generation context 6
  Pyrolysis, biodegradable waste, and bioenergy generation context 9
  Biochar and biodegradable waste context 11
  Life cycle analysis context of biodegradable waste, biochar, and bionergy systems 13
CHAPTER 3: SITE SPECIFIC CONTEXT 16
  BMW generation and treatment in GCV 16
CHAPTER 4: METHODOLOGY 24
  Data collection and construction 24
  LCA scenarios design 25
  Calculation methodologies 27
    GHG release indicators 28
    GHG abatement indicators 29
    Economic indicators 38
CHAPTER 5: ANALYSIS AND DISCUSSION OF RESULTS 42
  LCA for Garden and Green wastes 42
    First case scenario 42
    Second case scenario 44
    Third case scenario 46
  LCA for CD and CI wood 49
    First case scenario 50
    Second case scenario 50
  Summary of all LCAs 53
    Analysis of results by waste treatment case scenario 54
    Analysis of results by feedstock 55
    Analysis of indicators by life cycle phase 57
  Economic results 60

Capacity needed ... 63

Cost-benefit analysis ... 66

GHG mitigation and landfill diversion potential ... 68

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS ... 70

REFERENCES ... 75

CHAPTER 1: INTRODUCTION

Global warming is indisputable, given the evidence related to increases in global average air and ocean temperatures, widespread melting of the ice caps, and a rise in the global average sea level **(IPCC, 2007).**

To address this issue, the European Unions's aim is to set up a limit to less than 2°C of the global average temperature by 2050, compared to pre-industrial levels. This action could limit the climate change impacts and their further irreversible consequences of the global ecosystem. To achieve its aim, the European Council has concluded that this will require atmospheric concentrations of GHG to remain below 550 ppm of CO_2-eq **(European Commission, 2007).** In 2008**, Anderson et al (2008, p. 2)** suggested that this stabilization concentration implies an 82 % probability of exceeding 2°C. Their analysis concludes that, in order to have a 93 % probability of not exceeding this temperature, the concentration would need to be stabilized at, or below, 350 ppm of CO_2-eq below current levels.

To achieve these stabilization concentrations, it will be imperative for local governments to design and implement strategies to mitigate the release of GHG emissions generated by anthropogenic activities. The main objective of these strategies will have to be the identification of potential actions to deliver a more sustainable management of the natural resources. One of these actions could be the development of integrated systems to treat more efficiently the biodegradable waste produced as a result of processing natural resources for consuming activities.

In the current context, post-consumer waste is just a small contributor to global GHG emissions (less than 5%, with total emissions of approximately 1300 Mt CO_2 -eq in 2005). However, the importance that the waste sector has in the mitigation of global GHG emissions has frequently been underestimated because waste management decisions are often made locally without efficient strategies to quantify GHG emissions (**Bogner et al,**

2007). Thus, efficient waste-management practices can provide a significant mitigation of the emissions related to this sector.

In recent years, several environmentally effective technologies have been developed to mitigate methane emissions (which is the most important GHG generated by the decomposition of waste), while at the same time, provide public health and sustainable development benefits. For example, landfill technologies have been designed to recover the methane generated. Moreover, other techniques such as composting, have been designed to avoid significant GHG generation. Apart from this mitigation, the sustainable benefits reside in the fact that the energy contained in the gas recovered can be used to generate electricity or combined heat and power if used in an efficient way.

Nowadays, there is a huge potential for accelerating both the mitigation of GHG emissions from waste as well as indirect reductions within other sectors (**Bogner et al, 2007**). For example, if thermal treatment technologies, such as pyrolysis, start to receive more attention, the emission mitigation could increase significantly not only because of the fossil fuel emissions displaced by the electricity generated that this technology could offer, but also by the fixation of carbon which is part of the biological charcoal (biochar) produced during waste treatment activities. Moreover, indirect reductions in the agricultural sector can be enhanced by the application of this material as a fertilizer for soils.

In order to effectively quantify and monitor GHG emissions and their potential reduction during the life cycle of waste, the application of methodologies such as life cycle assessments (LCAs) are essential since they consider the direct and indirect impacts of waste management strategies, policies, and technologies (**Thorneloe et al, 2002**). By using LCAs as a decision-support tool, many abatement strategies that can be cost-effectively implemented by any sector can be analysed and improved (**Bogner et al, 2007**).

Hence, this study will focus on the implementation of LCAs to analyze not only the potential that pyrolysis has as an emerging system to treat biodegradable waste in a developed country, but also its ability to contribute to quantifiable and significant GHG emission reductions by means of producing green energy and biochar, which are the main abatement pathways that this environmentally-sustainable technology can offer.

Rationale

Biochar production and waste treatment by pyrolysis represent an attractive solution to decrease carbon dioxide atmospheric concentrations and to enhance the enrichment of soils by treating in a more sustainable way the biodegradable waste generated in urban or rural areas. However, its application in developed regions (such as Scotland) is still uncertain due to the consolidation of other disposal and treatment technologies in the waste market.

Therefore, it is necessary to analyze this technology and compare it, from an environmental and economical point of view, with other waste treatment and disposal technologies that are currently operating in Scotland, such as landfill disposal or anaerobic digestion.

Objectives

The first objective of this study is to identify several biodegradable waste feedstocks generated in a specific region of Scotland that could potentially be treated by emerging waste treatment technologies such as anaerobic digestion or pyrolysis.

The second objective is to apply the LCA methodology to compare the GHG emission and abatement impacts, and the economic costs and benefits of traditional and emerging waste management systems in a specific region of Scotland.

CHAPTER 2: GENERAL CONTEXT

The aim of this chapter is to explain the role that a LCA approach could have in the analysis of the future of pyrolysis as an emergent technology for waste management in a specific region of Scotland (Glasgow and Clyde Valley area). However, it is essential to explain first, in a general way, the current context of each one of the aspects that constitute pyrolysis systems (biomass availability, waste treatment, bioenergy generation, and biochar production) and how these are related between them.

Bioenergy crops or biodegradable waste: current biomass debate context

Biomass is now considered to be an important contributor to sustainable development. The main reason is that, since it is an important energy source, it could have an important role in achieving a region's energy security. In addition, biomass energy can have a positive effect on degraded land by adding organic matter to the soil and can help significantly in the mitigation of global warming, since its use in energy production offsets fossil fuel GHG emissions (**Hoogwijk et al, 2003**).

The main biomass forms usually considered for sustainable purposes are bioenergy crops and biodegradable waste or residues. Bioenergy crops are materials usually harvested to be used specifically for biofuel production. Biodegradable residues are generated as by-products from agricultural and forestry activities, or by households in the form of food waste. Unlike bioenergy crops, these are not specifically produced as an energy resource (biofuels) since they are the result of the production of goods and services in almost all sectors of the economy (**Cherubini et al, 2009**).

More recently, there has been much debate about the contribution of bioenergy crops in mitigating global warming and their ability to help nations develop in a more sustainable way. At the centre of the debate is the fact that the demand for biofuel feedstocks is overwhelming a supply system that was already pressured by an increasing food demand, and that it affects even non feedstock crops, such as rice and wheat, as farmers use land to harvest biofuel feedstocks instead of using it to produce food (**Tenenbaum, 2008**).

Moreover, research has found that the potential clearing and preparation of land to grow biofuel crops releases more carbon than the one that would be saved by the biofuels made from the harvested crops. In a long term scenario, the production of biofuels could create a "carbon debt" by releasing 17 to 420 times more CO_2 than the annual GHG reductions these biofuels provide by displacing fossil fuels (**Fargione et al, 2008**).

In contrast, bioenergy produced from biodegradable waste does not incur significant environmental impacts, carbon debts, or compromise the use of land already designated to produce crops for human consumption. This is because its generation in urban or agricultural areas would already occur in a business as usual scenario. If used for energy generation, biodegradable waste, such as wood, garden or food waste, is considered as "carbon neutral" because its combustion releases the same amount of CO_2 that was captured by the biomass during its growth. Thus, the bioenergy generated has an almost closed CO_2 cycle, while fossil fuels release considerable amounts of this gas that has been locked up for millions of years (**Cherubini et al, 2009**).

Because of these reasons, this study will explore only the availability of biodegradable waste feedstocks for bioenergy generation systems and will focus on the potential pathways that this form of biomass contributes to the mitigation of global warming and to achieve a more sustainable development in Scotland. A more detailed explanation about the feedstocks used and the specific context of the region that will be studied is included in **Chapter 3**.

Biodegradable waste and bioenergy generation context

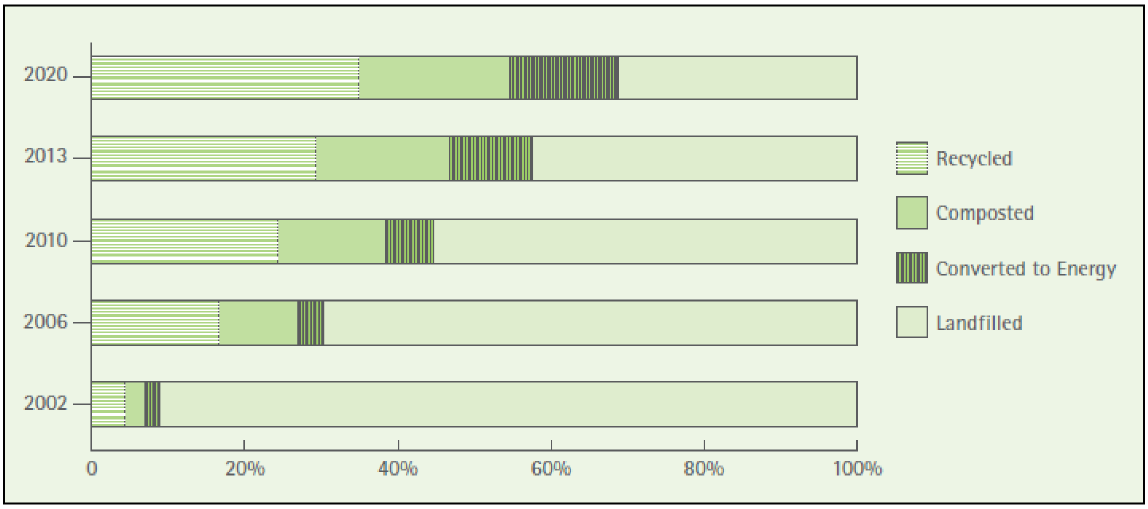
The MSW generated in Scotland is managed by eleven different waste areas and most of it ends up being disposed of in landfills since this waste treatment system has been the most traditional and cost effective one in recent years. Of the totality of MSW generated in urban areas, BMW constitutes 60% of it (**NWP, 2003**).

Relying on landfills as a solution for waste generation, however, has many negative consequences. For example, it presents a risk to human health, it provokes impacts on the environment (such as the pollution of surface water, groundwater, soil, and air), and it exacerbates the problem of global warming since GHG, such as methane, are constantly released to the atmosphere.

In order to mitigate these impacts, the European Union Landfill Directive was created in 1999, and the UK brought it into force in 2002 as the Landfill Regulations. One of the main objectives of these regulations is to reduce the amount of BMW disposed of in landfills (which are a major contributor to the production of the greenhouse gas methane) by setting ambitious reduction targets.

Since then, the disposal of waste in Scottish landfills has decreased from approximately 91% down to 70% in 2006 (**see Figure 1**), and will continue to do so mainly because of the local authorities' obligation of investing in other waste management strategies in order to divert more BMW.

Figure 1. Waste management in Scotland



Source: NWP, 2003

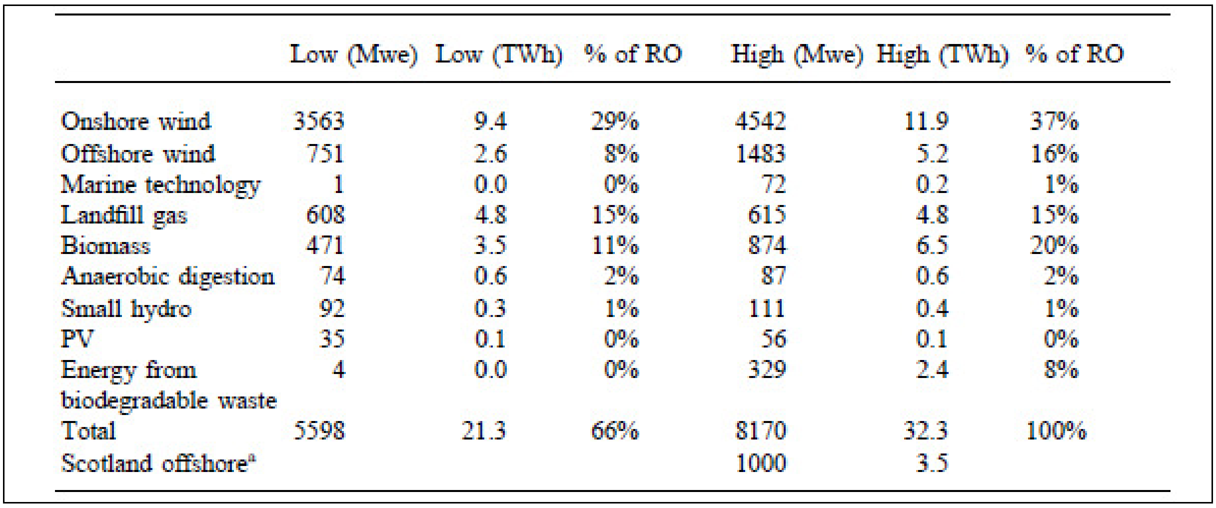
Moreover, the recovery and production of energy from biodegradable waste could play an important role in meeting the landfill directive targets. Nevertheless, the percentage of energy recovered in Scotland continues to be small. In 2006, for example, only about 5% of it was converted to energy (**NWP, 2003**).

However, this situation is expected to change in the short term with the establishment of directives such as the Scottish Renewables Obligation (RO). This directive is the main support mechanism for renewable energy projects in the UK, and it places a requirement on energy companies to supply an increasing portion of their electricity generation from a choice of different renewable sources.

The logic of this directive is simple. Once energy suppliers invest in renewable technologies, they have to demonstrate their compliance with the RO through the production of Renewables Obligations Certificates (ROCs). Each ROC equals 1 MWh of electricity and can be earned by supplying the green energy purchased from generators, or by selling any surplus of ROCs to other suppliers. The revenues collected by the regulator body (OFGEM) are administered in a fund which is then redistributed to suppliers in relation to the number of ROCs presented by each one of them. In this way, the generation of these certificates and the earnings derived from them represent an additional economic stimulus for companies that in the end help them to meet their obligation (**Connor, 2003**).

As a result of the RO implementation, it has been projected that electricity from biodegradable waste could represent approximately 8% of the total renewable energy generated by 2010 in the UK (**see Table 1**). However, only waste containing 90% or more biomass will be eligible to receive ROCs in Scotland. According to the Scottish Executive **(2007, p. 7),** "exceptions to this rule include the biomass element of waste treated by advanced conversion technologies".

Table 1. Projected electricity generation in 2010



	Low (Mwe)	Low (TWh)	% of RO	High (Mwe)	High (TWh)	% of RO
Onshore wind	3563	9.4	29%	4542	11.9	37%
Offshore wind	751	2.6	8%	1483	5.2	16%
Marine technology	1	0.0	0%	72	0.2	1%
Landfill gas	608	4.8	15%	615	4.8	15%
Biomass	471	3.5	11%	874	6.5	20%
Anaerobic digestion	74	0.6	2%	87	0.6	2%
Small hydro	92	0.3	1%	111	0.4	1%
PV	35	0.1	0%	56	0.1	0%
Energy from biodegradable waste	4	0.0	0%	329	2.4	8%
Total	5598	21.3	66%	8170	32.3	100%
Scotland offshore[a]				1000	3.5	

Source: Connor, 2003

Considering this context, it could be implied that the conditions for making biodegradable waste one of the most important factors of the present and future bioenergy generation in Scotland have been created. With the passing of time, these mechanisms will increasingly contribute to the diversion of biodegradable waste from landfills and its advanced treatment for bioenergy generation by emergent conversion technologies such as gasification, anaerobic digestion, or pyrolysis.

Of all the technologies mentioned, pyrolysis can offer more interesting pathways that could help meet the bioenergy generation, sustainable waste treatment, and climate change mitigation objectives that the Scottish executive has now set up. Thus, this study will focus on the role that this technology could have in the achievement of these objectives.

Pyrolysis, biodegradable waste, and bioenergy generation context

Thermal treatment covers different technologies, such as incineration, gasification, or pyrolysis. The common process is the heating of biomass in the absence or presence of oxygen in order to produce energy and to reduce the mass and the volume of the material. Facilities for waste thermal treatment are regulated under the Waste Incineration (Scotland) Regulations of 2003, and SEPA has published Thermal Treatment Guidelines which offer strong support for the efficient capture of the energy embedded in waste (**Scottish Executive, 2007**).

These guidelines are based on the fact that any new thermal treatment facilities would be expected to be as efficient as possible. In other words, facilities should be more efficient when the process of converting any specific fuel delivers more useable energy at a specific period of time.

For example, facilities that are able to use the heat and power generated as a result of the conversion process (CHP facilities) are more efficient than those that only use the power generated (electricity only). Thornley et al **(2009, p. 897)** estimated that thermal treatment facilities with gasification, combustion or pyrolysis processes can achieve efficiencies of between 20 and 30% if they generate electricity only, while higher ones of between 65 and 85% if they generate CHP. The electricity generated is usually delivered to the national grid, while the heat can be distributed and used in district heating systems if these are available in the area where the facility has been installed.

If compared to incineration, pyrolysis is an emergent technology that is in a demonstration stage. However, it has been under research and development for nearly 20 years (**Bridgewater et al, 2000**) and with all the economic incentives and guidelines mentioned before, it can be expected to achieve a commercial status in a short or medium term. Several plants have been built and operated in Austria, Germany, Italy, Korea, Switzerland and Japan (**Malkow, 2004**). Some of them seem to have worked satisfactorily during the demonstration stage, showing that it could become a viable option in the future. However, the world's two largest plants at Karlsruhe and Fürth, in Germany, have both closed because they could not meet their design specifications (**Mistry et al, 2008**).

The process of pyrolising biodegradable waste materials involves three parallel pathways: slow pyrolysis, where biochar and gases are formed, fast pyrolysis, where liquids and tars are formed, and gasification, where almost all the material treated is gasified (**Amonette et al, 2009**). Of these pathways, fast pyrolysis and gasification are potential candidates for power production (**Chiaramonti et al, 2007**) since they produce big quantities of liquids and gases that can be further processed to generate electricity or CHP. Moreover, fast pyrolysis is also beneficial since the liquid fuel can be stored and transported from the generation point to the site where the energy is required.

Mistry et al **(2008, p. 5)** estimated in 2008 that "from a total of 13,730,000 tonnes of waste generated in Scotland in 2007, 9,634,000 tonnes were technically suitable to be processed in a thermal treatment plant to obtain bioenergy". The energy content of these biodegradable wastes was assessed at 2,233,000 MWh of biogas from anaerobic digestion, and 15,483,000 MWh for thermal treatment. In comparison, the amount of natural gas used in Scotland was around 85,540,000 MWh. Thus, anaerobic digestion and thermal treatment processes such as incineration or pyrolysis could help substitute between 2.6 and 18% of the total natural gas consumed, and in the subsequent reduction of GHG emissions.

However, if compared against these technologies, pyrolysis could become a more attractive waste management strategy in the following years for several reasons. The first is that investment in incineration could decrease, since this treatment system has grown unpopular with the public, mainly because of the health effects of emissions generated by these facilities. Additionally, incineration is receiving less ROC incentives from the generation of renewable energy in contrast to other emergent technologies. Moreover, pyrolysis could become more attractive than AD because of its capability of generating higher electricity outputs per tonne of feedstock treated.

Finally, an important factor to consider, and that could contribute to the consolidation of pyrolysis in the waste market, is that it is the only technology that is capable of generating biochar as a result of the waste treatment process. Biochar, as a waste management strategy, can offer multiple benefits, as it would be explained in the following section.

Biochar and biodegradable waste context

In the context of climate change that we are facing nowadays, several geo engineering techniques are starting to be researched and developed in order to mitigate the increasing GHG and the effects of global warming, such as solar radiation management or carbon capture and storage. Although most of these technologies are still subject to criticism and there is no general consensus about the desirability and feasibility of developing them due to different economical, technical, or environmental aspects (**Schneider,2008**), some of them are starting to emerge as viable technologies in addressing global warming.

The production of biochar from biomass is one of them. Biochar is a black carbon material produced by pyrolysis processes (heating biomass with a limited supply of oxygen). It is resistant to degradation or decomposing processes since its molecular configuration makes it a highly stable material. Thus, biochar represents an attractive way of removing carbon dioxide from the atmosphere because it is capable of stabilising for many years the carbon that composes the organic matter. According to the International Biochar Initiative, the sequestration of approximately one gigatonne of carbon dioxide per year could be achievable by 2050 if enough resources are assigned for the research and development of this technology on an industrial scale (**Tenenbaum, 2009**).

Moreover, biochar could contribute not only to the mitigation of global warming, but also to the sustainable development of countries since pyrolysis offers the generation of green energy and a more efficient management of waste. The material itself can be used as soil amendment for agricultural activities, enhancing thus the potential enrichment of soils.

Analyzing specifically its value as waste management strategy, biochar systems could offer a more environmentally sustainable way of treating biodegradable waste from urban areas. Biochar, as mentioned previously, can be produced from agricultural or urban biodegradable waste. This waste generated in rural areas is a valuable resource as soil amendment, feedstock for animals, or as a construction material. Therefore, its availability is generally limited (**Lehmann et al, 2009**). In contrast, biodegradable waste from urban areas is generated in higher proportions and usually ends up being disposed of in landfills. Thus, if diverted from landfills, it could represent an attractive material for the production of biochar in an industrial scale.

However, in order to be successful, biochar technologies would need to have efficient biodegradable waste collection and separation systems in order to secure a continuous supply of feedstocks. In urban areas, this implies the separation and collection at its generation source. To achieve this, the implementation of kerbside collection systems would be essential to manage, for example, garden and green, food, or even wood generated at households, commercial, or industrial sites. In Scotland, estimations show that these collection systems will be widely implemented in the short term (**CEC, 2009**).

Moreover, transportation of biowaste is also an important factor to consider when designing potential biochar systems since it contributes significantly to overall costs. **Lehmann et al (2009, p. 151)** conclude that, in contrast to agricultural waste, "BMW from urban and industrial areas may provide opportunities to keep transportation needs low because they are already aggregated, and, in many cases, close to energy consumption needs".

Finally, the carbon abatement pathways that biochar systems offer could have a significant influence on the efficiency of biodegradable waste management in the future. Although there is no current evidence to support this argument, this fact can be deduced by making a comparison with waste recycling schemes. These schemes, for example, have been constantly increasing the waste recovery rates mainly because the recycled material has an aggregated value in the market. Thus, in a scenario where carbon offset prices are incrementing, the carbon abatement opportunities offered by biochar production would have an aggregated value that could influence the waste management companies' interest in recovering more biodegradable waste.

In this context, in order to have efficient and reliable biochar systems, it is necessary to create scenarios in which the recovery of biodegradable waste and the potential achievement of GHG abatement efficiencies can be accurately calculated and monitored. The most suitable way of performing this is with LCAs, a tool used to compare environmental or economical benefits and impacts associated to the life cycle phases (for example, generation, management, and treatment) of any given material.

Using this methodology, the current and future scenarios of biochar and biodegradable waste in Scotland and their association with the mitigation of GHG emissions and the improvement of waste management systems can be reliably addressed, as will be explained in the following section.

Life cycle analysis context of biodegradable waste, biochar, and bionergy systems

LCA is an environmental and economic management tool used to understand how a product or service is provided from a "cradle to grave" point of view. This technique examines every stage of the life cycle, in which the inputs, such as raw materials, economic resources, and energy, and the outputs, such as air or water emissions, and waste generation, are calculated. The application of this methodology allows for a better understanding of products and services processes (**McDougall, 2001**).

One of the values derived from the application of LCA to analyze waste management and bioenergy production systems is the identification and quantification of the potential environmental benefits and impacts associated to them. These benefits and impacts may differ depending on the type of feedstock sources, conversion technologies, system boundaries and reference energy systems to which the bioenergy chain is compared (**Cherubini et al, 2009**). Regional differences can be also significant, since if the biomass production patterns and the reference energy system vary, so will do the LCA results.

Khoo **(2009, p. 1893)** suggested that "LCAs for common waste management and bioenergy systems has gained importance in comparing the many parameters within the different treatment options and generation of by-products, and has become the principal support tool for decision and policy makers at all levels for waste management strategies". However, most of these assessments focus in the production of bionergy from MSW or bionenergy crops only, and the parameters studied are related to the monitoring of GHG emissions and the energy balances of the systems.

For example, Thorneloe et al (**2002, p. 1000-1011**) used a LCA approach to study the impact of MSW on GHG emissions. Khoo (**2009, p. 1892-1900**) used it to determine the environmental impacts of different thermal treatment technologies for waste conversion and delivered some conclusions about the most cost effective ones. Moreover, Thornley et al (**2008, p. 890–903**) analyzed the technical, environmental, and economic impacts of entire bioelectricity systems based in bionergy crops (miscanthus, straw, etc.), with a number of life-cycle indicators as outputs to facilitate comparison.

However, none of the assessments examined in the literature reviewed focus on the thermal treatment of biodegradable waste generated in urban areas for producing bioenergy and biochar at the same time. The closest assessment found with a similar scope to this study was performed by Gaunt et al (**Gaunt et al, 2008**), where the energy balances and emissions associated with the production of bioenergy and biochar with pyrolysis technologies were estimated. Nevertheless, it focus on bioenergy crops only.

Hence, it is considered that the research performed in this study is valuable, since the scope of work proposed has not been addressed previously. In this research, the LCAs performed will be strictly addressing the life cycle stages of some biodegradable waste feedstocks generated in the GCV area, its treatment by three different waste management systems (landfills, anaerobic digestion, and pyrolysis), and the environmental and economical benefits associated with the utilization of the products derived from them.

The system boundaries of these LCAs are defined by the main life cycle phases of the current biodegradable waste treatment scenarios and the potential biochar and bioenergy production technologies. The results obtained will be compared against coal, natural gas, and grid electricity systems, which are the common reference energy systems in a business as usual scenario. A more detailed specification of the feedstocks used and how these LCAs were designed is included in **Chapters 3 and 4**.

The logic of applying this methodology to this specific context is that a comparison of these waste management systems can be realistically performed by quantifying the potential benefits and impacts associated to the treatment of biodegradable waste and the production of biochar. The main outcome expected is the analysis of the potential role that pyrolysis, as a waste management and biochar production system, could have in the GCV area as a sustainable technology in the future.

CHAPTER 3: SITE SPECIFIC CONTEXT

BMW generation and treatment in GCV

The GCV area has the highest density population of Scotland. This area, comprised by 8 councils (East Dunbartonshire, West Dunbartonshire, Glasgow, Inverclyde, North Lanarkshire, South Lanarkshire, East Renfrewshire, Renfrewshire), is the waste strategy area that generates more MSW, compare with the rest of the country (approximately 1,151,000 tonnes per year, (**WDD, 2008**)).

BMW, composed mainly by garden and green, food, wood, paper, cardboard, and sewage sludge waste, represents 60% (690,000 tonnes) of the totality of MSW generated (**SEPA, 2003**). Most of it (approximately 75%, or 526,000 tonnes) was disposed of in the 11 landfills located in the GCV area (**WDD, 2008**).

Apart from the landfills, each council has its own windrow composting plant and one in-vessel composting facility is being operated by Scottish Water Waste Services in Cumbernauld, North Lanarkshire. This facility treats approximately 18,000 tonnes of garden and green waste per year. According to Smith **(2009, personal communication**), the Cumbernauld composting facility will be expanded to a 30,000 tonne per year and one MW AD plant that will be operative by April 2010 and will be able to treat kitchen waste as well.

The feedstocks chosen to be analyzed for this study are garden and green, sewage sludge, food, and wood waste, as well as the potential digestates produced from the future AD plant. Paper and cardboard are excluded, since these materials are already subject to consolidated recycling schemes in Scotland.

The following sections explain the current generation context of each of the feedstocks analyzed, as well as their main properties and their treatment and disposal methods. The properties included are used to calculate mass balances and abatement efficiencies, as it will be explained in the calculation section included in **Chapter 4**.

Garden and green waste

This feedstock, composed mainly by grass, flower cuttings, and hedge trimmings, has a collection coverage in the area of between 20 and 100% (**Remade Scotland, 2008**). The report developed by Remade Scotland provides figures of garden waste collected among each of the Scotland councils in units of kilograms per household per year. The total amount of garden and green waste available in 2007 is approximately 68,800 tonnes. This figure was calculated using the household projections for 2009 published by the General Register Office for Scotland in 2004.

No specific information about the final disposal destiny of this waste collected was available for review. However, according to **Booth** (**2009, personal communication**) approximately 7,300 tonnes generated in this city in 2008, were sent to the in-vessel composting facility mentioned before. Additionally, 18,300 tonnes were chipped, shredded, and mulched within the councils' own parks for their reuse. Therefore, it is expected that the rest of the garden and green waste generated in the GCV area ends up being composted at any of the windrow composting facilities located in each council, or disposed of at landfills.

The properties of this feedstock are shown in **Table 2.** Garden and green waste has higher total solid and biogas yield parameters compared to other waste feedstocks (a fact which makes it special for its treatment at AD facilities). It also has a high calorific value (if used in a dry basis) which is a valuable characteristic for thermal treatment processes such as pyrolysis.

Table 2. Garden and green waste properties

Property	Unit	Value
Calorific value (dry basis)	MJ/kg	18[1]
Biogas yield	m^3 /kg	0.5[2]
Total solids	%	70[3]
Volatile solids	%	90[4]

The main reasons of choosing this waste as a feedstock for the LCA analysis reside not only in the valuable properties mentioned before, but also in the fact that a successful separation and collection system has been implemented to recover it in each of the eight councils that comprise the GCV area.

Food waste

Approximately, food waste constitutes between 18 and 24% of the municipal solid waste generated in Glasgow (**Booth, 2009**). If it is assumed that this tendency is repeated in the rest of the locations, then the amount of food waste available would be of approximately 241,000 tonnes considering a generation of 1,151,000 tonnes of MSW per year.

In 2006, no food waste was collected along the GCV area but this situation has been changing since 2008, when the Scottish government started providing funds to perform food collection trials. As a result, these trials have been implemented at East Renfrewshire, Glasgow, and Inverclyde (**Parfitt et al, 2009**), and the food waste collected is being treated at the Cumbernauld composting facility (**Armstrong 2009**).

By the time this analysis was performed, no information about food collection or composting statistics was available for review. However, it is expected that with the

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[1] ECN, 2009
[2] Steffen, 1998
[3] Steffen, 1998
[4] Steffen, 1998

construction of the new AD plant in Cumbernauld, the separation and collection systems will increase in the area and the waste food generation figures will become more accurate.

Moreover, the properties of this feedstock are shown in **Table 3**. These properties are similar to the ones associated with garden and green waste except for the Total Solids parameter, which is considerably lower. However, the high volatile solids and biogas yield parameters, as well as the calorific value, are significant enough to consider this feedstock for treatment at an AD or pyrolysis plant.

Table 3. Food waste properties

Property	Unit	Value
Calorific value[5]	MJ/kg	17
Biogas yield	m^3 /kg	0.6[6]
Total solids	%	10[7]
Volatile solids	%	80[8]

Construction and Demolition (CD) and Commercial and Industrial (CI) wood waste

The GCV area is the waste strategy area that generates the largest quantities of CD waste in Scotland (approximately 2,500,000 tonnes, or 41.4% of the total generation) and SEPA estimates that 60% of it ends up being disposed of in local landfill sites. Wood waste constitutes 1.7% of this waste stream, and has an approximate recovery rate of 35%. In 2006, approximately 42,300 tonnes were generated, collected, and managed (**SEPA, 2006**).

The treatment given to wood waste from construction activities depends on whether it is segregated at the site by the companies or not. Segregated waste such as off-cuts or sawdust, are usually sold for combustion or sent for recycling. Unsegregated wood waste is likely to be bulked, or sent for recovery or disposal. Moreover, wood waste from

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[5] Rand, et al, 2000, ECN 2009

[6] Steffen, 1998

[7] Steffen, 1998

[8] Steffen, 1998

demolition activities includes windows and doors, skirting boards, furniture, and architraves. The wood waste that is not reclaimed will either be segregated for recycling or taken to a waste transfer station in an unsegregated form for its disposal (**BFM, 2004**).

In any case, since there are no specific separation or collection systems (such as kerbside) to recover the majority of wood mixed in the CD streams, it is expected that a big amount of it ends up being disposed of in landfills as well. However, wood waste at CD sites is increasingly being separated from the general waste stream for recycling in this area (**Armstrong 2009**).

Regarding the CI sector, it has been estimated that a total of between 56,400 (**Mc Laurin et al, 2006**) and 83,300 (**Mistry et al, 2008**) tonnes per year of waste are generated in the wood processing and production of furniture, pulp, paper and cardboard industry. No figures were available for review, relating to the specific generation of wood waste and its treatment or disposal. Hence, for the purpose of this analysis, it will be assumed a generation of 50% of the average of both quantities reported (approx. 35,000 tonnes per year).

Moreover, wood, no matter its generation source, is not commonly treated by AD facilities because this material is hardly degradable under anaerobic conditions due to its high lignin content (a fact that affects the biogas yield parameter, which is important for the capturing of energy) and often causes process failures (**Steffen et al, 1998**). However, its high calorific value of 20 MJ/kg makes it a suitable material to be treated by pyrolysis technologies if it is used in a dry basis.

A possible problem related to the treatment of this waste is that, since it is usually mixed with other CD materials, it could be contaminated with heavy metals or other chemicals such as adhesives. Thus, the presence of these substances in the product or digestate is not desirable, as it is often used as a fertilizer in agricultural areas. However, a potentially contaminated biochar could be used in other processes such as cofiring (under controlled circumstances), or even landfilled.

Sewage sludge

Unlike other wastes generated in Scotland, sewage sludge is not managed and treated by waste strategy area, but by water authorities. The GCV area is located in the West of Scotland Water Authority (WoSWA), and approximately 49,400 tonnes of sewage sludge were generated in 2002 (**WDD, 2002**). Of this total amount, 64.4% or approximately 33,600 tonnes, were disposed of in the landfills of the area.

Sewage sludge, if compared with garden and green waste or food waste, does not have high biogas yield or calorific value parameters (see **Table 4**). Thus, the amount of energy that can be recovered from this waste is significantly lower if compared to the other feedstocks. However sewage sludge is commonly treated in AD plants due to the high value of its volatile solid parameter (**Mistry et al, 2008**), and it becomes a valuable feedstock for this process if mixed with other materials.

Table 4. Sewage sludge properties

Property	Unit	Value
Calorific value	MJ/kg	15[9]
Biogas yield	m^3 /kg	0.31[10]
Total solids	%	8.5[11]
Volatile solids	%	80[12]

Moreover, it is reasonable to include sewage sludge as a potential feedstock either for AD or pyrolysis, not only because of the big quantities generated in the area, but also because it is a waste whose generation is secured by a continuous treatment process of sewage

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[9] ECN, 2009

[10] Sosnowski et al, 2003

[11] BEAT2, 2008

[12] BEAT2, 2008

waste water. Also, this waste is less influenced by recycling activities that other waste materials have, such as wood, or garden and green waste.

AD digestate

The digestates produced by AD treatment processes can be classified as waste or not, depending of the input materials used during the treatment process. In general, the digestate is considered as waste if the input materials were waste. However, the Waste Management Licensing Regulations (WMLR) 1994 allow the use of digestate from anaerobic treatment of animal and vegetable waste as a fertilizer if there is a benefit to agriculture or ecological improvement. In this context, the utility of digestate in other parts of the UK has been as a fertilizer or as a landfill cover.

Currently, no digestate is being produced by AD waste treatment activities in this area. However, it is expected to become available when the 30,000 tonne per year AD Cumbernauld plant starts operations in April 2010.

No information about the potential amount of digestate that will be produced is still available for review. However, according to the calculations performed in this study (**see Chapter 4 and Appendix B**) it has been estimated that a generation of approximately 0.83-0.98 tonnes of digestate per tonne of feedstock could be achieved, a factor that depends directly on the waste treated in the plant.

Although the CV of this feedstock (6.3 MJ/kg[13]) is not as valuable as the ones of the feedstocks mentioned before, it has been considered as feedstock for biochar production. As it happens with sewer sludge, its generation will be secured by a continuous treatment process of organic waste. Moreover, no other LCA studies have considered it before for biochar production purposes.

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[13] ECN, 2009

The only possible problem foreseen from the digestate current context is that this material is usually given for free to farmers for agricultural activities. Hence it would be practically impossible its utilization for pyrolysis treatment if a gate fee has to be paid for it.

CHAPTER 4: METHODOLOGY

Data collection and construction

General information about waste generation and management in the GCV area is available for review from SEPA or other organizations or consultancies. For example, MSW or BMW arisings and treatment statistics were collected from the SEPA webpage[14], which reports this information annually in its Waste Data Digest after gathering it through Waste Data Flow, a system used by Scottish councils to report and monitor their waste generation, recycling, and disposal networks.

However, the Waste Data Digest does not include specific figures regarding the waste that composes the BMW such as wood, kitchen waste, or garden and green waste. Thus, a literature review of several waste reports performed by different consultancies that include the management of these type of wastes was consulted.

Moreover, information related to specific disposal or treatment figures in any of the landfills or composting facilities of the area is not publicly available. Therefore, several local authorities and waste management companies were contacted to request this information via the Freedom of Information Act.

Information about GHG emissions related to waste collection and treatment activities in the GCV is nonexistent. Therefore, the numbers used in this LCA were estimated following the methodologies explained in the "LCA scenario design" and "Calculations" sections.

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[14] httpLMMwww.sepa.org.ukMwasteMwasteqdataMwasteqdataqdigest.aspx

LCA scenarios design

Five different LCAs were performed in this dissertation project, one for every type of feedstock described in **Chapter 3**.

As mentioned previously, landfills, as a solution for waste disposal, have begun to be replaced in recent years by other waste treatment systems in order to comply with the Landfill Directive regulations, and thus, give a more sustainable management of the waste generated in Scotland.

Hence, in this context, three case scenarios were designed for the LCAs of food, garden and green, and sewer sludge waste. The first case scenario deals with the present situation of the GCV area, where an important amount of BMW is disposed of in landfills. The second one considers the Cumbernauld AD plant as a new waste management system that will divert BMW from landfills. The third one considers a potential pyrolysis facility that could either divert BMW from landfills or compete with the future AD plant. In the second and third scenarios, it is considered that the product generated as a result of the treatment system (digestate or biochar) is always used as fertilizer for soils.

In the case of CD and CI wood waste, only two scenarios were considered, since this type of waste is not treated by AD facilities. Thus, the first scenario deals with the disposal of wood in landfills, and the second one the treatment of it in a pyrolysis facility. In this specific case, the second scenario considers two options for the utilization of the biochar produced from wood waste; the first one, as soil amendment (if it comes from feedstocks that have no concentrations of contaminants), and the second one, as fuel for combustion activities in power generation plants (if it comes from feedstocks that were contaminated).

To design each case scenario, it was important to include the life cycle phases of every type of waste, which are variable depending of the waste management system (**see Table**

5). For example, while three life cycle phases are considered for AD and pyrolysis, only two are considered for landfills since there is no production of any by-product (digestate or biochar) as a result of waste treatment.

Table 5. Life cicle phases considered in the design of each waste management case scenario

	Life Cycle Phase			
Case scenario	**Waste transportation Phase**	**Waste treatment Phase**	**Product transportation phase**	**Product Utilization Phase**
Landfill disposal	Yes	Yes	No	No
AD treatment	Yes	Yes	Yes	Yes
Pyrolysis treatment	Yes	Yes	Yes	Yes

In these scenarios, each waste transportation phase differs according to the type of feedstock management. In the case of waste wood disposal in Glasgow, for example, transportation to landfills involves two stages (from collection point to transfer station, and from transfer station to the treatment facility), while for sewer sludge, food, and garden and green waste, transportation to the composting facilities involves only one (from households or waste water treatment plants, to waste treatment facility (**Booth, 2009**).

Regarding the product transportation phase, two stages were considered for biochar and digestate production (from pyrolysis or AD facility to selling point, and from selling point to application site).

Moreover, for each LCA, three indicators were estimated. The first two, named as "GHG release and abatement efficiencies" indicate the amount of GHG emissions released or abated per tonne of feedstock. The third one, named as "revenue", is an economic indicator related to the costs and benefits associated with the treatment of the feedstocks in each case scenario.

However, not all the indicators were calculated for each one of the life cycle phases since it is impossible to associate GHG releases or abatement with each phase. For example, the act of transporting waste or a product only releases GHG, while landfills does not incur in abatements associated to the storage of carbon in a material since this treatment system does not generate any physical product (biochar or digestate) like the other two technologies. **Table 6** explains more specifically how these indicators were designed, and the following section explains more in depth the meaning of each indicator.

Table 6. LCA indicators design

	GHG release indicator	GHG abatement efficiency indicators			Economic indicator
Life cycle phase	**Direct GHG emissions generated**	**GHG emissions avoided by electricity generation**	**GHG emissions stored in the product**	**GHG emissions avoided by utilization of product**	**Revenue gained from the waste treatment process**
Waste transportation	Yes	No	No	No	Yes
Landfill disposal	No	Yes	No	No	Yes
AD treatment	No	Yes	Yes	Yes	Yes
Pyrolysis treatment	Yes	Yes	Yes	No	Yes
Product transportation	Yes	No	No	No	Yes
Product utilization	No	No	No	Yes	Yes

Note: This table explains if the indicators can be associated directly or not to each one of the life cycle phases. Thus "yes" and"no" means if the indicators were calculated or not.

Calculation methodologies

Each indicator was estimated using different calculation methodologies which vary depending of the case scenario or the life cycle phase. This section explains the considerations, formulas, and values used to calculate each one of them.

GHG release indicators

The direct GHG emissions indicator accounts for direct emissions released by waste or product transportation activities, as well start-up fuel consumption activities at the AD or pyrolysis plants. These are considered as positive feedbacks (and thus, expressed in positive numbers) due to their anthropogenic origin and its destabilizing character in the GHG natural cycle. The carbon dioxide emissions generated from the recovery and flaring of methane in landfills are not accounted for since these are considered to be carbon neutral as they are part of the natural carbon cycle.

Direct emissions generated from waste or product transportation activities

These are emissions released by the combustion of fuels (diesel, petrol, etc.) in each waste or product transportation vehicle. The emission factors are based on road freight statistics of the Department for Transport , estimated from a survey on the average miles per gallon and average loading factor for different sizes of rigid vehicles, combined with test data from the European ARTEMIS project showing how fuel efficiency, and hence CO_2 emissions, varies with vehicle load (**DEFRA, 2009**).

Transportation distances may vary according to the life cycle phase of each case scenario. For example, the longest distance travelled by a waste vehicle from a transfer station to a landfill site is of 20 km (12 miles), according to the Glasgow Council (**Booth, 2009**). But the distances associated with the distribution of biochar or digestate could be longer since these products could be applied anywhere in the UK. Thus, a 20 km distance was considered for waste transportation stages, while a distance of 100 km was considered for each product transportation stage.

To express the amount of emissions released by any vehicle per tonne of feedstock or product transported, it was considered that each vehicle's lorry has a carrying capacity of

20 tonnes (**Sistech, 2005**). A carbon dioxide multiplier (or emission factor) of 0.895[15] kg CO_2 per km was used, which accounts all the GHG released during the combustion process (carbon dioxide, methane, and nitrous oxide) and an average load of 56% per lorry (**DEFRA, 2009**).

Direct emissions generated from start-up fuel consumption activities

The direct emissions released by natural gas combustion from start operations in pyrolysis facilities were calculated using an average natural gas consumption per start up operation of 342 MJ/ MWhe (**BEAT2, 2008**), and the emission factor of 0.051 Kg CO_2 -eq per MJ associated with natural gas combustion activities.

The direct emissions released by natural gas consumption from start operations in AD facilities were not calculated since no information was available for review.

GHG abatement indicators

This indicator can be composed of one or several elements or “abatement pathways”, depending on the waste treatment case scenario.

The first pathway is the “emissions avoided by electricity generation” (or electricity offset), which are avoided emissions associated to the combustion of fossil fuels in a business as usual scenario, and that are displaced by the output electricity generated during the waste treatment process (in this case, normalised to 1MWhe generation). These are considered as a negative feedback and thus, expressed in negative numbers that account for the displacement of coal and natural gas combustion emissions, and the mixture of both fuels in the UK electricity grid. The appropriate baseline for comparison is the emissions generated by the combustion of natural gas, coal, and the mixture of all generation sources in the electricity grid.

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[15] DEFRA, 2009

The second pathway is the "emissions stored in the product" (or storage offset), which are avoided emissions stored or captured as carbon in the material produced by the treatment process (digestate or biochar). The amount of carbon captured depends on several factors, such as the initial amount of carbon content in the feedstock, or the treatment process temperature.

The third pathway is the "avoided emissions by the utilization of the product" (or utilization offset), which result from the utilization of the product (digestate or biochar) either as fertilizer for soils, or as fuel for electricity generation (in the case of biochar).
For each LCA, these three elements are additive. Once added, they are reported as a total abatement efficiency indicator expressed in negative numbers.

GHG abatement by landfill disposal

Landfills have two GHG abatement pathways: the first one is the electricity offset generated by recovering the methane produced from the decomposition of biodegradable waste. The second one is by fixating carbon as a result of calcite precipitation reactions occurring inside the landfills. However, this study considers only the first pathway since no information regarding carbon fixation by calcite precipitation was available for review. This omission could tend to overestimate the relative carbon abatement efficiency of pyrolysis compared to landfills.

To calculate the methane emissions recovered from the disposal in landfills of different BMW feedstocks (see Chapter 5 and Appendix A), a mass balance method based on the IPCC Guidelines for National Greenhouse Gas Inventories (**Houghton et al, 1997**) and adjusted by Gaunt et al (**Gaunt et al, 2009**) was used, based in the following equations:

$$CH_4\,(tonnes\ recovered\ per\ tonne\ of\ dry\ biomass) = MGP \times (1 - R) \times (1 - OX) \qquad (1)$$

$$MGP = MCF \times DOC \times DOC_f \times F \times \frac{16}{12} \qquad (2)$$

Where:

- MGP stands for methane generation potential;
- R is the recovered methane. Approximately 70% of the methane generated was captured by landfills in the UK during 2006 (**Jackson et al, 2009);**
- OX is an oxidation factor, with 0.1 as a default value for managed landfills;
- MCF means methane correction factor, with 1 as a default value for managed landfills;
- DOC stands for degradable organic carbon and has a different value for each type of waste (see **Table 7**);
- DOC_f is the fraction of DOC that is dissimilated, and has a default value of 0.5;
- F is the fraction of CH_4, by volume, in generated landfill gas and has a default value of 0.5;and
- 16/12 is molecular weight ratio CH_4/C.

Table 7. DOC values for different feedstocks

Type of waste	**DOC Value (% of dry waste)**
Wood	50[16]
Garden and green	49[17]
Food	38[18]
Sludge	12[19]

Of the methane emissions recovered per tonne of waste, approximately 32% were used for electricity generation in 2006 (**Jackson et al, 2009**). This utilization factor was applied to each waste in order to calculate the electricity offset. The rest of the methane emissions recovered (38%) are flared as carbon dioxide and thus, are not contemplated in this study

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[16] IPCC, 2006

[17] IPCC, 2006

[18] IPCC, 2006

[19] Jackson et al, 2009

since flared emissions are considered to be carbon neutral as they are part of the natural carbon cycle.

Key assumptions and considerations made:

1. Of the eleven landfills located in the GCV area, at least two (Auchinlea landfill located in Cleland, North Lanarkshire, and Greenoakhill landfill located in Glasgow) recover landfill gas to produce electricity. The rest either do not recover methane emissions, or they flare them (**WDD, 2008**). For simplicity reasons, the LCAs were performed considering a scenario where methane emissions are recovered and used to generate electricity;
2. The emission factors used to calculate the electricity offset are 0.051, 0.091, and 0.149 Kg CO2 eq per MJ for natural gas, coal, and grid electricity respectively[20]. This same consideration is used for the AD and pyrolysis case scenarios;
3. All abatements are reported per tonne of feedstock treated.

GHG abatement by anaerobic digestion

AD has three abatement pathways since this process generates electricity, and the digestate produced can store carbon in it and avoid emissions when utilized as fertilizer. Thus, three GHG offsets were calculated.

In order to know the electricity and storage offsets, it was necessary to calculate first the methane emissions released during the AD process and the digestate produced by performing a mass balance (see Appendix B) based in the AEA and North Energy life cycle assessment methodology developed in their Biomass Environmental Assessment Tool (**BEAT2, 2008)**. First, this methodology calculates the amount of waste biomass

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[20] Carbon Trust, 2009

needed to generate one megawatt hour of electricity (MWhe). The following equations were used:

$$NEOR = TI \times \left(\frac{TEF}{100}\right) \times \left(1 - \frac{IEU}{100}\right) \tag{3}$$

$$BG = 1MWe \times \left(\frac{TI}{NEOR}\right) \times 3.6 \times \left(\frac{1000}{CV \times F}\right) \tag{4}$$

$$Waste\ input\ (tonnes) = \frac{\frac{BG \times 100}{100 - L}}{\frac{Ts}{100} \times \frac{Vs}{100} \times BY \times 1000} \tag{5}$$

Where:

- NEOR means net electrical output rating, expressed in MW;
- TI is the thermal input rating of the plant, with a default value of 10 MW[21];
- TEF is the thermal efficiency of the plant (25%)[22];
- IEU is the internal electricity use (15%)[23];
- BG means Biogas generated (methane), expressed in m^3;
- CV stands for calorific value of methane, which is 37 MJ/ m^3 ;
- F is the fraction of methane in the biogas (65%);
- Ts is the total solids, expressed in %;
- Vs means volatile solids, expressed in %;
- BY is the biogas yield, expressed in m^3 /kg;
- 3.6 is the conversion factor from Mega joules to Kilowatt-hour.

The values for Ts, Vs, and BY vary according to the type of feedstock (**see Chapter 3**).

Moreover, the amount of digestate produced was calculated with the following formula:

$$Digestate\ (tonnes) = Waste\ input - BG \times \left\{\left[\frac{F}{100}\right] \times MD + \left[\left(\frac{100-F}{100}\right) \times CDD\right]\right\} \tag{6}$$

Where :

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[21] BEAT2, 2008
[22] BEAT2, 2008
[23] BEAT2, 2008

MD stands for methane density, with a value of 0.000717 tonnes / m^3 , and CDD stands for carbon dioxide density, with a value of 0.001977 tonnes / m^3.

The electricity offset was calculated then, using the amount of electricity generated (1 MWhe) and the emission factors associated with the combustion of coal and natural gas in a business as usual scenario.

The storage offset was calculated using figures about the carbon content for different feedstocks and the percentage of carbon fixed in the digestate produced (see **Table 8**).

Table 8.Percentages of carbon content for different feedstocks and their corresponding digestate

Feedstock	Carbon content of feedstock (%)	Carbon content of digestate (%)
Sludge	35[24]	20[25]
Garden and green	46[26]	20
Food	48[27]	20

Finally, the utilization offset was calculated using the figure of 16.2 kg CO_2-eq per tonne of digestate reported by Barton et al (**2007, p. 696**), where the abatement benefits of the digestate were estimated from offsetting emissions of the production of peat by soil conditioning.

Key assumptions and considerations made:

1. Only the carbon content of digestate produced from food waste was available in the literature. Thus, it is assumed that the carbon content of the digestate produced from all the feedstocks analyzed in this study is the same;

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[24] Tap et al, 2001, Tsai et al, 2009

[25] ECN, 2009

[26] ECN, 2009

[27] ECN, 2009

2. To calculate the electricity offset, it was considered that the facility will generate electricity only and not CHP (no information about the current or future existence of district heating systems in the GCV area was available for review);
3. For simplicity, the energy output produced by the facility operation (1 MWh electricity) does not change since it is assumed that the electricity demand of GCV area will remain constant;
4. All abatements are reported per tonne of feedstock treated.

GHG abatement by pyrolysis

Pyrolisis, as AD, has three abatement pathways since this process generates electricity, and the biochar produced can store carbon in it and avoid emissions when utilized as fertilizer. Thus, three GHG offsets were calculated.

In order to know the electricity and storage offsets, a similar methodology based in the AEA and North Energy life cycle assessments was used. Assuming 1MWh of electricity as output, a mass balance was performed (see Appendix C) to calculate the waste input using the following formula:

$$Waste\ input\ (tonnes) = \left[\frac{1\ MWe \times \left(\frac{3.6}{CV}\right)}{1 - BChY}\right] \times \frac{100}{Ef} \qquad (7)$$

Where:

- CV is the calorific value, expressed in MJ/ m^3 , that varies according to the type of feedstock (see **Chapter 3**);
- BChY stands for biochar yield, expressed as a percentage of the waste input;
- Ef is the efficiency of the process (25%).

Moreover, the biochar generated is calculated by multiplying BChY by the waste input obtained by the mass balance performed for each feedstock.

The electricity offset was calculated then using the amount of electricity generated (1 MWhe) and the emission factors associated with the combustion of coal and natural gas in a business as usual scenario.

The storage offset was calculated using figures about the carbon content for different feedstocks and the percentage of carbon fixed in the biochar generated (see **Table 9**).

However, the carbon content of biochar produced from municipal food waste, AD digestate, garden and green waste was not available in any of the literature reviewed. Therefore, an average of carbon content information available for biochar produced from different types of food waste (such as rice hulls, olive pits, peanut shells, grapefruit, grape residues) was used to calculate this specific data. In the case of the digestate, it was given the same value as sewer sludge. For garden and green waste, it was assumed the carbon content of biochar produced from switchgrass.

Table 9. Carbon content percentages for different feedstocks and their corresponding biochar

Feedstock	Carbon content of feedstock (%)	Carbon content of biochar produced from a specific feedstock (%)
Wood	50[28]	72[29]
Sludge	35	38[30]
Garden and green	46	50[31]
Food	48	62[32]
Digestate	20	38

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[28] Lamlom et al, 2003

[29] Rpu et al, 2007

[30] Shinogi et al, 2003

[31] ECN, 2009

[32] ECN, 2009, Blasi et al, 1999, MarquesxMontesinos et al, 2002, Della Rocca et al 1996, Rei et al, 1986, Cukierman et al, 1999

Finally, the utilization offset was calculated using the figures reported by Gaunt et al (**2009, p. 332**). These estimations are reported per tonne of biochar applied, over a ten-year period, at an application rate of five tonnes of biochar per hectare. Since all the abatement values will be reported considering the amount of waste generated in the GCV area during one year, the Gaunt estimations were adjusted for a one-year period and took into account an average of the avoided emissions reported for broccoli, winter wheat, and maize, which are crops that are regularly harvested in Scotland (**Russell et al, 2000**).

Key assumptions and considerations made:

1. Waste feedstocks, and more specifically food, and garden and green waste, have certain levels of moisture. A complete characterization study would be necessary to determine the exact levels of moisture contained in the feedstocks generated in the GCV area. Therefore, it will be assumed that all the waste feedstocks for AD or pyrolysis plants are used in a dry basis and have low levels of moisture (10%). This moisture percentage implies an energy penalty since more energy must be supplied to the pyrolysis process in order to evaporate it;
2. Once in the pyrolysis plant, the feedstock is placed into the tunnel and treated at a given temperature. The process outputs are pyrolysis liquids and biochar. The liquids are then gasified and used by a turbine to generate electricity only;
3. Biochar yields differ under different temperature and pyrolysis processes. At a constant temperature (for example 500 C), charcoal yields of about 10% can be achieved for fast pyrolysis processes, while yields of 35% are achieved for slow pyrolysis processes (**Brown, 2009**). Therefore, two different biochar yields (10 and 35%) were considered for the production of biochar;
4. The carbon content of biochar is proportional to the variation of the temperature. Thus, if the temperature is increased, the amount of carbon stored or fixed increases (**Joseph et al, 2009**, **Ryu et al, 2007**). These carbon variations were found in the literature for wood waste, but not for the other feedstocks considered. Thus, this analysis assumes that the biochar produced was pyrolysed at the same

temperature and the carbon fixed does not vary if the biochar yield parameter is changed;

5. To calculate the electricity offset, it was considered that the facility will generate electricity only and not CHP (no information about the current or future existence of district heating systems in the GCV area was available for review);
6. According to the literature, the 25% efficiency parameter considered is the most common efficiency achieved by pyrolysis processes that generate electricity only[33]. This efficiency was calculated using inputs and outputs reported by McCarl et al (**2009, p. 347**) for the treatment of dried maze. At an input 10 t/h, and a CV of 19 MJ/kg, an energy input of 190 GJ/h is obtained. The gross electrical output given as 12.9 MWe by the authors equals 46.44 GJ/h. Therefore, the energy ratio of output to input is 46.44/190, that equals 0.244 or 24.4%. This efficiency is similar in magnitude for the one obtained (27%) from the input and output data reported by Meier (**2007, p. 4**);
7. For simplicity, the energy output produced by the facility operation (1 MWh electricity) does not change since it is assumed that the electricity demand of GCV area will remain constant;
8. All abatements are reported per tonne of feedstock treated.

Economic indicators

The economic indicators calculated are the revenues gained from the waste treatment process, which vary depending on the costs and the benefits associated to each waste treatment case scenario. A summary of the costs and benefits gathered from the literature is included in **Table 10**.

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[33] Although this is the most common efficiencp achieved, mass balances and the consequent abatements were also calculated considering 35, 20, and 15% efficiencies (the results are included in Appendix C). However these results were not used for the LCAs.

Table 10. Costs and benefits indicators associated to each waste management case scenario

	Costs		Benefits					
Case scenario	Transport. (£/tonne of feedstock)	Operation (£/tonne of feedstock)	Gate fee (£/tonne)	ROCs (£/ MWh)	Electricity price £/MWh	Fertilizer price (£/tonne)	Biochar price (£/tonne of feedstock)	Offsets price £/ t CO2 eq
Landfill	-34.00[34]	-16.00[35]	50.00[36]	13.25[37]	40[38]	15[39]	8[40]	11[41]
AD	-75.00[42]	-50.00[43]	22 to 45[44]	106	40	15	8	11
Pyro.	-75.00	-72.00[45]	22 to 45[46]	106	40	15	8	11

The main costs considered for each waste treatment scenario are the operational and transportation costs, which vary significantly depending of the treatment technology. AD and pyrolysis have higher operational costs than landfills since the first two are treatment technologies that are in the process of being consolidated in the waste treatment market. Moreover, transportation costs are also higher for AD, since waste has to be separated at source in order to divert it from landfills. Transportation costs for pyrolysis processes were assumed to be the same ones for AD.

Moreover, the benefits considered for the analysis are the profits generated by the waste treatment process. These profits can be earned in the following ways:

Gate fees: these are charges levied upon a given quantity of waste that is received at the processing facility and are useful to offset the construction and operation costs. In the case of landfill operations in the UK, the gate fees include the landfill tax, which is expected to

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[34] SEPA, 2003
[35] EC Directive, 2002
[36] Let's recycle, 2009
[37] See next page
[38] BERR, 2004
[39] Holliday L., 2005
[40] McCarl. et al, 2009
[41] Point Carbon, 2009
[42] SEPA, 2003
[43] Let's recycle, 2007
[44] Let's recycle, 2009
[45] Khoo, H., 2009
[46] Let's recycle, 2009

rise to £50 per tonne of waste by April of 2010. However, lower gate fees have to be established for other waste treatment technologies in order to encourage the diversion of BMW from landfills. AD, for example, has reported average gate fees of £22 or £45 per tonne of green or food waste received, respectively. However, no information about the potential gate fees that a pyrolysis facility could charge was available for review. Therefore, it was considered that the pyrolysis case scenario will operate with the same gate fees for AD, assuming that both treatment scenarios will compete during the following years in the GCV area.

ROCs: these are green certificates issued to a facility that generates renewable electricity within the United Kingdom. The amount of ROCs issued per MWh of eligible renewable output generated (also called ROC banding) varies depending of the treatment technology. The policy driver behind ROC banding is to increase the deployment of less established technologies that are perceived as being higher risk by increasing the number of ROCs granted to those technologies. Conversely, renewable energy technologies that are considered to be more established and/or require relatively low levels of capital will, in future, receive less support from the ROC regime (**Pure Energy Professionals, 2009**).

In this context, this system assigns 0.25 ROCs per MWh of electricity produced to established technologies such as landfills, and two to emerging technologies, such as AD or pyrolysis. Therefore, considering the current price of ROCs (£53 per ROC[47]), the generation of electricity would make these emerging technologies eight times more profitable than landfills.

Electricity sales: In addition to the ROCs issued, the income generated from the sale of the renewable electricity produced represents another important profit. The price of electricity per MWh produced is assumed to be the same for every case scenario, since this energy ends up being incorporated into the same grid.

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[47] OFGEM, 2009

Product sales: these are charges associated to the sale of the biochar or digestate produced. Depending on the location and the social context, digestates are either sold or given for free to the agricultural sites located nearby the composting facilities. However, it will be considered that it will be marketed at a cost to farmers from the beginning of the AD plant operation because otherwise, if it is given for free, it would potentially be difficult to ask people to pay for it thereafter. Moreover, there is still no consent about the potential price of biochar. Thus, this assessment considers the biochar prices reported by McCarl et al (**2009, p. 354**).

Offsets: these are profits earned by the sales of the offsets generated by the abatement of GHG emissions. Only the abatement achieved by the carbon storage in biochar was considered in this analysis as potential offsets for sale. The main reason for this assumption is that the abatement achieved by the displacement of fossil fuels from green electricity generation is already considered to be an offset (electricity offset). Thus it receives an incentive from ROCs. In this sense, It avoids counting the offsets twice.

Key assumptions and considerations: These costs and benefits are based in current (2009) prices. However, it is expected that the carbon offsets, ROCs, biochar, and electricity benefits could increase in the future as part of the consolidation of these emergent technologies in the waste market.

An analysis and discussion of all the results obtained by the calculations performed following this methodology is included in the following chapter.

CHAPTER 5: ANALYSIS AND DISCUSSION OF RESULTS

Five LCAs (one for every type of feedstock) were performed in total. The elaboration of each LCA implied obtaining a considerable amount of information associated to each case scenario and to the indicators mentioned before. Therefore, a detailed description of only two LCAs (garden and green waste, CD and CI wood waste) and a summarized version of the other ones (digestate, food waste, and sewage sludge) is going to be included in the following sections. **Appendix D to H** includes all the detailed results.

LCA for Garden and Green wastes

The LCA considers that this feedstock could be diverted from any of the landfills located in the GCV area, to either the Cumbernauld AD plant or to a potential pyrolysis plant. Therefore, three case scenarios for waste management are considered (landfills, AD, and pyrolysis).

First case scenario

The LCA for the first case scenario assumes that garden and green waste is collected, transported from the generation point to a transfer station, and from there to the landfill (two transport stages). The methane recovered emission results and their correspondent abatement are presented in **Tables 11 and 12.**

Table 11. Methane recovery results from waste disposal in landfills

Methane Recovered (kg/tonne of waste)	Methane utilized (kg/tonne of waste)	Methane flared (kg/tonne of waste)	Energy output efficiency (MWh/tonne)
44.10	14.11	30.60	0.20

Table 12. LCA for garden and green waste disposed of in landfills

Life cycle phase	Direct GHG emissions generated	GHG emissions avoided by electricity generation	All emissions (Total Carbon Abatement efficiency)
Natural gas displacement			
Waste transportation (two stages)	0.90	0.00	0.90
Landfill disposal	0.00	-37.04	-37.04
Total (Kg CO2eq / t feedstock)	0.90	-37.04	**-36.14**
Coal displacement			
Waste transportation (two stages)	0.90	0.00	0.90
Landfill disposal	0.00	-66.09	-66.09
Total (Kg CO2eq / t feedstock)	0.90	-66.09	**-65.20**
Electricity from grid displacement			
Waste transportation (two stages)	0.90	0.00	0.90
Landfill disposal	0.00	-108.33	-108.33
Total (Kg CO2eq / t feedstock)	0.90	-108.33	**-107.44**

As explained previously, it was considered that only 70% of methane generated is recovered. Once recovered, 32% is used to generate electricity, and the rest (38%) is flared as carbon dioxide.

The direct GHG emission indicator has a positive value for the waste transportation phase (since these are anthropogenic emissions released to the atmosphere) and a value of zero for the landfill disposal phase because the carbon dioxide emissions generated from methane flaring are considered to be carbon neutral as they are part of the natural carbon cycle (and thus, not counted). Specific methane leakages related to this feedstock were not available for review.

The results suggest that the highest electricity offset is achieved when electricity from the grid is displaced. This is due to the fact that the grid supplies electricity generated by the combustion of natural gas and coal. Thus, the emission factor, reported by DEFRA and the Carbon Trust, takes into consideration the emission factors calculated individually for both fossil fuels.

This situation is repeated in each case scenario analyzed for the different feedstocks. Therefore, for simplicity reasons, only the electricity grid displacement indicators will be reported from now on (the results for the other fossil fuels are included in Appendices section).

Second case scenario

The second case scenario of this LCA is the "waste treatment by anaerobic digestion", in which it was considered that this waste is collected and transported directly to the Cumbernauld composting facility (one transport stage). The methane recovered emission results and their correspondent abatement are presented in the following tables:

Table 13. Methane recovery results for garden and green waste treatment in AD facilities

Unit of output (MWhe)	Thermal efficiency (%)	Biogas generated (m3)	Mass balance-waste input (tonnes)	Digestate output (tonnes)	Digestate production ratio (tonnes per tonne of waste)	Energy output efficiency (MWh/tonne)	Carbon stored in digestate (tonnes)	Carbon storage in digestate efficiency (tonnes/tonne of feedstock)
1.00	25.00	612.15	1.96	1.63	0.83	0.51	0.20	0.05

Table 14. LCA for garden and green waste treatment in AD facilities

Life cycle phase	Direct GHG emissions generated	GHG emissions avoided by electricity generation	GHG emissions stored in the digestate	GHG emissions avoided by utilization of digestate in soils	All emissions (Total Carbon Abatement efficiency)
Electricity from grid displacement					
Reference spstem (landfills)	0.00	108.33	0.00	0.00	108.33
Waste transportation (one stage)	0.45	0.00	0.00	0.00	0.45
AD Treatment	0.00	-273.57	-172.01	0.00	-445.57
Digestate transportation to (two stages)	4.48	0.00	0.00	0.00	4.48
Digestate utilization at site	0.00	0.00	0.00	-13.49	-13.49
Total (kg CO2eq / t feedstock)	4.92	-165.23	-172.01	-13.49	**-345.80**

This scenario has as a reference system the disposal of garden and green waste in any of the landfills of the GCV area, meaning that this plant could substitute the role of these as a waste management strategy.

Comparing the carbon abatement efficiencies of both scenarios, the abatement emissions reported as negative feedbacks in the landfill case scenario (-108 kg CO_2-eq per tonne of feedstock) are reported as positive for AD, since the benefits achieved by displacing fossil fuels from electricity generated by landfills would be avoided if waste is treated by AD instead of landfills.

Moreover, the avoided emissions displaced by electricity generation are higher for the AD case scenario. The reason is that only a small portion of the methane recovered in landfills is used for energy production, and thus, the potential of producing electricity is lower in this treatment system.

For the digestate transportation phase, it was considered that it could be applied in any part of the UK where it could be purchased by farmers. Thus, two transportation stages (from AD plant to store, and from store to application site) would be required for its distribution.

Overall, the highest value of carbon abatement emissions is achieved by the electricity offset, followed by the storage offset of the digestate and the utilization offset achieved by the application of this material in soils. This is mainly because the amount of carbon that digestates are able to fix during the treatment process is very low (20%).

No direct GHG emissions associated to natural gas consumption for start up operations were included for the AD treatment phase since no information was available for review.

Third case scenario

The third case scenario is the "waste treatment by pyrolysis" scenario, which considers that pyrolysis could displace landfills or AD as waste management strategy in this area. The mass balance and abatement results are presented in the following tables:

Table 15. Mass balance results for garden and green waste treatment in pyrolysis facilities

Unit of output (MWhe)	Process efficiency (%)	Biochar Yield	Mass balance-waste input (tonnes)	Biochar output (tonnes)	Energy output efficiency (MWh/tonne)	Carbon stored in biochar (tonnes)	Carbon stored in biochar (tonnes/tonne of feedstock
1.00	25	0.10	0.89	0.09	1.13	0.23	0.95
1.00	25	0.35	1.23	0.43	0.81	0.23	0.69

Table 16. LCA for garden and green waste treatment in pyrolysis facilities

Life cycle phase	Direct GHG emissions generated	GHG emissions avoided by electricity generation	GHG emissions stored in the biochar	GHG emissions avoided by utilization of biochar in soils	All emissions (Total Carbon Abatement efficiency)
Electricity from grid displacement					
Reference spstem (landfills)	0.00	108.33	0.00	0.00	108.33
Reference spstem (anaerobic digestion)	0.00	273.57	0.00	0.00	273.57
Waste transportation (one stage)	0.45	0.00	0.00	0.00	0.45
Pyrolysis Treatment 10%BCHY	19.62	-604.13	-949.61	0.00	-1,534.12
Pyrolysis Treatment 35%BCHY	14.17	-436.31	-685.83	0.00	-1,107.97
Biochar transportation to site (two stages)	4.48	0.00	0.00	0.00	4.48
Biochar utilization at site 10% BCHY	0.00	0.00	0.00	-20.63	-20.63
Biochar utilization at site 35% BCHY	0.00	0.00	0.00	-72.22	-72.22
Total (Kg CO2eq / t feedstock) 10%BCHY (replacing landfills)	24.54	-495.79	-949.61	-20.63	**-1,441.49**
Total (Kg CO2eq / t feedstock) 35%BCHY (replacing landfills)	19.09	-327.98	-685.83	-72.22	**-1,066.93**
Total (Kg CO2eq / t feedstock) 10%BCHY (replacing AD)	43.64	-330.56	-949.61	-41.27	**-1,276.26**
Total (Kg CO2eq / t feedstock) 35%BCHY (replacing AD)	19.09	-162.75	-685.83	-72.22	**-901.70**

The energy output and carbon storage efficiency values included in **Table 15** are lower for slow pyrolysis (35%BCHY) than for fast pyrolysis (10%BCHY). This is because the mass balance was calculated considering a single unit of output (1 MWh), which means that the output energy produced will always remain constant. Thus, the amount of waste input required to produce more biochar while generating the same output energy increases and consequently, the values of the energy output and carbon storage efficiencies decrease.

The value of carbon stored in biochar (**see Table 15**) has a constant value for both yields because of the assumption made that the biochar produced was pyrolysed at the same temperature and therefore, the carbon fixed does not change.

For the waste transportation phase, it was considered that garden and green waste is collected and could be transported directly either to a landfill or to the Cumbernauld composting facility (one transport stage). However, the biochar distribution phase consists of two stages, where the biochar produced is transported to a store where it will be purchased, and then to the application site.

Direct emissions were included and these numbers indicate that there is a lower release of carbon dioxide from natural gas consumption from start-up operations associated with the slow pyrolysis treatment phase.

The results obtained for the electricity and storage offsets (**see Table 16**) have lower values for slow pyrolysis than for fast pyrolysis. This is because the energy output and the carbon stored expressed per tonne of feedstock are lower for slow pyrolysis. However, if the electricity output is lowered for slow pyrolysis (considering the same amount of biochar yield), the storage offset values become higher for slow pyrolysis since less amount of feedstock is required for the process, and the electricity offset decreases considerably (See **Appendix K**).

Moreover, the storage offset indicator results are expressed per tonne of feedstock. These results can be found expressed per tonne of biochar produced in **Appendix C**.

The storage offset obtained for slow pyrolysis (-685 kg of CO_2-eq per tonne of feedstock) is similar in magnitude to the value of -0.720 kg of CO_2-eq per tonne of green waste treated by slow pyrolysis reported by Gaunt et al (**2009, p. 329**). However, it was not possible to perform a comparison of this indicator obtained for the other feedstocks since the authors do not include any other MSW in their analysis and no other information was available in the literature reviewed.

Regarding the utilization offsets, these are higher for slow pyrolysis. The reason is that the numbers calculated by Gaunt et al (**2009, p. 332**) are reported per tonne of biochar, and when transformed to be expressed per tonne of feedstock, these decrease if a higher input of biomass is needed.

Unlike AD, the highest value of carbon abatement emissions by slow or fast pyrolysis is achieved by the storage offset followed by the electricity and the utilization offsets. This is mainly because pyrolysis processes can fix more carbon in the biochar produced than the amount of carbon that AD processes are able to fix in the digestate.

Finally, AD has more potential than landfills to displace fossil fuel emissions by electricity generation. Therefore, if pyrolysis displaces landfills, the total carbon abatement efficiency would be higher than if it substitutes AD.

LCA for CD and CI wood

Since wood cannot be treated in AD plants, this LCA considered that these feedstocks could only be diverted from any of the landfills located in the GCV area to a pyrolysis plant. Therefore, two case scenarios for waste management are considered (landfills and pyrolysis). Moreover, this analysis considers that the biochar produced will be used either as fuel for power production or as fertilizer for soil amendment.

First case scenario

The first case scenario assumes that wood waste generated in the GCV area is collected, transported from the generation point to a transfer station, and from there to the landfill (two transport stages). Following the same methodology used for the garden and green waste LCA, the total carbon abatement achieved was of **-109.65** Kg CO_2-eq per tonne of feedstock (considering a displacement of electricity from grid).

Second case scenario

The mass balance and emission results for pyrolysis of waste wood are presented in **Tables 17 and 18**.

Table 17. Mass balance results for wood waste treatment in pyrolysis facilities

Unit of output (MWhe)	Process efficiency (%)	Biochar Yield	Mass balance-waste input (tonnes)	Biochar output (tonnes)	Energy output efficiency (MWh/tonne)	Carbon stored in biochar (tonnes)	Carbon stored in biochar (tonnes/tonne of feedstock
1.00	25	0.10	0.80	0.08	1.25	0.36	0.45
1.00	25	0.35	1.11	0.39	0.90	0.36	0.33

Table 18. LCA for wood waste treatment in pyrolysis facilities, using biochar for combustion in power plants

Life cycle phase	**Direct GHG emissions generated**	**GHG emissions avoided by electricity generation**	**GHG emissions stored in the biochar**	**GHG emissions avoided by combustion of biochar as fuel**	**All emissions (Total Carbon Abatement efficiency)**
Electricity from grid displacement					
Reference spstem (landfills)	0.00	109.65	0.00	0.00	109.65
Waste transportation (two stages)	0.90	0.00	0.00	0.00	0.90
Pyrolysis Treatment 10%BCHY	21.80	-671.25	-1,651.50	0.00	-2,300.95
Pyrolysis Treatment 35%BCHY	15.75	-484.79	-1,192.75	0.00	-1,661.80
Biochar transportation to power plant (one stage)	2.24	0.00	0.00	0.00	2.24
Biochar combustion at power plant	0.00	0.00	0.00	-1,432.00	-1,432.00
Total (Kg CO2eq / t feedstock) 10%BCHY	24.94	-561.60	-1,651.50	-1,432.00	**-3,620.16**
Total (Kg CO2eq / t feedstock) 35%BCHY	18.88	-375.14	-1,192.75	-1,432.00	**-2,981.01**

Table 19. LCA for wood waste treatment in pyrolysis facilities, using biochar soil fertilizer

Life cycle phase	**Direct GHG emissions generated**	**GHG emissions avoided by electricity generation**	**GHG emissions stored in the biochar**	**GHG emissions avoided by utilization of biochar in soils**	**All emissions (Total Carbon Abatement efficiency)**
Electricity from grid displacement					
Reference system (landfills)	0.00	109.65	0.00	0.00	109.65
Waste transportation (two stages)	0.90	0.00	0.00	0.00	0.90
Pyrolysis Treatment 10%BCHY	21.80	-671.25	-1,651.50	0.00	-2,300.95
Pyrolysis Treatment 35%BCHY	15.75	-484.79	-1,192.75	0.00	-1,661.80
Biochar transportation to site (two stages)	4.48	0.00	0.00	0.00	4.48
Biochar utilization at site 10% BCHY	0.00	0.00	0.00	-20.63	-20.63
Biochar utilization at site 35% BCHY	0.00	0.00	0.00	-72.22	-72.22
Total (Kg CO2eq / t feedstock) 10%BCHY	27.17	-561.60	-1,651.50	-20.63	**-2,206.56**
Total (Kg CO2eq / t feedstock) 35%BCHY	21.12	-375.14	-1,192.75	-72.22	**-1,618.99**

For the waste transportation phase, it was considered that wood is transported from the generation point to a transfer station, and from there to the pyrolysis plant (two transport stages). However, the product transportation phase differs in both cases since the distribution of this product can differ depending on its use.

For example, if used as a soil amendment, the biochar could be applied in any part of the UK. Thus, it would be necessary to transport it to stores where it could be purchased by farmers, and two transportation stages (from pyrolysis plant to store, and from store to application site) would be required for its distribution. On the other hand, if biochar is used as a fuel to generate electricity, it would only be necessary to transport it to the closest power plant and then, only one transportation phase would be required (from pyrolysis plant to combustion facility).

The same tendency showed in the garden and green waste LCA results is showed in these ones (more GHG emissions abatement from storage offset than from electricity offset, lower total carbon abatement for slow pyrolysis, etc.). This tendency is repeated in the rest of the LCAs included in this report.

Finally, the total carbon abatement efficiency indicators obtained are higher if the biochar produced is used as a fuel for electricity generation, rather than if it is used as a soil amendment. The reason is that biochar has a calorific value of 24 MJ/Kg[48] (higher than any other type of biomass) which allows for a higher energy output if combusted. Therefore, the emissions avoided by the displacement of energy from fossil fuels are higher than the potential emissions avoided if biochar is used as a fertilizer.

Summary of all LCAs

A summary of the total abatement efficiencies calculated in each LCA is included in **Table 20**. A discussion of these results from a case scenario and feedstock point of view is included below.

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[48] Mahinpey et al, 2009

Table 20. Total abatement efficiencies calculated for every feedstock (displacing electricity grid)

Scenario	Total abatement efficiency (kg CO2 eq / t feedstock)
CD and CI waste wood	
Landfills	-109.65
Pyrolysis (10% BCHY, biochar as fuel consumption)	-3,620.16
Pyrolysis (35% BCHY, biochar as fuel consumption)	-2,981.01
Pyrolysis (10% BCHY, biochar as fertilizer)	-2,206.56
Pyrolysis (35% BCHY, as fertilizer)	-1,618.99
Garden and green waste	
Landfills	-107.44
AD	-345.80
Pyrolysis (10% BCHY, replacing landfills)	-1,441.49
Pyrolysis (35% BCHY, replacing landfills)	-1,066.93
Pyrolysis (10% BCHY, replacing AD)	-1,276.26
Pyrolysis (35% BCHY, replacing AD)	-901.70
Sewage sludge	
Landfills	-25.64
AD	-11.80
Pyrolysis (10% BCHY, replacing landfills)	-909.96
Pyrolysis (35% BCHY, replacing landfills)	-648.46
Pyrolysis (10% BCHY, replacing AD)	-918.07
Pyrolysis (35% BCHY, replacing AD)	-656.57
Food waste	
Landfills	-83.12
AD	4.11
Pyrolysis (10% BCHY, replacing landfills)	-1,643.09
Pyrolysis (35% BCHY, replacing landfills)	-1,219.29
Pyrolysis (10% BCHY, replacing AD)	-1,685.42
Pyrolysis (35% BCHY, replacing AD)	-1,261.61
AD digestate	
Pyrolysis (10% BCHY)	-298.96
Pyrolysis (35% BCHY)	-215.17

Analysis of results by waste treatment case scenario

Comparing AD vs. landfills, the results vary depending of the feedstock treated. For example, while AD seems to be a better abatement system to treat garden and green waste, landfills offer higher abatement efficiencies for food waste and sewer sludge. These differences are associated directly to the biogas yield and solid percentage properties of each waste, which are lower for food waste and sewage sludge.

Of the three case scenarios, it can be observed that pyrolysis is the waste treatment strategy where the highest abatement efficiencies were obtained. This situation is mainly related to the number of abatement pathways offered by each treatment system, the levels of carbon stored in the materials produced, and the output energy efficiencies.

For example, while landfills offer only one abatement pathway (displacement of fossil fuel emissions), AD and pyrolyisis offer three (displacement of fossil fuel emissions, storage of carbon in the material produced, and utilization of the material either as fuel for combustion activities, or as a fertilizer for soils). Thus, AD and pyrolysis have more "opportunities" to mitigate carbon emissions.

Although composting offers the same abatement pathways than pyrolysis, the output energy efficiency (amount of energy output per tonne of feedstock) achieved by the decomposition of waste in anaerobic conditions is much lower than if it is pyrolised because it requires a higher amount of feedstock to produce the same amount of energy (1MWh). Moreover, the output efficiencies of AD and landfills are significantly lower than those of pyrolysis because of the small percentage of methane used for electricity generation in the case of landfills, and the low biogas yields of the feedstocks treated by AD.

Finally, the amount of carbon stored in the treated product is much lower for digestate than for biochar. Thus, the abatement emissions achieved by this pathway are significantly lower for the AD case scenario.

Analysis of results by feedstock

Of all the feedstocks, CD and CI wood, garden and green, and food waste are the ones that have the higher abatement efficiencies. This can be explained by the fact that these materials have higher calorific values than sewer sludge and digestates, and the carbon content of the biochar produced from them is higher too. Thus, these abatement results are a direct function of both properties.

Of these three feedstocks, CD and CI wood offers the higher abatement efficiencies if its biochar product is used as combustion in power plants. If the wood collected is not contaminated and thus, the biochar produced is used as fertilizer, the abatement emission efficiencies are still significantly higher than the ones reported for garden and green and wood waste since wood has the highest calorific value of all.

Moreover, the lowest abatement is achieved by the pyrolysis of digestate which has the lowest carbon content and calorific values.

On the other hand, the results suggest that AD is not a convenient strategy to treat food waste or sewage sludge. In the specific case of food waste, no abatement efficiency is reached at all (the indicator has a positive value). The main reason for this situation is that, although AD can individually achieve an abatement efficiency from the processing of this waste (see **Figure 2**), the overall balance is affected when the emissions from landfills are counted as a result of the scenario substitution. This is because AD has lower electricity offsets than landfills for the treatment of food waste.

Overall, if biochar is only used as a soil amendment, the total emission abatement efficiencies achieved by the landfill case scenario increase from -0.25 up to -2,206 kg CO_2-eq per tonne when the carbon storage, electricity, and utilization offsets are accounted for in the pyrolysis case scenario. A major factor that contributes to this variation is the emissions related to conventional feedstock management, which varies widely between alternative waste management practices that are dependent on the anaerobicity degree, and the extent of methane capture (**Gaunt et al, 2009**).

Finally, there are two issues to highlight regarding the treatment of wood waste by pyrolysis.

The first one is that, although fast pyrolysis can achieve a higher electricity offset than slow pyrolysis, it might produce unusable biochar contaminated with toxic materials. According to Grange (**2009**), when CD wood waste is pyrolysed by both processes, the concentrations of PAHs are higher for fast pyrolysis than for slow pyrolysis (approximately 25 mg per kg of biochar). PAHs are toxic chemical compounds formed when certain fuels and wastes are incompletely burnt and could provoke health issues if accumulated in soils or groundwater at high concentrations. During the last years, the UK Environment Agency has aimed to ensure that there is no risk of these effects from environmental exposures.

The second one is related to the use of contaminated biochar for fuel combustion. In this context, power plants using fossil fuels are regulated under the Large-Combustion Plant Directive (LCPD). On the other hand, waste incineration units are regulated under the Waste Incineration Directive (WID). WID has tougher emission controls than the LCPD. Thus, if contaminated biochar is sent to a power plant, it could be forced to comply with WID requirements, which could make the process economically unviable due to tougher compliance limits.

In any case, in order to know the potential of wood waste to be used for biochar production, it would be necessary to perform characterization studies before and after the feedstock is pyrolysed.

Analysis of indicators by life cycle phase

A comparison of the abatements achieved and the contribution of each life cycle phase to the total abatement of each treatment case scenario is included in **Figures 2 and 3**.

Figure 2. Comparison of total GHG abatement efficiencies achieved by each waste treatment case scenario

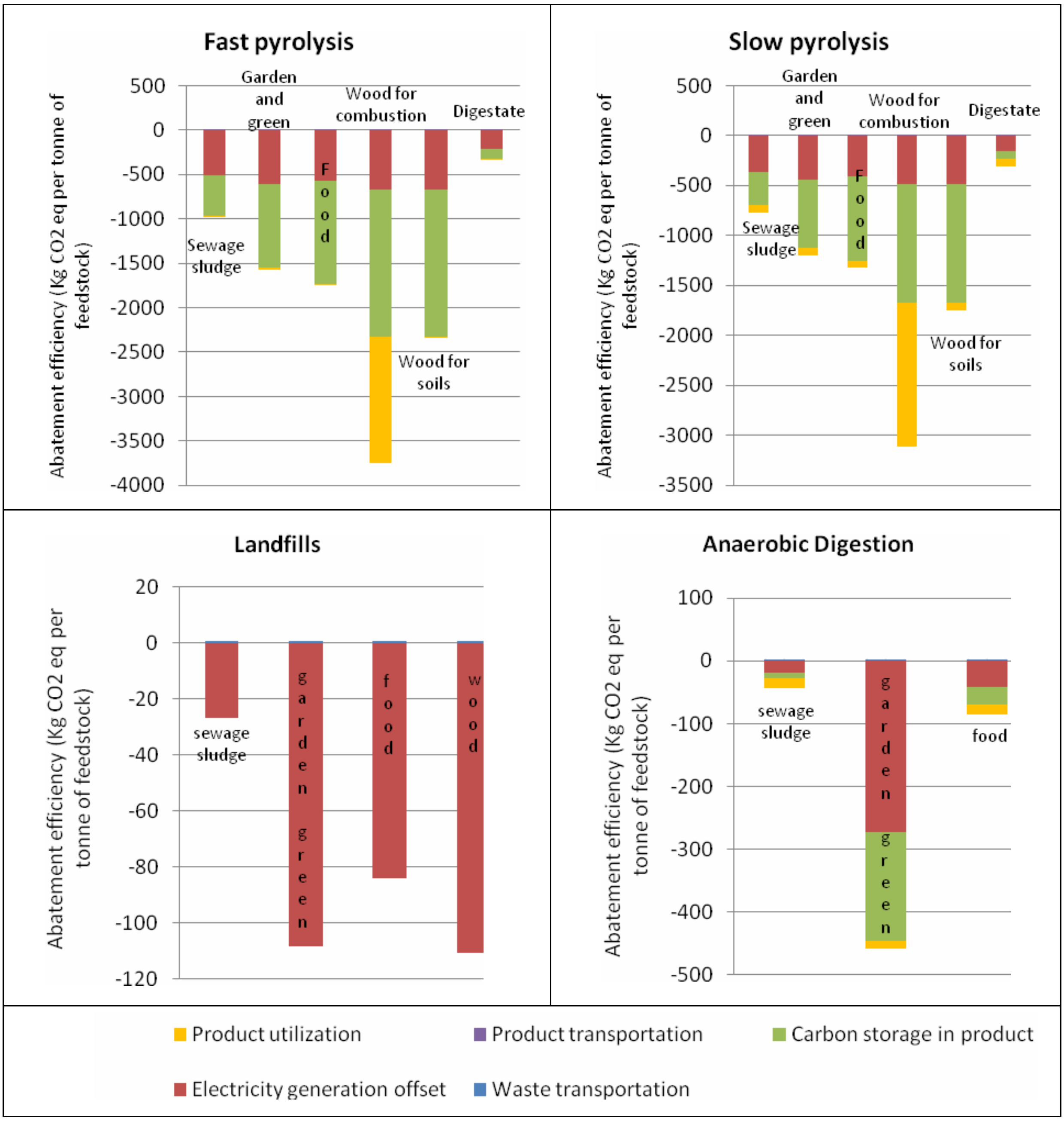
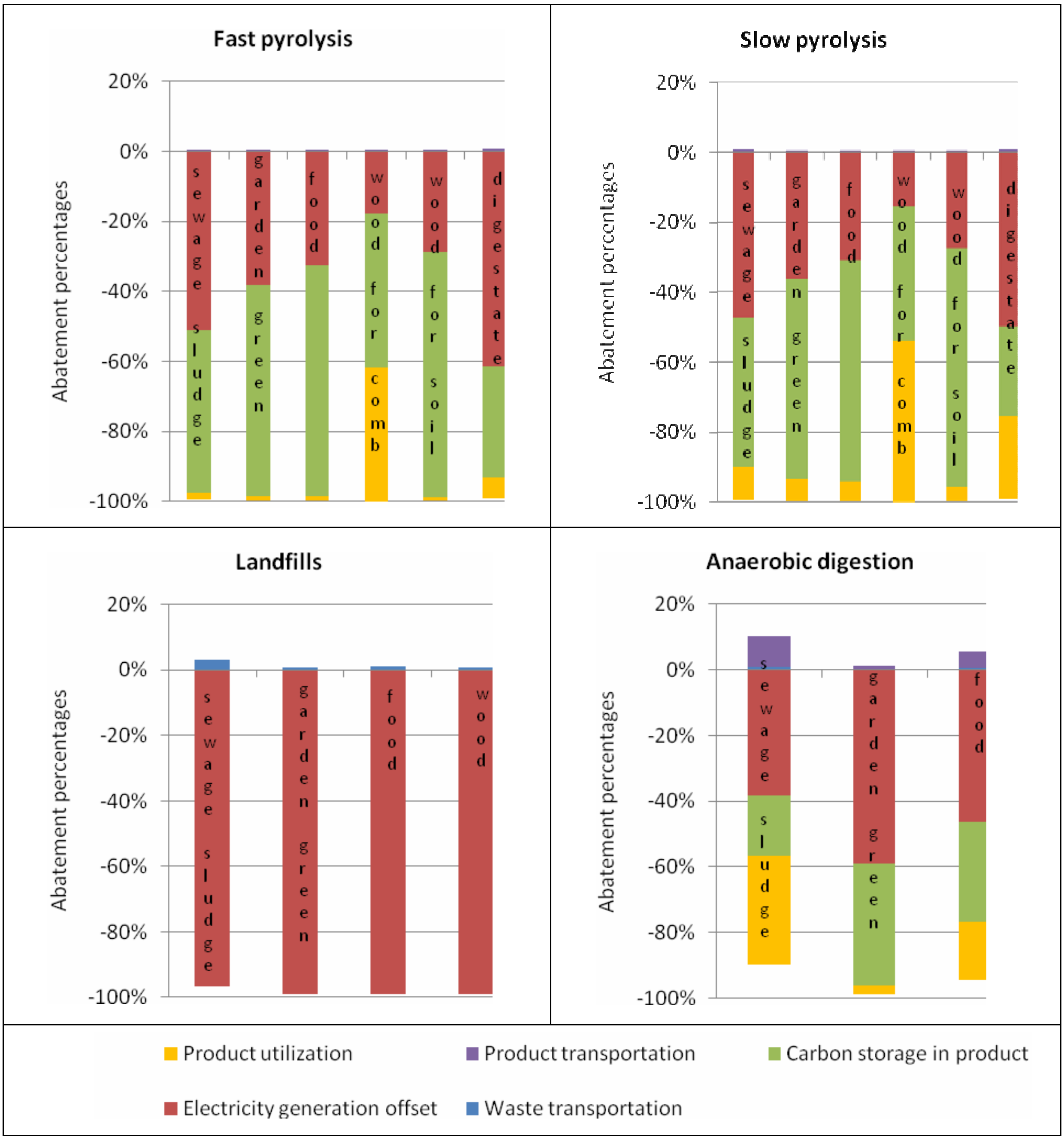


Figure 3. Contribution of each life cycle phase to the total abatement efficiencies achieved in each waste case scenario



For any of the case scenarios, it can be concluded that the direct emissions released by natural gas combustion for start operations and transportation activities are insignificant if compared to the abatement efficiencies achieved by these treatment systems.

The electricity offset indicator is the most representative one from the point of view that it is the only one that is present in all of the case scenarios analyzed. It has an important value for each treatment system, since the displacement of emissions from fossil fuels contributes significantly to the overall abatement of GHG emissions while at the same time, points to a considerable amount of revenue as a result of the ROC and electricity sales. While this pathway contributes to higher abatements in the case of AD and landfills, its abatement contribution is just surpassed by the carbon storage offset achieved by the production of biochar in pyrolysis processes.

Moreover, the abatements achieved by carbon storage are more significant when the feedstocks are treated by pyrolysis than when they are treated by AD. This is because biochar has a greater potential of fixing carbon than digestates. If all the feedstocks are pyrolysed then, this abatement indicator becomes the most important of all (except when the biochar produced from wood waste is used for combustion activities) and more specifically for food, garden and green, and wood waste, which are the feedstocks with the higher carbon contents. If both pyrolysis modes are compared, it can be concluded that fast pyrolysis achieves more carbon storage than slow pyrolyis since the first one has higher carbon storage efficiencies.

Finally, if the biochar is used as soil amendment, the GHG emissions avoided are just a low percentage of the total abatement achieved by the pyrolysis case scenario. It is expected that this abatement could improve if the utilization rate of biochar increases over time. On the other hand, if biochar is used as fuel for combustion activities, the abatement increases significantly. This is because an extra electricity offset is being accounted for.

Economic results

The total revenues were calculated using the costs and benefits available in the literature and reported in Chapter 4. The results are presented in **Table 21.**

Table 21. Total revenues achieved per tonne of feedstock in each waste treatment case scenario

		Costs		Benefits					
Feedstock	**Energy MWh/tonne**	**Trans. £/t of feed.**	**Opera. £/ t feed.**	**Gate fee £/t of feed**	**ROCs £/ t of feed**	**Electricity price £/tonne**	**Product price £/t of feedstock**	**Offsets price £/ t of feed**	**Total Reven. (£/ tonne)**
Case Scenario: Landfills									
Sludge	0.05	x34.00	x16.00	50.00	0.65	1.98	n/a	n/a	**2.63**
Food	0.16	x34.00	x16.00	50.00	2.07	6.26	n/a	n/a	**8.33**
Garden and green	0.20	x34.00	x16.00	50.00	2.67	8.07	n/a	n/a	**10.74**
CD wood	0.21	x34.00	x16.00	50.00	2.73	8.23	n/a	n/a	**10.96**
BI wood	0.21	x34.00	x16.00	50.00	2.73	8.23	n/a	n/a	**10.96**
Case Scenario: AD									
Sludge	0.03	x75.00	x50.00	22.00	3.64	1.37	14.83	n/a	**-83.16**
Food	0.08	x75.00	x50.00	45.00	8.23	3.11	14.62	n/a	**-54.05**
Garden and green	0.51	x75.00	x50.00	22.00	54.00	20.38	12.49	n/a	**-16.13**
Case Scenario: Pyrolysis									
Sludge fast pyrolysis	0.94	x75.00	x72.00	22.00	99.38	37.50	8.00	5.03	**24.91**
Sludge slow pyrolysis	0.68	x75.00	x72.00	22.00	71.77	27.08	8.00	3.64	**-14.51**
Food fast pyrolysis	1.06	x75.00	x72.00	45.00	112.63	42.50	8.00	12.76	**73.89**
Food slow pyrolysis	0.77	x75.00	x72.00	45.00	81.34	30.69	8.00	9.22	**27.25**
Garden and green fast pyrolysis	1.13	x75.00	x72.00	22.00	119.25	45.00	8.00	10.45	**57.70**
Garden and green slow pyrolysis	0.81	x75.00	x72.00	22.00	86.13	32.50	8.00	7.54	**9.17**
CD wood fast pyrolysis, fuel combustion	1.25	x75.00	x72.00	25.00	132.50	50.00	10.00	18.17	**88.67**
CD wood slow pyrolysis, fuel combustion	0.90	x75.00	x72.00	25.00	95.69	36.11	10.00	13.12	**32.93**
CD wood fast pyrolysis, soil amendment	1.25	x75.00	x72.00	25.00	132.50	50.00	8.00	18.17	**86.67**
CD wood slow pyrolysis, soil amendment	0.90	x75.00	x72.00	25.00	95.69	36.11	8.00	13.12	**30.93**
AD fast pyrolysis	0.39	x75.00	x72.00	15.00	20.87	15.75	8.00	1.21	**-86.17**
AD slow pyrolysis	0.28	x75.00	x72.00	15.00	15.07	11.38	8.00	0.87	**-96.68**

The results indicate that even though pyrolysis has higher operational costs, it could achieve higher revenues than AD or landfills depending on the type of pyrolysis process applied and the feedstock treated. For example, fast pyrolysis is between 5.3 and 9.4 times more profitable than landfills[49]for all the feedstocks. However, slow pyrolysis is more profitable than landfills only for food and wood wastes. A comparison against AD is difficult to make, since AD seems to have negative revenues if the current transportation and operation costs are considered (it is recommended performing this economic analysis again, using real case results, once the Cumbernauld AD facility is operative).

The first possible explanation of this is that fast pyrolysis has higher energy output efficiencies. Thus, it has the potential to make more profits from selling the assigned ROCs and the electricity produced. The second is that landfills receive less ROCs per MWh of electricity generated (0.25 ROCs/MWh) than AD or pyrolysis (2 ROCs/MWh). Therefore, the profits gained from the sale of ROC certificates are more favourable for the latter.

Moreover, the assumption made about the gate fees charged to treat BMW by a potential pyrolysis process is essential for the overall cost-benefit balance. For example, if the gate fee is considered as a benefit (companies or councils pay the pyrolysis company for the treatment), then fast and slow pyrolysis would be more profitable than landfills. But if gate fees are considered as a cost (the pyrolysis company has to cover the cost of transporting the waste from the generation source to the plant), only fast pyrolysis would be profitable for treating garden and green and wood waste, and slow pyrolysis would present negative revenues.

Thus, this context then makes fast pyrolysis the most attractive waste treatment technology, where food, garden and green, and wood waste could be efficiently treated

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[49] This depends on the feedstock. Sewage sludge and garden and green waste are 9.5 and 5.3 times more profitable if treated by fast pyrolysis than by landfills. Of all the feedstocks treated by fast pryolysis, waste wood is the most profitable one. This tendency is completely different if compared to AD, since the revenues associated to the feedstocks managed by this technology are negative.

from an economic point of view. Sludge and digestates do not represent a viable option for this technology.

Finally, considering the current price of the carbon offsets and biochar, the profits generated from the offsets created when the emissions stored are accounted for, and the sale of the biochar itself are also important. For fast pyrolysis, their contribution to the total benefits is between 30 and 50 % depending of the feedstock treated. If not considered, fast pyrolysis would still be more profitable than landfills due to the incomes gained from electricity and double ROCS. However, for slow pyrolysis, considering these factors is essential to make this technology more profitable than landfills.

This situation could improve if the price of the carbon in the markets continues to gain more value in the coming years. For example, if the predictions of the IPCC about a price of about £50 per tonne of carbon become true by 2030 (**Tirpak, 2008**), then the total contribution of offsets would make slow pyrolysis more profitable than landfills.

Capacity needed

An analysis to know the potential capacity that a pyrolysis treatment facility would require in this area, and the total benefits that could be generated by the treatment of these feedstocks was performed and the results are included in **Table 22.**

Table 22. Potential capacities of pyrolysis treatment facilities an economic benefits

Scenario	Feedstock	Amount generated in the area (tonnes per year)	Total Emission abatement (tCO2eq / t feedstock)	Total Revenue (£/ tonne)	Capacity of facility (tonne per year)	Emission mitigation potential (tCO2eq)	Total revenue potential (£)
Fast pyrolysis	Sludge (Replacing landfills)	33,574	-0.91	25	6,715	-6,110	167,256
Fast pyrolysis	Food (Replacing landfills)	241,000	-1.62	74	48,200	-78,202	3,561,498
Fast pyrolysis	Garden and green (Replacing landfills)	68,800	-1.44	58	13,760	-19,835	793,893
Fast pyrolysis	CD wood (soil amendment)	42,327	-2.21	87	8,465	-18,679	733,667
Fast pyrolysis	CI wood (soil amendment)	35,000	-2.21	87	7,000	-15,446	606,666
				Total	**84,140**	**-138,273**	**5,862,980**
Slow pyrolysis	Sludge (Replacing landfills)	33,574	-0.65	-15	6,715	-4,354	-97,435
Slow pyrolysis	Food (Replacing landfills)	241,000	-1.20	27	48,200	-55,289	1,313,637
Slow pyrolysis	Garden and green (Replacing landfills)	68,800	-0.90	9	13,760	-14,681	126,167
Slow pyrolysis	CD wood (soil amendment)	42,327	-1.62	31	8,465	-13,705	261,799
Slow pyrolysis	CI wood (soil amendment)	35,000	-1.62	31	7,000	-11,333	216,481
				Total	**84,140**	**-99,362**	**1,820,650**

Focusing only in sewage sludge, garden and green, food, CI, and CD wood waste[50], a total amount of approximately 421,000 tonnes of biodegradable waste is available in the GCV for treatment by any of the case scenarios considered in this study. To treat such amount of biomass in only one AD or pyrolysis plant would be physically impossible. Moreover,

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[50] The total revenues do not vary significantly if waste wood is either used as soil fertilizer of for combustion activities. Therefore, only the LCA of waste wood with the potential of selling biochar as soil fertilizer was considered to calculate the total revenues and capacities needed. Moreover, this analysis does not consider digestates, since the pyrolysis of this feedstock is not profitable at all.

an unknown percentage of this amount is treated by either wood recycling companies, composting plants established in the area, or disposed in landfills. Therefore, considering this context, it was assumed that a fifth of the total biomass generated could be treated by a pyrolysis plant every year.

If a treatment target of one fifth is set up, then an 85,000 tonne per year capacity plant would be required. This treatment facility could have the potential of producing 16 MW of power, 136,000 MWh[51] of electricity (able to power approximately 27,000 households[52], or approximately 3.4% of the total households in the GCV area), and approximately between 8,500 and 30,000 tonnes of biochar, depending on if the waste is treated by a fast or slow pyrolysis process. This figures were obtained following the results obtained by McCarl et al (**2009, p. 345**), who estimated that a 70,000 tonne per year pyrolysis operation has a gross electrical output power production of about 13 MW at the same processing rate.

The results included in **Table 22** indicate that operating at this capacity, a fast pyrolyis plant could achieve more revenues and a higher GHG mitigation than a slow pyrolysis plant. The situation is again associated to the higher energy output ratios and abatement efficiencies achieved by a fast pryolysis treatment.

In this scenario, the treatment of food waste generates the highest benefits (approximately 60% of the total revenue), followed by garden and green waste, and waste wood. At a capacity of 85,000 tonnes, the only way of maximizing the revenues is by treating only food waste or treating the totality of CD and CI wood waste generated. However, the second option does not seem feasible, since this would imply that there are no wood recycling activities in the area. Thus, an interesting conclusion derived from this analysis is that in order to generate high revenues, the treatment of food waste is essential.

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[51] Considering a processing rate of 10 tonnes per hour.

[52] Considering that each household consumes 5,000 kWh (BERR, 2009).

Cost-benefit analysis

A cost benefit analysis was performed using the total capital investment cost estimates of £14 million ($24 million USD) reported by McCarl et al (**2009, p. 345**). Considering a 20 year lifetime of the facility, a discount rate of 12%, and the costs and benefits reported in **Tables 21 and 22**, it was found that neither a fast nor a slow pyrolysis facility operating in this area would be profitable at all (the net present value for fast pyrolysis equals minus £62,000,000, see **Appendix J**).

A sensitivity analysis was performed then to analyze how critical the inferences performed in this study are, leading to the following results assuming that all the other elements are held constant:

- Fast pyrolysis becomes profitable when the operation cost decrease from £72 to £20 per tonne of feedstock. Slow pyrolysis shows no sensitivity to the decrease of operation costs since it continues being unprofitable;
- Fast pyrolysis becomes profitable when the transportation cost decrease from £75 to £25 per tonne of feedstock. Slow pyrolysis shows no sensitivity to the decrease of transportation costs since it continues being unprofitable;
- Fast pyrolysis becomes profitable when gate fees increase from £22 or 45 to £140 per tonne of feedstock. However this scenario is unrealistic because gate fees will never reach these values since they have to be lower than landfill taxes in order to allow the technology to be competitive in the waste market;
- Fast pyrolysis becomes profitable when the price of ROCs increase from £53 to £100 per MWh. Slow pyrolysis only when this benefit increases up to £150;
- Fast pyrolysis becomes profitable when the price of electricity increases from £40 to £135 per MWh. Slow pyrolysis only when this benefit increases up to £230;

- Fast pyrolysis becomes profitable when the price of biochar increases from £8 to £110 per tonne of feedstock. Slow pyrolysis only when this benefit increases up to £170;
- Fast pyrolysis becomes profitable when the price of biochar increases from £11 to £100 per tonne of CO_2-eq. Slow pyrolysis only when this benefit increases up to £180.

Both technologies become more sensitive if all the costs and benefits are slightly varied at the same time, for example:

- Fast pyrolysis becomes profitable if the operation and transportation costs fall from £75 and £72 to £50 per tonne of feedstock, while increasing at the same time the benefits from ROCS from £53 to £60 per MWh;
- Fast pyrolysis becomes profitable if the operation and transportation costs fall from £75 and £72 to £60 per tonne of feedstock, while increasing at the same time the benefits from ROCS from £53 to £60 per MWh, the electricity price from £40 to £50 per MWh, and the price of biochar and carbon offsets from £8 to £20 per tonne of feedstock, and from £11 to £20 per CO_2-eq, respectively;
- On the other hand, slow pyrolysis becomes profitable if the operation and transportation costs fall from £75 and £72 to £50 per tonne of feedstock, while increasing at the same time the benefits from ROCS from £53 to £70 per MWh, the electricity price from £40 to £50 per MWh, and the price of biochar and carbon offsets from £8 to £30 per tonne of feedstock, and from £11 to £25 per CO_2-eq, respectively.

These scenarios are more realistic, since it is expected that the operation and transportation costs will decrease as soon as this technology starts to consolidate. For example, transportation costs for landfill are only £34 per tonne of feedstock. Moreover, it is expected that the price of ROCs will be increasing constantly in order to encourage the implementation of more green technologies, while the price of biochar can get higher as soon as the markets realize than it could work as an efficient soil fertilizer.

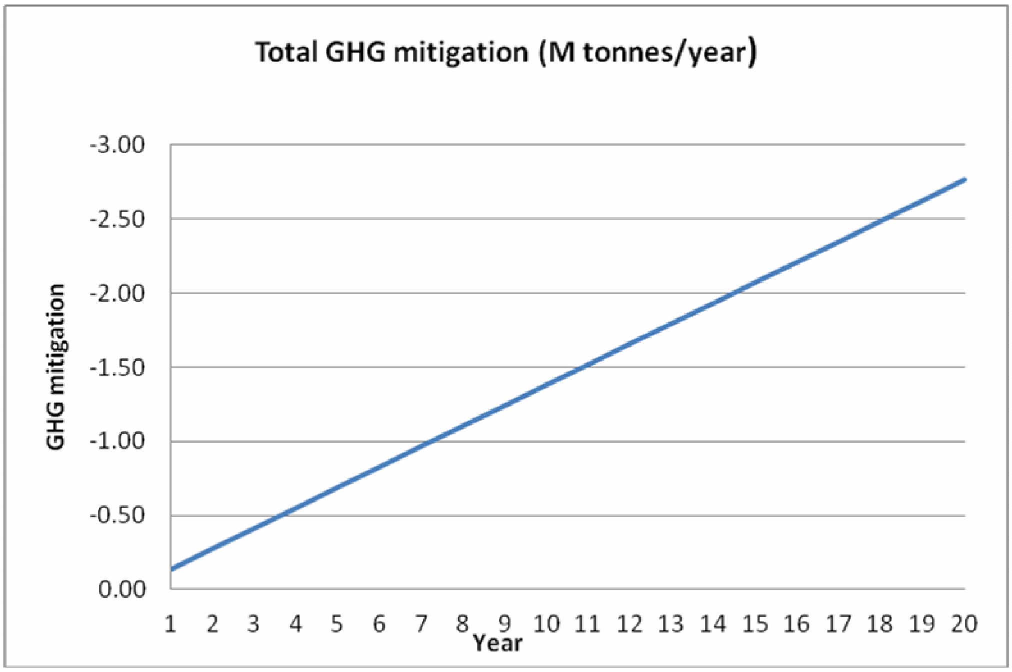
From this analysis, it can be concluded as well that the most important factors for the success of the project would be the contribution that double ROCs and gate fees have to the overall revenue. Without these factors, a project of this magnitude would not be profitable at all. For example, McCarl et al (**2009, page 353**) conclude that a 70,000 tonne capacity facility operating in the USA would not be profitable under the current (2009) energy-from-waste context of the U.S.A. This context considers that the production of renewable energy does not account for ROCs, and that the plant should assume the costs of transporting the BMW to the treatment facility.

GHG mitigation and landfill diversion potential

Furthermore, the operation of a fast pyrolysis plant could have an emission mitigation potential of approximately 138,000 tonnes of carbon dioxide equivalents per year. If an accumulation factor is considered (**Figure 4**), the total GHG emission mitigation expected during a 20-year would be of approximately 2.8 million tonnes (2.8 M tonnes).

Finally, one plant with the aforementioned treatment capacity would be able to divert approximately 16% of the 526,000 tonnes of BMW that are landfilled every year only in the GCV area. A second plant could contribute with an extra 16%, but only if it treats food waste exclusively.

Figure 4. Total GHG mitigation potential in a period of 20 years



CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

Historically, the waste management strategies of Scotland have depended heavily on landfills for disposing the large quantities of BMW that are generated every year. This situation is changing for good, mainly because of the current environmental context, in which the government has created several regulations to promote a more sustainable treatment of waste and help with the mitigation of climate change. Their main objectives are the diversion of BMW from landfills by setting up specific diversion targets, and the creation of incentives in order to increase the financial benefits associated to the production of green energy by emergent waste treatment technologies, such as AD or pyrolysis.

Of all the waste strategy areas of Scotland, the GCV area is the most important one in terms of waste biomass availability due to the big quantities of BMW generated every year (approximately 690,000 tonnes). Most of this waste (approximately 75%) is disposed of in any of the landfills of the area, of which at least two have been capacitated to recover energy. Since the landfill directive targets are increased constantly by the authorities every year, it could be expected that the amount of BMW that will have to be diverted from these landfills, and which could be treated in a more sustainable way, will grow in considerable proportions.

In this context, pyrolysis could have a huge potential as a waste management strategy in the area. Although it is certain that it would be competing against technologies that have lower operation costs (such as landfills or the current in-vessel composting initiatives) and against the future AD plant that will be operative by 2010 in North Lanarkshire, the evidence in the literature suggests that this technology could offer several advantages that the other waste treatment technologies don't. For example, it has more GHG abatement pathways than landfills, and it has the capacity of treating feedstocks that AD facilities usually do not treat, such as wood waste.

However, an in-depth analysis of the environmental and economical benefits that these three waste treatment technologies could offer has not been previously done. Thus, five LCAs were performed in this study, in which a comparison of economic and GHG release and abatement indicators was made, resulting in the determination of the following highlights and advantages.

Key highlights

Overall analysis

- Direct emissions from fuel-start up operations and transportation activities are insignificant for the quantification of the GHG emissions generated by each life cycle phase;
- The highest electricity offset is obtained when electricity from the grid is displaced by the one generated from any of the three waste treatment technologies.

Comparing pyrolysis processes against AD or landfills

- Pyrolysis processes obtain higher total carbon abatement efficiencies than AD or landfills, mainly because they offer more abatement pathways, and the biochar produced has higher carbon storage offsets than digestates;
- Fast pyrolysis obtains higher revenues than landfills, AD, or slow pyrolysis for any of the feedstocks analysed (except digestates), mainly because of the revenues gained by higher electricity offsets. In this scenario, the treatment of food waste generates the highest benefits (approximately 60% of the total revenue), followed by garden and green waste, and waste wood;

- Slow pyrolysis obtains higher revenues than landfills or AD only for food or wood waste, since it generates lower electricity outputs and thus, lower offsets;

Comparing fast and slow pyrolysis processes

- Considering the 1MW electricity output assumption, fast pyrolysis obtains higher total carbon abatement efficiencies and revenues than slow pyrolysis, mainly because of the electricity and storage offsets achieved by the generation of higher electricity outputs and carbon storage efficiencies;
- Comparing the three different offset pathways offered by both pyrolysis processes, the abatement achieved by the storage offset is always higher than the abatement achieved by the electricity or utilization offsets, except when wood waste is used for fuel combustion;
- Considering the 1MW electricity output assumption and comparing only the storage offset of both pyrolysis processes, fast pyrolysis achieves higher values than slow pyrolysis. However, if the electricity output is lowered for slow pyrolysis, the storage offset achieved is higher than the one achieved by fast pyrolysis.

Key advantages of fast pyrolysis

The potential advantages that this technology is able to offer, considering the assumptions made in this study, are the following ones:

- It could help with the compliance of the Landfill Directive by diverting from landfills a minimum 84,000 tonnes of BMW per year;
- It could mitigate approximately 138,000 tonnes of CO2 eq per year, and help with the compliance of the future GHG mitigation targets established in the Scottish Climate Change Bill;
- It could help with the displacement of electricity from fossil fuels by generating approximately 136,000 MWh per year of green electricity;

- And, it could help in the promotion of more sustainable agricultural practices by generating approximately 8,500 tonnes of biochar per year, which could be used as fertilizer for soils (only if this material is not contaminated).

According to these highlights, it can be concluded that fast pyrolysis has the potential of being the best technology to treat the wastes considered in this study. The incentives created by policies such as the Scottish Renewable Obligation or the Landfill Directive could have an important role in this case scenario.

Nevertheless, the cost-benefit analysis performed suggests that the current operational and capital investment costs of pyrolysis technologies would not make the operation of this technology profitable nowadays. However, as mentioned in the sensitivity analysis, a slight decrease of the operation and transportation costs and a slight increase of the different revenues derived from the offsets and the sales of biochar would make fast pyrolysis more profitable in a medium term scenario.

Finally, the multiple advantages that pyrolysis offers represent a perfect example of the environmental sustainability concept since it has the possibility of solving several environmental concerns by providing a more sustainable treatment and management of the waste biomass generated. This sustainable management could not only help the authorities in complying with their obligations, but also could contribute to the mitigation of climate change by generating green energy and biochar at the same time. Thus, the evidence generated by this study suggests that pyrolysis has the opportunity to play an important role as a waste treatment technology in the future.

Further recommendations

Some important recommendations derived from this study are the following:

- The BMW generated in the GCV, and more specifically waste wood, has to be characterized in order to know if it has potential toxic compounds that could interfere in the treating process and that could end up in the biochar produced. The results of this characterization are essential, because the final usage given to the biochar (as fuel for combustion or as fertilizer for soils) could depend on them. If the results indicate high concentrations of contaminants, then this feedstock will have to be completely discarded for pyrolysis processes;

- According to Ogawa et al (**2006, p. 429**), three subjects concerning the properties and production of biochar must be clarified before incorporating biochar carbon into the carbon credit system: quality standard of biochar, stability of biochar in soil, and methods for monitoring biochar utilization. Thus, before considering pyrolysis as a waste management strategy that could economically depend on the benefits derived from carbon offsets, it is necessary to study first the quality of biochar produced from feedstocks available in the GCV area, and develop standardized mechanisms to monitor its utilization and the environmental and economic benefits derived from it;
- To have a more realistic comparison of the abatement and economic indicators, it would be best to perform a LCA of the North Lanarkshire AD facility once it becomes operative in 2010;
- To have more realistic figures about the potential availability of biomass treatment by pyrolysis, it would be best to perform data collection platforms that include generation and recycling rates of the feedstocks mentioned, once the Kerbside collection systems are fully implemented in this area.

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