Assessing the multifunctional role of anaerobic digestion in England

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To the Edwards Tickner

To Edward George Tickner (1939–1997), whose memory I cherish,

who provided me with so many opportunities in life, including completing this thesis;

I aspire to do as much for my family.

To Edward Louis Tickner (2012–), who brings so much joy and laughter to our lives;

I hope to provide as many opportunities for him as my father did for me.

Abstract

The main drivers behind today's energy policy dialogue relate to the impacts of energy generation on the environment; the finite resources used to generate energy; and the nation's desire to provide an affordable and secure source of energy. Bioenergy is recognised as playing a significant role in helping the UK to meet its low-carbon objectives by 2050. Thornley *et al*. (2009) emphasised the importance of accurate information regarding the relevant impacts on entire bioenergy systems when making choices relating to the development of new bioenergy capacity.

Motivated by the environmental and economic challenges provoked by the impact of increasing energy demands and resource competition on the biosphere, this thesis assesses a single bioenergy conversion technology – anaerobic digestion (AD). By examining the technology's capacity to generate energy, mitigate GHGs and manage biowaste materials, this research aims to establish the role that AD might play in England.

Adopting a novel approach to assessment, this research combines life-cycle and economic measures in a single computer model, which is used to assess four different potential methods for the deployment of AD in England, including the hub-and-pod concept, not used in this country to date.

The energy-generating, agricultural and waste management sectors of the UK collectively emitted approximately 259.4 $MtCO_{2eq}.a^{-1}$ in 2011 (DEFRA, 2013b). In 2013, the UK generated 359 TWh electricity (DECC, 2013a: Chapter 5). This research demonstrates that in the three regions of England investigated, using the hub-and-pod method explored by this thesis, AD could mitigate 4.072 $MtCO_{2eq}.a^{-1}$ (1.6 per cent) of these UK annual GHG emissions, and could generate 5.45 TWh (1.5 per cent) of electricity generated annually by the UK. These figures represent 10 per cent of the government's renewable energy target for 2020 (EU, 2009).

Acknowledgements

The author is enormously grateful for the support offered throughout this research from both Professor Andrew Lovett and Dr Jane Powell, who jointly supervised this work. Both provided endless advice, guidance and support, from which I have learnt an enormous amount. A special thank you to you both for your patience, particularly when reading my work. Thanks must also go to Dave Knott, who showed me that MS Excel can do far more than add and subtract; Andrea Finegan, who provided an insight to the world of energy finance; and Dr Neill Mackay, who sang to us all in the office during our dark days of research, and enlightened me in some mathematics.

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Abbreviations and notations

~	approximately
≡	equivalent to
ABPR	Animal By-Products Regulation
AD	anaerobic digestion
ADEE	Anaerobic Digestion Environmental and Economic model
AHVLA	Animal Health and Veterinary Laboratories Agency
a.i.	active ingredients
ARR	accounting rate of return
BOKU	Universität für Bodenkultur Wien (University of Natural Resources and Life Sciences, Vienna)
C&I	commercial and industrial
CAD	centralised anaerobic digester (now community digester)
CAPEX	capital expenditure
CCC	Committee on Climate Change
CCGT	combined-cycle gas turbines
CCS	carbon capture and storage
CH_4	methane
CHP	combined heat and power
CO	carbon monoxide
CO_2	carbon dioxide
CO_{2eq}	carbon dioxide equivalent
COD	chemical oxygen demand
CSTR	continually stirred tank reactor
DA	Disadvantaged Area
DAF	dissolved air flotation (a treatment process for organic waste materials)
DCLG	Department for Communities and Local Government
DECC	Department of Energy and Climate Change
DEFRA	Department for Environment, Food and Rural Affairs
DM	dry matter
DUKES	Digest of United Kingdom Energy Statistics
EA	Environment Agency
EfW	energy from waste
EP	Environmental Permit
ETF	Environmental Transformation Fund
EU	European Union
EWC	European Waste Catalogue
FAO	Food and Agriculture Organization of the United Nations
FBI	farm business income
FIT	Feed-in Tariff
FM	fresh matter
FW	fresh weight

FYM	farmyard manure
GER	gross energy requirement
GHG	greenhouse gas
GJ	gigajoule (1,000 MJ)
GVA	gross value added
GWh	gigawatt hour (1,000 MWh)
GWP	global warming potential
ha	hectare (10,000 m^2)
HRT	hydraulic retention time
IEA	International Energy Agency
iLUC	indirect land-use change
IPCC	Intergovernmental Panel on Climate Change
IRR	internal rate of return
ISO	International Organization for Standardization
kg	kilogram
kW_e	kilowatt (electrical energy)
kWh	kilowatt hour ($\equiv$ 3.6 MJ)
kW_{th}	kilowatt of heat energy
KTBL	Kuratorium für Technik und Bauwesen in der Landwirtschaft
LATS	Landfill Allowance Trading Scheme
LCA	life-cycle assessment
LCI	life-cycle inventory
LDCe	levelised discounted cost of energy
LEC	Levy Exemption Certificate (climate change)
LFA	Less Favoured Area
LUC	(direct) land-use change
MAFF	Ministry of Agriculture, Fisheries and Food
MJ	megajoule (0.27778 kWh)
MRF	materials recovery facility
MSW	municipal solid waste
$Mtoe.a^{-1}$	million tonnes of oil equivalent per annum
MW	megawatt
MW_e	megawatts of electricity
MWh	megawatt hour (1,000 kWh)
NERS	National Electricity Registration Scheme
NFU	National Farmers' Union
NM^3	cubic newton metre (volume at 1 atmosphere and 0 °C)
NNFCC	National Non-Food Crops Centre
NOx	generic term for mono-nitrogen oxides, such as NO (nitric oxide), N_2O (nitrous oxide) or NO_2 (nitrogen dioxide)
NPV	net present value
NVZ	Nitrate Vulnerable Zone
Ofgem	Office of Gas and Electricity Markets
OFMSW	organic fraction of municipal solid waste
OLR	organic loading rate
OPEX	operational expenditure

ORC	Organic Rankine Cycle
OSR	oil seed rape
PAS 110	British Standards Institute publically available specification 110
PV	Photovoltaic
RCV	refuse collection vehicle
RHI	Renewable Heat Incentive
RO	Renewables Obligation
ROC	Renewables Obligation Certificate
ROCE	return on capital employed
ROI	return on investment
RPI	retail price index
RTFO	Renewable Transport Fuels Obligation
SIC	standard industry classification
SNS	soil nitrogen supply
SOC	Substance Oriented Classification
t	tonne
tpa	tonnes per annum
TWh	terawatt hour
UKERC	UK Energy Research Centre
VFA	volatile fatty acids
VS	volatile solids – the biodegradable fraction of the feedstock that produces biogas
WRAP	Waste and Resources Action Programme

Chapter 1: Introduction

'There are two spiritual dangers in not owning a farm. One is the danger of supposing that breakfast comes from the grocery, and the other that heat comes from the furnace.'

Aldo Leopold (1887–1948) – *A Sand County Almanac*

1.1 INTRODUCTION

Anaerobic digestion (AD) is the breakdown of organic material in the absence of oxygen. Its products include methane (CH_4), which can be used as an energy source, and fertiliser (digestate – the remaining material). The process has been controlled by man for millennia, with the first known site in the UK based in Exeter (1896), where the captured gas was used for street lighting (FAO, 1992). AD is a highly versatile technology, which, if organised meaningfully, could have a significant role in helping the UK to meet several EU directive targets for the reduction of waste to landfill, the generation of renewable energy and the mitigation of greenhouse gases (GHGs).

This chapter discusses how the expansion of AD technology aligns with current energy and climate change policy, and the political motivation behind the specific use of this technology over other bio-renewables. It highlights the importance of the technology's utility, and sets out the aims and outline of this thesis.

1.2 BACKGROUND

Energy plays a fundamental role in society today: it drives economic growth and the services we need to sustain ourselves, yet it also has significant impacts on the environment. Increasing demand for energy in human society is relentless, as more of our daily activities become automated and mechanised to improve productivity in the workplace and enjoyment during leisure time. But more than that, energy serves to meet basic human needs, such as cooking, heating and lighting. For quite some time, there has been a question over the planet's sustainability. Brundtland (1987: 5) defined sustainable development as the ability of humanity 'to meet the needs of the present without compromising the ability of future generations to meet their own needs'. By this, Brundtland was implying that we need to lessen our dependence on energy generated from fossil fuels and look towards technologies that reduce the demands on global resources and diminish stress on the world's ecosystem services.

The natural environment provides the resources and fuels necessary to construct our power plants and generate our energy, as well as the sink into which we place its waste products. Often, these resources and fuels are not found in the same region as where they are required; and the emissions from resource extraction and power generation activities, which do not recognise state boundaries, impact upon the environment both locally and globally (Dincer, 1999).

Consequently, the main drivers behind today's energy policy dialogue relate to:

- the impacts of energy generation on the environment and climate change, since energy and the environment are inextricably linked
- the finite fossil fuel resources used to generate energy
- the nation's desire (in this case, the UK) to provide an affordable and secure source of energy.

Therefore, the primary issues for the energy sector remain to increase efficiency of use and decarbonise the energy system, with the aim of mitigating the effects of increased GHG emissions on climate change. Climate change is the product of many human activities, but the greatest contributor to the change in our climate is an increase in the greenhouse effect produced by carbon dioxide (CO_2). The majority of CO_2 emissions are derived from the burning of fossil fuels, which we use predominantly to generate energy (IPCC, 2007). GHGs act as a blanket on the world, of which CO_2 is just one part, and increasing GHGs could have significant impacts. The consensus is that taking 'a business as usual approach' will result in a probable doubling of carbon dioxide equivalent (CO_{2eq}) concentrations by 2050 (MacKay, 2009: 10). This would have roughly the same effect as a 2 per cent increase in the intensity of the sun, or an approximate increase in global temperature of 3 °C. Such temperatures have not been seen on earth for over 100,000 years, and could lead to a rise in sea level of several metres and cause significant changes to weather patterns across the globe (MacKay, 2009: 10).

As part of a suite of measures, a strategy needs to be implemented on both the supply and demand sides of energy if global GHG atmospheric concentrations are to be stabilised. This will include reducing energy demand by utilising more energy-efficient technologies, as well as supplying energy more efficiently, so that less energy is lost through transmission over long distances or wasted at source. Decarbonising the energy supply may happen in several ways: nuclear energy seems likely to play an essential role; however, whilst uranium is a finite resource like fossil fuels and biomass, there is 1,000 times more uranium in the sea than in the ground; and finding an energy-efficient and cost-effective method of extracting this uranium remains a key challenge (MacKay, 2009: 162). The UK government has also placed considerable emphasis on the use of carbon capture and storage (CCS) within the energy-generating sector, and on it becoming safe, secure and affordable. However, considerable uncertainty remains over the economic and environmental costs and benefits of energy generation combined with CCS and the use of nuclear energy. It is these uncertainties that are sustaining our current dependence on the use of fossil fuels. Finally, energy generation from renewable technologies will also be required (DECC, 2011b). There is already substantial interest, particularly in those renewables that do not pollute or cause global warming, and that provide a more secure and sustainable source of energy generation (for example, wind and solar). The International Energy Agency (IEA, 2014) reported that renewable technologies now produce 19.5 per cent of global electricity generation.

Although fossil fuels are a finite resource, they remain in considerable supply. Total world annual coal production has increased from 1,853.4 Mtoe.a^{-1} in 1965 to over 3,845.3 Mtoe.a^{-1} in 2012, of which China is the largest consumer, at 1,873.3 Mtoe.a^{-1} (BP, 2013). The UK saw a gradual decline in coal consumption from 1965 until 2010, when it started to increase, with the latest figures showing a 25.7 per cent increase between 2011 and 2012 (BP, 2013; see Figure 1-1). Since there are only eight CCS facilities operating globally and none in the UK (CCSA, 2014), one can only assume that this current drive is to provide a cheap energy supply to promote commercial activity and help offset price increases that could exacerbate the level of fuel poverty in the present difficult economic climate.

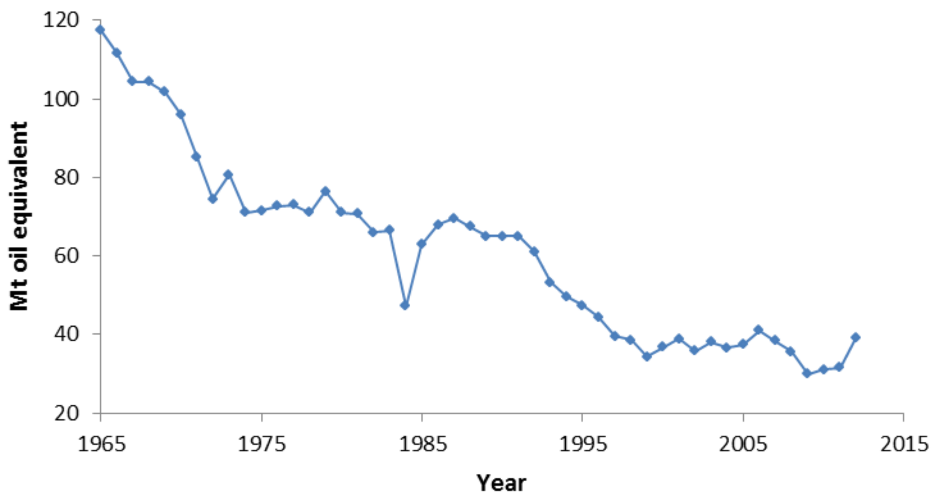


Figure 1-1 Annual coal consumption in the UK, 1965–2012. Adapted from: BP, 2013

In addition, the government is putting in place incentives to promote hydraulic fracturing of shale rock in England (Cameron *et al.,* 2014). Government POSTNOTE 374 (O'Driscoll, 2011) suggested that unconventional gas reserves in the UK may add 50 per cent to the UK's potentially recoverable gas resource. This could impact considerably on renewable energy generation in the UK. Gas is considered an excellent alternative source of fossil fuel, not only due to its abundance, but also because it helps to decarbonise the energy supply, with a global warming potential (GWP) emission factor of 0.184 $kgCO_{2eq}.kWh^{-1}$, compared with 0.307 $kgCO_{2eq}.kWh^{-1}$ for industrial coal or 0.268 $kgCO_{2eq}.kWh^{-1}$ for fuel oil (DECC, 2013a: 230).

Despite the steady move away from the use of coal in the UK energy mix, and with some of that gap being filled by renewable technologies (DECC, 2013), the current energy supply (see Figure 1-2) is still dominated by the use of fossil fuels, which accounts for 67 per cent overall.

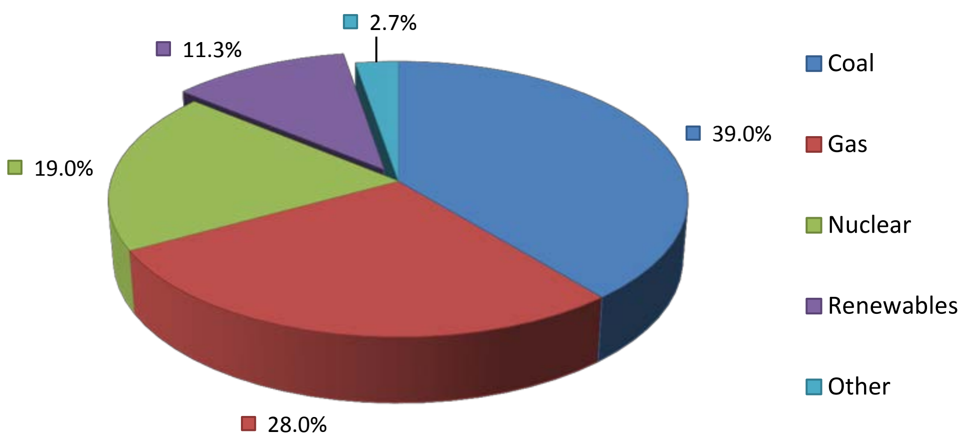


Figure 1-2 UK electricity generation by fuel type, 2012. Adapted from: DECC, 2013b

Renewable energy is described within the Renewable Energy Directive (2009/28/EC) as energy from resources that are continually replenished on a human timescale; resources including sunlight, wind, water and geothermal stores. Technologies using these resources include solar energy (photovoltaic (PV) and thermal); biomass (and all associated); wind turbines; hydroelectricity (tidal and wave); and air- and ground-source heat pumps. These are technologies which, whilst not entirely benign, release much lower quantities of CO_2 than fossil fuels. (This is explored in more detail in Chapter 8. See, Table 8-14.)

It would be impossible for current bio-renewable technologies alone to provide the main energy supply for the UK. As MacKay (2009: 204) points out, to meet the heating requirements for 2050 of 30 kWh.d^{-1} from biomass and energy crops would require 30,000 km^{2} of land, or 18 per cent of the UK's agricultural land, with an energy density of 0.5 W.m^{-2}. MacKay (2009) puts this into perspective, stating that a nuclear power station such as Sizewell, occupying less than 1 km^{2}, has an energy density of 1,000 W.m^{-2}.

However, renewables have an important part to play in our marginal energy mix, and a more central role in helping the government to decarbonise the energy sector. The Climate Change Act 2008 established the world's first legally binding climate change target: for the net UK carbon account for the year 2050 to be at least 80 per cent lower (34 per cent lower by 2020) than the 1990 baseline of the aggregate amount of net UK emissions of CO_2 for that year and net emissions of each of the other targeted GHGs for the relevant base year for each gas (HMSO, 2008). The UK ratified the EU Directive (2009/28/EC) target to produce 15 per cent of its total energy mix from renewable sources by 2020 (EU, 2009).

1.3 ENERGY AND THE ENVIRONMENT

The use of fossil fuels in the European Union (EU) has created several major issues, including the destruction of fisheries and forests and the corrosion of buildings and monuments across Europe (Levy, 1992). However, the greatest burden caused by the combustion of fossil fuels is the impact on the global climate. Emissions from their combustion represent a major source of GHG emissions (IPCC, 2013). Figure 1-3 displays the greatest contributions to GHG emissions across Europe by business sector, showing energy generation and agriculture to be two of the five largest contributors.

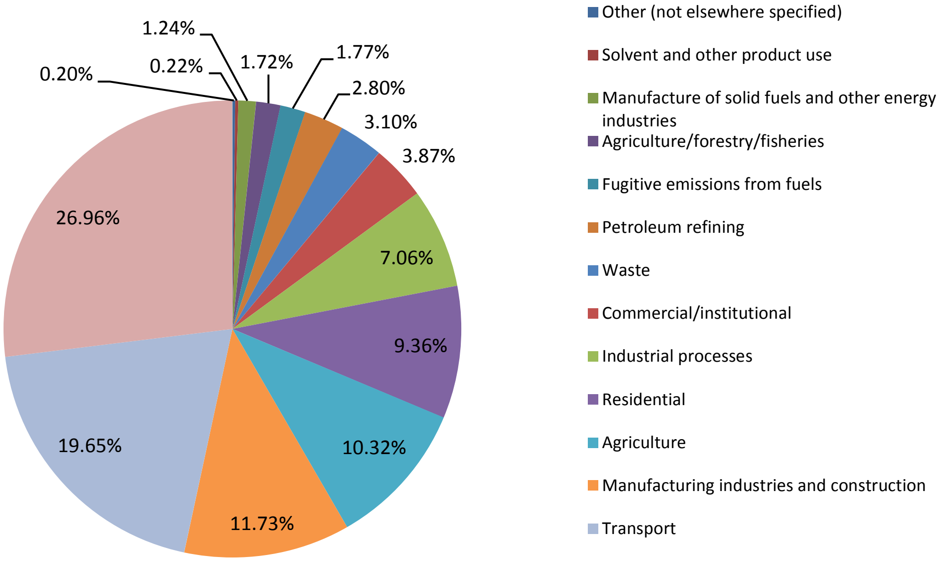


Figure 1-3 EU28 GHG emissions (CO_{2eq}), 2012. Adapted from: EEA, 2012

Energy supply is the greatest source of GHG emissions in the UK (190.9 $MtCO_{2eq}.a^{-1}$); combined with waste management (17.3 $MtCO_{2eq}.a^{-1}$) and agriculture (51.2 $MtCO_{2eq}.a^{-1}$), it accounts for 46.6 per cent of all UK emissions (see Figure 1-4) (DEFRA, 2013b). The agricultural sector is the fifth largest source of UK GHG emissions, derived from a range of activities and practices, including energy use in food production, manure and slurry stores, and general nutrient management – the latter could potentially deliver the greatest carbon mitigation, with a theoretical reduction in GHGs of 1.4 $MtCO_{2eq}$ per annum (DECC, 2013b).

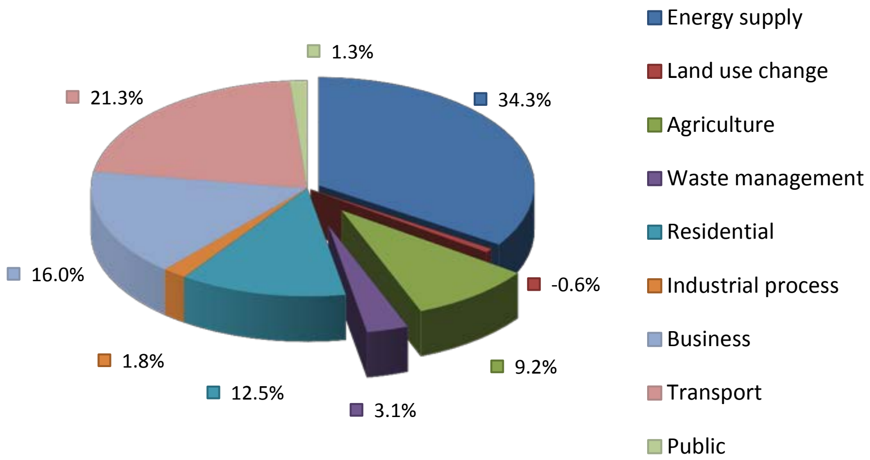


Figure 1-4 The source of UK GHG emissions by sector, 2011. Adapted from: DECC, 2013b

DEFRA has been tasked with reducing emissions from the agricultural sector by 3 Mt CO_{2eq} between 2007 and 2020. To help monitor their progress, DEFRA created a framework to assess agricultural emissions (DEFRA, 2013b). At the start of 2013, this indicator suggested that a reduction of 1.08 Mt CO_{2eq} had been achieved to date.

Currently, electricity generation from renewable sources is dominated by wind energy (see Figure 1-5), but energy generated from biomass also plays an important role in delivering the government's renewable energy targets, with the majority of the bioenergy generated from landfill gas and sewerage sludge digestion. Both of these rely on anaerobes to produce methane that is used to generate the energy.

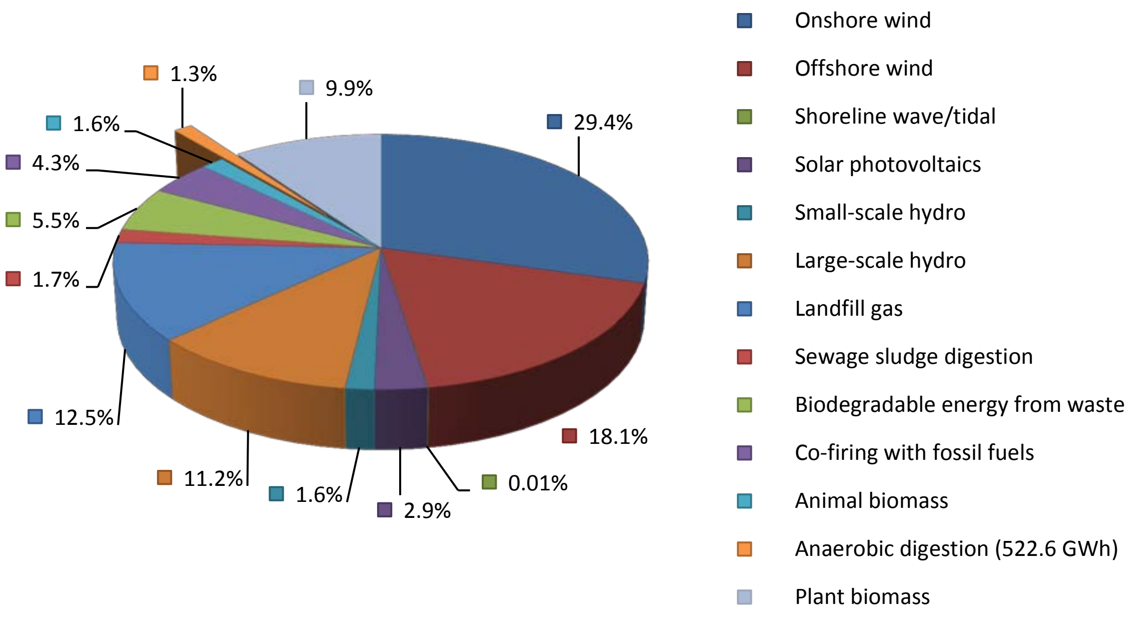


Figure 1-5 UK renewable electrical energy generation (GWh) by category, 2012. Adapted from: DECC, 2013a

The total quantity of electricity generated from biomass in 2012 was 15,198.2 GWh, representing just under 37 per cent of the total renewables energy generation. However, when taking into account the use of other energy generated from biomass – that is, heat and transport fuels – the picture is slightly different (see Figure 1-6).

1.4 BIOENERGY

Bioenergy is the energy (heat, electricity or fuel) derived from biomass. Biomass is described by the UK government as 'biological material derived from living, or recently living organisms' (Biomass Energy Centre, 2014). In the context of biomass for energy, this is often used to mean plant-based material, but biomass can equally apply to both animal- and vegetable-derived material.

Biomass is one of the more versatile renewable energy sources (compared to wind, for example) and can be a source for different types of energy, such as gas, liquid or solid fuels, heat or electricity (DECC, 2012a). Depending on the chosen energy conversion process, biomass can be burnt to make heat and/or electricity, converted to a liquid biofuel or gas to be utilised in a combined heat and power (CHP) generator, or injected into the national grid system.

Bioenergy has a significant role in the UK renewable energy system (see Figure 1-6), especially when generated from waste sources (41 per cent of current bioenergy generation), and in particular, landfill gas (currently 19 per cent of bioenergy generation). The main issue, or threat, represented by methane produced from biowaste (defined in Section 1.4.2 below) in landfill sites is that these sites are not designed for the capture of gases.

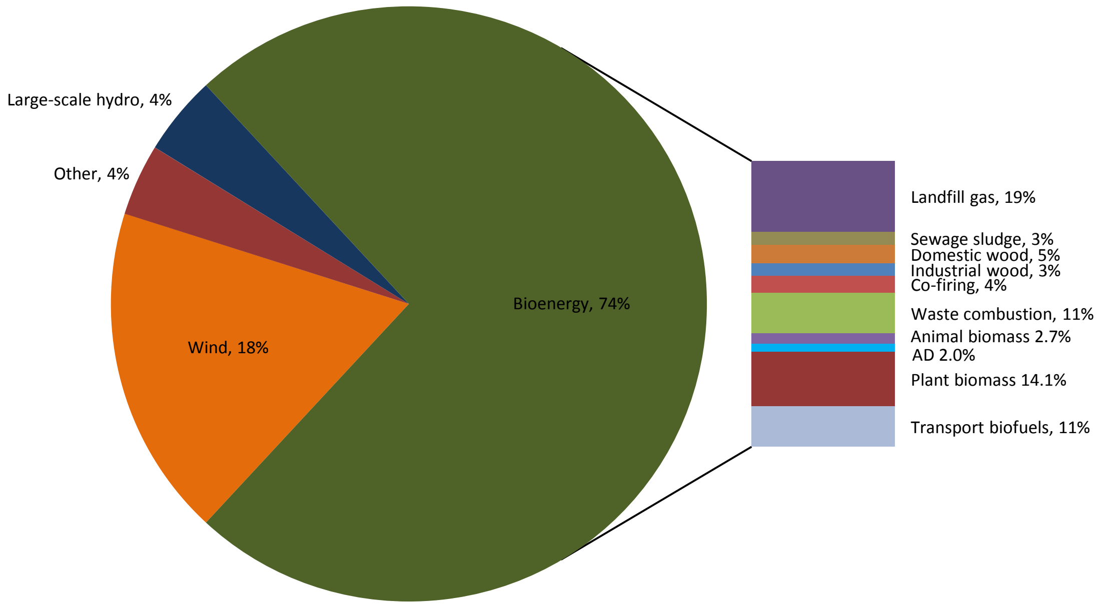


Figure 1-6 Renewable energy sources, 2012. Adapted from: DECC, 2013d

1.4.1 Sustainability

Bioenergy is often described as carbon-neutral, in that the carbon it emits during combustion is offset by that absorbed by plants from the atmosphere during growth. Ekins *et al.* (2013: 4) highlight the 'prospect for negative emissions with CCS', but also caution that bioenergy is clearly not zero-carbon and can be as high-carbon as some fossil fuels. It is therefore essential to conduct thorough assessments of the potential environmental impacts from the use of these different organic resources and transformation technologies. Ideally, such an evaluation should include: the availability of the feedstock types and their impact on the environment of cultivating such a resource; land-use changes and the impacts to biodiversity; GHG and energy balances; and political, socioeconomic and regulatory issues (Thornley *et al*., 2009).

Some have cast doubt on the sustainability of biomass as a source of renewable energy, particularly in the UK (MacKay, 2009). Others argue that bioenergy has an important role for many countries, in meeting their future energy supply and GHG mitigation targets (Chum *et al*., 2011; Lovett *et al*., 2014). Ekins *et al*. (2013), in forecasting UK energy supply to 2050, commented that all modelled scenarios had varying quantities of bioenergy requirements. This reflected the uncertainty of costs in the different treatments of biomass, and the quantity of bioenergy likely to be available – being constrained by land availability, due to competition from food production and the maintenance of biodiversity and recreational activities.

Bioenergy is recognised as having a significant role to play in helping the UK to meet its low-carbon objectives by 2050: 'excluding biomass from the energy mix would significantly increase the cost of decarbonising our energy system – an increase estimated by recent analysis at £44 billion' (DECC, 2012a: 6). Bioenergy also has an important role in the government's plans to meet the Renewable Energy Directive objectives in 2020 (DECC, 2011b).

The Committee on Climate Change (CCC), as an independent, statutory body established under the Climate Change Act 2008, aims to provide independent advice to the UK government and devolved administrations on setting and meeting carbon budgets and preparing for climate change. It conducts independent analysis into climate change science, economics and policy, and monitors progress in reducing emissions and achieving carbon budgets. The CCC recommended that the government aim to generate no more than 10 per cent of total UK primary energy from biomass. DECC has argued that a figure of 12 per cent could be achieved without 'jeopardising' sustainability (DECC, 2012a). However, DECC caveats this by highlighting (1) the risks and uncertainties associated with the use of bioenergy, including whether it genuinely contributes to carbon reduction in some circumstances; (2) the relationship between the use of land for bioenergy and other land uses (e.g. for food production); and (3) the other uses of biomass (e.g. building materials). Other risks and uncertainties that should be taken into account include the environmental impacts on air quality, biodiversity and water resources.

However, the generation of energy from biomass need not necessarily be derived from virgin biomass (trees, coppice or crops), as significant energy generation can be achieved from waste materials. For example, waste wood from the building sector is already recognised as having great potential for generating electricity. It is estimated that recovering energy from 2 million tonnes of waste wood could generate 2,600 GWh electricity and save 1.15 $MtCO_{2eq}$ emissions, with greater benefits available by recovering heat as well as power (DEFRA, 2008). In addition to waste wood, energy can be generated from food waste materials discarded across the food production chain, currently achieved through the collection of landfill gas.

In terms of national biogas production in Europe (see Table 1-1), in 2006, the UK was second in the EU25 group of countries, producing just under 12 per cent less than Germany, and more than four times the quantity of the next country, Italy. Looking back to Figure 1-5, which displays the split in energy generation from renewable technologies, it can be observed that the predominant production of biogas in the UK is from the anaerobic processes present in landfill sites and sewerage treatment works.

Table 1-1 EU25 biogas production (ktoe), 2001–2006

Country	2001	2002	2003	2004	2005	2006
Germany	600	659	685	1291	1594	1923
United Kingdom	904	1076	1151	1473	1600	1696
Italy	153	155	155	203	344	354
Spain	134	168	257	275	317	334
France	196	302	322	359	220	227
The Netherlands	161	149	154	110	119	119
Austria	56	59	64	42	31	118
Denmark	73	62	62	93	92	94
Poland	57	63	72	43	51	94
Belgium	45	56	56	43	84	83
Greece	33	42	42	32	36	69
Finland	18	18	18	17	64	64
Czech Republic	-	-	-		56	60
Ireland	28	28	28	19	34	35
Sweden	112	147	147	120	30	33
Hungary	-	-	-	2	7	11
Portugal	-	76	76	76	10	9
Luxembourg	2	2	2	5	7	9
Slovenia	-	-	-	7	7	8
Slovakia	-	-	-	3	5	5
Estonia	-	-	-	3	1	1
Malta	-	-	-	-	0	0
TOTAL	**2572**	**3062**	**3291**	**4216**	**4707.7**	**5347**

Adapted from: EurObserv'ER Biogas barometer (2013)

1.4.2 Biowaste management

Biowaste is defined by the European Commission as biodegradable garden and park waste; food and kitchen waste from households, restaurants, caterers and retail premises; and comparable waste from food-processing plants. This definition will be used throughout this research, rather than any wider description that might be found in other publications.

DEFRA's 2030 food strategy (2010c) suggested that total food waste in the UK is estimated at between 18 and 20 Mt per annum (see Figure 1-7), at least 40 per cent of which is disposed of in landfill sites, equating to 3 per cent of the UK's domestic GHG emissions and 6 per cent of its global water footprint. Whilst the single largest contributor is domestic households (7.3 Mt), more than half of the food waste still comes from within the supply chain.

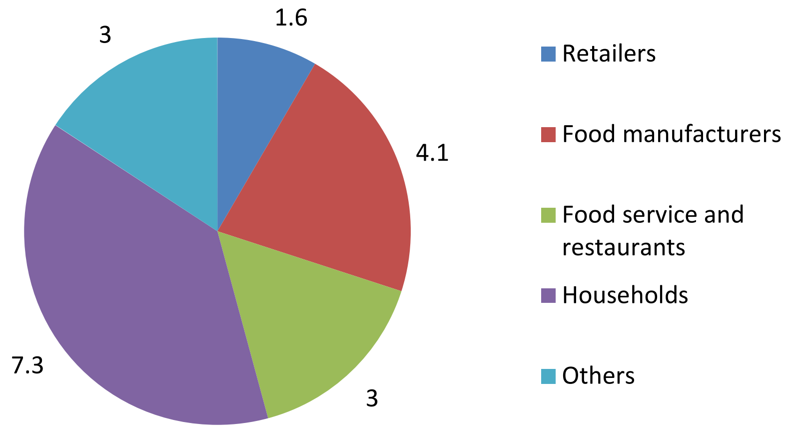


Figure 1-7 Estimate of total food waste (Mt) in the UK. Adapted from: DEFRA, 2010c.
Note: 'Other' includes food waste from agriculture, horticulture and commercial food waste (e.g. hospitals, schools).

The EU Landfill of Waste Directive (1999/31/EC) obliges member states to reduce the quantity of biodegradable municipal waste being sent to landfill by 65 per cent (based on 1995 levels) by 2016 (2020 for some countries). However, the Landfill Directive does not prescribe the treatment of biowaste. Whilst the Commission would like this resource to be used efficiently in producing good quality compost and generating energy, it recognises that most member states are likely to opt for the easier and seemingly cheaper option of incineration, disregarding the real environmental benefits and costs. To change this, the Commission has prepared a set of guidelines on how to apply life-cycle assessment (LCA) in order to assist decision-makers, within their national strategies, in making the best use of biodegradable waste in line with the waste hierarchy (see Figure 1-8).

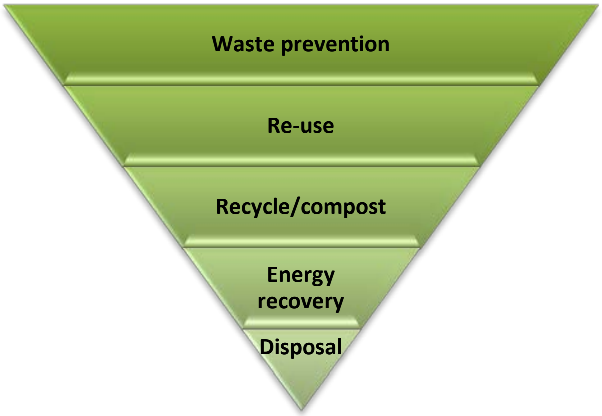


Figure 1-8 The waste hierarchy. Adapted from: DEFRA, 2011b

The EU Waste Framework Directive (2008/98/EC) sets out the protocols and regulations that govern the use of the materials, and the mechanisms that set the quality criteria and end-of-waste criteria. To summarise the other related legislation, the Industrial Emissions Directive (2010/75/EU) lays down the principles for the control of biowaste treatment installations with capacities exceeding 50 $t.d^{-1}$ (~18,250 $t.a^{-1}$); incineration of biowaste is governed by the Waste Incineration Directive (2000/76/EC); and the rules relating to composting and biogas facilitys which treat animal by-products are provided in the Animal By-Products Regulations (ABPR).

Article 11(2)(a) of the revised Waste Framework Directive (2008/98/EC) prescribes a target for households to recycle 50 per cent (by weight) of their total waste by 2020. Article 22, more specifically relating to biowaste, requires that Member States will take measures to encourage:

- the separate collection of biowaste with a view to the composting and digestion of biowaste
- the treatment of biowaste in a way that fulfils a high level of environmental protection
- the use of environmentally safe materials produced from the biowaste treatment.

As a member of the EU, the UK is obliged to adopt these directives within its laws and agree to meet the targets set. The government's review of waste policies in England (DEFRA, 2011b) highlighted food waste as a priority waste stream for review, as it accounts for almost 50 per cent of all waste CO_{2eq} emissions. DEFRA's (2011b) preferred option for the treatment of food waste is AD (offering the greatest environmental benefit), followed by composting and incineration with energy recovery. The review also goes on to state that the total quantity of organic waste from both domestic and all industrial sources, amounts to approximately 90 Mt per year (DEFRA, 2011c).

At a meeting of the Waste Strategy Board in 2009, it was forecast that based on future prospects for waste treatment infrastructure, the UK was on course to divert more municipal waste material from landfill than its proposed landfill diversion targets for 2020. The Board was asked to consider how to utilise any potential over-capacity from waste infrastructure in 2020, and to use this to tackle commercial and industrial (C&I) waste. Crucially, it was posited that the biggest issue was the lack of available data to help shape the C&I waste policy (Jones, 2009).

It has been demonstrated that government policy for both renewable energy generation and waste management suggests that AD could play a significant role. Whilst all the documents and reports suggest that AD is also one of the better technologies for decarbonising these industries, it does not quantify these attributes or suggest that targets for carbon reduction ought to be set for using this technology. The next section provides a more in-depth discussion of AD, its attributes and how the government has sought to develop and deploy the technology.

1.5 ANAEROBIC DIGESTION

This research focuses specifically on the use of the natural process of the digestion of organic material by micro-organisms, in the absence of oxygen – anaerobic digestion. The organic material considered here comes from a number of sources, including agriculture (crops and agricultural waste products) and the food-processing, catering and hospitality sectors (biowaste). Each material or feedstock type has its own biochemical qualities that dictate its capacity to produce methane (see Section 2-2).

Humans have learnt how to control and use the anaerobic digestive process for their own gain. This research explores a strategy of how AD could be used most efficiently that optimises its multiple benefits. AD is unique within the bioenergy technologies in that it can utilise a number of different feedstock types and be used to produce different fuel types, dependent on the chosen conversion pathway. The technology spans three DECC defined sectors (DECC, 2013a) and benefits each one. For this reason, not only could it help the government to meet its renewable energy targets, but it has a potentially greater role in reducing carbon emissions, and, as a consequence, the technology is covered by considerably more legislation than its counterparts.

AD generates energy from landfill sites and sewage treatment works, but the use of the technology goes much wider. In diverting the waste materials (biowaste) that would have gone to landfill, it reduces the quantity of CO_{2eq} emitted from these sites (in the form of methane leaking from fissures in the ground covering the sites); in treating the manure and slurry wastes from animal production, CO_{2eq} emissions are reduced from the farmyard manure and slurry heaps; and by recycling back to land the nutrients still present in the processed materials, AD helps to reduce the quantity of CO_{2eq} emitted from the production of mineral fertilisers used in agriculture (DEFRA, 2011c), and may improve soil quality and agricultural productivity (Walsh *et al.*, 2012). These are the qualities that set the technology or process of AD apart from other bio-renewable technologies. The following sections represent some of the main environmental roles and benefits of AD as a technology.

1.5.1 Generating energy with anaerobic digestion

Section 1-4 highlighted that biomass has an important role as a renewable energy source. AD is recognised as a key technology in converting low dry-matter (DM), and therefore low lignocellulosic, biomass to energy. However, there are a number of concerns about utilising AD (as well as other biomass technologies) to generate energy, including competition for land for growing food and the potential polluting aspects of AD. These are discussed more fully in the literature review. However, no biomass resource is as efficient in converting mass to energy when compared to the more traditional sources, such as coal, gas or nuclear – biomass simply cannot compete with the energy densities (biomass (50 per cent moisture) ≡ 8 $GJ.t^{-1}$; coal ≡ 28 $GJ.t^{-1}$; liquefied natural gas ≡ 56 $GJ.t^{-1}$ (McKendry, 2002)).

The two main sectors that have adopted this process for energy generation to date are the sewage treatment sector (since 1896) and, more recently, the waste management sector. However, the waste management sector did not set out to actively harness the power of this process; it was a result in general waste treatment regulations requiring the sector to treat the methane escaping from landfill, following several incidents in the 1970s and 1980s, such as the explosion in Loscoe in 1986 (Williams and Aitkenhead, 1991). Initially, the gas was flared on landfill sites, but as incentives were provided, energy was generated. We have seen that this has had a significant impact on the generation of renewable energy in the UK (see Figure 1-5 above) and will show a significant reduction in GHG emissions (see Figure 1-9).

AD has traditionally been seen as a technology for generating energy. It is only more recently that the technology’s other merits of waste management and GHG mitigation have been highlighted (Banks *et al*., 2011). However, incentives for the technology only relate to its energy generation, and not to its carbon mitigation qualities. In the future, therefore, it could be seen as an expensive method of generating energy.

The waste sector is not the only source of biomass whose energy could be harnessed for electricity generation, and it is not the only sector that requires the technological process of AD to help reduce the environmental impacts of GHGs. The agricultural sector is the fifth largest source of GHG emissions in the UK (see Figure 1-3 above), and many of these emissions come from methane and nitrous oxide (N_2O) from poor manure management.

1.5.2 Mitigating greenhouse gases with anaerobic digestion

There are many different GHGs (including CO_2, CH_4, N_2O, O_3 and H_20) and several principal sources, both natural and man-made. Methane is just one. Its GWP over 100 years is 24 times greater than that of CO_2. The three main sources of methane in the UK between 1990 and 2011 were consistently from agriculture, energy generation and waste management (DECC, 2013d; see Figure 1-9). The energy-generating sector has reduced its methane emissions through changing its source of fuels (from coal to gas) and using more advanced technology. The waste management sector started capturing the methane trapped in old landfill sites and installed better systems for capturing the gas in new landfill sites. However, even with these mitigating measures, GHG emissions from landfill in the UK were five times greater than those from German municipal solid waste (EU, 2010). Methane emissions from agriculture have been consistent over this 21-year period and have only fluctuated proportional to livestock numbers.

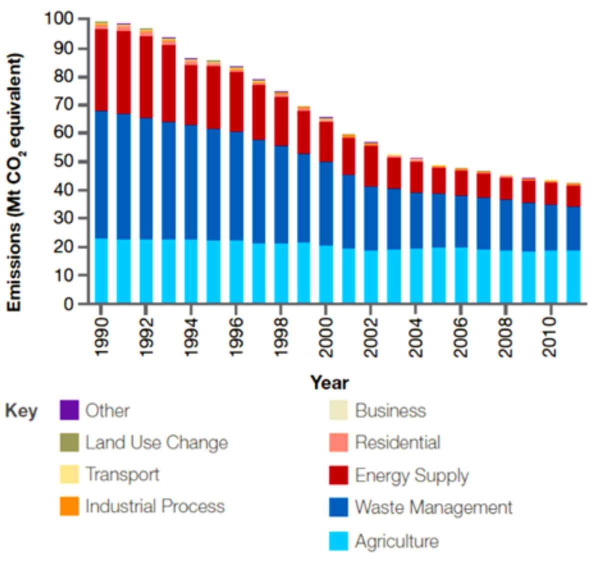


Figure 1-9 Methane: GHG inventory summary factsheet. Source: DECC, 2013d

The following sections discuss the main environmental benefits of using AD as a technology. They also represent four of the core environmental measures captured by the computer model developed for this research and used in calculating the environmental credentials of AD.

1.5.2.1 Emissions from energy production

Generating energy using AD offsets energy that would normally have been generated from fossil fuels. The technology is deemed to be carbon-neutral, since the carbon released during the combustion of the methane produced is 'offset' by the growing material that it has used or will use in the future – that is, crop feedstock types. In addition, AD mitigates GHG emissions by using (biowaste) materials that break down naturally, but which, if treated conventionally, would emit CO_2 and CH_4.

1.5.2.2 Emissions from waste management

In past decades, approximately 10 per cent of methane gas escaped through the landfill capping system, adding to the UK's global emissions (Gregory *et al.*, 2003). Methane leakage from landfills still accounts for approximately 3 per cent of total UK GHG emissions, even after a 59 per cent reduction in emissions between 1990 and 2007 (Fowler, 2010). The reduction in GHG emissions was achieved by capturing some of that gas to generate energy (see Table 1-1 above), and in 2006, the UK was the second greatest biogas producer in the EU25 member countries. However, the GHG emission contribution from landfill was still so great that further legislation and incentives were needed to encourage biowaste material to be diverted from landfill (EU Landfill of Waste Directive (1999/31/EC)). AD offers an answer to this issue by providing a purpose-built structure designed for treating the waste responsible for the methane production.

1.5.2.3 Emissions from agriculture

The agricultural sector is responsible for 9 per cent of total UK GHG emissions (49 $MtCO_{2e}$ in 2009; DEFRA, 2011d), of which 36 per cent is from CH_4. 90 per cent is enteric, with the remainder derived from dairy and non-dairy manures and slurries. Between 80 and 100 Mt of slurries and manures are produced from animals in the agricultural sector each year, which represents a considerable quantity of material requiring treatment in order to reduce the 10 per cent (non-enteric) methane emissions from agriculture. However, AD is the most appropriate technology to help achieve this. Section 3.7 explores the low inherent energy value of this material and the need for it to be treated cheaply and with other organic materials.

1.5.2.4 Emissions from fertiliser manufacture

Digestate is the solid material remaining at the end of the digestion process. It has a high content of nutrients, in particular plant-available nitrogen, phosphorus and potassium. The use of digestate as a soil amendment replaces the requirement for mineral fertilisers. Mineral fertilisers are manufactured using grid energy, which is also an energy-intensive process. The displacement of these man-made fertilisers has significant impacts, reducing indirect carbon emissions from mineral fertiliser production and thereby adding to the overall benefits of using AD as a closed-loop recycling technology.

It is clear that there are many benefits associated with the AD process and that these benefits cross many business sectors. The government has put in place a number of policies that directly and indirectly promote the use of AD in England. The next section focuses on the Anaerobic Digestion Strategy and Action Plan (2011), which was a government document setting out how AD might best be deployed in the UK.

1.6 ANAEROBIC DIGESTION STRATEGY AND ACTION PLAN (2011)

In 2011, DEFRA and DECC jointly published the Anaerobic Digestion Strategy and Action Plan, to assess and break down barriers that could slow down the use of AD technology. The plan set out the government's commitment to developing energy from waste through AD and how it intended to achieve this. Whilst in the executive summary it states that the document does not represent a comprehensive road map of increasing energy from waste using AD, it focuses on the treatment of biowaste and the diversion of this waste stream to landfill.

1.6.1 Anaerobic digestion facilities in the UK

DEFRA (2011c) reported that in April 2011, there were 54 operational AD facilities in the UK, 32 on-farm and 22 off-farm (excluding sewage sludge treatment plants). The number of AD facilities in the UK doubled between 2011 and 2014, yet AD is still in its relative infancy in the UK when compared with some other EU countries (see Figure 1-10). Styles (2013) reports that in early 2013 there were 110 non-wastewater AD facilities operating in the UK. Of these, 45 used agricultural feedstock types only; 48 treated some degree of food waste and other municipal feedstock types; and 17 were industry-based, treating on-site waste materials. There were 15 facilities under construction, with a further 73 with planning permission and 41 having submitted planning to the authorities.

In 2012, AD in Europe was dominated by Germany (see Figure 1-10), in terms of the number of operational plants – in excess of 6,800 facilities, compared to 84 in the UK –with Austria, France, Switzerland, the Netherlands and Sweden all having more than double the number of UK facilities.

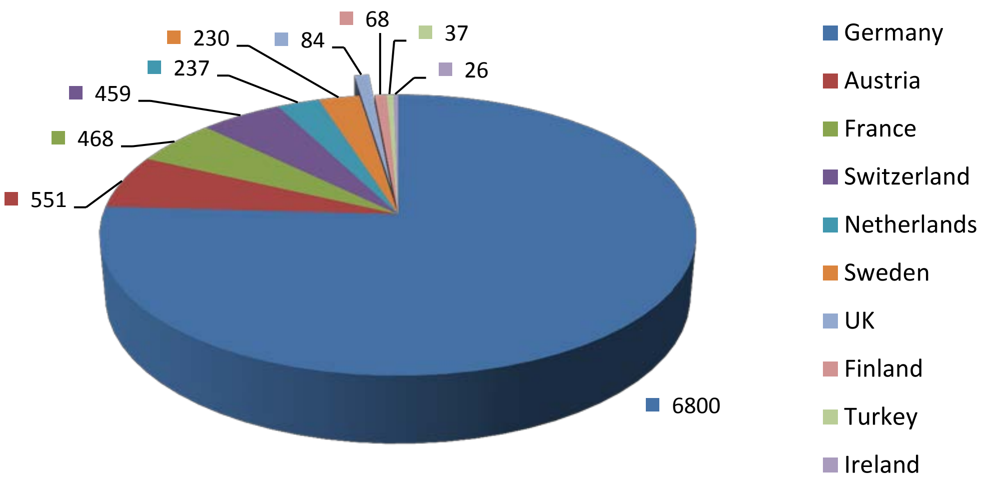


Figure 1-10 Operational AD facilities across Europe, 2012. Source: IEA, 2013

1.6.2 The Strategy and Action Plan

1.6.2.1 Raison d'état

The three main reasons for the government's interest in AD are energy generation, waste management and GHG mitigation. To review, these are the EU Renewable Energy Directive, requiring the UK to source at least 15 per cent of its energy from renewable sources by 2020; the EU Landfill Directive, requiring the UK to reduce, by 2020, the volume of biodegradable municipal waste sent to landfill to 35 per cent of the amount produced in 1995 (recycling a minimum of 50 per cent of waste from households); and finally, to reduce GHG emissions by 80 per cent by 2050, compared to 1990 levels.

1.6.2.2 The strategy

The aim of the Strategy and Action Plan was to understand how AD functions as a technology, what its capabilities are and how these can best be harnessed in helping the government to meet its EU directive targets. It set out to assess what the barriers were to the mass deployment of AD and how to address these, by offering the right incentives and breaking down existing legislative barriers that were delaying development. The four main issues that had either been addressed or were in the process of being addressed were: (1) the introduction in 2010 of new exemptions from the need for an Environmental Permit for AD at both agricultural and non-agricultural premises; (2) revision of the EU's standard permitting rules for AD, making it quicker and easier for applicants to meet the standard rules; (3) the government's intended amendment of planning rules that would aid AD; and (4) DECC's assessment of the possibility of a gas licence exemption for onshore gas production, making it easier for AD facilities to inject into the gas-grid system.

1.6.2.3 The action plan

A number of actions needed to be implemented to ensure the removal of barriers to promote the use of AD, including:

- the dissemination of information, particularly in the area of relevant regulation
- the development of best practices, an agreed framework for skills and training
- further research relating to barriers, particularly regarding connection to the gas grid
- research into the barriers relating to markets for digestate
- research into the use of generated methane as a transport fuel
- research into the impacts of the use of crops grown specifically for AD.

The Strategy and Action Plan set no targets, nor provided any regional strategies; rather, its purpose was to help ensure that there are 'no unnecessary obstacles' to the technology's development, by addressing the barriers identified by industry. It states that 'it will ultimately be up to local authorities, communities and industry to decide which technologies are most suitable for their waste and energy needs'.

1.6.3 Incentives

Several financial incentives were made available to support AD, including the Renewables Obligation (RO), Feed-in Tariffs (FITs), the Renewable Heat Incentive (RHI) and the Renewable Transport Fuels Obligation (RTFO). The range of incentives available demonstrates the versatility of the technology to deliver different fuel types to the market. The strategy's committee estimated that, based on the information available at the time, and if real and perceived barriers were removed, the potential for AD would reach between three and five terawatt hours (TWh) by 2020.

A number of other incentives have been launched in rural areas, such as the Waste and Resources Action Programme (WRAP) Rural Community Energy Fund (available from June 2013), which supports rural communities in England developing renewable energy projects. The Anaerobic Digestion Loan Fund (available from October 2013) is a £10 million fund designed to support the development of new AD capacity in England. The aim is for the fund to support the diversion of 300,000 t of food waste from landfill to AD. Finally, the On-Farm

AD Fund (available from April 2014) has been developed to help farmers in England gain financial support to build small-scale AD facilities on their farms. This offers access to funds in two stages: first, a grant of up to £10,000 to investigate the environmental and economic potential of building an AD facility on the farm; and second, a capital loan of up to £400,000 (or a maximum of 50 per cent of the project costs) for AD facilities producing up to 250 kW of power.

1.7 SUMMARY AND THESIS OUTLINE

This research has been funded by the UK Energy Research Centre (UKERC), under their Energy and the Environment research theme. The principal aim of this theme is to develop strategies for marine- and land-based energy production and GHG technologies that limit impacts whilst safeguarding or even restoring the ecosystem. In addition, it seeks ways to integrate into technology the socioeconomic valuations of ecosystem goods and services that permit the evaluation of the impacts of energy production and GHG mitigation technologies on the UK's carbon footprint.

The geographical scope of the UKERC research theme is in fact global in its approach, although national in its focus. This thesis knits well with the overall aims of the Energy and the Environment research theme in that it provides a strategy that seeks to optimise the energy generation capacity and GHG mitigation potential of a sustainable technology.

UKERC's interest in this research might be to:

- identify the current role of AD in the bioenergy industry in England
- acquire a better understanding of the role AD could play in the bioenergy industry of England
- assess the potential environmental impacts of a developing AD industry could have on helping to meet the government's renewable energy and GHG emission targets
- assess the potential economic impacts of a developing AD industry on the rural economy in particular.

The general aim of this thesis, therefore, is to explicate the role of AD in England, understand how AD could develop, and evaluate the energy potential and possible environmental impacts from an increase in the deployment of AD in England. To achieve this aim it is necessary to identify the quantity of feedstock types available. It is also important to understand how the deployment of AD could help to meet the government targets mentioned earlier in this chapter. This research also seeks to evaluate if the current primary role of AD is one of energy generation, carbon mitigation or waste management.

Chapter 2 reviews the recent literature and interdisciplinary research approaches used to evaluate AD in its capacity to generate energy and mitigate GHG emissions at a regional scale, and to assess the potential gaps in the knowledge base. It reviews previous literature on life-cycle assessment (LCA), as well as the literature on the economic assessment of AD in particular. It also reviews some of the challenges incurred during this review, in particular the available data for feedstock, as well as the treatment and processing of the feedstock and digestate.

Four main methodologies (questionnaires with interviews, LCA, economic assessment, and constructing an MS Excel model) and other general approaches are used in addressing the aims of this research; these are set out in Chapter 3.

Chapter 4 details the importance of the case studies within this research and how the data were obtained, through the development of a questionnaire and a series of interviews (primarily for the collection of financial information).

Chapter 5 explains which databases were used and how these, along with the data obtained from the questionnaires, were used in developing the various attributes of the ADEE model. The calculations present within the model are also discussed here.

The validation process is discussed in Chapter 6. It was important to establish that the model was reliable and that the outputs were robust, so as to bring authority to this research. The validation process was completed against the case studies used in this thesis, as well as against the outputs of a number of research groups.

Chapter 7 sets out the development of a series of optimised model-runs applicable to a number of different AD facilities, based on herd and farm size, and refines the hub-and-pod scenario (see Section 2.4.5). This chapter also explores a series of sensitivity analyses completed on the model-runs, aimed at highlighting the strengths and weaknesses of the optimised model-runs against external market forces.

Chapter 8 discusses the results of the different scenarios developed (see Section 3.6) for the three English regions (see Section 3.3.4) chosen for this research, to assess the four potential different pathways for AD in England. These results are then compared against other research groups' results and data that compare AD to other energy-generating technologies. Finally, Chapter 9 sets out the conclusions and recommendations for further work.

Chapter 2: Literature review

'Knowledge is like a garden: if it is not cultivated, it cannot be harvested.'

African proverb

2.1 INTRODUCTION

The AD process occurs naturally and is similar to the process which takes place in animals' stomachs. It is the natural breakdown of organic material in the absence of oxygen, forming, inter alia, methane, carbon dioxide and water. AD is a complex set of biochemical processes involving four main stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis.

The process operates in nature at many temperatures, but for the purposes of the treatment of organic materials in the built environment, the process can be placed into three separate temperature categories: psychrophilic, mesophilic and thermophilic.

Psychrophilic digestion takes place at temperatures below 20 °C. At this temperature, the hydraulic retention time within the digester is in excess of 100 days, and, as a result, requires large storage and digester volumes. This is very uncommon.

Mesophilic digestion occurs at temperatures between 25 and 40 °C, requiring hydraulic retention times of 25–40 days. This temperature range is the most frequently used as it provides the most stable environment, allows for a great number of bacteria species to function more efficiently, and, economically speaking, provides the best trade-off between capital and operational expenditure.

Lastly, thermophilic digestion occurs at temperatures between 50 and 70 °C, with retention times as short as 12–15 days. This temperature ranges are highly dynamic and unstable, requiring high operational costs, in terms of monitoring equipment and maintaining the higher temperatures, particularly if the facilities are situated in colder climates.

The temperature and DM content of the feedstock being digested dictates if the process is classified as a wet or dry process. The most common process used in England is a wet process completed in a continually stirred tank reactor (CSTR) (see Figure 2-1).

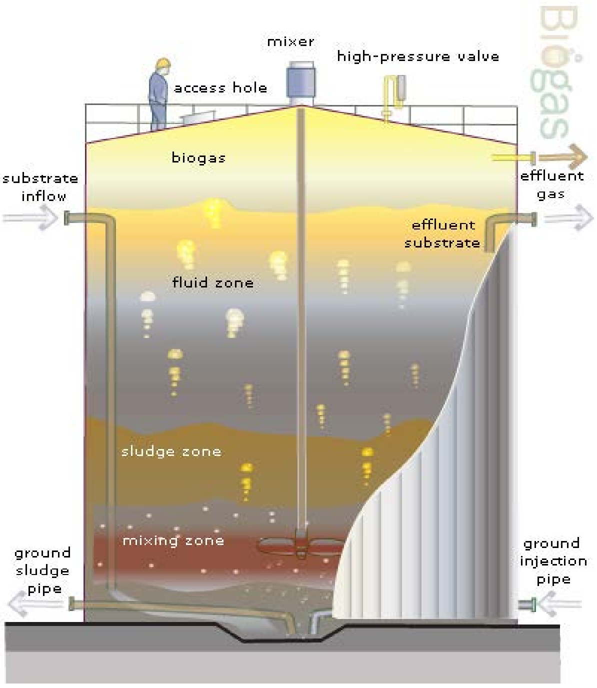


Figure 2-1 A typical CSTR for wet anaerobic digestion. Source: www.r-e-a.net

Considerable research has been completed globally concerning AD. Much of this relates to the various biological processes inherent in the process (Herrmann *et al*., 2011); the substrates on which AD successfully operates (Bouallagui *et al*., 2009; Bruni *et al*., 2010; Lehtomäki *et al*., 2007; Vervaeren *et al*., 2010); and the ways in which the process can be optimised, making it more efficient and safer to use (Banks and Zhang, 2010; Zaki-ul-Zaman *et al*., 2011). The general aim is to speed up the reaction time, thereby reducing the size of capital required and essentially improving the overall economics and efficiency of the technology.

Figure 2-2 displays the general AD process, setting out some of the different types of feedstock that can be utilised (excluding the collection and use of biowaste; see Figure 2-3 for one collection and treatment method), the point at which digestion occurs in the process, and the different uses of the gas and solid products from the process.

This research focuses on the evaluation of AD, and this chapter reviews both the valuation methods and the identification and selection of data used in this evaluation. The chapter can be divided into two main parts. The first part relates to the two accepted methods of evaluating technologies, in terms of their environmental cost benefits (see Section 2.2) and their economic cost benefits (see Section 2.3).

The second part assesses in more detail some of the key challenges relating to the extended LCA of AD that require special attention here, including: feedstock (see Section 2.4) and the paucity of available primary data; an introduction to the hub-and-pod concept; and the impact of certain feedstock characteristics on the modelling of AD. This includes the polluting aspects of livestock waste, including GHG emissions from livestock prior to being spread to land (see Section 2.5.1); the use of pre-treatment and ensiling processes on some feedstock types (see Section 2.5.3); and the impact on gas yields of co-digesting feedstock types simultaneously (see Section 2.5.4). The discussion then moves on to the basic characteristics of digestate and its application, and finally, the various options for the biogas.

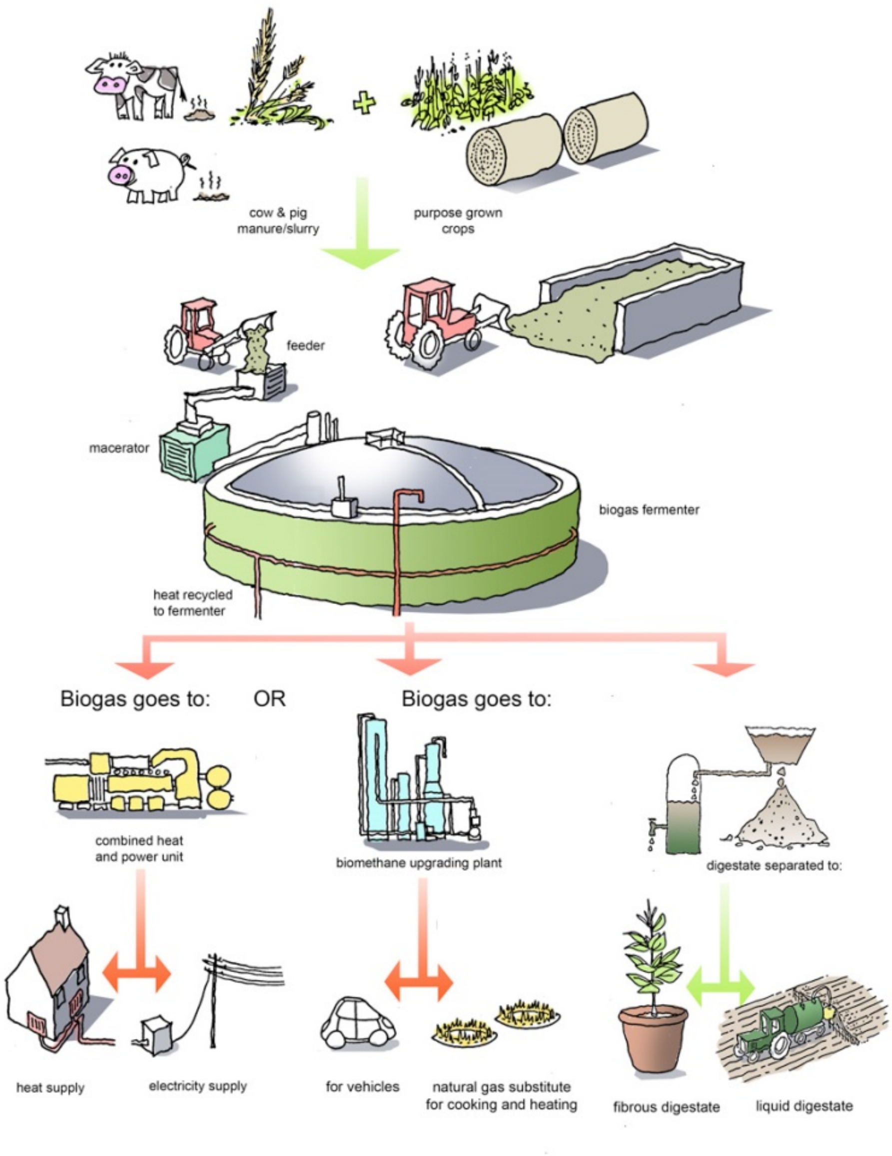


Figure 2-2 A schematic diagram of an on-farm-based AD process.
Source: Nethy Energy (www.nethyenergy.co.uk)

2.1.1 Evaluation of anaerobic digestion

This research is concerned with the role that AD might play in England and, in particular, the quantities of energy generated and GHGs mitigated that AD could achieve in a financially viable context. To achieve this, an evaluation of the materials used, energy generated and financial costs and rewards needed to be assessed. Therefore, two accepted methods of appraisal were assessed for their suitability for this research. These included LCA (see Section 2.2) and a number of different economic indicators (see Section 2.3).

As a consequence of policy incentives across Europe, there has been considerable research and modelling of AD, both in the UK and across Europe. This has taken many forms, including governmental and regional reports specifically for the UK (Köttner *et al*., 2008; Jones, 2010; Mistry *et al*., 2011a and b), and other academic research on specific feedstock types (Bruni *et al*., 2010; Mezzullo *et al*., 2012), mass and energy balances (Poeschl *et al*., 2010; Banks *et al*., 2011), and LCA (Berglund and Borjesson, 2006; De Vries *et al.*, 2012). However, the use of different datasets, allocation methods and modelled assumptions, along with a range of different functional units, impairs the comparison of different LCA bioenergy studies (Cherubini and Strømman, 2010).

2.2 LIFE-CYCLE ASSESSMENT OF ANAEROBIC DIGESTION

It is generally accepted that there are two forms of LCA: consequential and attributional (Finnveden, 2008; Brander *et al*., 2008). Consequential LCA models the causal relationships originating from a decision to change the output of the product. It therefore seeks to inform policymakers on the broader impacts of policies that are intended to change levels of production.

Attributional LCA (used in this research) provides information about the impacts of the processes used to produce (and consume and dispose of) a product, but does not consider indirect effects arising from changes in the output of a product. Attributional LCA generally provides information on the average unit of product and is useful for consumption-based carbon accounting. Examples include the specification for the assessment of GHG emissions from the life cycle of goods and services (BSI, 2011); and, to an extent, ISO (2006b). These are, in effect, accounting studies reflecting the technical aspects of the system at a specific point in time (Wrisberg *et al*., 2002).

However, LCA is a highly developed and widely used environmental assessment tool for comparing alternative technologies (Clift, 2013). An LCA represents a rigorous account of the environmental costs and benefits arising from the production of a good or service. There are some issues associated with the allocation of environmental burdens (Heijungs and Guinée, 2007); however, ISO (2006a) recommends that the environmental benefits of recovered resources should be accounted for by widening the system boundaries to include the avoided burdens (Eriksson *et al*., 2007), and is the approach used here. There are four main stages to an LCA (goal definition, inventory, impact assessment, and interpretation and improvement), which will be discussed in greater detail later (see Section 3.3.2).

Crumby *et al*. (2005) completed an LCA of a single centralised anaerobic digester (CAD) facility in Holsworthy, Devon. At the time, the facility was still taking on-farm wastes (it is now only treating food wastes); its feedstock was 57 per cent farm slurry, 19 per cent blood, 11 per cent food waste, 8 per cent chicken manure and 5 per cent other on-farm wastes. On average, it took in 277 $m^3.d^{-1}$ feedstock, produced 10,085 $m^3.d^{-1}$ biogas and 1.32 MW_e.

Recommendations from Crumby *et al.'s* (2005) findings included the following: (1) covering digestate stores reduced NH_3 emissions and reduced acidification and nitrification potential by approximately 95 per cent, but would increase the eutrophication potential; (2) deep-injecting the digestate into the land could also abate 85 per cent of NH_3 emissions and, again, reduce the acidification and eutrophication potentials. The following discussion, whilst predominantly chronological, is the structure upon which other regional-scale LCA has developed in the UK, and which the general LCA discussion is made. No further weight should be impressed upon the discussion than that.

Patterson *et al*. (2011) assessed the potential of biogas at a regional scale, treating 275,900 $t.a^{-1}$ municipal waste, based on either five centralised AD facilities or a distributed system of 11 AD facilities. Using life-cycle techniques, they compared AD with CHP, and AD with gas upgrade with injection into the grid, or gas upgrade for transport fuel. They concluded that CHP with 80 per cent heat use had the least impact. The end-use for domestic heating provided the smallest environmental benefit.

Mezzullo *et al*. (2012) carried out an LCA of a small-scale AD facility using cattle waste from 130 animals. Their conclusions demonstrated that the environmental and energy impacts from the capital construction contributed very little to the overall whole-life environmental impacts; that the displacement of fertiliser had significant benefits; and that energy supply from AD was beneficial in terms of GHG emissions and fossil fuel use over alternatives, but with the caveat that respiratory emissions (NH_3) were an issue, although these could be dealt with through simple control measures (covering digestate storage tanks).

Poeschl *et al*. (2012a and b) sought to assess the environmental impacts of biogas deployment at two different scales, small (<500kW) and large (>500kW), using attributional LCA. Their key findings included:

- a 53-fold increase in transport emissions from treating municipal solid waste (MSW) over cattle manures
- the utilisation of imported fossil fuel-sourced energy within the AD system increased non-methane volatile organic compounds
- 70 per cent more CO_{2eq} emissions could be mitigated by coupling small-scale CHP units with external heat utilisation, compared to electricity-only outputs
- feedstock mixtures of predominantly agricultural and food waste materials accounted for just 1 per cent of agricultural land-use change impacts, compared to mixtures predominantly of purpose-grown crops
- the utilisation of heat from CHP engines is the most sustainably viable pathway from biogas production
- recovery of residual biogas from the digestate storage area, reduces the environmental impact tenfold in comparison to systems with open storage facilities.

Styles *et al*. (2013) used a consequential LCA method to assess the expanded boundaries of AD and other bioenergy options. They modelled four baseline farms: a large dairy farm (481 milking cows; 250 hectares (ha)); a medium dairy farm (142 milking cows; 85 ha); a large arable farm (400 ha); and a large (undefined) arable farm receiving pig slurry. They concluded that co-digesting dairy slurry with food waste was an effective option for reducing GHG emissions and improving resource efficiency. They also concluded that associated acidification and eutrophication risks could be minimised through high-quality design and good management of a system. Growing crops was found to be detrimental to the environment, with the exception of utilising small quantities to supplement the other feedstock types and in areas where maize could be used as a break crop to optimise crop rotations.

Evangelisti *et al*. (2014) sought to compare the environmental impacts from the treatment of the organic fraction of municipal solid waste (OFMSW) by AD, by incineration with energy recovery by CHP, and by landfill with electricity production. Their research was specific to Greater London. AD represented the overall best option when using the digestate as a fertiliser and using the waste heat, thereby displacing energy used for fertiliser production and grid-based energy for heating purposes, coming in second to incineration only in terms of photochemical ozone and nutrient enrichment potential.

Finally, Börjesson and Berglund (2006 and 2007) took a general overview of AD, assessing the use of different feedstock types and end-uses for the biogas; referenced against alternative systems for energy generation, waste management and agricultural production. They made several observations, including:

- the extensive handling of the raw materials contributes a significant source of GHG emissions
- uncontrolled losses from stored digestate or from biogas upgrading also contribute significantly to GHG emissions
- biogas systems generally lead to environmental benefits, which in some cases can be significant
- these benefits can often be due to indirect changes in land use and handling of organic waste products, and can often exceed the direct environmental benefits achieved when fossil fuels are replaced by biogas: 'such benefits are seldom considered when biogas is evaluated from an environmental point of view' (Börjesson and Berglund, 2007: 326)
- raw materials can be transported for up to 200 km (manures) and 700 km (slaughterhouse waste) before the energy balance turns negative (Berglund and Börjesson, 2006).

Whilst each of the research studies above used a number of different assumptions, the overall conclusion is that, in general, AD, when deployed correctly, is a suitable method of treatment for on-farm waste and organic materials and off-farm biowaste material, generating renewable energy and mitigating carbon. The general concerns raised were of emissions from transport (Poeschl *et al.*, 2012a and b), emissions from digestate storage (Börjesson & Berglund, 2007; Mezzullo *et al.*, 2012) and the utilisation of energy generated (Patterson *et al.*, 2011; Poeschl *et al.*, 2012a and b; Evangelisti *et al.,* 2014). In the next section, there is a brief discussion of some of the software and databases that were employed by some of the researchers discussed above.

The overarching theme behind all of these LCA studies is that the assessment was only completed for a single digester, with a single feedstock type, or in some cases the co-digestion of a number of feedstock types under specific conditions and assumptions. Only Mistry *et al.* (2011a and b) assessed the potential of the technology in England. They used a combination of different farm-related assessment tools (such as MANURES-GIS, ALOWANCE and NEAP-N) to complement other research to complete their LCA. Some of the areas they deemed as 'no go' areas for AD, due to population density, nutrient levels or biodiversity, may have had AD facilities already in operation there. They estimated that England and Wales combined had the potential for approximately 900 facilities when including food waste in their mix. However, this reduced to just 196 if only agricultural feedstock types were allowed.

2.2.1.1 LCA software and databases

LCA, as an environmental management method, is extremely data-intensive. There are a number of commercially available software packages that include complex modelling algorithms and a choice of inventory databases of the more commonly used materials, processes and products. However, most of these programs (see Table 2-1) are more specific to the general waste management industry.

Table 2-1 Main software packages reviewed for this research

Software name	Link
EASETECH	www.easetech.dk/
WRATE	www.ricardo-aea.com/cms/wrate-2/?stage=Live
MSW-DST	www.rti.org/page.cfm?nav=13
ORWARE	www.ima.kth.se/im/orware/English/index.htm
SimaPro	www.simapro.co.uk/
GaBi 4	www.gabi-software.com/uk-ireland/index/
Open LCA	www.openlca.org/

Two of these programs (WRATE, MSW-DST) were too heavily focused on the waste management sector and did not provide the flexibility to account for the agricultural aspects of this research. ORWARE and EASETECH (then EASEWASTE) were unavailable, as the former was no longer supported and the latter was in the process of being updated and the old software had been removed.

GaBi and SimaPro seem to be the most popular among the research community, being used almost equally. SimaPro from PRé Consultants seemed to offer the greatest flexibility, containing several inventory databases and impact assessment methods which can be edited and expanded without limitation (Adams, 2011), however, the next section also highlights some of the issues associated in using these tools and is a reason why this research used its own purpose built assessment tool.

2.2.1.1.1 Advantages and disadvantages of using LCA software

The main benefits in using LCA software may be summarised as follows:

- providing the framework to access a number of databases relevant to each calculation
- the ability to handle a considerable amount of data quickly and efficiently

- providing a number of different results and presenting them in a structured and readily understandable manner.

However, it is the overarching need for data to produce accurate results that can be the cause of many errors. Two of the key attributes of LCA software tools that provide the cautionary note in using such software are described by McManus (2001) as:

- the black box problem – understanding the results produced and how to analyse them properly
- not understanding the processes involved, leading to inaccurate or misleading results, providing no assurance of the reliability of the data produced.

One of the main issues in choosing one of these programs for this research related to the ‘black box’ dilemma. The other concerned the potential lack of flexibility in a program, not being able to model the economic and agricultural aspects of this research, (i.e. the various operations required for the different crops grown specifically for the purpose of energy generation). Therefore, none of these programs was chosen and a model was built in MS Excel.

2.3 ECONOMIC ASSESSMENT OF ANAEROBIC DIGESTION

In the last decade, a number of reports and papers have been published, investigating the advantages and disadvantages of AD in the UK. Similarly to the LCA research, a range of financial and economic evaluation methods have been adopted for assessing technologies and investment projects, such as constructing an AD facility. These include:

- an appraisal method used by governments to assess the state support required to promote energy technologies, in particular, the levelised discounted cost of energy
- more simple measures (for investors), such as payback period and return on capital employed (ROCE)
- more sophisticated measures, such as internal rate of return (IRR) and net present value (NPV).

Each of these methods is used either individually or in conjunction with the other methods by those wishing to purchase, invest or loan. All of these measures are discussed in greater detail in Section 3.4. However, these evaluation methods require the existing compensatory figures within their calculations which, and these are discussed next.

2.3.1 UK support mechanisms for anaerobic digestion

This section discusses the compensatory mechanisms that have been put in place in the UK, and the research that has been carried out using these mechanisms to assess the potential of AD. There are four main support mechanisms (DEFRA, 2011c), which, whilst not specific to AD, have been reviewed and placed in bands specific to its requirements and attributes. The Renewables Obligation (RO) is discussed below with Feed-in Tariffs (FITs). The Renewable Heat Incentive (RHI) is designed to support those wishing to upgrade the biogas produced for injection into the UK gas-grid system; it also supports small CHP genset facilities, using heat up to 200 $kw_{th}.a^{-1}$, but DECC is currently reviewing this to provide support to larger heat-using CHP facilities. Finally, the Renewable Transport Fuels Obligation (RTFO) is designed to compensate those wishing to upgrade the biogas produced to manufacture transport fuel.

2.3.1.1 UK government electricity-generating support mechanisms

With policy incentives now firmly established at both the EU and the UK level, the development of the technology both on the Continent and in the UK has increased substantially over the last decade. Until 2010, when FITs were introduced for smaller energy-generating sites, Renewables Obligation Certificates (ROCs) were the only form of remuneration for energy generation.

Effective from 2002, the RO became the main supporting mechanism for renewable electricity projects in the UK. ROCs are the certificates issued to accredited operators for generating energy. They are tradable commodities, with no fixed price; the price is struck between the supplier and the generator. The generators sell their ROCs to suppliers (or traders), which allows them to receive a premium in addition to the wholesale electricity price. For the purposes of government financial planning, the long-term value of one ROC includes the buyout price (the payment avoided by the supplier for presenting the ROC to Ofgem and meeting their RO) and the recycle value (Ofgem, 2012), which was roughly £46 per ROC in 2012/13 prices. The scheme will close to new generators on 31 March 2017, when a new scheme will be introduced.

FITs are another method of payment for the generation of clean or renewable energy. They provide a fixed payment, which varies according to the method of generating the energy and the generating capacity of the facility, for the generation of each kilowatt hour (kWh) of energy. For AD, FITs are banded into three categories, dependent on the CHP genset qualifying power output (kW) (<250 kW = 15.16 p/kW; >250 kW<500 kW = 14.02 p/kW; >500 kW = 9.24 p/kW). The facility is guaranteed this rate (which is index-linked to the retail price index (RPI)) for a period of 20 years. It was aimed at encouraging individuals and businesses to gain access to compensation and certainty for their investment in small to medium-sized facilities generating energy.

2.3.1.2 Other areas of income for anaerobic digester operators

On 31 March 2013, compensation through the Climate Change Levy, a tax on UK business energy use, was withdrawn. This provided AD facilities with an additional 0.512 p.kWh^{-1}. Gate fees from accepting municipal, commercial and industrial food waste as feedstock also provide an income to the digester operator. The value of this varies considerably across England, and is also dependent on the quality (in terms of contamination) of the waste feedstock received at the AD treatment facility. Waste materials that have been heavily sorted and have few contaminants command the smallest gate fee (£20–£25 per tonne), whilst waste material that requires considerable sorting at the facility commands a considerably higher value (up to £65 per tonne).

Finally, the digestate produced also has value in terms of its nutrient content and other inherent qualities. These offset the purchase of mineral fertiliser if used on the AD facility's land, but also have (much higher) value if exported to neighbouring land.

2.3.2 Economic and regional scenario-based research

There have been very few published articles or reports on the economics or financial viability of AD. The following discussion assesses five of the most recent reports. The first, Köttner *et al.* (2008) is the earliest report completed and assessed the financial viability of a number of farms in the South West of England. Jones (2010) focused on a typical dairy farm in the South of England and a typical arable farm in the East of England. Mistry *et al.* (2011) sought to evaluate the potential of England and Wales; whilst Hughes (unpublished) and Graham (unpublished) sought to assess AD in the South West and Scotland respectively.

Each employed very different measures to assess the viability of AD, ranging from a straight forward profit and loss with payback period (Köttner *et al.,* 2008) to IRR (Mistry *et al.,* 2010). Some of the parameters and assumptions made by the different investigators of these reports are compared below (see Table 2.2). There are a number of other papers, discussed chronologically below, in addition to the five mentioned above, which focus on the viability of certain feedstock.

Table 2-2 Comparison of different key model parameter assumptions from five other research projects

Operational expenditure parameters	Hughes (unpub.)	Graham (unpub.)	Mistry *et al.* (2011)	Jones (2010)	Köttner *et al.* (2008)
Interest rate (%)	7	n/a	n/a	4	7
Maintenance (%)	2	5	n/a	2.5	2–3
Digestate storage capacity	n/a	90 days	n/a	n/a	6 months
Travel distance for agri-wastes	n/a	n/a	5 km	n/a	Varied
Electrical efficiency of engine (%)	n/a	35	35	35	Varied
Food waste considered	No	Yes	Yes	No	Yes
NVZ restrictions apply	Yes	n/a	Yes	n/a	Yes
Project life	10 years	20 years	n/a	10 years	20 years
Payback period	<8 years	n/a	n/a	n/a	n/a
IRR (%)	11	n/a	15 or >0	n/a	n/a
Wholesale price of electricity (£/kWh)	0.08	0.03	0.06	n/a	0.055
FIT <250 kW_e (£/kWh)	0.14	0.14	0.14	0.145	ROCs
FIT 251–500 kW_e (£/kWh)	n/a	n/a	0.13	n/a	ROCs
FIT >=500 kW_e (£/kWh)	n/a	n/a	0.09	n/a	ROCs
Heat for export (%)	0	n/a	50	0	Varied
Heat income (£/kWh exported)	n/a	n/a	0.02	n/a	n/a
Food-waste gate fee	n/a	£15.00	£35.00	n/a	£45.00
Wheat (whole crop) silage cost	n/a	n/a	£25.00	£84.70	£32.00
Maize silage cost	n/a	n/a	£22.00	£17.50	£25.00
Grass silage cost	n/a	£22.00	£17.40	£30.00	£22.50

Note: NVZ = Nitrate Vulnerable Zones

Dagnall (1995) set out a proposal for the treatment of on-farm wastes across the UK. He recognised that there were economic issues in treating small quantities of these feedstock types and suggested that farmers form cooperatives so that feedstocks could be treated in quantities that were viable, ‘in the size-range of 0.1–1 MW_e’.

Jones (2010) and Hughes (unpublished) adopted the approach of 'typical' and 'average' farm sizes respectively. Jones (2010) sought to assess how AD could fit into typical arable and dairy farming systems. Specifically, he assessed the commercial concerns in adopting AD within a large-scale housed dairy herd, typical of the South of England (550 cows plus followers), and an arable farm typical of the East of England (312 ha). Hughes (unpublished), meanwhile, based his research on average herd sizes of 121 head and 250 head of dairy cattle in the South West of England. Köttner *et al.* (2008), Redman (2010) and Kaparaju and Rintala (2011) looked at specific farm or farm-size scenarios from a consultancy perspective, whilst Mistry *et al*. (2011a and b) categorised AD facilities into those that were centralised waste AD facilities and those that were farm-based.

Redman (2010), on behalf of the National Non-Food Crops Centre (NNFCC), produced a computer model, available online (to NNFCC higher-level members), enabling these members to assess the potential of AD for their own purposes. As part of this work, a detailed report on AD was produced, which included a basic case study of a farm importing food waste for its digester. The report focused predominantly on AD facilities primarily using purpose-grown crops and/or on-farm waste materials. Since there were so few AD facilities in England when their research was completed, only two digesters in England were used as case studies; their other case studies were based in mainland Europe. The English case studies included a very small dairy farm AD facility based at an agricultural college, and a significant AD facility based on a pig farm (with 23,000 finisher pigs), capable of taking 42,000 t of feedstock per annum (30,000 t of which was food waste). The other three case studies included a Danish on-farm digester that enhances its gas yield by using glycerine (in digester terms, rocket fuel), and a Danish centralised system, supporting up to 80 individual farms, in addition to food waste received from various sources. At the time of their report, there were 20 centralised digesters in operation in Denmark, treating up to 547 $t.d^{-1}$ (199,655 $t.a^{-1}$), generating in excess of two megawatt (MW) per hour (the Lindtrup facility). Others inject directly into the grid, but this is generally only economically viable at a larger scale. One of the potential issues relating to facilities of this size is the requirement for the considerable number of transport movements of both feedstock and digestate. This reduces the overall environmental efficiency of the system. Other issues include the need for cooperation, greater capital and a tight control on the supply chain.

Köttner *et al*. (2008) undertook an economic study on behalf of the Cornwall Agri-food Council on the viability of on-farm AD in the West Country (mainly Cornwall and Devon). Eight farms were interested in adopting the technology. All but one of the farms sought to support an AD facility within their existing business profile, whilst the other was interested in introducing food waste into the mix to enhance the energy yield. They were all slurry-based systems, either pig or cattle slurry, supplemented with grass and straw, with a couple using maize, grass, wheat or potatoes. Apart from the farm looking to introduce food waste into its feedstock mix, which could generate in excess of 800 kW, they all had sub-500 kW CHP capacities.

When this study by Köttner *et al*. (2008) was completed, the FIT scheme did not exist, and the government had only just increased the number of ROCs attributable to AD to two per MW generated. Half of the farms generated small business profits. Two of the farms had payback periods of less than 10 years; for three farms, the payback period was between 10 and 20 years; for two, it was in excess of 25 years; and two more would never pay back the costs (one of the farms was tested for two scenarios). The general conclusion, then, was that the financial incentive was too low and the compensatory mechanism too uncertain to the farmer – as we have already mentioned, ROCs are not fixed, but tradable, and their value can go up as well as down. Köttner *et al*. (2008) recommended that a fixed system, similar to that in Germany, be introduced, in addition to a series of grants that would reduce the payback period and make the project more attractive, making it easier to obtain finance from banks. This was indeed what happened with FITs and limited grants being made sporadically by DEFRA through WRAP.

Jones (2010) used linear programming to demonstrate the commercial profitability of AD energy production at the farm level within arable and dairy systems, assessing the effects of scale, impact on other farming activities, use of different feedstock types, labour requirements, and digestate and nutrient recycling, based on the applicable incentives of the day. Land utilisation varied to maximise the net economic margin of the farm against the backdrop of the various economic and environmental externalities experienced over the usual farming cycle. He calculated that recycling the nutrients using the digestate produced a 16 per cent improvement in the net margin in arable settings, but had far less impact on dairy farms where the cattle ‘recycled’ their nutrients whilst out in the fields.

Jones (2010) showed that on arable farms of approximately 300 ha, AD was viable in facilities of up to 0.5 MW when the model assessed the optimal size in relation to an appropriate rotation of crops that it also chose, thereby not relying on the import of any additional material. However, extreme changes in crop price or FIT value either made the facility unviable or reduced the viability to a much smaller 85 kW facility. This alone would make long-term planning and financing impossible. However, once a facility is constructed, it cannot shrink or expand according to the value of the crop feedstock or increases or decreases in on-farm available yield, as business loans need to be serviced. In 2007, there was a maize failure across the world which saw maize values triple. Many of the AD facilities in Germany had to either close down or start introducing other feedstock types, as they diverted their own maize harvest to the food market, where they received a higher value for the crop. Therefore, prudence would suggest that it is important to strike a balanced mix of feedstock types.

From the perspective of crop production to energy return, Jones (2010) concluded that based on the FITs applicable at the time, triticale and rye would require a 3 per cent increase in the FIT, barley 13 per cent and grass silage 52 per cent, or an equal drop in the value of production, in order to divert the crop to AD from other uses. This would only be useful, however, if one was seeking to target specific feedstock types, which would then require caveats on receiving that FIT against the use of that specific feedstock.

With respect to AD facilities based on a large livestock farm (550 head of dairy cattle on 610 ha), Jones (2010) suggested that the dairy farm model was slightly more robust than AD facilities based on arable farms, due to crop-price fluctuations, since the majority of the feedstock used in the dairy farm scenarios did not compete with the other farming activities. However, digestion facilities were smaller and generated less energy.

Finally, whilst Jones (2010) argues that the greatest barrier to the development of on-farm AD is the cost of borrowing, he suggests there is no need for gate fees (which is assumed to mean that the introduction of food waste to an on-farm digester is not required or desired). Whilst this may be the case with the large dairy herd modelled by Jones (2010), it does not account for the treatment of slurries and manures of smaller herds (or quantities). It is unclear how a facility constructed under one set of economic conditions would maintain its viability under harsher economic conditions. For example, 'with the reduction in the value of the feed-in-tariff by 50 per cent… the AD unit remains viable on the farm, but falls in generating capacity from 495 kW (electricity output) to 85 kW' (Jones, 2010: 46). Mechanically, this is an unrealistic scenario. The impression given is that the digester can grow or shrink as and when appropriate feedstocks are available and cost-effective for use, an analogy being the ability to sell off part of a herd when fodder is too expensive, or when a better price can be achieved by selling the crop to the market. An AD facility is expensive to build, and once built to a specific capacity, whilst it is possible (within limits) to vary the quantity of feedstock being digested, the income generated from its outputs is still required to meet the demands of the loans and operational costs that support it. In short, it was not clear from the research that the continued viability of the facility was being measured, or that the work was being completed from a feasibility assessment.

Hughes (2012) investigated the ‘affordability’ (ability to payback a loan) of an AD facility, utilising the income generated from AD on an average Cornish dairy farm (121 dairy cows plus followers) to generate funding for investment in the technology. Hughes (2011: 2) aimed to support the DEFRA (2009) initiative by ‘identifying the realistic amount to potential net annual revenue that could be realised through the introduction of an AD system onto a farm and using it as a basis on which to borrow to finance the necessary Capital… within an acceptable payback period. However, financial feasibility may require alternative approaches to realising AD, particularly for the smaller farm with less generating potential.’

Mistry *et al*. (2011a and b) sought to assess the potential scope for co-digestion (2011a) and impacts from AD on agriculture and the environment under a number of different scenarios (2011b). They combined a suite of sophisticated agricultural-based models developed over the previous decade or more. The research divided potential AD users into two groups or digester types: large commercial AD facilities, predominantly taking C&I waste and municipal waste (type 1); and smaller farm AD facilities, using in excess of 85 per cent slurries, manures and crops (type 2). Both groups could take purpose-grown crops, but the other prevailing factor was that the first group would require an internal rate of return (IRR) of ≥15 per cent (termed economically attractive), whilst it is assumed that the latter group (farmers) would be satisfied with an IRR of >0 per cent <15 per cent (termed economically viable). The research concluded that any restriction of the use of food-waste feedstock would restrict the development of AD, and, in agreement with Hopwood (2011) and Redman (2010), that on-farm livestock AD facilities are only viable when co-digesting with either crops or waste. Whilst all of these reports acknowledged potential feedstocks such as food wastes, none sought to truly integrate food waste with on-farm scenarios. There may be very good arguments for not doing so in terms of potential biohazards associated with such material, but these research groups ignored the fact that a number of digesters across the country had achieved this. Neither, Mistry *et al.*’s model nor its databases were available for use or closer inspection. Conclusions from Mistry *et al*. (2011a) included the following:

- When co-digesting farm wastes with crops specifically grown for AD, the number of AD facilities in the UK that are economically attractive reduces by 81 with 50 per cent crop input (from the 333 baseline, with zero crop use), whilst the number of AD facilities that are economically viable increases from 309 to 451.

- Using agricultural wastes reduces IRR below the 15 per cent threshold, but still increases the amount of feedstock treated.
- The amount of land required, including economically viable facilities, is approximately 116,000 ha.
- Energy output for economically attractive facilities falls from 1 TWh to zero, but increases from 2.3 TWh to 7.3 TWh for economically viable facilities.
- Likewise, GHG savings from economically attractive facilities reduces to zero, whilst economically viable facilities increases from 0.6 $MtCO_{2eq}.a^{-1}$ to 1.5 $MtCO_{2eq}.a^{-1}$.
- When all waste streams are considered:
  - the number of economically attractive facilities decreases from 429 with no silage to 220 with 50 per cent silage, whilst economically viable facilities increase from 1,020 to 1,095 under the same conditions
  - the quantity of land required, including economically viable facilities, is approximately 270,000 ha
  - energy output for economically attractive facilities decreases from 7 TWh to 6 TWh, but increases from 11 TWh to 22 TWh for economically viable facilities;
  - similarly to the crop-only scenarios, GHG savings from economically attractive facilities are reduced significantly, whilst savings from economically viable facilities increase from 5 $MtCO_{2eq}.a^{-1}$ to 7 $MtCO_{2eq}.a^{-1}$.

The number of AD facilities does not exceed 1,059 in any of Mistry *et al.*'s different scenarios, probably due to the restraint of the minimum quantity of food waste required under normal circumstances to be economically viable (economically attractive, as defined by Mistry *et al.*, 2011a), thereby reducing the number of facilities that the total biowaste can be spread across.

Hopwood (2011) sought to improve the use of on-farm AD. It was stated that in some circumstances, AD of slurries only was possible, but to enhance energy yields and ensure financial viability, additional feedstock types would be required. Hopwood used maize silage and grass silage in their analysis. Hopwood's aim was therefore to assess how much of these additional feedstocks would be required to make an AD facility viable on three different-sized dairy farms with followers: a small (130 head, housed for 200 days), medium (250 head, housed for 200 days) and large (or cooperative) farm (500 head, with zero grazing).

Using data from DEFRA, Hopwood looked at herd size against average farm area for such a herd size. Then, calculating the quantity of available land for growing crops after providing food/grazing for the livestock, she modelled various scenarios up to that maximum. No scenario returned a positive IRR on the smallest herd sizes; three of the medium-sized farms provided positive IRRs, but none exceeded 2 per cent; however, all of the large farm-scale scenarios provided positive IRRs, with one exceeding 12 per cent. The last scenario had a reduced IRR since it fell into the lower FIT bracket; in reality, the facility would have been optimised at crop quantities that enabled it to remain within the higher FIT bracket and to reduce the payback period significantly.

Hopwood (2011) concludes that only one scenario would be financially attractive (IRR >12 per cent), stating that to avoid securing land and other farm assets against a loan, an IRR of 15 per cent would be required. Hopwood highlights that cost of feedstock and capital costs are the greatest burden; and that waste feedstock is impractical, since it increases biosecurity issues and requires considerably more capital equipment, taking it further out of the reach of most farmers. Hopwood suggests that unless there is a sharp decline in capital costs for small and medium-sized animal waste AD facilities, these will not be built – or at least, not without increasing the capacity of the facility and requiring significantly more crop feedstock types. At the larger scale, it is more attractive. Finally, it was stated that whilst crop-only AD facilities are feasible, 'it is unlikely that farms will use crops above a level… due to such projects being highly sensitive to change in feedstock costs over time' (Hopwood, 2011: 30).

Patterson *et al.* (2011) sought to assess the treatment of food waste across Wales. Their functional unit was 275,900 $t.a^{-1}$ of municipal food waste (16 per cent of the total produced in Wales). Their scope excluded the collection of the source-separated waste, the displacement of energy used in the production of mineral fertiliser and alternative gas treatment methods. FITs were not current for sub-500 kW AD facilities, and, as they only had one FIT category for sub-500 kW, one assumes that none of their scenarios came in to the sub-250 kW FIT category. The gate fee at £65 per tonne seemed high for source-separated food waste. Digester statistics included: 130 $m^3.t^{-1}$ food waste, 30-day retention time and 3.9 $kg.m^{-3}.d^{-1}$; electrical efficiency was 32 per cent (most new CHP gensets currently operate between 38 and 42 per cent electrical efficiency, with Organic Rankine Cycle engines potentially adding a further 10 per cent); thermal efficiency was approximately 50 per cent; and electrical parasitic load was up to 20 per cent. The parasitic load of a digester is very much dependent on size: smaller digesters will have a higher parasitic load of about 20 per cent, but the assumptions made by Patterson *et al*. (2011) would most likely be found with sub-250 kW engines. Fugitive emission assumptions were also high, at 3 per cent. Most operators would require that their system lost no more than 1 per cent of the gas produced, since it is the gas that provides the energy and therefore their revenue. Most AD facilities built now have fugitive emissions of approximately 1 per cent.

Patterson *et al.* (2011) concluded that CHP with 80 per cent heat use was the most environmentally attractive, followed by gas upgrade to transport fuel; upgrade to gas-grid injection performed least well.

Styles *et al.* (2013: 3) sought to 'provide a quantitative and comprehensive comparison of the environmental and economic performance of a plausible range of farm AD scenarios on dairy and arable farms'. They then compared this to other bioenergy options. They created their own LCA tool and combined the outputs with outputs from similar modelling tools used by Mistry *et al*. (2011a and b), mainly MANNER-NPK and Farm-Adapt models. Styles *et al*. (2013) concluded that, on the scales that they had modelled, using maize silage or grass silage had positive GHG emissions per kWh, whilst using slurry only or slurry with food waste returned negative emissions (or GHG savings) per kWh.

Evangelisti *et al.* (2014) undertook a case study to assess the treatment of 35,574 t of source-separated food waste collected from South East London. Some of their assumptions included only accounting for the transport from the transfer station; an AD operating temperature of 35 °C (which is reasonable, if slightly low, but would affect the thermal demand of the digester); fugitive methane emissions from across the facility at 2 per cent; electrical conversion efficiency of 32 per cent; and 50 per cent thermal efficiency, which they took from Patterson *et al.* (2011).

Evangelisti *et al.* (2014) concluded that AD provided the best overall form of treatment in terms of CO_2 and SO_2 mitigation, compared to incineration with CHP and landfill with energy generation, when heat and the digestate were used as fertiliser; but it came a close second to incineration in relation to photochemical ozone and nutrient enrichment. The latter could be mitigated, to some degree, through improved delivery and farming techniques.

2.3.3 Summary

From the research discussed above, it is clear that the assessment of AD falls into two camps: the majority of this work focuses on single digesters that are either fictitious or feasibility studies for particular farm scenarios or centralised AD facilities. Only Mistry *et al.* (2011a and b) and Patterson *et al.* (2011) sought to assess the potential of AD at a national scale, and only Mistry *et al.* (2011a and b) used their appraisal method to include a multiple of feedstock types.

2.4 FEEDSTOCK

There are a considerable number of feedstock types that could be treated by AD. This section discusses these, dividing them into two different categories: on-farm and off-farm.

2.4.1 On-farm feedstock

There has been considerable research of the different feedstock types, assessing how much methane they produce, if it is viable to generate energy from various feedstock types, and how the process can be optimised and accelerated to reduce digester size – and therefore capital and operational costs – ensuring economic viability. On-farm feedstock types can be categorised into two types: livestock waste materials such as animal slurries and manures, which have been estimated to total 96 $Mt.a^{-1}$ (DEFRA, 2009b and 2014); and crops specifically grown for the generation of energy.

2.4.1.1 Feedstock database

To achieve this research's objectives, a computer model was built (see Chapter 5) that required a database that used basic physico-chemical description of the most common feedstock types utilised in AD, to make its calculations. Many individual research papers provided data of some of their possible feedstock types, but often these were presented in such a way that it was impossible to calculate some of the basic characteristics (percentage DM, and percentage volatile solids (VS), biogas and methane yield ($l.kg^{-1}$ VS)).

The first two databases found were in Cropgen (2007) and Redman (2010). The Cropgen (2007) database had units that differed between feedstock types, and whilst the database was extensive, many of the data relating to the individual feedstock types were generally incomplete. Redman's (2010) data were within the model, which was not 'visible', although some data could be gleaned through putting in one tonne of feedstock to view what results were provided and using those. However, the most complete database made available in 2012 was the EU AGRO-BIOGAS (2010). This was part of the EU AGRO-BIOGAS (2010) project funded by the 6th Framework Programme for Research and Technological Development, involving a number of different European institutes, with Kuratorium für Technik und Bauwesen in der Landwirtschaft (KTBL) and Universität für Bodenkultur Wien (BOKU) as the consortium leaders. This database was more complete and up-to-date than either Cropgen (2007) and Redman (2010).

The EU AGRO-BIOGAS dataset is still being updated; however, the majority of data was completed by January 2010. To complete their database, three different approaches were used in calculating the properties of the various feedstock types: values obtained from the laboratory, standard values and values provided by Buswell (1952).

- **Laboratory values** – aggregate mean yield values for biogas and methane based on a large number of laboratory batch tests were collated. These values provided reliable predictive yield values under laboratory conditions.
- **Standard values** – where no statistically significant mean values could be obtained as above, recommended biogas and methane yields were discussed and agreed by a panel of experts.
- **Buswell values** – based on algorithms provided from research by Buswell and Muller (1952) and Boyle (1976), these data provide the most unreliable figures, in which gas yields can be as much as 30 per cent lower in practice, depending on the quantity of lignocelluloses present in the feedstock. These figures are only used where no reliable laboratory-based information was available; and they represent the theoretical maximum biogas and methane yields from the feedstock materials, based on their average chemical make-up. However, this method does represent a significant proportion of the database, since there are large numbers of different crop varieties that increase annually as new varieties come to the market.

Of the databases reviewed, the EU AGRO-BIOGAS Feedstock Atlas (KTBL, 2010) was the most complete, providing data for the majority of usable feedstock statistics (gas yields, DM content and VS content) (see Table 2-3 for a selection of feedstock types).

There are a considerable number of different feedstock types available from the EU AGRO-BIOGAS Feedstock Atlas (KTBL, 2010); however, many of these would not be used for economic reasons, such as their economic value as a food crop being greater than it would be for generating energy. Only about two dozen of these may be used on a regular basis. However, there were times when even this database was insufficient (see Section 4.4, case study 13), and more exotic feedstock types were then added. The feedstock database holds the information that enables the model to convert the value of fresh-weight feedstock into kWh_e, based on a feedstock type's potential energy content. A sample of the database is shown below (see Table 2.3). Values for nitrogen, phosphorus and potassium removed from the soil during growth were taken from The *Fertiliser Manual* (DEFRA, 2010a).

Table 2-3 A selection of feedstock data

Substrate	Dry weight (TS %)	Biogas M^3/t fresh mass	% VS	CH_4 L/kg VS	CH_4% of gas	M^3 CH_4 t/FM	Biogas l/kg VS	N (kg/t FM)	P (kg/t FM)	K (kg/t FM)
Cattle muck (fresh)	27.80	97.73	83.70	209.00	50.00	48.63	420.00	5.17	2.24	3.97
Leftovers (rich in fat)	19.70	159.83	92.30	512.00*	58.00	93.10	879.00	8.10	1.30	3.40
Maize silage	30.70	203.76	95.50	365.00[#]	53.00	107.01	695.00	3.80	1.60	4.50
Lucerne silage (alfalfa)	30.00	143.10	90.00	292.00	55.00	78.84	530.00	5.50	1.50	6.50
Oil seed rape (OSR) (whole crop) silage	20.00	138.76	86.40	438.00	55.00	75.69	803.00	3.50	15.10	17.50
Barley (whole crop) silage	29.80	160.60	92.60	375.00	64.00	103.48	582.00	3.50	8.60	11.80
Wheat (whole crop)	39.60	195.08	92.60	298.00	56.00	109.28	532.00	3.50	8.40	10.40
Potatoes (main crop)	22.00	156.25	93.70	389.00	51.00	80.19	758.00	3.50	1.00	5.80

Adapted from, inter alia, EU-AGRO-BIOGAS (2010), *Online European Feedstock Atlas* and RB209, *Fertiliser Manual,* DEFRA (2010)

*** Figure verified by case studies 2 and 3 as being significantly accurate.**

[#] Species variety PR34G13 taken from Amon *et al*. (2007) as a more realistic figure in comparison with several case study outputs.

Note: FM = fresh matter; TS = total solids

2.4.2 Off-farm feedstock: biowaste materials

These materials include the biodegradable garden and park waste; food and kitchen waste from households, restaurants, caterers and retail premises; and comparable waste from food-processing facilities. They do not include forestry or agricultural residues, manures, sewerage sludge or other biodegradable waste, such as natural textiles, paper or processed wood. Also excluded are those by-products of food production that never become waste (EU, 2008:2). DEFRA (2010c) estimated this to amount to 19 Mt (see Figure 1-7).

This section comprehensively assesses biowaste in the UK. Chapter 1 explained why this feedstock has been targeted for treatment by AD and its importance within UK and EU legislation. However, this feedstock type does provide considerable uncertainty to the AD industry, in that the quantity of material produced and the quantity of material that is or could be available is not measured. There are few reports that try to tease out these data; Jones *et* *al.* (2007) (see Section 2.4.3.2) and Papineschi *et al*. (2008) (see Section 2.4.3.3) in particular, provided an in-depth analysis of waste arisings in the East of England (see Section 2.4.3.5); but all such reports highlight the high degree of uncertainty in their estimations or calculations.

2.4.2.1 Waste categories

Most waste constitutes a hazardous material; this is true of biowaste, in particular, which could harbour disease and/or attract vermin at the treatment site. The handling and disposal of biowaste and animal by-products are therefore highly regulated by a number of legislative regulations, enforced by both EU and UK law. These include:

- Derogations from the Animal By-Product controls under Regulation (EC) 1069/2009
- Amendments to the Animal By-Product Regulations (EC) 142/2011
- Regulation on the hygiene of foodstuffs (EC) 852/2004
- Regulation (EC) 854/2004
- The Animal By-Products (Enforcement) (England) Regulations 2011 SI No. 881/2011
- The Animal By-Products (Enforcement) (Scotland) Regulations 2011 SI No. 171/2011
- The Animal By-Products (Enforcement) (No 2)(Wales) Regulations 2011 SI No. 2377/2011 (W.250)
- The Animal By-Products (Identification) Regulations No. 614/1995 (as amended).

Within these rules, biowaste material has been categorised into three main types (see Table 2-4); these rank the types by the potential hazard and risk that they might have for man, animals or nature.

DEFRA (2011c) suggested that the treatment of food waste should occur in sludge treatment facilities, since they already have the potential to be an efficient method of generating energy from waste, particularly as many of these facilities are located close to urban areas, the source of much of this material. In contradiction, an earlier piece of research for the government completed by Butwell *et al.* (2010), using life-cycle analysis, stated that this would be neither cost-effective nor more environmentally beneficial than having special collections and then treating the waste by AD, collecting the energy and utilising the digestate. Butwell *et al.* also found AD to be more beneficial than in-vessel composting of co-mingled waste.

Table 2-4 UK waste category descriptions

Category	Description
1	The highest-ranking risk material, consisting principally of material considered to harbour a disease, including transmissible spongiform encephalopathy (TSE) risk or bovine spongiform encephalopathy (BSE; e.g. bovine brain and spinal cord). This category includes pet animals; zoo and experimental animals; and some wild animals, if these are suspected of carrying communicable diseases.
2	Additional high-risk material, including fallen stock, manure and digestive tract content. It is the default category for any material not defined by Category 1 or Category 3 materials. This material can be disposed of by incineration, rendering or at an authorised landfill site. If processed to the required standards, it is permitted to recycle Category 2 materials for uses other than feed after appropriate treatment, such as biogas, composting or oleo-chemical products.
3	Low-risk materials, including parts of an animal passed fit for human consumption in a slaughterhouse that are not intended for consumption, either because they are not part of the animal normally eaten (e.g. hides, bones, hair or feathers), or are used for commercial reasons. This category also includes former foodstuffs, either from food factories or retail premises (butchers and supermarkets), and catering or household kitchen wastes. Disposal can take place in a number of ways, including incineration, rendering, landfill (as before), composting, AD, use in an approved pet-food plant or use in a technical plant.

These biowaste materials can be treated in a number of ways, including landfill, incineration, composting and AD. In addition to these four main treatment processes, the method in which the biowaste is treated can vary slightly. In terms of AD, this usually means that the biowaste material is collected and treated centrally; alternatively, the waste material could be collected and treated in more remote, smaller sites (see Section 2.4.4). However, estimating the availability of these different feedstock types is extremely difficult.

2.4.3 Waste reporting

Considerable uncertainty has been created by the variance in the methodologies, calculations and results for quantifying organic waste across the UK. There is no requirement to report waste type, just bulk quantities. Special or toxic wastes do carry greater demands on reporting, but with respect to organic materials, this mainly relates to ABPR Category 1 organic waste types (see Table 2.4). When some of the governmental powers were devolved to the English regions, several of these regions were in the process of assessing the different waste streams.

However, the English Regional Development Agencies were abolished in 2012, and the process remained incomplete.

The definition of organic waste has also been difficult to pin down. Some research has excluded green waste (arboreal and graminoidal cuttings from gardens and public spaces), whilst others have incorporated all waste into one figure, without proper description. Research completed by Enviros Consulting (2009), on behalf of WRAP, completed a synthesis of past research surveys and concluded that there was still a lack of:

- understanding of European Waste Catalogue (EWC) codes by both producers and waste management site operators
- consistency in describing the types of waste that should be considered 'organic waste' assigned to Substance Orientated Classification (SOC) category 9
- agreement of types of SOC 9 and EWC suitable for treatment by AD or composting
- traceability of organic waste arisings against their resulting waste management route
- clarity in EWC codes, which often made it difficult to determine if a waste was from a C&I source or from a municipal source, particularly for green waste. Their argument was that that it was not possible to identify the specific sector producing the waste, whether from household, food and drink processing, or the retail and hospitality sector, using the EWC code interrogator.

2.4.3.1 Statistical interpolation of waste arisings

Several surveys of waste in the regions have been completed and those available are discussed below. Statistical methodology for the interpolation of regional waste data from a limited survey was first used by Jones *et al*. (2007) in calculating waste volumes for the North West of England, with survey data collected by the Environment Agency (EA). Since then, other research has used similar methodologies and datasets to achieve the same goal for all eight regions in England (Jones, 2010; Yellen and Bailey, 2010; Graham *et al*., 2010). However, there is no split in waste material type for commercial waste, and industrial waste content remains based on the EA survey of 2000.

2.4.3.2 Jones *et al*. (2007)

Jones *et al*. (2007) extrapolated regional data for the North West following a survey that included the following:

- 981 C&I companies within the region, including retail, representatively distributed by company size, industrial sector and location

- all wastes produced on a company's site and sent off-site for treatment, disposal or recycling, recorded by waste type and annual tonnage
- hazardous and non-hazardous wastes data submitted under conditions of a permit issued under the requirements of the Pollution Prevention and Control Regulations 2000
- the waste management method used for each waste (e.g. landfill, recycling) and the contractor used
- the possibility of the waste being recycled or the energy recovered
- waste that was exported from the region for treatment, disposal or recycling.

The following were not included in their survey:

- companies with fewer than five employees
- agricultural, construction and demolition wastes
- one-off wastes (e.g. from refurbishments or site clearances)
- waste that would not have an impact on external treatment or recycling facilities (e.g. waste landfilled on-site, or waste recycled or reused on-site).

Companies with fewer than five employees were not included in the North West survey as it was viewed that much of this waste stream would be captured in municipal waste statistics. Their analysis of this business group size indicated that the statistical sampling at this scale and diversity of business or activity would have been inappropriate.

2.4.3.3 Papineschi *et al*. (2008)

This research group used standard industry classification (SIC) codes of economic activities to compile 12 different categories or typologies of business that fell into the 'manufacturer of food products and beverages' classification. Using FAME (Financial Analysis Made Easy, a database of primarily financial online information published by Bureau van Dijk), they were able to target the top 15 per cent of all companies in the SIC classification and a selection of 10 per cent of the remaining companies. Five typologies were excluded, for reasons set out in Appendix 4 of their research. Secondary typologies were developed that produce small but quantifiable non-ABPR biowastes in excess of 1,000 tonnes per annum (tpa), whilst four key biowaste typologies were established with significant tonnages of biowaste streams.

In contrast to the Jones *et al*. (2007) research, which used number of employees to determine size, Papineschi *et al*. (2008) used turnover and, in the case of some of the smaller businesses, current assets (as turnover was not reported) to determine business size, since these two matrices were deemed to show the strongest relationship to waste generation (although it was thought that the latter could produce uncertainties of up to 50 per cent in the results). A comprehensive guide to their other methodologies adopted for analysis of waste from the C&I sector is presented in Appendices 5–9 of their research.

The most recent survey for the East of England, completed using 2006/7 data, stated that 'the capture rate of green wastes is very high compared to the national average, with a total of 426 $kt.a^{-1}$ (82 per cent of arisings) estimated to be captured' (Papineschi *et al*., 2008: 22). Following the analysis of a large number of sets of compositional data across the UK, they reported that food waste arisings were fairly consistent across all authorities, ranging between 200 and 250 kg per household per annum. This is higher than the Butwell *et al*. (2010) figure of 2.9 kg/week (150 kg/a), which they revised themselves in a footnote to 3.3 kg/week (172 kg/a).

This had an impact on the quantities of food waste collected, as compared to that calculated to be produced. As you might expect, as food-waste collection participation increased, so did the average capture rate per household. Taking estimates from Cambridgeshire, Herefordshire and Suffolk, the average weight collected per household for these authorities is 325 $kg.a^{-1}$, 197 $kg.a^{-1}$ and 233 $kg.a^{-1}$ respectively.

2.4.3.4 Jones (2009)

Jones (2009) compared data surveyed by Jones *et al.* (2007) for the North West waste survey (of 1,000 businesses) and a survey completed by the EA in 2002/3. Of the survey results, 50 per cent were based on company records, 48 per cent on company estimates and 2 per cent on surveyor estimates. However, the commercial retail sector was the focus of the EA survey, whilst Jones *et al.* (2007) survey had a greater focus on the industrial sector.

Yellen and Bailey (2010) took data from the EA 2002/3 survey and two other reports (West Midlands Regional Spatial Strategy and SLR Consulting) to complete their own analysis. They suggested that the data provided by SLR could be an overestimate due to the considerable uncertainty surrounding the amount of this type of waste, since some of it is diverted to animal feed or land. They suggested a more conservative annual figure of approximately 300,000 t biowaste.

Graham *et al*.'s (2010) survey of the 2009 business year (see Table 2-5) showed a national total for England of 5,516,000 t of biowaste (including that from mixed waste collection).

Table 2-5 Total organic waste arisings per region for 2009 (000s t.a^{-1})

Region	Animal and vegetable wastes	Animal and vegetable wastes in mixed waste fraction	Total
North East	159	81	239
Yorkshire & The Humber	491	189	680
East Midlands	576	161	738
West Midlands	484	180	664
East of England	394	186	580
London	367	272	639
South East	368	267	635
South West	357	184	541
North West	561	239	800
Grand total	3,757	1,759	5,516

Adapted from: Graham et al. (2010), Tables 24 and 25

2.4.3.5 Household arisings calculations

Butwell *et al*. (2010) calculated food waste per household at 2.9 kg per household per week (151 kg.a^{-1}). They used data collected by Biffaward (2002), Bolzonella *et al*. (2003) and WRAP (2008a) to identify the character and quantities of municipal waste: fruit and vegetables (60–70 per cent); bread, pasta, rice and cereals (7–30 per cent); and meat and fish (5–13 per cent). Butwell *et al.* (2010) assumed that all households participated. Research by WRAP (in Butwell *et al.,* 2010) indicated that not all food waste is collected, since some unopened packaged food and food residues on packaging are discarded with the black-bin waste and fluids to the sewers.

2.4.4 Processing methods for biowaste

Currently, biowaste is collected and treated in two main ways. Municipal waste is collected by councils, either separated or co-mingled with all the other black-bag rubbish. This waste is sent to a materials recovery facility (MRF) for sorting, and then on to either a composting site or an AD facility for further treatment. The remaining black-bag waste is sent to landfill. Whilst some C&I waste is collected by the waste collection authorities, the majority is collected by the waste management companies and sent directly to treatment facilities, depending on the amount of contamination.

The impact of this collection and processing method on AD is considerable. A range of additional expensive machinery is required to treat this unrefined material within the regulatory regime. This includes reception halls, de-packaging and decontamination equipment, and pasteurisation plant. The cost of this type of equipment makes the treatment of this type of material unviable for the smaller facility. The next section discusses an alternative processing method in which the biowaste is collected and treated centrally before being forwarded on for energy recovery at an AD facility. This removes the requirement for the AD facility to purchase the majority of the additional equipment thereby reducing the quantity of this type of feedstock required to supplement other feedstock types and still remain financially viable.

2.4.5 Hub-and-pod anaerobic digestion

Carruthers (2010) gave an account of the Organic Resource Management Inc.'s operation in Canada. In essence, they collect various different types of organic waste materials, homogenise and pasteurise them, and then sell them on to AD facilities based on farms. In the UK, this process has been described as the hub-and-pod system. In March 2013, DEFRA set out regulatory guidelines for this type of system. However, there is no operating hub-and-pod system in the UK to date (September 2014).

The hub-and-pod concept (see Figure 2-4) is a simple system designed to allow the agricultural community to access biowaste materials in a less hazardous manner. The collection and treatment of the biowaste is completed (by a third party) at the 'hub', before being transported onto a number of receiving 'pods' for treatment by AD and subsequent generation of energy. Municipal, industrial and commercial food waste (biowaste) can all be collected from various sources and sent to the central hub for treatment. The biowaste is processed at the hub, including de-packaging, homogenising and pasteurising the material in accordance with ABPR (see Section 2.4.2.1). The pasteurised material is then transported to AD facilities for digestion (AHVLA, 2014).

Both sites (hub and pod) require pasteurisation units and Animal Health and Veterinary Laboratories Agency (AHVLA) approval or licenses. Only Category 2 and Category 3 materials (see Section 2.4.2.1) can be processed at a pod. Following digestion and pasteurisation, the digestate is safe to be spread to land as a fertiliser and soil amendment, completing the life cycle of food.

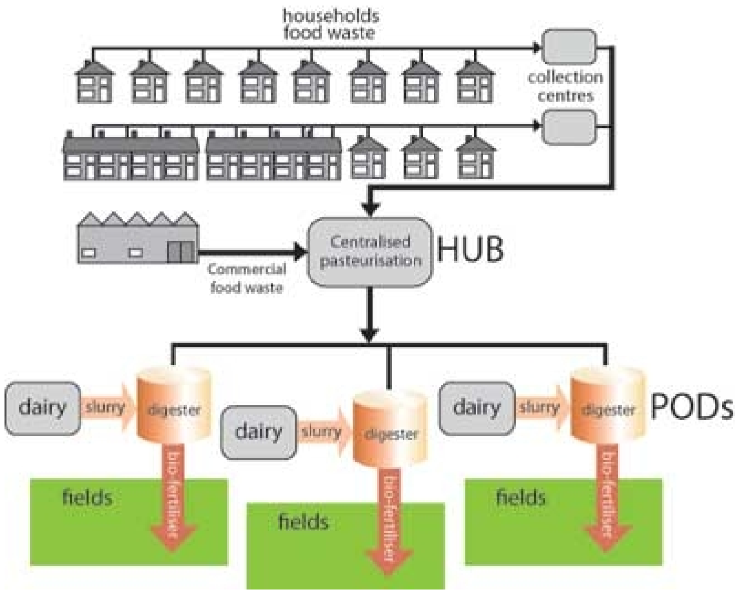


Figure 2-3 The hub-and-pod concept. Source: www.waste-management-world.com

Only one academic paper has been found on this subject (Banks *et.al.*, 2011), which sought to evaluate the feasibility of centralised pre-processing and pasteurisation of source-separated municipal food waste, followed by co-digesting the material with cattle slurry in an agricultural setting. They assessed a medium (141) and large (294) dairy herd size in the county of Hampshire, housed either for 50 per cent of the year or all year round.

Banks *et al*. (2011) assumed that food waste would be distributed equally among the energy-from-waste (EfW) facilities in Hampshire, each facility treating 25,478 $t.a^{-1}$ (509 t per week). Working five days a week, they calculated that the material would be dealt with in four batches per day, in 30 m^3 pasteurisation units costing around £54,000 each, and a shredder costing approximately £30,000, in order to comply with ABPR. They assumed that all other equipment, including housing and energy requirements, would be met by the EfW plant.

Their conclusions were positive in terms of the use of the hub-and-pod concept. Whilst their life-cycle analysis scope did not include the benefits of GHG reduction from the removal of organic material from landfill, nor the potential emissions increases from open digestate stores, it did include the benefits of manure treatment and the offset of energy/carbon emissions associated with mineral fertiliser production. The results from their different scenarios all had GHG savings of between 307 $tCO_{2eq}.farm^{-1}.a^{-1}$ for the smaller farms and 933.4 $tCO_{2eq}.farm^{-1}.a^{-1}$ for the larger farms.

2.5 FEEDSTOCK CHARACTERISTICS IMPACTING ON THE ASSESSMENT OF ANAEROBIC DIGESTION

Having explored some of the different types of feedstock that can be treated by AD, and some of the issues related to the quantification of their availability, the following discussion assesses some of the potential hazards associated with some feedstock types; the requirements of treating this material at an AD facility; and the benefits of pre-treating certain feedstock types, as well as the benefits of co-digesting certain feedstock types simultaneously.

2.5.1 Emissions from manures, slurries and digestate

GHG emissions from manure management in the EU27 in 2008 were estimated at in excess of 472 $MtCO_{2eq}.a^{-1}$ (Eurostat, 2012), of which 21 per cent was contributed by dairy cattle. Considerable research has been completed on GHG emissions in agricultural systems. However, there is also a great deal of uncertainty in this area. One of the greatest natural phenomena is the nitrogen cycle. The dynamic of nitrification or de-nitrification is dependent on many variables, including pH, solar radiation, temperature and DM (carbon) content (Sommer, 1997), and, as such, emissions occur across the whole of the 'manure management continuum' (Chadwick *et al*., 2011: 1).

Manures and slurries represent a considerable source of GHGs in agriculture; however, carefully selected management practices have the scope to reduce those emissions and influence the magnitude of these losses (Chadwick *et al*., 2011: 515). Emissions from slurries and digestate applied to land also suggest that using a splash plate has the greatest negative environmental impact, followed by trailing hose and direct injection – the latter being not only the most environmentally beneficial, but also agriculturally beneficial, in terms of directing the nutrients to the crops.

Atmospheric ammonia (NH_3) reacts with atmospheric acids to form ammonium (NH_4^+). This is an important component of aerosols and an actor in precipitation (Erisman *et al*., 1988). Deposition and run-off of NH_4^+ is a major contributor to acidification and eutrophication of groundwater. Nitrous oxide (N_2O), on the other hand, plays a significant role in climate change as a GHG, being significantly more potent than CH_4.

The discussion above highlights the importance of applying certain measures to the storage and application of the digestate. DEFRA (2014) reported concerns of increased atmospheric NH_3 emissions across the UK that could have potential effects on human health, and these have been potentially linked to AD. However, the data presented were based on average figures for 2010–12, when there were fewer than 60 operational AD facilities across the country (DEFRA, 2011c). Figure 2-4 shows emission density patterns for England against the backdrop of operational facilities in April 2014. The pattern is more in line with livestock farming than with AD facilities. If anything, this highlights the importance of improving slurry and manure management and using AD as a method of doing so, providing the community with funds that do not just mitigate GHG and polluting emissions, but provide energy generation and nutrient recycling.

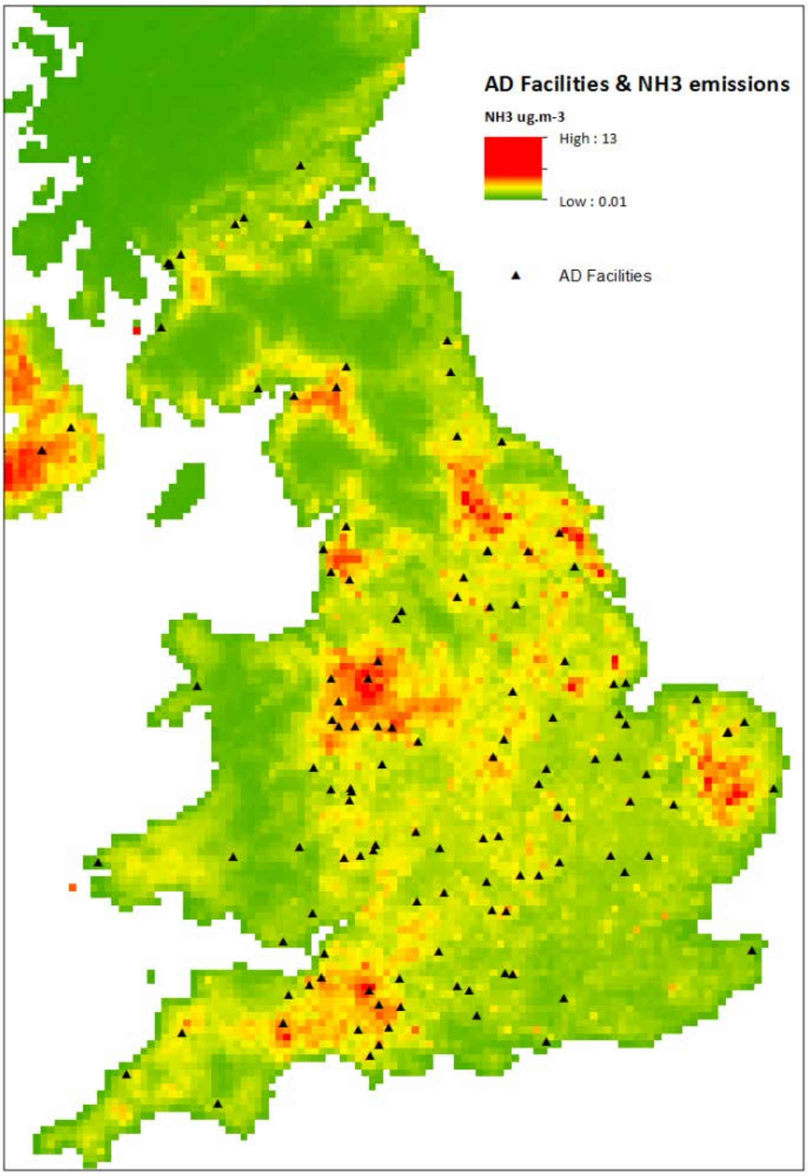


Figure 2-4 Mean NH_3 emissions in England and Wales, 2010–12, against the location of AD facilities in April 2014. Source: emissions data from Hall, 2014; AD facilities data from The Official Information Portal on AD, 2014

Leytem *et al*. (2013) measured GHG and NH_3 emissions from an open free-stall dairy (10,000 Holstein cows) in Southern Idaho. They concluded that NH_3 emissions from the uncovered holding ponds were considerably greater as a result of the anaerobic digestion of the waste water before reaching the ponds. This transformed the organic nitrogen into more labile mineral ammonical nitrogen. Warmer temperatures (varying by day and by season) increased this activity, with emission rates ranging from 0.6 g $NH_3m^{-2}.d^{-1}$ to 13.7 g $NH_3m^{-2}.d^{-1}$. Sommer (1997) measured NH_3 emissions from holding tanks at 3.3 kg NH_3 Nm^{-2}, 0.27 kg NH_3 Nm^{-2} and 0.1 kg NH_3 Nm^{-2}, dependent on the level of physical cover over the digestate – uncovered, straw or clay-pebble cover respectively.

The IPCC (2006: Chapter 4, Table 4.12) calculates default emissions from slurry tanks, anaerobic lagoons and open pits below animal housing, and from anaerobic digesters, to be 0.001 kg N_2O-N/kg N excreted. However, solid storage facilities have significantly increased emissions, at 0.2 kg N_2O-N/kg N excreted. Both have considerable uncertainty ranges, between −50 per cent and +100 per cent. The main inference is that inorganic nitrogen within the manure management continuum is only converted to N_2O either through nitrification or de-nitrification if there are aerobic and acidic conditions (Zhang *et al*., 2005; Misselbrook *et al*., 2001; Chadwick *et al*., 2011). Leytem (2013) calculated emissions of between 0.03 g $N_2Om^{-2}.d^{-1}$ and 0.92 g $N_2Om^{-2}.d^{-1}$, representing a considerable environmental burden of GHG emissions. Conditions that bring this about, such as aeration of the tank and addition of organic litter (e.g. straws), provide surfaces in which the exchange of oxygen can occur and stimulate the production of N_2O (Loyon *et al*., 2007; Molodovskaya *et al*., 2008). Maintenance of an anaerobic environment suppresses the production of N_2O. Separating the digestate into its solid and liquid fractions can cause an increase in N_2O emissions, particularly if the solid heap is not covered (Fangueiro *et al*., 2008). In summary, therefore, the GHG fluxes from farming are impossible to control; however, there are a number of methods that can help to reduce the quantity of ammonia and nitrous oxide emissions through various best practices, such as covering slurry and manure heaps prior to these high nitrogen-based products being spread to land.

Mistry *et al.* (2011a) used a sophisticated nitrate leaching model, NEAP-N, to assess areas of the country suitable to build AD facilities, particularly in relation to Nitrate Vulnerable Zones (NVZs). However, similar to other issues raised in the discussion above, modelling the nitrogen cycle beyond the digester and storage facility is highly dynamic, and dependent on soil type, cover crops and weather patterns.

2.5.2 Agricultural greenhouse gas reduction indicator framework

DEFRA (2013b) developed a GHG reduction indicator framework in which to assess the agricultural sector's progress in achieving a reduction in GHG emissions of 3 $MtCO_{2eq}$ by 2020 from the 2007 baseline. There are ten main indicators: attitudes and knowledge, uptake in mitigation methods, soil nitrogen balance, pig sector (feed conversion ratio for fattening herd), grazing livestock sector (beef and sheep breeding regimes), dairy sector (ratio of dairy cow feed production to milk production), poultry sector (feed conversion ratio for table birds), cereals and other crops (manufactured fertiliser application), slurry and manure, and organic fertiliser application.

AD could significantly influence the last two, slurry and manure, and organic fertiliser application. DEFRA (2013b) estimates that the maximum technical potential GHG reduction from mitigation methods for slurries and manures is approximately 0.018 Mt CO_{2eq} (excluding AD), of which 0.004 Mt CO_{2eq} had been achieved by 2013.

DEFRA's GHG reduction indicator framework summary report (DEFRA, 2013b) omits AD as a tool in aiding the reduction of GHGs from the agricultural sector. It cites in Section 9 (slurry and manure) the start-up and operational costs of AD as the barrier, with only 1 per cent of all farms processing slurries for AD.

A survey (Coleman *et al*., 2010: 63) demonstrated that the greatest savings from agriculture would be from improving the timing of manure-N (nitrogen) application (1027 ktCO_{2eq}), with a further potential saving of 568 ktCO_{2eq} per annum with the anaerobic digestion of livestock slurries and manures on large (undefined) dairy, poultry and beef units.

2.5.3 Feedstock pre-treatment and ensiling

There are a considerable number of regulations (see Section 2.4.2.1) for the treatment of biowaste materials at AD facilities, but the main ones require that there is a reception hall, and that the material is macerated to 50 mm or less and pasteurised at 57 °C for five hours or 70 °C for one hour (ABPR, SI No 881/2011). Other pre-treatment options available to AD operators are not compulsory; however, some may have beneficial results, as discussed below.

Herrmann *et al*. (2011) obtained positive effects of increasing methane yield by up to 11 per cent by using ensiled crops rather than un-ensiled crops; this was attributed to an increase in the presence of organic acids and alcohols during the ensiling process. Kafle and Kim (2013) also observed increased yields of up to 15 per cent on a variety of different food waste materials.

Other research has assessed the use of enzymes (Rintala and Ahring, 1994; Davidsson *et al.,* 2007) or special bacteria (Hasegawa *et al.*, 2000; Elliott and Mahmood, 2007) to enhance the speed and efficiency of the process, to great success. This remains outside the scope of this research, but it is assumed that some AD facilities will use enzymes, catalysts and other chemicals to control the reaction within the digester.

It can only be assumed that it was the merits of ensiling crops discussed above that led Köttner *et al*. (2008), Mistry *et al.* (2011a) and Styles *et al.* (2013) to all use grass silage and maize silage as the two crops most suitable for AD within their modelling, in addition to their suitability as break crops within a farming system.

Biogas yields for grass silage and maize silage are 151.77 $m^3.t^{-1}$ and 203.76 $m^3.t^{-1}$ respectively. The difference is sufficient to make grass silage significantly less financially attractive than maize. Alfalfa silage, oil seed rape (OSR) silage , pea silage and spring barley silage (all whole crop) have similar biogas yields per tonne, at 143.10 $m^3.t^{-1}$, 138.76 $m^3.t^{-1}$, 203.94 $m^3.t^{-1}$ and 160.60 $m^3.t^{-1}$ respectively (KTBL, 2010), with pea and barley silage being the most attractive to an AD facility manager. Another important consideration, in particular in using maize as a feedstock type, is the timing of its harvest, which is also dependent on the variety grown. Amon *et al*. (2007a and b) demonstrated that harvesting maize at milk ripeness (97 days of vegetation) produced improved methane yields of between 9 and 37 per cent over full ripeness (151 days of vegetation).

2.5.4 Co-digestion of feedstock

Co-digestion is simply when two or more feedstock types are treated simultaneously. This can only be seen as prudent from a farmer's point of view, given that if a single crop should fail, the farmer would be left having to either buy in feedstock or allow the digester to stop operating. Therefore, research was also completed on combinations of different feedstocks, to assess if there were any benefits, such as enhanced methane yields.

Viswanath *et al.* (1992), Alkaya and Demirer (2011), Callaghan *et al.* (2002), Murto *et al.* (2004) and Borowski and Weatherley (2013) all found that co-digestion enabled increased yields of up to 50 per cent on the individual constituent parts. Callaghan *et al*. (1999) demonstrated that co-digesting cattle slurry with a range of other organic wastes, including chicken manures, fruit and vegetable waste, and abattoir wastes, showed positive increases in methane yield (to varying degrees) when compared to digesting cattle slurry alone. Lehtomaki *et al*. (2007) also demonstrated improved methane yields when co-digesting cow manure with the addition of up to 30 per cent crop material; and Amon *et al*. (2007b) showed increases in methane yield of up to 25 per cent when co-digesting cattle slurry with maize. Most AD facilities in Germany co-digest between three and five different feedstock types concurrently (FAL, 2009), realising a minimum 10 per cent uplift in biogas yields (Poeschl *et al*., 2012a). Similar observations were seen by Giuliano *et al*. (2013), Asam *et al*. (2011) and Li *et al.* (2010).

Zhang *et al*. (2012) found that co-digestion permitted increased organic loading rates, and Hartman and Ahring (2005) also found that co-digestion provided a more stable process. Comino *et al*. (2012) suggested that the co-digestion of cattle slurry and cheese whey had a similar energetic potential for AD as energy crops such as maize. Magbanua *et al*. (2001) observed significant increases in methane yields when co-digesting pig and poultry waste, compared to treating each feedstock type alone. Finally, Banks *et al*. (2011) indicated that co-digestion of food waste and cattle slurry offered significant advantages in terms of resource conservation and pollution abatement, when compared to the centralised AD treatment of food waste or energy recovery from thermal treatment.

Having discussed the input material for AD, the following discussion of the use and storage of the digestate produced from the anaerobic process relates to one of the outputs from the AD process that has a significant impact on both the economic viability of an AD facility and environmental aspects, particularly GHG emissions and potential pollution to watercourses.

2.6 DIGESTATE

Digestate is the solid material that is left after the digestion process. It is normally greater in volume than the feedstock added, due to the addition of water to enable the movement of the material through the AD system; and depending on the end requirement of the digestate, it can be dewatered into its liquid and solid derivatives.

Digestate has considerable benefits (soil fertility, improved microbial community and the reduction of carbon emissions) for the land and the environment (Walsh *et al*., 2012a and b). Compared to the cattle slurry feedstock input material, its digestate contains nitrogen which is almost 70 per cent more readily available to facilities (Ørtenblad, 2000; WRAP, 2011), improving crop yields under well-managed application (Möller *et al*., 2008; Möller and Müller, 2012). Digestate is rich in nutrients (see Table 2-6), which is indicative of the feedstock input into the digester. The digestate allows land users to substitute digestate for mineral fertilisers, thereby reducing their farm production costs and the GHG emissions offset from not using mineral fertilisers (Banks *et al*., 2011). Mineral fertilisers are expensive and energy-intensive in their production.

Table 2-6 An illustration of nutrient values of an 'average' digestate

	Total Kg/m[3*]	Plant available Kg/m^3	Value per m^3 digestate
Nitrogen N	7.5	5.5	£4.90
Phosphate P_2O_5	0.3	0.2	£0.17
Potassium K_2O	2.0	1.8	£1.17
Total fertiliser value per m^3 digestate			£6.30

Source: Redman (2010)

Notes: Based on granular fertiliser values of 34.5% N at £225/t, 46% P_2O_5 at £255/t, and 60% K_2O at £320/t.

*** WRAP, 2008b: Appendix D**

There are other metals, or trace elements, found in digestate: elements such as zinc, copper, nickel, sulphur and magnesium, which are all essential to plant growth (Schattauer *et al.*, 2011). Other elements, such as lead, cadmium and chromium, are not essential and can cause human and animal health issues in large quantities (Castañoa *et al.*, 2012). For this reason, careful monitoring and management of the digestate is required, so as not to overload the soil environment. Again, the physical and chemical profile of the digestate and quantities of these trace elements are a function of the constituent parts of the feedstock used. However, if the feedstock is purely on-farm, this can be construed as closed-loop recycling if all the digestate is returned to the land.

As nutrient management in the UK is highly regulated, the treatment of nutrient fluxes should be discussed here. Potassium is ubiquitous in soils and stable; it is also non-toxic to humans and animals, unless found at ultra-high concentrations (>2000 mg.l^{-1} in plant material; Elliott, 2008). Similarly, phosphorus is relatively stable and does not volatilise, but under certain conditions it can be susceptible to run-off and could be the cause of eutrophication in large freshwater bodies.

Nitrogen, on the contrary, is highly volatile and mobile. Forms of nitrogen are potentially a GHG and a pollutant to watercourses (Holm-Nielsen *et al.*, 2009). Operators must be very careful not to allow nitrate to either volatilise to the atmosphere or be applied excessively to land, which could potentially promote the leaching of nitrates to watercourses, particularly in certain sensitive areas, known as NVZs (DEFRA, 2013d). Nitrate problems are so widespread in England that approximately 70 per cent of the country's water bodies have been identified as nitrate-polluted, of which approximately 60 per cent originates from agricultural activities (DEFRA, 2009).

2.6.1 Delivery of digestate to land

The delivery of the digestate and/or slurries to land is also an important consideration. Considerable attention has been paid to the spreading of the digestate to land, for reasons of emissions to air and leaching to watercourses (see Section 2.6), and improving crop yields. Careful timing of the digestate application is essential, since the nutrients are more available to facilities than nutrients from undigested materials. Application should occur at the point at which the crop/vegetation needs the nutrients most – that is, at the beginning of the growing cycle (Möller and Müller, 2012). As ammonical nitrogen is highly labile, research has assessed the most effective methods of delivery (Lukehurst *et al.*, 2010). Four different delivery methods (see Table 2-7) were assessed for their effectiveness in terms of efficiency, cost, intrusiveness and mitigation.

There are many considerations for a farmer to take into account when deciding which technology to use. The splash plate seems to be the cheapest method, but there are negative implications in terms of the risk of crop contamination, odour management and GHG emissions. Injection into the soil is likely to be the most expensive method in terms of operational and capital costs, but there are considerable environmental and agricultural benefits to the farmer. The information provided by Lukehurst (2010), displayed in Table 2-7 suggests that the most generally favourable method of delivering digestate or slurries to land might be the trailing hose, enabling the greatest spread of material in an economic manner, with a high degree of agricultural and environmental benefits; but from the point of view of odour management and climate change, possibly the most effective option would be application by injection.

Table 2-7 Summary of characteristics of four digestate/slurry application methods

	Trailing hose	Trailing shoe	Injection	Splash plate
Distribution of slurry	Even	Even	Even	Very uneven
Risk of ammonia volatilisation	Medium	Low	Low or none	High
Risk of contamination of crop	Low	Low	Very low	High
Risk of wind drift	Minimal after application	Minimal after application	No risk	High risk
Risk of smell	Medium	Low	Very low	High
Spreading capacity	High	Low	Low	High
Working width	12–28 metres	6–12 metres	6–12 metres	6–10 metres
Mechanical damage of crop	None	None	High	None
Cost of application	Medium	Medium	High	Low
Amount of slurry visible	Some	Some	Very little	Most

Source: Lukehurst et al. (2010)

2.7 BIOGAS TREATMENT OPTIONS

Biogas produced in an AD reactor contains a mixture of different gases, with carbon dioxide (CO_2), methane (CH_4) and hydrogen sulphide (H_2S) being the main three. Other trace elements, including ammonia (NH_3), oxygen (O_2) and carbon monoxide (CO), are also normally found, along with siloxanes in some circumstances (Jensen and Jensen, 2000; Rasi *et al*., 2007; Igoni *et al*., 2008).

The level of 'cleaning and stripping' of the unwanted gases depends on the final use of the gas. Most CHP engines are able to remain unaffected by small amounts of trace elements, such as sulphur, without suffering corrosion. Ordinarily, biogas with low sulphur content can be controlled within the digester by introducing minute quantities of oxygen, removing the sulphur by transforming it to sulphate, and precipitating it in the digestate (Petersson and Wellinger, 2009). If the quantities are greater or the requirement for a cleaner gas is desired then, inter alia, iron filings can be used.

Both digester process and energy conversion performance is affected by the methane content; however, sulphides from certain feedstock types, such as swine and poultry manures, have a significant impact and need to be 'stripped' out, to a degree, before combustion/injection, dependent on the end-use and the proportion of these high-sulphide feedstock types to the whole (Anon, 2012).

2.7.1 Potential biogas pathways

There are three possible pathways: direct production of heat and/or power; upgrading for injection into the gas-grid system; and upgrading to produce fuels for transport.

Typically, the gas from a small farm AD unit (~3 m^3/hr), which may be fed from a small herd of only 100–150 head of cattle, will be burnt directly to heat the water used to wash down the yard and milking parlour, along with heating the farmhouse and associated inhabited buildings. Only when herds become larger or the farmer is able to supplement the feedstock with other feedstocks, does it become viable to start purchasing CHP engines. It is only with medium-sized AD units, which may be fed from many different sources, that the choice of biogas processes becomes available. CHP units become affordable when the methane yield becomes sufficient to maintain a 500 kWh engine (>160 m^3.hr), but at present it is not thought that it is viable to build a system based on gas-upgrade-to-grid unless the methane yield could maintain the equivalent 1 MW engine (≥330 m^3.hr) (Steentje, 2012).

There are several techniques for gas upgrade to remove the various impurities to produce an almost pure methane gas. These are well documented and described by Petersson and Wellinger (2009), and include:

- pressure swing absorption
- absorption
  - water scrubbing – use water at pressure or not
  - organic physical scrubbing – use organic solvents such as polyethylene glycol
  - chemical scrubbing – use amine solutions
- hollow fibre membrane gas separation.

New technologies include:

- cryogenic upgrading
- in situ methane enrichment
- ecological lung.

Absorption processes are possibly the most commonly used across Europe, with water scrubbing being the most common, however, the dry membrane separation technique used in the UK, such as at the AD facility at Poundbury, Dorset, could offer a strong alternative. The technology has developed away from its initial troubles and now operates at lower pressures and is more reliable, with minimal methane losses and reduced maintenance costs.

Microdigesters that might burn the gas in a boiler to generate hot water have not been included, since these remain outside the scope of this research, as does the upgrading of biogas to a usable fuel for transport, which was excluded due to a lack of available data.

Currently (September 2014), there are 145 operational AD facilities in the UK. Of these, 140 are classified as a CHP operation and only five upgrade the gas produced for injection into the gas system (AD biogas, The Official Information Portal on Anaerobic Digestion). Two were commissioned in 2010 and the others in 2012, 2013 and 2014. This highlights the fact that the technology for gas upgrade to the grid or transport fuel is considerably less developed, with fewer manufacturers, and remains at a premium for the biogas producer. At the time this research commenced, there were still unresolved issues in the regulations for the injection of gases into the national grid system. The fuel (methane) needs to be almost pure (>98 per cent methane), and therefore sophisticated stripping and purification methods need to be employed.

2.8 CONCLUSIONS

Both the European Commission and the UK government view AD as a technology that could offer significant help in meeting several of their environmental challenges and agreed targets for renewable energy generation, carbon mitigation and waste management. The literature argues that AD technology is potentially the best available technique to treat biowaste. It is also preferred as one of the most environmentally beneficial technologies, in terms of its ability to generate electricity from renewable sources and mitigate CO_{2eq} from agricultural (Banks *et al.,* 2011), energy and waste management (Evangelisti *et al.*, 2014) sectors. However, there are still many concerns about using the technology, particularly as regards its potential to pollute water and air, as well as its potential, if inappropriately funded or regulated, to compete with food production.

In terms of economic viability, this is still very much in the balance. The older research (Köttner *et al*., 2008) suggests that AD is not economically viable. However, at the time, double ROCs had only just been introduced and FITs had not yet come into being. Mistry *et al*. (2011a) also suggest that there are difficulties, particularly if AD facilities are not able to use a certain quantity of biowaste materials. With several upward revisions in government incentive schemes over the last decade, there are still only approximately 136 commissioned facilities (145 to date, see above) in the UK as of September 2013 (AD biogas, The Official Information Portal on Anaerobic Digestion).

In considering the discussions in this chapter, within the context provided in Chapter 1, a number of issues clearly require further investigation. Topics such as the value of the digestate to soil properties and crop production, as well as some of the mitigation methods for potential pollution uncertainties are outside the scope of this research.

In reviewing the literature for this research, it is apparent that there are gaps in assessing the AD technology at scale in terms of both life-cycle assessment and economic assessment. Only one report provided a partial combined economic and life-cycle assessment of AD (Mistry *et al*., 2011a and b); however, this never mentions that an LCA method was adopted, and only a single financial measure was provided in assessing AD. Thornley (2009) emphasises the importance of adopting a multidisciplinary approach in assessing bioenergy systems, which seems conspicuously absent in the appraisal of AD.

The technology is clearly flexible in the number of different feedstock types it can treat (or generate energy from), as well as in its ability to operate under a wide range of environmental conditions (not reviewed here). Few LCA research papers have addressed if the scenario under investigation is either economically viable at a small scale or at what scale their feedstock does become viable.

This research aims to address this knowledge gap. In evaluating what role AD has currently (waste management, energy generation or carbon mitigation), as well as what role AD could have, this research aims to establish what could be accomplished should the technology be deployed with the aim of maximising its environmental and energy-generating potential. Therefore, the areas that require further investigation to help address the overarching objectives of this research include:

- characterise and quantify the main available feedstock types available in England
- investigate the best method to maximise energy generation and GHG mitigation within an economically viable context
- understand how AD could be developed in order to maximise the mitigation of GHGs
- identify how to maximise net energy generation utilising AD technology
- assess how AD could be deployed in order to maximise energy generation and GHG mitigation, without having a negative impact on food production
- compare the economic and environmental efficacy of AD against other renewable energy technologies.

Chapter 3: Methodology

'True contentment is a thing as active as agriculture. It is the power of getting out of any situation all that there is in it. It is arduous and it is rare.'

G. K. Chesterton (1874–1936)

3.1 INTRODUCTION

In undertaking this research, a variety of different methodologies were adopted to assess the original research objectives. The methodologies were selected as the most appropriate method in addressing the research questions. This chapter outlines the four main methodologies and other general approaches used in this thesis in the following sections:

- Questionnaires and case studies (Section 3.2)
- Life cycle assessment and anaerobic digestion (Section 3.3)
- Economic assessment using financial investment methods (Section 3.4)
- Assessing anaerobic digestion using a computer model (Section 3.5)

Following the discussion of these four different methods adopted, we explore the current and future role of AD in England is explored by developing four different scenarios (see Section 3.6), with the aim of meeting this research's objectives. Finally, there is a closer inspection of the general approach used throughout this thesis (see Section 3.7), demonstrating how the model was used in conjunction with other calculations, with the research's end goals in mind.

3.2 QUESTIONNAIRE AND CASE STUDIES

There were three main reasons for using a questionnaire and having case studies:

- there was a lack of capital and operation data available to model the technology at different scales
- to gain an understanding of some of the issues and barriers the operators had experienced in planning and operating AD facilities
- to ensure that there was a real-world aspect to the data and experiences and, where possible to have data to validate the model post-construction.

To achieve this, a number of AD operators were approached, within the three chosen regions, to participate in this research (see Section 3.3.4). In March 2011, there were fewer than

75 AD facilities in England, and not many were prepared to be interviewed, in view of the sensitive nature of the data being requested. Over 40 businesses were approached; of these, 12 agreed to be interviewed (although one only on the basis that no financial information was to be given). The case study facility owners/managers were interviewed predominantly in March and April 2011. Three case studies were found to represent the East of England, four to represent the South West and five to represent the West Midlands. One further case study manager agreed to participate in 2012, but was outside of the three chosen regions.

A detailed questionnaire (later modified in 2012; both, see Appendix 2) was completed (generally in part) either in person, during an interview that lasted approximately one hour, or by email and telephone correspondence (case study 13). The main aim was to collect the capital and operational expenditure data, so questions included details of feedstock used, capital and operational expenditure, and outputs in terms of biogas and methane yield, electricity generated and use of heat. However, since the technology development in England was relatively immature, questions relating to their experiences in gaining planning, commissioning their facilities and early operation were also asked. In return for the generous time offered, the owners received a copy of the output from the model, which provided the net GHG offset by their facility, demonstrating their contribution to England's GHG abatement. Chapter 4 is dedicated to a more in-depth discussion relating to the case studies and interviews.

3.3 LIFE-CYCLE ASSESSMENT AND ANAEROBIC DIGESTION

3.3.1 Background

The International Organization for Standardization (ISO) defines LCA as 'the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system, throughout its life cycle' (ISO, 2006a).

LCAs are structured and follow a set of principles specified in ISO 14014 (ISO, 2006a) and ISO 14044 (ISO, 2006b). The LCA represents 'a tool of analysis of the environmental burden of products at all stages in their life cycle – from the extraction of resources, through the production of materials, product parts and the product itself, and the use of that product to the management after it is discarded, either by reuse, recycling or final disposal' (from cradle to grave) (Guinné, 2004: 5). In addition, by identifying the energy used and emissions released, an LCA provides a method of identification for environmental improvement (Cherubini *et al.*, 2009).

This research, whilst conscious not to undermine the importance of the different measures within an LCA, was not equipped to perform a full LCA (see Section 2.2.1.1), and is predominantly focused on measuring the global warming potential (GHG emissions) of the three main business sectors that AD traverses, in particular the energy sector.

However, it was still the aim of this research to provide a robust assessment based on the structure of an LCA, but reporting solely on GHG emissions, net energy balance and energy generation. The discussion below sets out the structure used in developing the model (see Chapter 5) based on an LCA framework. The financial aspect of the model (see Section 3.4) knits in around the LCA framework, ensuring that it follows the same scope. The scope (boundaries used both in the model and the LCA) of this research was quite wide, as it took in a number of processes and activities across three different DECC defined sectors – energy, agriculture and waste management (see Figure 3-3).

3.3.2 Life-cycle assessment methodology

There are four main stages in the LCA (goal definition, inventory, impact assessment, and interpretation and improvement – see Figure 3-1), which are described in greater detail, with particular reference to this research, in the sections below.

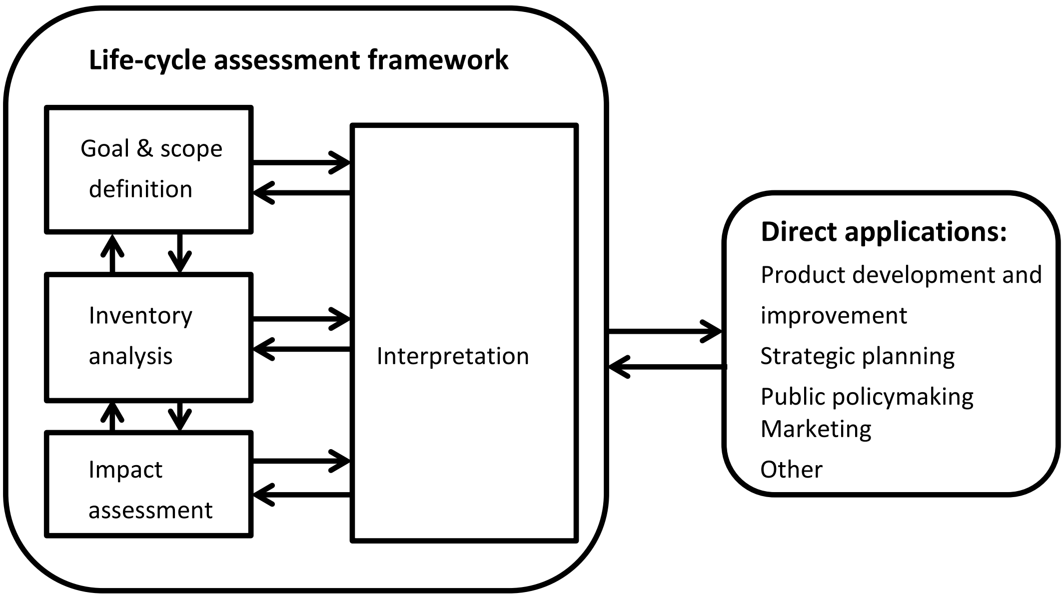


Figure 3-1 The main stages of life-cycle assessment. Source: Guinné (2004)

3.3.2.1 The functional unit

The functional unit describes and quantifies the properties of the product (or service). These properties may describe functionality, appearance, durability and so on, and are usually determined by the market in which the product/service is sold (Weidema *et al.,* 2004); however, the functional unit does not relate to production volumes, only their function (Baumann and Tillman, 2004).

In a multifunctional process (expanded) analysis, different functional units could be used, depending on the scope of the LCA – that is, the interdisciplinary nature of the research, the multifaceted nature of the technology, and the different audiences that the research could reach, in this case, academics, policyholders, farmers, and so on. The functional unit used in this research is the energy-generating capacity from available biowaste, on-farm waste materials and crops grown specifically using AD technologies in a chosen English region.

3.3.3 System boundaries

System boundaries are decided during the goal and scope of an LCA; however, these may alter slightly as information is gathered and the system is investigated (Baumann and Tillman, 2004). System boundaries need to be specified in several dimensions (Tillman *et al.,* 1994), and help to characterise the beginning and end ('cradle and grave') of the life cycle. These include:

- boundaries in relation to natural systems (see Section 3.3.5)
- geographical boundaries (see Section 3.3.4)
- time boundaries (one year)
- boundaries within the technical systems (see Section 3.3.5):
    - Relating to production capital, operation boundaries
    - Relating to other products requiring allocation procedures.

Figure 3-2 displays the scope of a general AD facility treating on-farm materials only. A number of different activities and capital are required when accounting for biowaste materials. The extended boundaries for including biowaste materials were seen in Figure 2-3.

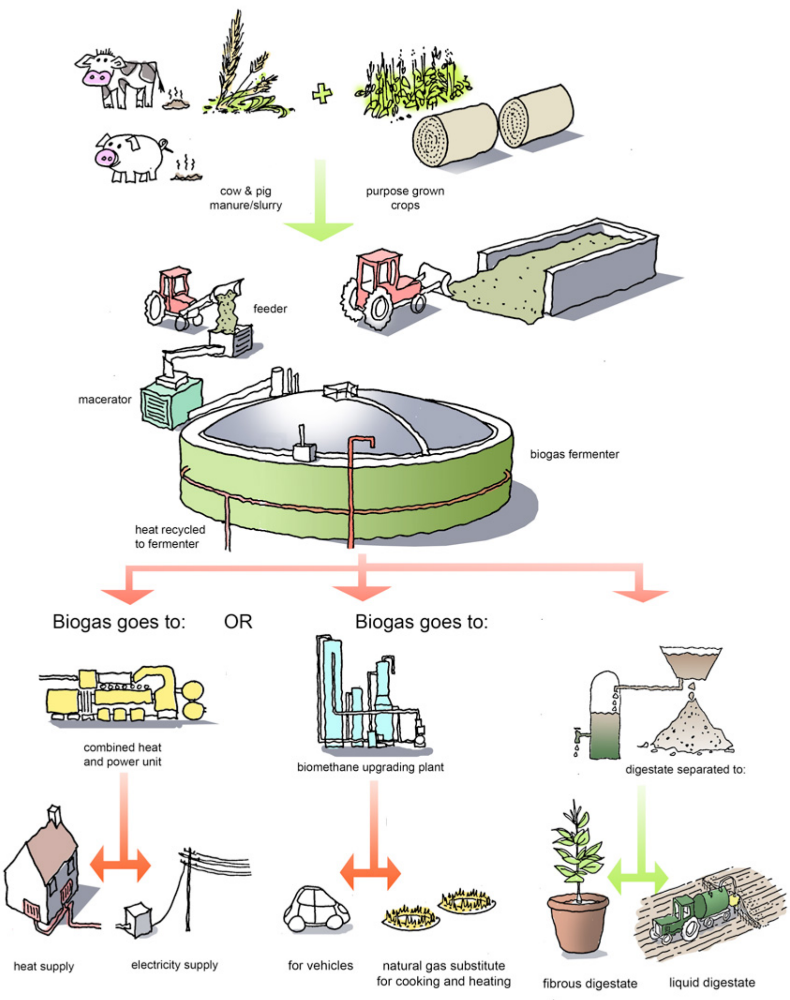


Figure 3-2 A schematic view of the boundaries of an on-farm AD facility with some available options for utilising the biogas and digestate. Source: Nethy Energy

The following section discusses the geographical boundaries of this research. As such, the following discussion also provides the reasons for choosing the regions investigated.

3.3.4 Three English regions

At the start of this research (2010), there were fewer than 75 operational AD facilities spread randomly across the country, with no single region having significantly more than another; therefore, this provided no reason to focus on one region over another. The AD technology is concerned with the digestion of organic material with a view of generating energy and mitigating GHG emissions. In order to assess how AD might develop across England the most important aspect of AD needed to be assessed – that is how much of the different feedstock types were available nationally and, where possible, regionally. Feedstock availability depends on several factors: population density in each region; the distribution of the food-processing, retail and commercial sectors; and, finally, the distribution of livestock and, therefore, the slurries and manures that they produce. This section explains briefly the reasoning behind the three regions chosen and then provides a more detailed description of each one.

Three regions of England were chosen to be representative of the different sets of physical characteristics that determine the agricultural mix and intensities across England:

- East of England
- South West of England
- West Midlands.

The East of England and the South West of England represent the two most important agricultural regions of England in terms of gross output from agriculture to the nation. Respectively, they represent £1,304 million (RBR, 2012b) and £1,332 million (RBR, 2012c) of England's total gross value added (GVA) from agriculture of £7,331 million (DEFRA, 2012a).

Their demographic statistics are similar in terms of population and household numbers (see Table 3-1), but their environmental and farming attributes are contrasting. Table 3-1 also highlights that of the three regions, the South West has the largest agricultural area, but the smallest comparable percentage of land area allocated to crop growth.

Table 3-1 Regional data

Region	Population (2011)	Number of dwellings in region	Household waste per annum (t)	Cropped area (ha) (2010/11)	Total agricultural area (ha) (2011)
East of England	5,847,000	2,550,010	510,000	987,275	1,380,809
South West of England	5,289,000	2,342,980	468,600	466,432	1,758,096
West Midlands	5,602,000	2,387,400	477,500	356,061	915,412

Source: population and no. of dwellings (DCLG, 2012); own household waste calculations; farm data from the Farm Business Survey (RBR)

In the specific context of renewable energy and AD, Robertson (2013) reported that in the East of England there was reduced availability of seasonally rented land for agricultural production, as a result of maize growers being willing to pay very high rents (£590/ha) for AD feedstock. In the South East, Robertson (2013) cites evidence that cooperative-backed planning applications for AD facilities have been submitted, with forage maize being the main feedstock (also serving as a good break crop), as farmers in the region seek to take advantage of the benefits resulting from a developing AD sector.

As well as the different feedstock types available from typical farming activities, other non-crop feedstock types were also assessed for the regions. Municipal wastes were thought to be uniform across the country (Papineschi *et al.*, 2008), and information relating to C&I wastes are either unobtainable or unreliable (Enviros Consulting, 2009). However, the main divide across the English regions was associated with the farming activities of each one. This was principally dictated by local topography, climate and other environmental attributes. The East of England was chosen as the predominant region of crop production and pig farming; the West Country was chosen for its prominence in livestock production; whilst the West Midlands provides a good example of a more balanced crop and livestock production.

The three regions chosen for this thesis represent different aspects of English agriculture. The South West of England represents the largest livestock farming community, whilst the East of England represents the largest arable farming community, both in terms of quantity (head of livestock and hectare of arable land farmed respectively) and GVA per English region to the national economy (see Table 3-2). At the other end of the spectrum, the West Midlands represents the second smallest agricultural region in England.

Table 3-2 Summary of agricultural production and income accounts for the English regions

Region	Total crop output (£M)	Total livestock output (£M)	Gross value added at basic prices (£M)	Total income from farming (£M)	Area (sq. km) (ranking)
England	7,724	8,443	7,250	4,436	130,395
North East	215	330	294	227	8,592 (8th)
North West	335	1,278	703	292	14,195 (6th)
Yorkshire & the Humber	916	1,075	937	688	15,420 (5th)
East Midlands	1,422	891	936	643	15,627 (4th)
West Midlands	798 (10.3%)	1,055 (12.5%)	854 (11.3%)	467 (10.5%)	13,004 (7th)
East of England	1,980 (25.6%)	1,038 (12.3%)	1,279 (19.2%)	944 (21.3%)	19,120 (2nd)
South West	828 (10.7%)	2,064 (24.4%)	1,324 (17.7%)	714 (16.1%)	23,829 (1st)
South East (+ London)	1,231	711	922	460	19,095 (3rd)

Source: 2011 – Agricultural statistics 2nd estimate (DEFRA, 2012a)

3.3.5 Life-cycle goal and scope definition

The goal definition represents the stage at which the aims or objectives are stated and justified; it states what the main inputs are and what the desired outputs should be. It also specifies the intended use of the results and for whom they are intended (i.e. stakeholders and the commissioner of the study). The scope definition step establishes the main characteristics of the proposed project. The scope covers temporal and geographical issues, as well as technological coverage. The scope also covers the justification of the main choices in terms of functional unit, phases of inventory analysis, and impact assessment and interpretation (Guinné, 2004; Finnveden *et al*., 2007).

Defining the scope of the model (see Figure 3-3) required extensive deliberation. Key issues included:

- When does a feedstock become a feedstock?
- Which activities ought to be included?
- What represents the end-point – the end of the digestion process or the disposal of the digestate?

The aim of this research was to capture all the activities and processes of anaerobic digestion (production), the associated activities of its different feedstock types (raw materials acquisition), and the use and disposal of its products (biogas and digestate). The goals of this LCA are twofold, to explore the GHG balance and the net energy balance in using AD within a regional context. To that end, the LCA was not a 'full' or 'complete' LCA, in that the number of different impacts was restricted. The model (see Chapter 5) sought to quantify the net energy balance and GHG emission fluxes from a number of different scenarios, derived from:

- the embodied energy and GHG emissions from the largest capital components and from the AD process
- the collection and transport of the different feedstock types used and the transport of the digestate from the treatment facility
- all farm activities associated with the crops grown specifically for use in an AD system.

To help achieve this, the scope was broken down into several smaller modules that covered specific aspects of the AD life cycle. These modules (see Figure 3-3) were natural breaks within the overall scope of the AD life cycle. They included:

- the collection, transport and treatment of off-farm (biowaste) feedstock materials, including offsetting GHG emissions from landfill had the same amount of material been sent to landfill
- the field preparation, cultivation, harvest and transport of all crops specifically grown for digestion, including the manufacture and use of fertilisers and sprays
- all processes associated with AD completed at the AD facility, including the calculation of inherent energy and GHG emissions associated with the materials used in the construction of the AD facility
- the treatment of the biogas
- the treatment and disposal of the digestate.

The energy use within the dairy unit of a farm was also included, as not only are the dairy washings often used in an AD facility to help maintain the required DM content within the AD process, but they also have a small inherent energy value. The dairy unit also represents an on-site heat and electrical load that is part of the normal farm operations, and therefore represents part of the broader scope of the life-cycle system. This also represents an important offsetting of GHG emissions, either from fuel oil (kerosene) that would normally be used to heat up the water around the farm, or from grid electricity, both of which can now be offset by the heat and electricity generated by a CHP genset engine.

3.3.5.1 Feedstock materials

Organic materials were included from when they were deemed to be feedstock. For example, municipal household waste becomes feedstock when the consumer puts it in their bin; and the same applies to commercial waste. Only processes before disposal were not included, as the feedstock is deemed a by-product of the process it was created for. In contrast, all processes were included for crops (whole or otherwise) that were specifically grown for energy generation (see Section 3.3.5.9).

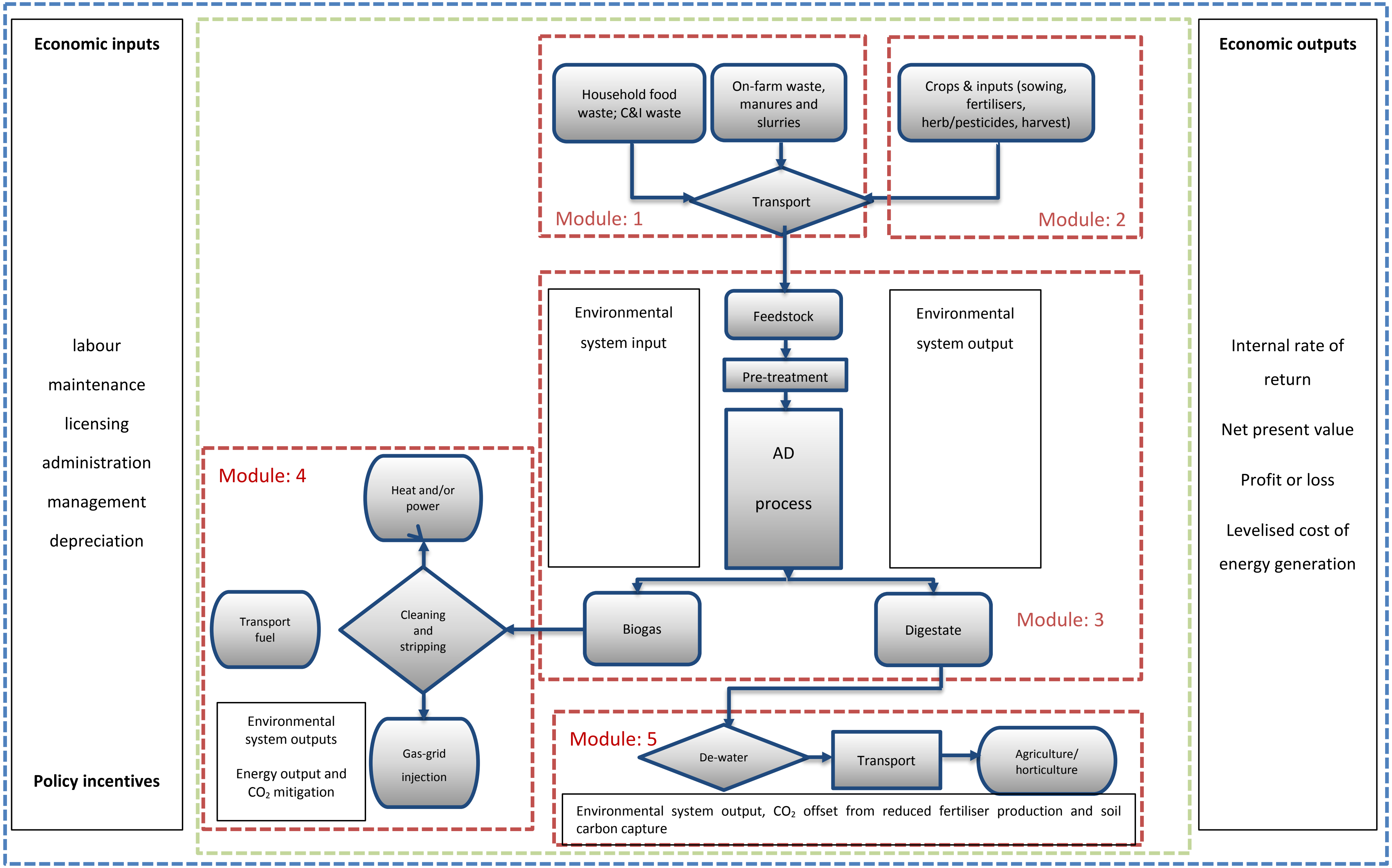


Figure 3-3 Anaerobic Digestion Environmental and Economic model

3.3.5.2 Livestock wastes

Excreta quantities (t) are calculated from the number of head of herd, drove or flock. To calculate the quantity of slurry and manure produced, the number of animals is multiplied by the weekly production factor for that animal and then by the number of weeks they are expected to be housed. For herd sizes of 400 head or more, the housing period was assumed to be 44 weeks, whilst anything below this limit was 22 weeks, representing the national average. When calculating regional scenarios, 28 weeks, 28 weeks, 20 weeks and 24 weeks were used for north, east, south and west respectively (Moreton, 2012). Pigs are assumed to be housed for 36 weeks of the year, whilst chicken layers are housed for 48 weeks, and chicken broilers for 52 weeks per annum (Moreton, 2012).

A brief calculation of the available fraction of national livestock excreta production (see Table 3-3), based on the assumption that both beef and dairy cattle are housed for 28 weeks a year and the annual excreta production for pigs and poultry (based on the above housing requirements), demonstrates the magnitude of the feedstock that requires treating as a GHG mitigation measure. By 'available', it is meant the excreta that could be collected whilst the animal is housed, or in the farmyard for milking, and so on. Livestock excreta in the field are not accounted for.

Table 3-3 England livestock numbers and excreta based on 28 weeks' cattle housing

	Numbers	Estimated annual excreta production ($t.a^{-1}$)
Dairy cows	1,158,447	10,801,360
Steers and heifers	5,521,386	30,610,564
Pigs	3,606,117	5,841,910
Poultry – layers	35,629,573	1,402,380
Poultry – broilers	78,788,030	1,761,700
TOTAL		**50,417,914**

Adapted from: June Census of Agriculture and Horticulture data, DEFRA, 2011

3.3.5.3 Grass and maize silages

Grass and maize were both chosen because of their inherent energy properties and ability to grow in most regions of England (although this is less the case with maize, as it has a later growing season since it requires warmer soil temperatures to germinate, and is therefore more difficult to grow in the more northerly regions of England). Both generate similar quantities of fresh matter (FM) per hectare (approximately 45 t) and have approximate biogas yields of 152 $m^3.tFM^{-1}$ and 204 $m^3.tFM^{-1}$ respectively. This does not preclude the use of other feedstock types; in fact, there are many existing AD facilities that utilise wheat (whole crop) silage, sugar or fodder beets and potatoes, to name just a few. However, these are main crops, not break crops, and compete more directly with food production. Many areas of the West of England have large areas of permanent pasture, for a number of reasons, including that many herds have reduced in size due to changing environmental or economic conditions (Anon., 2011). Therefore, AD could provide these farms with an alternative source of income generation, whilst supporting their smaller herds, or indeed helping to build them up again.

The challenge, therefore, became how to treat the greatest quantity of on-farm waste materials (slurries and manures) using the least quantity of grass silage and maize silage materials, without impacting on crops for food. If this were not possible, then we would need to look at alternative feedstock types that provide the energy content to make the system financially viable.

3.3.5.4 Co-digestion

The co-digestion of certain materials has a positive impact on gas yields (see Section 2.5.4). This positive impact was observed in the outputs of more than one case study co-digesting one or more feedstock types. The differences between expected and observed gas yields was variable; therefore, an 11 per cent uplift in methane gas yields was built into the model for crop or crop residues if co-digested with one or more farm manures or slurries, based on the mean observations from two case studies and the more conservative figures from the literature (see Section 2.5.4). This uplift was not accredited to the co-digestion of biowaste with slurries and/or manures, since they rarely had high lignocellulosic material in them (which is where the slurry would have the greatest impact). One case study did suggest a minor reduction in gas yield when adding cattle slurry to the main feedstock; however, this may have been a result of 'temperature shock', since they were adding cold slurry directly to the digester, whilst simultaneously adding feedstock from a pasteurisation unit.

3.3.5.5 Biowaste

Biowaste is defined by the Waste Framework Directive as 'biodegradable garden and park waste, food and kitchen waste from households, restaurants, caterers and retail premises and comparable waste from food-processing facilities' (EU, 2008: 2). Biodegradable waste is defined in the Landfill Directive (1999/31/EC) as 'any waste that is capable of undergoing anaerobic or aerobic decomposition, such as food and green waste, and paper and paperboard'. For the purposes of this project, the definition of biowaste follows that of the Waste Framework Directive.

These special materials require particular attention. Care must be taken not to bring these types of waste into contact with animals or crops, in order to minimise the risk of contamination or disease. In addition to this handling care, any health and safety risks of the resulting treated material must be free of contamination/disease as well. Therefore, these materials need to comply with ABPR rules (EU Directive 90/667/EEC), which require that they are macerated to a maximum of 12 mm and pasteurised at a minimum of 70 °C for one hour.

Due to the considerable additional capital expenditure demanded, these additional treatment requirements place the use of these potentially biohazardous materials 'out of the reach' of many farmers who desire to treat their own agricultural (low-energy) waste materials and do not have the space to grow crops specifically for AD. However, many farmers do not wish to become waste managers, but would rather see the import of small amounts of 'safe materials' (usually crops) in order to make the treatment of their on-farm wastes financially viable. An alternative method ought to be found, therefore, to permit a small amount of biologically safe waste material to be brought onto a farm, significantly reducing the risk of contamination to a point at which both farmer and regulator are content, from both a biohazardous and financial viewpoint.

For the purposes of this research, the energy value or methane yield for biowaste has been fixed at 107.93 m^3t^{-1} fresh weight (FW), based on the figure for source-separated food waste (Locke, 2012) in case study 1 (Chapter 4). This was a difficult decision, but there is little or no detail available on the different types and quantities of C&I waste streams in the English regions. However, the figure was deemed to be reasonable since, in aggregate, the feedstock stream could potentially resemble the energy content of source-separated food. The C&I waste stream includes vegetable wastes, abattoir wastes and cheese wastes, with methane yields of between 31.92 m^3t^{-1} FW and 458.22 m^3t^{-1} FW (KTBL, 2010), making it impossible to create an accurate regional picture. Biowaste, therefore, became the fifth mobile feedstock type used within the scenarios.

The quantity of feedstock transported at any one time is dependent on the carrier. Data provided by WYG (2012) suggests a refuse collection vehicle (RCV) with a 2.8 t food-pod to be the most efficient method of collecting household waste in urban areas. WYG (2012) estimated the average collection distance across England for municipal wastes to be approximately 200 miles per tonne per annum. In rural areas, a smaller, purpose-built food waste collection vehicle may be used; however, for convenience and uniformity within this research, an RCV with a 2.8 t food-pod is assumed for the collection and transport of municipal waste.

The partitioned volume used in an RCV represents one-third of its carrying capacity. Therefore, one-third of the fuel consumption is apportioned for the overall collection of food waste. Transport of the food-separated municipal waste from the MRF to the treatment facility is deemed to be carried out in articulated vehicles with an 18 t carrying capacity. There may be considerable national variation; however, this was the most common weight received at the gate of one the case studies in this research, and is the most likely option because of efficiency of haulage. It is also the size most likely to be used in order to keep the number of traffic movements as low as possible. Only for particularly remote sites with unsuitable access roads is the quantity of material likely to be less, being transported in a more suitable, smaller vehicle.

3.3.5.6 Digestate

The nutrient content of the digestate as a whole is calculated (but not split between solid and liquid) from the DEFRA *Fertiliser Manual* (DEFRA, 2010) and the *EU-AGRO-BIOGAS Online European Feedstock Atlas* (KTBL, 2010) databases. Assumptions used include wheat and barley being the same, and potatoes and swede likewise. The nutrient content factors are multiplied by the quantity of feedstock added to provide an expected weight (kg/t digestate).

The equivalent mineral fertiliser nutrients value is calculated based on the value £/kg provided by Nix (2012). Using data from Cropgen D25 (2004b), the ADEE model is able to calculate the energy and GHG saved from using the digestate rather than the manmade mineral fertiliser.

The economic value of digestate is calculated using the quantity of available nutrients in the digestate, less the value of the nutrients present in untreated on-farm manures and slurries, which would have been used had an AD facility not been there. Unfortunately, this value is not added back, should any of the digestate be sold and exported off-farm. This added value can represent between £3 and £4 per tonne of added revenue, and could amount to several thousand pounds modelled shortfall in revenue from the digestate exported. This is more important in scenarios in which large quantities of exogenous materials, high in nutrients, are brought onto the farm. If the farm (on which the AD facility is sited) has a below-average area, it is highly likely that the digestate will need to be exported. It is therefore important, when planning the installation of an AD facility, that there is either sufficient land to spread the digestate generated, or that close neighbours are willing to purchase the digestate as a fertiliser.

3.3.5.7 Transportation and farm activities

All transport movements are considered, including collection of the municipal, commercial and industrial waste from source to treatment centre (the AD unit). Similarly, all farm operations associated with crops specifically grown for energy are included, from the field preparation prior to sowing, right through to harvesting. Transport movements of on-farm slurries and manures were assumed to be negligible, since it was assumed that the AD facility would be sited close to the animal housing; however, if any of this material was imported, the known distance was included in the calculations.

Following digestion, transport movements from the treatment centre to their final destination are included. For the purposes of this research, it is assumed that all digestate is used as a fertiliser replacement and spread to land. The first choice is to spread the digestate to the farm on which the AD facility is sited, and the remainder is assumed to be spread to neighbouring farms. Transport costs relating to the digestate movement are calculated in the same way as the various feedstock types described above, with the assumption that the digestate is moved in 8 t batches to the nearest available area. The carrying capacity could be more than double this for centralised AD facilities exporting the majority of the digestate produced.

3.3.5.8 Dairy operations

If the scenario includes dairy cattle as an on-farm source of feedstock, the model calculates the electrical energy load ($kWh.cow^{-1}.a^{-1}$), the comparative energy requirement ($MJ.cow^{-1}.a^{-1}$) and associated GHG emissions ($kgCO_{2eq}$) for rearing a specific number of animals in a dairy herd, using data from Bilsborrow *et al.* (2010) and Mortimer *et al*. (2003) (see Table 3-4).

Table 3-4 Energy requirements and emissions from dairies in the UK

Dairy energy per cow			**Indirect energy emission data**			
325.00*	kWh/cow/year			**GER† (MJ/MJ)**	**Carbon ($kgCO_2/MJ$)**	**GHG ($kgCO_{2e}/MJ$)**
1170.00*	MJ/cow/year		Diesel	1.130	0.078	0.085
192.95*	kg CO_{2e}		UK grid electricity	3.090	0.150	0.162

*** Bilsborrow *et al.* (2010)** **† Gross energy requirement from *Mortimer et al*. (2003)**

Therefore, it is assumed that the physical location of an AD facility associated with a dairy herd is sited strategically to achieve these additional economic and environmental efficiencies – that is, reducing the distance that the feedstock or digestate needs to travel. Likewise, the heat energy needs to be utilised as close to the source as possible if the energetic benefits are to be realised, and if financial costs are to be constrained and profits optimised.

3.3.5.9 Farming activities for purpose-grown crops

It was essential to include all the various farming activities associated with all the different feedstock types used in the AD unit, to ensure that an accurate life-cycle and economic analysis of AD was completed. Therefore, where purpose-grown crops were included, all farming activities, from field preparation and sowing to harvesting, have been included in the life cycle.

To calculate the GHG emissions and energy used, first, the quantity of fuel utilised in these processes needed to be calculated. Fuel consumption figures (litres per hectare; see Table 3-5) were calculated by Salter (2011) and Downs and Hansen (2012), and figures were generated by this research in as much detail as possible, after finding fuel consumption figures for various-sized tractors, as well as specific figures for sprayers and some harvesters. Table 3-5 sets out a series of farming activities associated with growing crops in general, but utilised here for purpose-grown crops used in the AD unit.

It should be acknowledged that these figures are somewhat arbitrary, since fuel consumption is reliant on a considerable number of variables, including the age, size and efficiency of the tractor or machinery used; the type of soil and soil moisture content; and the topography of the land. Specialist operating vehicles may also be used in place of a tractor – for example, a dedicated spray vehicle, potato planter or combine harvester. These would have a considerable impact on fuel consumption.

It is assumed that Salter (2011) made his own calculations rather than measuring the fuel consumption of the different farming activities. Downs and Hansen (2012) made their own measurements for a number of different farming activities, based on US farming techniques, some of which are not relevant to UK agricultural methods. In addition, they provided average fuel consumption data (see Table 3-5, column 3), so that people could make their own calculations. Downs and Hansen (2012) place a disclaimer that their figures could change by as much as plus or minus 25 per cent, depending on topography, soil type and moisture content. Column 5 in Table 3-5 represents this research's calculations, based on the collection of average fuel consumption per hour of a variety of tractors used in the UK, of different horse-power, from several well-known manufacturers. The average time per hectare for each crop was calculated using Nix's (2012) contractor work rates, thereby providing an estimate of the fuel consumption per hectare of crop.

As mentioned above, not all farming practices can be modelled. Feeding and housing practices for livestock have an impact on feedstock quality and quantity, in the same way that local environmental characteristics (soil types, typography, climate) have an impact on what farming practices are employed across the crop cycle in any region.

Table 3-5 A comparison of fuel consumption (l/ha) for each farming activity

Farming activity	Salter (2011) fuel required (l/ha)	Downs and Hansen (2012) calculations	Downs and Hansen (2012) US measurements	Own calculations	Downs and Hansen (2012) fuel consumption +25%
Subsoiler	15.10	13.52		30.15	16.89
Plough	23.20	11.58	15.71	25.84	14.48
Harrow	5.70	7.72	3.74	17.23	9.65
Disc	6.80	6.81	8.89	10.62	8.51
Drill	2.80	8.13		12.68	10.16
Precision drill	1.50	5.79	3.27	9.03	7.24
Roll	1.10	6.71	3.27	10.46	8.38
Spray	0.90	2.03	0.94	3.17	2.54
Fertiliser (mineral)	0.70	1.73	6.08	2.69	2.16
Mechanical hoe	2.60	7.72	2.34	12.05	9.65
Maize hoe	3.30	6.81		10.62	8.51
Comb harrow	3.50	7.72	2.81	12.05	9.65
Combine harvester	18.00	3.76	14.97	29.60	4.70
Forage harvester	25.10	4.47	33.67	35.20	5.59
Ensile	4.60	6.00		4.60	7.49
Mow	3.30	6.71	5.61	10.46	8.38
Turn	2.90	18.09		28.21	22.61
Towed forage loader	6.50	18.09		28.21	22.61
Baler	4.60	4.06	4.21	6.34	5.08
Beet harvester	44.30	10.16	11.69	32.00	12.70
Transport (MJ/h/t)	1.10	1.02	5.61	2.27	1.27

Adapted from: Salter (2011); Downs and Hansen (2012); and own calculations

3.3.5.10 Fertilisers and sprays

Growing crops is intensive; it requires the preparation of land and the care of the growing facilities. Plants require nutrients to grow and various sprays to protect them from unwanted plants, fungi and insects that could impact on crop yields. Mineral fertilisers and sprays are all manufactured using fossil fuels, which have an impact on the environment. The digestate can offset the requirement for mineral fertilisers to a degree, but sprays still need to be accounted for in the LCA (see Section 5.3.2.3), as well as any additional mineral fertiliser requirement over and above the use of digestate or slurries and manures.

3.3.5.11 Embodied energy of digester and ancillary capital

Embodied energy is the quantity of energy required to produce a good or service. It should encompass all activities from extraction and processing of the raw materials to their final disposal after a useful life. Consideration of the embodied energy of the process is limited (see Section 5.3.3.3). Calculations for the size of plant are included for the digester, the digestate holding tank and silage bays. Construction is assumed to be of steel-reinforced concrete or steel construction for the digester. The holding tanks and silage bays are deemed to be of steel-reinforced concrete (with aggregate infill for the silage bays).

An elementary calculation (see Section 5.3.3.4) of the embodied energy of the CHP engine is based on the published weight data of the Type 3 and Type 4 GE-Jenbacher gensets. No attempt was made to calculate accurately the embodied energy of pumps, pipes or other peripheral machinery within an AD system, as these are design-specific to each individual AD treatment facility. However, to incorporate a crude embodied energy value for some of the peripheral capital equipment, an additional 15 per cent of concrete and 15 per cent of steel associated with the foundation materials calculations have been included.

3.3.5.12 Process energy

This section encompasses the heating and electrical requirements of the digestion and pasteurisation stages of the process, as well as all the energy required to pump the digestate around the system with data provided in Berglund and Borjesson (2006). For dairy herds, the model also calculates the energy requirements of running a dairy, based on the head of cattle stated at the input stage (see Section 5.3.3.3). The energy requirements for some of the output options are also included – for example, gas upgrade to grid injection and digestate separation. For simplicity, when modelling the scenarios, gas upgrade is not chosen, but only methane for on-site CHP use. The digestate is assumed to be separated into solids and liquid and the energy requirement is accounted for.

It is assumed that all agricultural establishments are remote, and off-grid for mains gas supply. The model also assumes that if an AD facility (generating energy using a CHP genset) is introduced into an agricultural setting, the existing heating and power requirements will be met by the CHP genset, displacing the existing fuel sources. Therefore, heating oil (kerosene) is assumed to be the fuel of choice for heating, including activities that require the heating of water — 10 per cent of the electricity and waste heat is assumed to fulfil these requirements, in addition to the separate calculations for the electrical requirement for the dairy. The model offsets the GHG emissions associated with these activities using the waste heat from the AD facility.

3.3.5.13 Emissions from landfill

It is well documented that organic materials ferment in landfill sites and emit methane (see Section 1.4.2). If biowaste is a chosen feedstock, the model assumes that the alternative treatment would have been landfill. The model calculates the offset emissions from diverting the material from landfill. Literature (Gregory *et al.,* 2003) suggests that 10 per cent of methane (and other gases) escapes through fissures in landfill-site caps. The model also assumes that there is 1 per cent escape from AD facilities throughout the process, and that 0.5 per cent of biogas is flared due to breakdowns and maintenance. These are based on discussions with case study facility operators. A net 8.5 per cent saving is therefore calculated, based on the expected methane yield from the diverted biowaste material digested at the AD facility. Other offset emissions calculations from various related activities are dealt with in the next section.

3.3.5.14 Biogenic carbon

Biogenic carbon represents the CO_2 emissions from the combustion of organic material other than fossil fuels – that is, from sources that are thought to be recycled/regrown. In this study, biogenic carbon is considered as neutral. The majority of feedstock types used in the model are from waste sources and represent closed-loop recycling. The two purpose-grown crops specified as additional feedstocks in the model grow continually (grass) or within a 12-month time frame (maize), maintaining a quick renewable status. Therefore, the GHG intensity factor for AD is treated as zero in this research.

3.3.5.15 Data sources

The ADEE uses a considerable amount of data, collected from a variety of sources. A summary of the main sources is displayed in Table 3-6. Other sources of data (not present in the table below) derived from the questionnaires and interviews completed (see Section 3-2)

Table 3-6 Source of databases utilised in the ADEE model

DATABASE	YEAR	DATA INCLUDED	COMMENTS
CROPGEN	2004b	Energy requirements (MJ/kg) and emissions (kg/kg) from fertiliser and control sprays (active ingredients) production	Whilst this is now a decade old, it still represents the best non-specific account of energy and emissions relevant to fertilisers and agricultural sprays.
CROPGEN	2007	Crop energy values Expected biogas yield Expected methane yield	Whilst the database had a considerable number of different feedstock types, it was found to be confusing, with missing information, when assessed.
KTBL	2010	Crop energy values Quantity of DM (%) Quantity of VS (%) Expected biogas yield ($m^3.FMt^{-1}$) Expected methane yield ($m^3.FMt^{-1}$)	This database forms the backbone of the data for the various feedstock types used in this thesis. It is continually being updated as new feedstock types are added or those represented by the Buswell calculation are replaced by measured data.
Nix	2012	Costs of production of crops Crop yields per hectare Agricultural wages Fertiliser and spray costs	This is an annual almanac. It is one of the most complete and up-to-date guides to farming activities and provided considerable information for this thesis.
DEFRA	2010a	Fertiliser requirements for different crops under differing environmental conditions Nutrient values inherent in crops and on-farm wastes (slurries and manures)	RB209 – *Fertiliser Manual* This is a guide intended for use by farmers and agricultural consultants. It enables the user to calculate crudely (without soil testing) the quantities of fertiliser required to grow crops, accounting for various other factors.
DECC	2013a	Emission data and conversion factors associated with the conversion of all fuel types into energy Annual emission factors from generating energy from the general mix of technology types	*Digest of UK Energy Statistics* (DUKES) This is a reliable and extensive guide to data relating to the energy sector.
Salter	2011	Farm activity requirements for different types of crops	Updated by Finch (2012) to include current farming practices.
Hammond and Jones	2008	Inventory of carbon and energy of various materials	This database was used to calculate the inherent energy and carbon of the capital equipment.

Data representing the inherent characteristics of some of the feedstock types were not available even in the databases used. Where direct measurements had not been observed in experiments, the KTBL database replaced observed data with expected yields provided by the Buswell calculation (see Section 2.4.1.1). However, some of these calculations were out of date, as new crop varieties had become available; or, in the case of municipal waste, these data were representative of another country, whose population has a completely different diet, and therefore this waste stream had different energy qualities to that found in the UK. When it was found that validating the model (see Chapter 6) against the case studies of this research provided more relevant data, these replaced the data provided in the KTBL database.

For example, gas yields from maize silage were found to be more in line with figures observed in Amon *et al.* (2007) (see case study 3); therefore, these data replaced the original data from the EU AGRO-BIOGAS database. Similarly, gas yields for municipal household waste were shown to be in excess of those in the database at two of the case study sites (1 and 12); therefore, these replaced the original database figures. Other feedstock type data (see Table 2-3) show some of the figures used within the model, including the amended figures from measured data.

3.3.6 Life-cycle inventory analysis

This part of the LCA procedure follows the requirements of ISO 14041 and involves data collection and calculation procedures (see Chapter 5). Data collection is made through literature (see Chapter 2) and/or primary data collection. Inventory analysis provides the list of environmental burdens or impacts (in this case, the various GHGs, such as CO_2, CH_4, N_2O) from the energy flows, transport, processes and waste management of the materials used and emissions released to air, land and water, both of the system investigated and of other systems affected.

Data collection is the most demanding aspect of completing an LCA (Baumann and Tillman, 2004). Databases are available which provide inventory data on various materials and processes; these are normally split into two categories, which in combination form the basis of a life-cycle inventory (LCI). These are:

- primary data: normally obtained from technology or process users, through direct measurement or analysis
- secondary data: concerning generic material, energy, transport and waste management systems, generally in the literature or databases.

Since this research only measured GHG emissions related to the global warming potential of the AD system, and not the other potential environmental impacts associated with AD (photochemical oxidant potential, eutrophication potential, acidification potential or resource depletion), a full LCI was not completed.

3.3.7 Life-cycle impact assessment

This part of an LCA aims to describe the impacts of the selected environmental burdens from the environmental load established by the LCI, as opposed to just reporting information on emissions and resources use. Other procedures completed within the assessment section include classification, characterisation and normalisation.

- Classification is simply the procedure of aggregating the inventory data according to the environmental impact category they contribute to – for example, GWP, acidification, eutrophication and resource depletion. (Note that inventory data can be assigned to one or more categories.)
- Characterisation is the calculation of the relative contributions to each environmental impact of the emissions and resources consumption.
- Normalisation translates the results into dimensionless units, to allow for comparison against a reference system such as emissions in a country or region over a specific time frame.

At impact assessment stage, an LCA software tool is normally employed that includes an LCI database. This research did not undertake a full impact assessment since it did not proceed beyond the classification stage. If these procedures are not completed, then the study is called an LCI, and not an LCA. This research is a restricted LCA, as it only reports on GHG emissions and the net energy balance of the AD system.

3.3.8 Life-cycle interpretation

Here, the results of the inventory analysis and the impact assessment are considered together. This section pools the information gathered to identify and implement areas of potential improvement. In accordance with ISO 14040 guidelines, this phase should deliver results that are consistent with the goals and scope defined at the start. Limitations should be explained, conclusions reached and recommendations made accordingly. It should also be stated that the results indicate potential environmental effects and do not represent a prediction of the actual impacts on category endpoints (issues of environmental concern, such as human health, resource depletion or animal extinction).

3.4 ECONOMIC ASSESSMENT USING FINANCIAL INVESTMENT METHODS

A fundamental concern of this research is to ensure that the environmental benefits of the AD facility are financially viable, and as financially beneficial as possible, either as a standalone business or as part of an integrated farming business. To this end, the model (see Section 3.5) accounts for the financial offset of the main farm business's existing energy load from the energy generated from AD. To ensure the appraisal is robust and as real-world as possible, a number of different appraisal mechanisms are employed.

This section aims to provide a discussion on the different financial and economic appraisal methods used in this research. There are five separate methods in total. The first four methods are those financial appraisal methods that might be used by either a prospective investor in the technology or a finance house considering offering a loan (Watson and Head, 2012): payback period, return on capital employed (ROCE), internal rate of return (IRR) and net present value (NPV); the final financial/economic method, the levelised discounted cost of energy (LDCe) is useful to governments wishing to assess the minimum required amount of revenue per unit of energy generated, in this case, megawatts. Prior to the discussion of these five methods, some of the main parameters used in calculating these financial appraisal methods are highlighted.

Before considering these various investment appraisal methods, a few assumptions used in this research need to be set out:

- The model operates on straight-line depreciation.
- The lifespan of the building and infrastructure is 20 years (although this may be as long as 30 years).
- The lifespan of the machinery, particularly the CHP genset is, 9 years.
- The project lifetime is 20 years.
- The interest rate used is calculated on a base rate (10-year gilt (2.5%) – the measure of risk-free value of investment) plus the calculated risk premium rate for a project – for this research, 5.5 per cent. This provided an overall total interest rate applicable to the AD project of 8 per cent.
- Capital and operational costs modelled are based on a number of different input parameters (see Appendix 3, Table 1.1)

The aim of investment is to enable a business to ensure the future generation of cash flows and/or to generate new cash flows now and in the future (Watson and Head, 2012). Since capital investments such as AD require large quantities of money, it is essential that careful evaluation of such a project is undertaken to ensure that the company remains profitable and avoids any negative strategic or financial consequences.

The cost of capital is the minimum rate of return (profit) required from an investment of funds. It is often described as the discount rate in the investment appraisal process, particularly in assessing the IRR and NPV. In general, it is assumed that a company attempts to find the cheapest and most efficient method of raising capital, which has the effect of increasing the NPV of that company's activities.

3.4.1 Financial parameters

3.4.1.1 Cash flows for finance

The model calculates two different net cash flows from the many costs and incomes attributable to the technology and business in general: cash flow for shareholders and cash flow for finance (see Table 3-7). It is the latter net cash flow that we are particularly interested in: the cash flow account from which debt repayment is made and from which the IRR and NPV are calculated. It is the balance after inflation-adjusted operational expenditure (OPEX) is deducted from inflation-adjusted income.

Table 3-7 The components in revenues and costs of cash flow in finance

REVENUES	COSTS
Electricity (ROCs, FITs, LECs etc.)*	Feedstock costs (purchasing or growing)
Heat (RHI, private agreement)*	Labour
Fertiliser value	Maintenance
Gate fees (where applicable)	General overheads
Other income	Rates and rent

Note: * including offsetting of own energy

3.4.1.2 The discount rate

The time value of money is a central concept in finance, to companies and investors alike. It is relevant to anyone who expects to receive or pay money over a period of time. Essentially, it states that the value of money changes over time; and it is particularly relevant at the time of writing (2014), with large quantities of money being printed by central governments across the world. The concept is especially important when substantial sums of money are exchanged, either for investment, finance or dividend payment.

The three main factors to be considered are:

- time: if you have money now, you can spend it, or invest it and receive the income from that investment (human nature dictates that we would rather have something now than wait)

- inflation: £100 received today buys a greater number or services or goods than in one or more years' time, as inflation undermines the purchasing power of money
- risk: in taking possession of the money today, you are not at risk of not being paid all or part of your money in the future (Watson and Head, 2012).

Grayson (1967) states that when using discounted cash flow investment appraisal methods, the discount rate can be regarded as having two components: the liquidity preference (preference for having the cash now) and the risk preference (the investor's preference for lower- rather than higher-risk investments, and the demand for greater compensation when financing higher-risk projects). Dependent on the type of investment and risk, risk-adjusted discount rates can sometimes increase, when assuming that there is a constantly increasing risk as the project/financing life increases. In contrast, a constant risk allowance might be appropriate, in which case, the risk-adjusted discount rate should decline over time.

It could be argued that this latter approach is appropriate for AD, since the funding aspect is fixed by the government and index-linked to encourage participants into the market. However, political uncertainty and feedstock security are far from risk-free. Therefore, for the purposes of this model, a constant discount rate has been applied over the period of the project life (20 years).

In the case of investment in AD, the discount rate is often in double figures. Zglobisz *et al*. (2010) used a figure of 10.7 per cent (calculated on the 10-year base rate of 4.67 per cent, plus 4.91 per cent risk premium and an unlevered beta coefficient of 1.29). Beta, or Beta coefficient is used with the capital asset pricing mechanism (not used in this research), which is a model that calculates the expected return of an asset based on its systemic risk and the expected market return. Research completed by Mistry *et al*. (2011a and b) chose 15 per cent discount rate for centralised AD facilities, and anything greater than zero for on-farm farm-waste AD facilities. However, it is difficult to believe that a farmer would treat his investments any differently to a waste management company, apart from not having multiple shareholders to answer to. A farmer also has to get his finance from the marketplace, and therefore has to produce a business plan based on sound principles. Compass Business Finance Ltd, the Anaerobic Digestion & Biogas Association's financial partner, and the Green Investment Bank's partners for AD all suggested 12 per cent was a reasonable hurdle rate for farm-size investment. Hopwood (2011) stated that in order to avoid securing a loan against existing assets, it was necessary to demonstrate that an IRR in excess of 15 per cent would be achievable. Issues arise with finance companies not including all the income (or offset income) attributable to the AD process – that is, nutrient value in the digestate and the value of selling on heat to neighbouring residences or businesses. This research uses a slightly higher figure than Zglobisz *et al*. (2010) of 12 per cent. This is lower than that used by Mistry *et al.* (2011a) and Hopwood (2011), but in line with current on-farm AD financing (Nelson, 2013).

A lengthy debate could ensue on this parameter alone, but is outside the scope of this research. The author's view, however, is that if European economic activities continue to worsen and interest rates remain low for longer (as in Japan), the likelihood is that investors will be prepared accept considerably lower expected returns, possibly as low as 8 per cent.

3.4.1.3 Hurdle rate

The hurdle rate is a simple measure that enables an investor to decide if an investment project is to proceed by assessing if the investment will offer the desired return on the investment. Should the IRR value equal or exceed the hurdle rate, the investment is deemed to offer the return expected; if not, the investment project is rejected. The hurdle rate represents, inter alia, the opportunity cost for investing money in one project over another.

3.4.1.4 Inflation and tax

The effects of inflation and tax on project cash flows need to be considered if rigorous capital investment decision-making is to be achieved, since these factors are inescapable. If an investment project is deemed to be viable using the NPV, the introduction of tax liabilities on profits is unlikely to change the investment decision (Watson and Head, 2010). However, viability can be affected if the profit on which the tax liability is calculated depends on cash flows that are different from what the project generates. This can arise from the introduction of capital allowances, although the impact is small (Scarlett, 1993); it is not of concern in this research, as capital allowances are not included.

Inflation, on the other hand, can have a profound effect on investment decisions, in that it reduces the real value of future cash flow whilst increasing uncertainty (Watson and Head, 2010). Therefore, future cash flows should be adjusted by an expected inflationary rate in order to express them in nominal terms – that is, in cash amounts paid for or received in the future. The amended cash flows are discounted by the nominal cost of capital using the NPV investment appraisal method described above.

The model allows the user to select the estimated tax and inflation rate and to account for both tax and inflationary pressures. However, the model is unable to accommodate fluctuating tax or inflation rates over the term of the project, or to account for specific rates of inflation – for example, construction or fuel inflation.

3.4.2 Payback period

The payback period method, whilst popular, does not allow for the accurate comparison of other uses of capital, suggesting that it should only be used as a screening method. Its advantages are that it is simple to calculate and understand. It does not take into account the uncertainty of future cash flows (Boardman *et al.*, 2006), however, and therefore, if used solely as an appraisal instrument, it does not provide any measure of risk as regards repayment and only implies that a shorter payback period may be more advantageous. The greatest disadvantage of this method lies in the method's inability to take into account the time value of money. The payback model gives equal weight to cash flows whenever they occur during the payback period. However, it ignores the cash flows generated outside the payback period, potentially leaving the investment appraiser to reject an investment that may prove highly profitable in future years. In practice, this probably does not occur, but it does highlight the inadequacy of the measure, although it is one of the main matrices used in the farming sector.

3.4.3 Return on capital employed

The ROCE measure is sometimes known as return on investment (ROI) or accounting rate of return (ARR). Their formulae are similar in that they employ accounting profit as an indicator of the capital employed in the investment project and use accounting profit within their calculations. Accounting profits are not cash flows, which are before-tax operating cash flows, adjusted to take account of depreciation. Depreciation is an accounting adjustment and is not representative of an annual cash flow. The ROI decision rule is to accept the project if the ROI is higher than the arbitrary 'hurdle rate' set by the decision board. If there are two or more mutually exclusive projects, then the one with the higher ROI would be accepted. Like the payback method, it is a simple method, easily compared to the primary accounting ratio used by financial analysts in assessing a company's overall performance. As mentioned, however, it is not based on cash flows, but on accounting profit, which is open to manipulation. Similarly to the payback method, the time value of money is not accounted for, giving equal weight to each future cash flow, regardless of when it occurs. Finally, because the measure is a percentage, and therefore relative, it ignores the size of the investment made.

3.4.4 Internal rate of return

This measure has a strong relationship with NPV (see Section 3.4.5), in that as the cost of capital used to discount future cash flows increases, the NPV of an investment project with conventional cash flows falls. Eventually, as the cost of capital continues to rise, the NPV falls to zero and becomes progressively negative.

The IRR (see Eqn 3-1) of an investment project is the cost of capital (or rate of return required), which, when used to discount the cash flows of a project, produces an NPV of zero. This type of appraisal calculates IRR by linear interpolation and compares it with a target, or hurdle rate. Therefore, the decision rule is to accept all independent investment projects which have an IRR greater than a company's required cost of capital or target rate of return.

Eqn 3-1 $$\mathbf{0 = I_0 - \sum_{n=1} \frac{C_n}{(1+r^{\#})^n}}$$

Where: I_0 = initial investment; C = number of future cash flows; and $r^{\#}$ = IRR.

Using IRR to appraise an investment project would lead the appraiser to accept all projects with an IRR that exceeded the company's required cost of capital (if there were no restriction on capital). However, if the projects are mutually exclusive, IRR does not make it possible to choose which is the best project for the funds and can often be in conflict with the NPV measure (discussed below).

3.4.5 Net present value

This appraisal method, first developed by Hirshleifer (1958), uses discounted cash flows to evaluate capital investment projects. Using the cost of capital or target rate of return, the measure discounts all future cash inflows and outflows to their present value. It then compares the present value of all cash inflows with the present value of all cash outflows. A positive NPV indicates that an investment in a particular project is expected to give a return in excess of the cost of capital, and will therefore lead to an increase in shareholder wealth.

Eqn 3-2 $$\mathbf{NPV = -I_0 + \sum_{n=1} \frac{C_n}{(1+r)^n}}$$

Where: I_0 = initial investment; C = sum of n future project cash flows occurring annually for n years; and r = cost of capital or required rate of return for the investment. Here, the decision rule is to accept all investment projects with a positive NPV if there are limitless funds. If, however, two or more projects are mutually exclusive, and only one can proceed, the project with the highest positive NPV would be selected.

NPV clearly offers advantages over the payback period and ROCE appraisal methods, since the time value of money is accounted for and cash flows are used rather than accounting profit. Both of these are key concepts in corporate finance, in that there are no constraints on capital and the measure offers sound investment advice. The only serious criticism of the measure is that it only accepts projects with a positive NPV, represented in a perfect capital market which has no restraints on available finance, and this limits the efficacy of the measure.

This measure assumes that the cost of capital is known and remains constant over the life of the project. In reality, the cost of capital is difficult to assess, and therefore selecting an appropriate discount rate is not a simple task. In fact, the cost of capital is likely to change over the life of the project, being influenced by the dynamic economic environment within which the company operates. However, if this change can be forecast, the NPV method can accommodate the change within its calculation.

3.4.6 Net present value verses internal rate of return

There are technical differences between the use of NPV and IRR. These depend on a range of parameters, including the length of the project and changes in the cost of capital over the lifetime of the project. Watson and Head (2012) state that 'there is no conflict' between the two measures when a single investment project with conventional cash flows is evaluated. However, the NPV method may be preferred when:

- mutually exclusive projects are being compared
- the cash flow of a project is not conventional
- the discount rate changes during the life of the project.

3.4.6.1 Mutually exclusive projects

In mutually exclusive projects, in which only one of two projects may progress, using the NPV decision rule, the project providing the greatest NPV would be the project to succeed; and so it is when using the IRR decision rule. Conflict arises where both the IRR values exceed the cost of capital and both NPVs are positive. In such cases, the project with the higher NPV value succeeds, even if the other project has a higher IRR value.

3.4.6.2 Conventional and unconventional cash flows

A conventional cash flow would be one that may be both positive and negative throughout the lifetime of the project – for example, when there are decommissioning or remediation costs at the end of a project. The NPV calculation can easily accommodate these fluctuations, whilst IRR cannot and could, on occasion, cause an analysis to reject the project. This is unlikely to occur in an AD appraisal, since the costs of decommissioning are not likely to be excessive and, depending on future energy and agricultural policy, might even be reduced.

3.4.6.3 Changes in discount rate

Some investment companies not only apply a fixed-term discount rate, but also apply several other discount rates, representing differing aspects or stages of the project, including a gradually diminishing discount rate. This is meant to represent the diminishing risk associated with paying off the loan over time. Once again, the IRR method is unable to account for these changes in discount rates, whilst the NPV method can. It could be possible to have fluctuating discount rates over the project lifetime of an AD facility, dependent on the lifetime of feedstock supply contracts or environmental changes affecting the long-term supply of feedstock.

In summary, the NPV method is held to be technically superior to IRR, due to its flexibility to measure accurately the financial strength of an investment against a number of differing changes to the parameters in its calculation. Watson and Head (2012) argue that measures using discounted cash flows are superior to more simplistic appraisal methods (payback period or ROCE); however, many companies use a basket of appraisal methods, which has made it difficult to assess the benefit of using a discounted cash flow approach.

Investment decisions in business projects are often evaluated by discounting future cash flows to the present value (see Section 3.4.5). Alternatively, they can be evaluated by the annual capital return expected from the capital investment (see Section 3.4.4).

3.4.7 Policy investment decision criteria

Two calculations are made in Section 8.8 that make an assessment of the cost of various energy-generating technologies over the expected lifetime of the technology (approximately 20 years). The first, the levelised cost of energy generation, is a calculation frequently used by governments, whilst the second is a measure devised specifically for this research. Both of these are discussed in the following subsections.

3.4.7.1 The levelised discounted cost of energy generation

The LDCe represents a method for identifying the price at which electricity must be generated (from a specific source) to provide a break-even value over the lifetime of an energy project. It is an investment tool frequently used by regulators and governments (Evans and Hunt, 2009) for recommending building plant types with the lowest LDCe. DECC (2011b) estimated the levelised costs of energy generation for a number of renewable technologies, including AD (see Table 3-8).

Table 3-8 Estimated levelised cost ranges (£.MW^{-1}) for electricity technologies

Technology	Offshore wind	Onshore wind	Solar PV	Dedicated biomass	Biomass co-firing	Biomass conversion	AD < 5MW	CCGT	Nuclear*
Max.	191	127	380	165	110	128	194	79	108
Min.	149	75	202	127	94	106	75	76	90

Source: Adapted from DECC (2011b) and (2013e: Table 6*)

CCGT = combined-cycle gas turbines

The same calculation (see Eqn 3-3) has been completed on the model-runs of this research to establish the levelised costs of energy generation associated with the four different scenarios (see Section 3.6).

Eqn 3-3

$$LDCe = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

Where: LDCe = average lifetime levelised electricity generation costs; I_t = all investment expenditures in the year *t*; M_t = all operational and maintenance costs in year *t*; F_t = all fuel expenditures in the year *t* (in this case, the cost of purchasing or growing feedstock); E_t = electricity generation in year *t*; r = discount rate (this was set at 12 per cent, the same as for calculating NPV); and n = lifetime of the project (20 years).

Evans and Hunt (2009) argue that the measure is a coherent accounting tool, yet they question its economic relevance to cost-minimising plant choice. Also, it only measures the costs from generating energy and cannot account for benefits such as technologies that generate electricity with lower GHG emissions.

This research has used the metrics as a measure of comparing the technology against other traditional and renewable energy sources (see Section 8.8.1), and against the different scenarios developed (see Section 3.6).

3.4.8 The levelised cost of carbon mitigation in energy generation

The aim was to compare the costs of mitigating 1 tCO_{2eq} from some renewable energy-generating technologies and from some traditional energy-generating technologies, such as nuclear and gas, against the same costs for coal. However, the only levelised cost figures found for coal (DECC, 2013e) were based on projects starting in 2025, including CCS, which is not currently operational in the UK. Therefore, the data were normalised against the second most popular energy-generating fossil fuel – combined-cycle gas turbines (CCGT).

The calculations used are as follows: for CCGT, the calculation is simply a matter of dividing the levelised cost of energy (*LC_E*) (£79) by the emission factor (*EF*) (930 kg CO_{2eq}.MW^{-1}), which is multiplied by 1000 to achieve t CO_{2eq}.MW^{-1} (see Eqn 3-4).

Eqn 3-4 $$LC_C = \frac{LC_E}{EF \times 1000}$$

To compare the additional cost of mitigating carbon against the cost of energy generation by gas, both the levelised costs and the emission factors of the technology are subtracted from the CCGT values. In doing this, the cost of mitigating CO_{2eq} is calculated against the cost of mitigating CO_{2eq} from CCGT (see Eqn 3-5).

Eqn 3-5 $$LC_C = \frac{LC_E - LC_{E\,CCGT}}{(EF - EF_{CCGT}) \times 1000}$$

In Section 8.8.2, the use of this calculation is discussed further, along with the results from this research compared to other energy-generating technologies.

3.5 ASSESSING ANAEROBIC DIGESTION USING A COMPUTER MODEL

This is the fourth method used in assessing AD in England. As previously summarised (see Section 2.2.1.1.1), certain 'off-the-shelf' computer models were thought to be inflexible or not transparent enough to realise this research's aims and objectives (see Section 2.8). To that end, the decision was made to build a computer model using MS Excel. A bespoke computer model (see Chapter 5) would provide the platform on which both the LCA and economic methods could be combined, using the data collected from a number of sources (see Section 3.3.5.15), and from the case study questionnaire and interviews (see Section 3.2), and which would enable this research's aims and objectives to be achieved. It was named the Anaerobic Digestion Environmental and Economic (ADEE) model.

The aim was to construct a model that required as few input variables as possible, but was flexible enough to model a number of different feedstock types under different regional environmental conditions. The outputs should be comprehensive and able to meet the research's aims and objectives, either alone or in conjunction with other outputs or calculations.

Once the computer model had been built and validated (see Chapter 6), a general approach (see Section 3.7) was sought to deal with the considerable quantity of data needed in assessing four different scenarios (see Section 3.6) of AD in three regions of England (see Section 3.3.4).

3.6 FOUR SCENARIOS OF ANAEROBIC DIGESTION IN ENGLAND

The final part of the methodology was to develop four scenarios that would explore four different pathways of the deployment of AD in England. The aim was to assess if there is a preferential pathway of deployment or scenario that achieves this research's objectives. This, in turn, would help to answer the research's aim of understanding if the current role of AD is one of waste management, carbon mitigation or energy generation (see Section 1.7).

Each scenario provides a focus on one or more of the government targets agreed in Europe in waste management (scenario one, two, four), renewable energy generation (scenarios two, three and four) and GHG mitigation (scenario two). The four scenarios are:

- scenario one: using biowaste only, in centralised AD facilities
- scenario two: adopting the hub-and-pod concept, providing an option to help treat the low-energy feedstock types
- scenario three: crop-only, large, on-farm AD facilities
- scenario four: a combination of scenarios one and three.

Creating the four different scenarios also allowed the comparison of the different environmental and economic costs or benefits associated with utilising specific feedstock types, and helped to develop a better understanding of which scenario might answer the research objectives most comprehensively. It also helped to assess the present scenario that AD is likely following, based on current incentives for the technology.

Scenarios one and three are the simplest to follow, with scenario four only offering a simple mix of scenarios one and three. Scenario two offers an alternative route, not currently seen in the UK, and seeks a use for the technology that makes use of the available waste feedstock types, with the aim of mitigating GHGs from three different business sectors (agriculture, waste and energy). Scenario two represents an alternative method of fully integrating the treatment of several different feedstock types, using a concept that brings potentially biohazardous waste materials to a farm setting hygienised and homogenised, thereby allowing the safe treatment and use of this material with other materials for beneficial purposes (see Section 2.4.5).

3.6.1 Scenario one: biowaste only

Four case studies fell into this category, either completely or partially. Two were dedicated biowaste treatment facilities that required full pasteurisation and decontamination facilities; two others were specialist waste treatment facilities, utilising creamery, and fruit and vegetable waste, respectively. Approximately one-third of the AD facilities back in 2010 were centralised AD facilities; however, few of these were in the three regions chosen for this thesis, and only two facilities were prepared to be interviewed or to provide any level of detail on their operations. This type of facility varies considerably across the country, ranging from the small (for this this type of facility), at approximately 500 kW capacity or 15,000 t biowaste per annum, to 100,000 t biowaste per annum with installed capacities in excess of 3 MW. For the purposes of this research, three different biowaste AD facilities were assessed, based on the quantity of feedstock treated and current trends. These were 15,000 t, 40,000 t and 100,000 t of feedstock being treated. As the quantity of feedstock increased, the transport distances of both feedstock and digestate also increased. The final model-runs chosen to represent this scenario were based on facilities treating 40,000 t biowaste per annum, which are financially viable, and operate within a catchment size that does not require the transport of large quantities of feedstock or digestate across great distances.

Whilst it is possible for a certain amount of feedstock to be transported across regional divides, it is highly unlikely that there would be international transport of the biowaste material because of the cost (both economically and environmentally). It is quite likely that the biowaste material will travel out from the centre of large urban cities into the surrounding regions. Areas such as London could represent a considerable source of this feedstock type and be able to support its neighbouring regions (the East of England; the South East of England). However, for the purposes of this research, it is assumed that each region is autonomous and self-contained.

3.6.2 Scenario two: the hub-and-pod concept

Section 2.4.5 introduced the hub-and-pod concept, a system whereby large quantities of biohazardous material can be safely treated away from livestock and agricultural produce, with the aim of introducing small quantities of the treated material to supplement the treatment of the low-energy (livestock) feedstock types. The reason for introducing this concept is to allow for more of the biowaste material to supplement the treatment of a greater quantity of some of the on-farm livestock wastes that would not otherwise be treated. These livestock wastes are pollutants in their own right (see Section 2.4.1), potentially emitting GHGs to the atmosphere whilst they wait to be spread to fields in a timely manner.

Whilst AD does reduce the quantity of GHG emissions to the atmosphere by capturing and utilising the methane from slurry and manure heaps, as well as emissions from landfill sites, it could act as a source of other air-emitting pollutants (ammonia) if the digestate is not kept covered (see Section 2.5). Like the untreated livestock slurries, digestate needs to be applied to land carefully and in a timely manner, to ensure that local watercourses are not polluted; but more importantly, so that the valuable nutrients within the digestate are delivered to the soils and crop when they are most required. AD helps to achieve these two mitigating measures: first, in providing a treatment process for these materials; and second, in providing a source of income (from energy generation) that can help towards the costs of some of the equipment (storage and delivery), without seeking government support from Common Agricultural Policy incentives.

3.6.2.1 Benefits

There are many benefits to adopting this system:

- Regulators and farmers should be more comfortable that the material brought on to their land is a significantly reduced biohazard to their livestock and crops, since it is both contained and pasteurised. The material is placed directly into a receiving tank, where it is held before mixing and the moving into the digester for treatment. It also provides a method for the farmer to gain access to a secure, long-term, good quality feedstock source.
- A greater number of farmers are able to treat their on-farm agricultural waste materials with the supplement of these biowaste materials, without having the added financial investment associated with facilities treating raw biowaste materials. This does, of course, come at a reduced gate-fee price in compensation for receiving pre-treated material; however, the pods should still be able to receive about half the gate fee.
- It could help the government to meet several of its environmental targets: the diversion of biowaste material from landfill, the generation of renewable energy, and the reduction of GHG emissions from three sectors that have had difficulty meeting their carbon reduction targets.

3.6.2.2 Costs

The environmental and economic costs should be no worse, particularly if the heat required for pasteurisation at the hub, is received from CHP gensets or other waste heat sources, which should be included within the overall strategy in developing the hub-and-pod method.

Financially, the hub-and-pod system permits the reduction of some of the additional capital equipment (and therefore costs) required at the pod for the complete on-site treatment of biowaste, including a large reception building, a decontaminant separation unit and other associated equipment. Depending on the quantities of materials and the degree of contamination (plastics, metals and other unidentified objects), this research estimated (from discussions with its case study operators) that the approximate additional cost would be a minimum of £600,000, based on an AD facility receiving approximately 15,000 t of municipal, commercial or industrial wastes per annum. Also, total labour costs would be lower, since the requirement to operate all the additional waste-treatment technologies is now off-site. Therefore, labour costs for the hub-and-pod system were fixed during modelling, so as not to take into account the additional activities that would occur at an AD facility receiving (and treating) biowaste materials. This is the same for the additional capital equipment that would normally be required at the AD treatment site, but would be removed under the hub-and-pod scenario, as these costs would now be associated with the 'hub', and not the 'pod'.

However, the biowaste material still needs to be treated in a compliant manner, as described by AHVLA (see Section 2.4.2.1), so that the safe treatment and disposal of these materials to agricultural land can occur. As part of that requirement, there is still a need to pasteurise the digestate, before it leaves the system, at 70 °C, for one hour.

Unlike scenarios one, three or four, the size of the treatment facility is not fixed, but is dependent on the size of the livestock farm where the AD facility is based, and therefore the quantity of expected slurry produced and the other available feedstock types in the region. The aim is not to maximise profits, but to enable the treatment of the greatest quantity of livestock feedstock in a given region. Chapter 7 sets out the detailed methods used in developing the individual model-runs that were used in building the hub-and-pod scenario.

3.6.3 Scenario three: crop-only facilities

The pathway to generating energy in this scenario is in crop-only facilities. A number of facilities have been built in the last few years that are making use of crops that have been designed specifically for digestion and energy generation. It is mainly maize and other grasses that are used, but root crops are also utilised, depending on the local soil and environmental conditions.

Grass and maize silage were the two crop derivatives chosen for the various model-runs whilst developing the hub-and-pod scenario. These two crops are well-used in England as feedstock types and have proved to be grown easily across the country. In the West of England, grass is commonly grown as a fodder crop and there are large areas where the topography makes it difficult to cultivate other crops.

However, when building the crop-only scenario, a third crop is introduced (barley (whole crop) silage) as a supplement to the two other crops. It is assumed that yield per hectare is less, at 30 $t.ha^{-1}$, than for grass and maize, which were both assumed to have a national average yield of 45 $t.ha^{-1}$ (Nix, 2012), but barley's biogas yield is slightly higher than grass silage's and offers an alternative to most regions. The chosen facility size was 26,000 t in total, comprising 18,000 t maize, 4,000 t grass and 4,000 t barley (whole crop) silage.

3.6.4 Scenario four: a combination of scenarios one and three

As the scenario title suggests, this is a combination of scenarios one and three. None of the other parameters change: the facility size and assumed feedstock types remain the same.

With this in mind, investigation is carried out on how the higher-energy feedstock types (such as biowaste materials and other mobile feedstock types) could best be distributed across the greatest number of farms producing low-energy waste materials (the static feedstock types), along with a small quantity of crops specifically grown for energy, without significantly impacting on existing farming practices or neighbouring businesses, or indeed causing direct or indirect land-use changes (LUC or iLUC respectively) that could impact on climate change or biodiversity.

Again, the aim was to compare the environmental outputs with scenarios two and three; therefore, the total installed electrical capacity was set as for the other two, and the number of facilities required was calculated as follows. The quantity of energy generated from biowaste is restricted by the available feedstock in the region, so the quantity of energy generated from this feedstock was calculated first. The total energy generated from scenario one was deducted from the total installed capacity calculated in scenario two (see Table 8-7). The remaining energy supply is generated from crop-only facilities, at the same scale modelled for scenario three. For example, if the total energy generation from scenario one was 20 MW, and the total electricity generated in scenario two was 100 MW, the remainder would be made up from crop-only facilities. If these were 4 MW facilities, then 20 additional crop-only facilities would be required to complete the scenario. This would be in addition to the number of biowaste-only facilities calculated for scenario one.

3.7 THE GENERAL APPROACH TO ASSESSING THE ROLE OF ANAEROBIC DIGESTION IN ENGLAND

Having developed the ADEE model encompassing LCA and economic methods of assessment, and defined four scenarios for the potential development for AD, the next challenge was to utilise the modelling tool meaningfully in order to address the research objectives using the methods defined above. This section, in conjunction with Chapter 7 discusses the various steps taken out to achieve this research's aims and objectives.

The general approach in assessing scenarios one, three and four was very similar and straight forward, since they were either single-feedstock facility types (scenario one), facilities co-digesting three crop types (grass silage, maize silage and whole-crop barley silage) (scenario three), or in scenario four, a mix of both facility-type digesters. This section will focus on the methods adopted for assessing these three scenarios, while the more complex scenario two will be explained in detail, with output examples, in Chapter 7, with the exception of the evaluation of biowaste. Biowaste feedstock types were utilised in three of the scenarios (one, two and four); therefore, the discussion on the quantification of this feedstock follows below, before the evaluation of scenario one.

3.7.1 Biowaste in England

For the purposes of calculating the quantities of biowaste available in the three English regions chosen for this research, biowaste was split into two types: first, municipal waste from household kitchens; and second, biowaste materials from C&I and retailing businesses.

3.7.1.1 Household food waste

Further to the discussion in Section 2.4.3, DEFRA (2011b) published national data for household food waste, calculating that approximately 7 Mt of household kitchen waste and 16 Mt of food waste were produced across the whole of the food industry per annum. Most analysis of national household waste uses a mass balance approach from data from the waste industry, and provides gross figures for a region or nationally. Hogg *et al*. (2007) calculated that household food waste in the UK equated to approximately 18 per cent of total household waste (approximately 216 kg per household per annum). A waste density map for England and Wales (see Figure 3-4) was produced by multiplying this figure of kitchen waste produced per annum by the number of households in England and Wales represented at the Lower Output Areas, as provided by the Department for Communities and Local Government (DCLG). As one would expect, the greatest density of waste produced per annum is from urban areas.

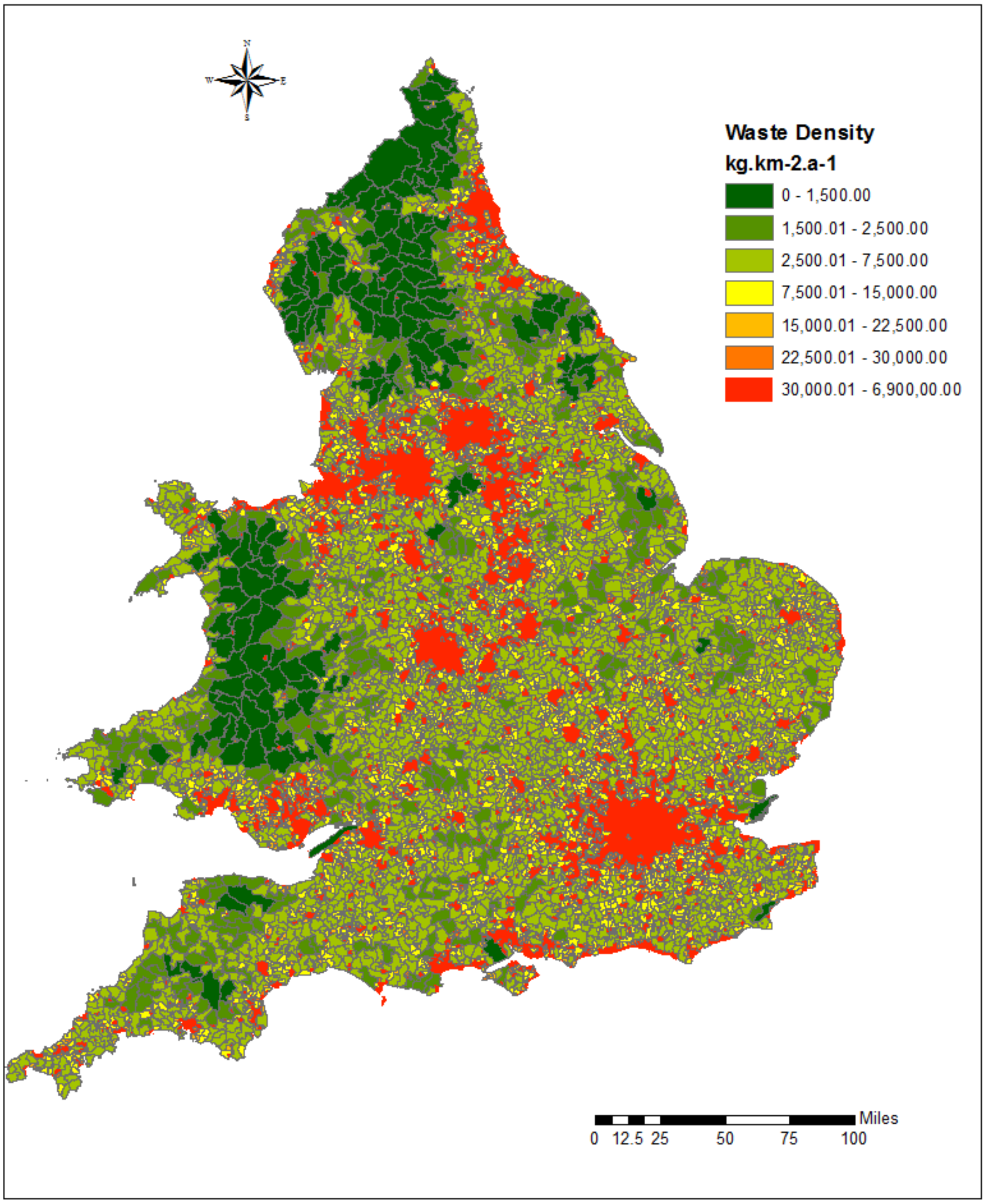


Figure 3-4 Household waste density map across England and Wales

Source: DCLG (2012) (number of households at Lower Super Output Areas), combined with Hogg et al. (2007) (household kitchen waste data)

3.7.1.2 Food industry biowaste

No detailed information of food industry biowaste at a national level was found, with only basic information found at the regional level (see Section 2.4.3). For the purpose of developing the model-runs at the national level, it was assumed that there were sufficient local quantities to develop each of the model-runs discussed here.

The model-runs with commercial, industrial and household food waste/biowaste all assumed that the material received would be processed through the hub-and-pod concept (see

Sections 2.4.5 and 3.6.2). In scenario four (see Section 3.6.4), it was assumed that the hub-and-pod concept would not be used, and that existing traditional methods of collection and treatment would take place.

3.7.1.3 Calculating the quantity of biowaste feedstock in the three chosen regions

The most challenging category of feedstock type to assess was the availability of municipal, commercial and industrial biowaste. No primary data were found or made available; all calculations in this research were based on figures produced from other researchers' estimated or modelled results. Quantities of C&I biowaste (see Table 3-9) were obtained from a number of sources, as individual research was commissioned by the different regions' development agencies. The most complete set of data for a single region was for the East of England (Papineschi *et al.*, 2008). The quantity of municipal household food waste in each region was estimated using the number of households in a region (provided by the DCLG), multiplied by the annual waste factor per household (Papineschi *et al.*, 2008).

Data highlighted in beige in Table 3-9 were used in this analysis to represent the biowaste material available for AD treatment in the region. The quantity of green waste was included for each region; however, it is possible that not all of this material would be suitable for the AD process, particularly the more woody (lignocellulosic) material from trees and shrubs, which would be better suited for composting. The figures used for C&I biowaste were taken from Graham *et al.* (2010). At the time of writing, this was still the most recently available dataset and echoed the data produced by Papineschi *et al.* (2008), who produced the most transparent method of calculations. Suffice it to say that the quantity of this type of feedstock either produced or available brings the greatest uncertainty to the modelling of AD at the regional level. There is probably more feedstock produced than displayed in Table 3-9, but at the same time, there is potentially less available, with the greater amount presently being landfilled or used for other purposes, such as incineration.

Table 3-9 Municipal, commercial and industrial biowaste calculated in three English regions

Parameter	East of England	South West of England	West Midlands
Number of households*	2,550,010	2,342,986	2,387,400
Author's calculated household food waste (t) based on 3.85 kg/hhd/wk (200 kg/hhd/a)	510 ktpa	468.6 ktpa	477.5 ktpa
Green wastes – gardens, parks, etc.	519 ktpa†	430 ktpa‡	400 ktpa§
Municipal food waste	524.4 ktpa†		
Food waste – healthcare sector	11.8 ktpa†		
Food waste – education sector	5.2 ktpa†		
C&I fruit & veg. (avail.)	82 ktpa (18 ktpa)†		
C&I red meat slaughtering (avail. Cat. 3)	64.4 ktpa (20.2 ktpa)†		
C&I poultry slaughtering (avail. Cat. 3)	231.8 ktpa (206.8 ktpa)†		
C&I food-processing (avail.)	99.1 ktpa (49.6 ktpa)†		
C&I other – brewing, baking, animal feed, etc. (avail.)	57.8 ktpa (4.7 ktpa)†		
C&I supermarkets	32.6 ktpa†		
C&I offices	41.3 ktpa†		
C&I high street	43.3 ktpa†		
C&I hotels/pubs/bars/restaurants	135 ktpa†		
TOTAL C&I arisings (available)	**787.3 ktpa (551.5 ktpa)†**		
OTHER RESEARCH OF C&I ORGANIC WASTE ARISINGS ESTIMATES			
Total C&I (Enviros Consulting, 2009)	884 ktpa	670 ktpa	609 ktpa
TOTAL C&I (Graham *et al*., 2010)	580 ktpa	541 ktpa	664 ktpa
Total MSW + C&I (Yellen 2010)			789ktpa
Total HH food waste (Mistry *et al*., 2011)	586,000	559,000	593,000
Total C&I food waste (Mistry *et al*., 2011)	550,000	441,000	358,000
Total garden waste (Mistry *et al*., 2011)	412,000	393,000	418,000
TOTAL C&I (Jones, 2009)	506ktpa	486.8ktpa	393.6ktpa
TOTAL C&I 2020 **est. reductions** (Jones, 2009)	-78.3ktpa	-33.6ktpa	-14ktpa

***DCLG (2012) from the 2011 census; †Papineschi *et al*. (2008); ‡ Fitzsimons and Larsson (2007); § Yellen and Bailey (2010)**

Having now established the available biowaste feedstock types and quantities in the chosen regions, the evaluation of the three scenarios utilising these figures (in beige) can be discussed.

Before assessing the scenarios, however, it is important to understand that a number of precursory model-runs and baseline parameter assumptions were made, so that a sensitivity analysis could be completed on the developed scenarios. These are discussed in Chapter 7 as part of the more complex analysis in the development of scenario two (see Section 3.7.3).

3.7.2 Assessing scenario one

Whilst a lot of time was spent researching the available quantities of various biowaste feedstock types for this thesis, for modelling purposes, this waste was all treated the same. This is not entirely ideal; but it was considered that whilst the output data would differ slightly between individual AD facilities, the overall results across the regions would be the same. It was very important to quantify the amount of biowaste available in a region, as this is the only scenario that is limited by the quantity of feedstock available. It is assumed that all regions are self-contained, with no movement of feedstock across their borders.

Using the computer model developed for this research, a series of model-runs was made, based on the treatment of different quantities of feedstock. The quantities were based on the capacities of two case studies and the common quantities of other digesters currently in operation in England (see Table 3-10).

Table 3-10 Examples of the input data for scenario one model-runs

	Biowaste 1	**Biowaste 2**	**Biowaste 3**
Quantity of biowaste used ($t.a^{-1}$)	15,000	40,000	100,000
Distance from source (miles)	20	50	100
Electrical conversion efficiency (%)	39	39	39
CHP genset size required (kW)	766	2,042	5,487
Feedstock gate fee (£)	25	25	20
Heat use in addition to parasitic requirement (%)	10	10	10

The second model-run was used in the calculations for scenario two. This was an arbitrary choice, since there were similar numbers of each (approximate-sized) plant across England. There were few data on the distances travelled by the feedstock or what happened with the digestate; this information was only available from the two case studies operating at the smaller scale. However, it was prudently assumed that as the quantity of feedstock increased, the catchment area would also increase to supply the AD facility.

To calculate the total energy generated and GHGs mitigated over a whole region, the total quantity of available biowaste in that region was divided by the quantity treated at a single facility, in this case 40,000 t. This provided the number of facilities (rounded up) required in a region, which could then be multiplied by the outputs of the single facility (see Section 8.2.1). This provided the potential for AD treating biowaste only in an English region.

3.7.3 Assessing scenario two

As mentioned in the introduction of this section, this was the most complicated of the four scenarios, and its development is best explained with results from the model. (see Chapter 7).

3.7.4 Assessing scenario three

This was calculated in a very similar manner to scenario one, with one exception, that in theory, the quantity of feedstock available for this scenario is only limited by the quantity of agricultural land in a region. Various combinations were used; however, due to the few data available at the time of investigation, the quantities followed those of case study 3 (model-run CropOnly2), shown in Table 3-11.

Table 3-11 Examples of the input data for scenario three model-runs

	CropOnly1	**CropOnly2**	**CropOnly3**
Quantity of maize silage used ($t.a^{-1}$)	14,000	18,000	28,000
Quantity of grass silage used ($t.a^{-1}$)	4,000	4,000	3,000
Quantity of barley silage used ($t.a^{-1}$)	4,000	4,000	4,000
Distance from source (miles)	6	6	6
Electrical conversion efficiency (%)	39	39	39
CHP genset required (kW)	1,042	1,244	1,716
Assumed heat use in addition to parasitic requirement (%)	10	10	10

The calculations required to estimate the regional results were slightly different to those for scenario one, as a result of the feedstock not being restricted in volume. Therefore, the outputs for scenarios three and four were made comparable to the outputs for scenario two's electricity generating capacity ($kW.a^{-1}$) in each region. Once scenario two's outputs had been established, the following calculation was made. The total electrical generating capacity was divided by the annual output of model-run CropOnly2. This established the number of AD facilities that would be required to generate the same quantity of electricity (rounded up). From this, all the other economic and environmental scenario outputs could be calculated, which allowed a direct comparison to be made between this scenario and scenario two; and, as will be explained next, between this scenario and scenario four (see Section 8.2.3).

3.7.5 Assessing scenario four

The assessment of scenario four was based on a combination of scenario one and scenario three. The model-runs (or facility scenarios) chosen to represent these two scenarios were also chosen to represent this scenario. Since biowaste was once again the restricting feedstock, the quantity of electrical capacity was subtracted from the total capacity established for scenario two. The remaining capacity was made up by the electricity generated by the facility model-run of scenario three. This established the number of AD biowaste facilities and crop-only facilities required to generate the same quantity of electricity as for scenario two (established in Chapter 7) and scenario three (established above), displayed in Section 8.2.4. From these calculations, a comparison between the four scenarios and other renewable technologies was made possible, as discussed in Chapter 8.

3.8 SUMMARY

In summary, this research uses the core methods of life-cycle and economic assessment to establish the most effective scenario for developing AD that maximises energy generation and CO_{2eq} mitigation. The ADEE model measures the economic viability as well as the GHG and net energy balances of an AD system, governed by the scope of assessment set out in the ADEE model diagram (see Figure 3-3). In following an expanded LCA method, the aim is to provide a rigorous evaluation of the technology that would be of interest to a number of interested stakeholders. The financial measures employed are commonly used in assessing investment projects of this scale.

This research aims to utilise the developed modelling tool to explore the potential role that AD could play in three regions of England, using four different scenarios, and assessing what impacts the technology might have on both the environment and the economy, depending on the incentives and regulations in force.

Chapter 4: Case studies

'I know of no pursuit in which more real and important services can be rendered to any country than by improving its agriculture, its breed of useful animals, and other branches of a husbandman's cares'.

George Washington (1732–1799)

4.1 INTRODUCTION

One of the greatest strengths of this research is the number of case studies that were used. There were fewer than 75 operating AD facilities in the UK at the time that this research began (2010), and interviews were secured with 13 of them. Previously, most research had focused on either a single digester (Mezullo, 2012) or on just two or three (Jones, 2010; Banks *et al.*, 2011; Styles *et al.*, 2013). However, as will be demonstrated in this chapter, each AD facility is different. Therefore, to ensure that the ADEE model being developed was accurate and robust, the following data were required: greater detail of the variability within the industry of the feedstock types digested or co-digested; the costs associated with the different feedstock types; and the variation between the observed data and the literature with regard to outputs.

4.2 PURPOSE

The three main reasons for using case studies were: to gather data not available in the literature; to verify the literature or expose differences; and to provide a means of validating the results of the model against real-world experiences. The aim, therefore, was to ensure that the model provided results of life-cycle and economic analysis of AD in England that were as accurate as possible, based on the inputs provided.

Previous research (see Chapter 2) had suggested that there were gaps in the published data relating to the capital expenditure (CAPEX) and operational expenditure (OPEX) of AD. Only three reports (Jones, 2010; Black and Veatch, 2010; and Mistry *et al.,* 2011a) had provided a method of calculating costs, two of which were unable to calculate the CAPEX of some of the case studies. Further investigation was required. There was little detail of system requirements at different scales, or of some of the finer details relating to construction materials and quantities used. Aspects of the technical design of a digester, which would help to inform the model of the required amount of capital, were also lacking. This was particularly important in assessing the embodied energy of the facility from the quantities and types of materials used in its construction.

The AD industry was still young when this research began, so the opportunity was taken to gain an understanding of the experiences of operators of setting up and running an AD facility. However, this was secondary to the other data collection; as such, 11 short, open-ended questions were put to the interviewee towards the end of the interview, if time allowed (see Appendix 2).

4.3 METHOD

4.3.1 Selecting case studies

When this research commenced in 2010, the official UK AD portal, run by NNFCC, estimated fewer than 75 AD facilities operational across the UK, with a further dozen in planning or construction. Many of these operational facilities had only been fully operational for a few years and were experiencing 'teething' issues that are discussed later (see Section 4.3.3). Therefore, there were few facilities nationally that had long-term experience.

UK maps of the number of AD facilities were produced in September 2011 (see Figure 4-1) and June 2014 (see Figure 4-2). There is a difference in the symbology between the two maps, explained at the bottom of each one. The 2011 map provided enough information, in most cases, to contact the owners of the AD facilities. The aim, therefore, was to contact the operators of as many facilities as possible, within each of the three (provisionally) chosen regions, that represented the different-sized AD facilities and different treatments of feedstock. Over 40 of the known operators were approached, either directly or via their technology provider, where stated on the AD portal or other websites. Many were not receptive to being interviewed, even though complete anonymity was assured. For this reason, the case studies could not be subject to an academic sampling strategy; willingness to participate was the prime driver in deciding which case studies to include.

The interviews of 12 case studies took place during March and April 2012: three in the East of England, four in the South West of England and five in the West Midlands. Seven additional examples were provided (as case studies) by two technology providers, who were interviewed and provided these data as examples to potential clients; two, in fact, were feasibility studies for one technology provider's customers, representing additional real-life case studies. Over a year later, a thirteenth technology user agreed to be a case study, but due to distance and time available, the interview was completed by phone and the questionnaire was completed by email in mid-2013.

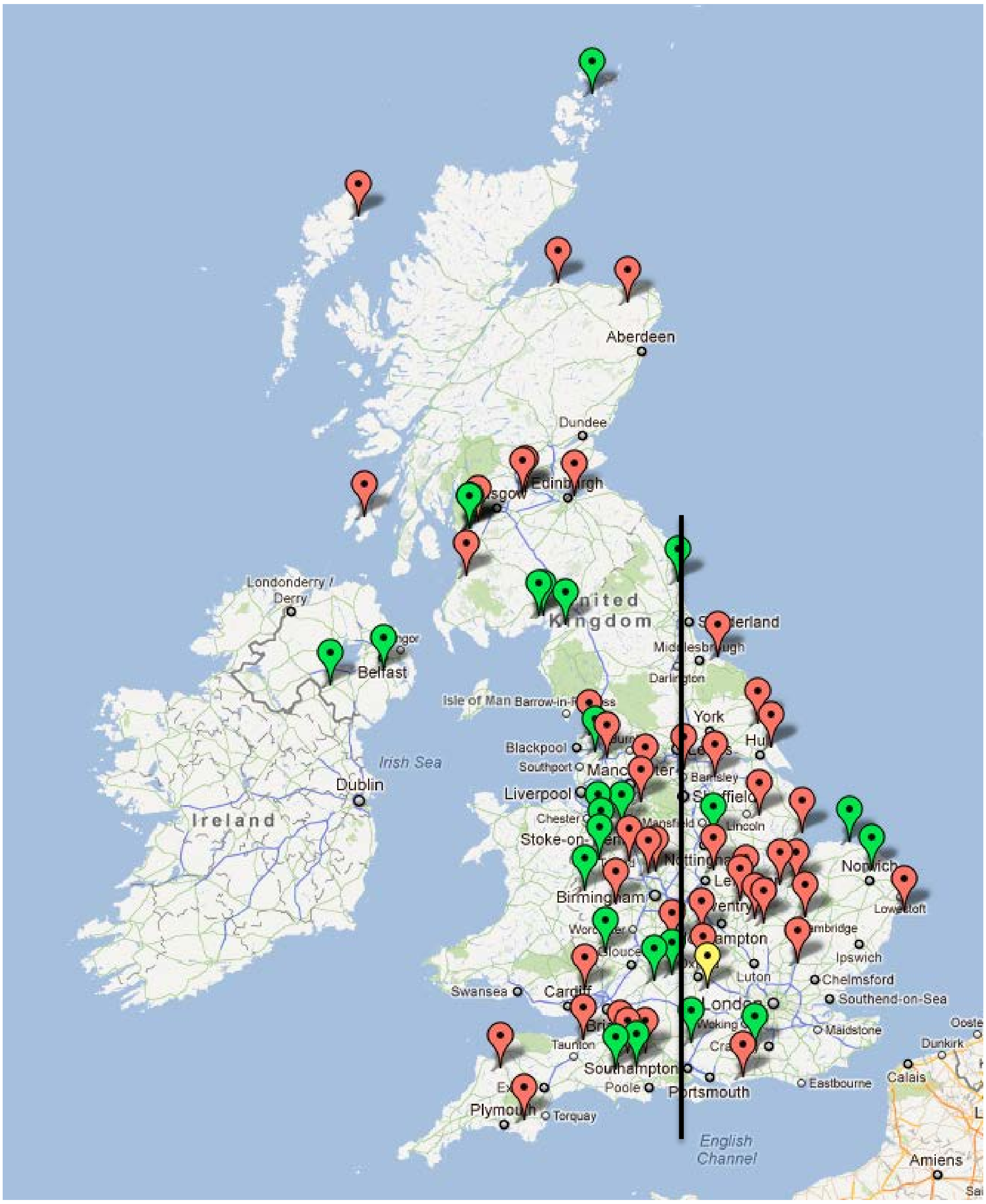


Figure 4-1 Approximately 70 AD sites operating across the UK, 2011. Source: The Official Information Portal on Anaerobic Digestion (accessed September 2011)
Notes: Green flag = agricultural-only digester; red flag = food-waste-only digester; yellow flag = AD facility injecting to the grid (only one operating at the time); black northing line = divide between the 'East' and West' descriptions used in this thesis

To maintain anonymity, each case study name is replaced with a number in this thesis, and the geographical location of each site is identified as either East or West. Of the 13 case studies used in this research, four were in the East and nine in the West. It is difficult to compare these two maps, since the categorisation changed between 2011 and June 2014, when the latest map was produced (see Figure 4-2). This makes it more difficult to assess which type of facility is beginning to dominate over another. However, there has been a significant increase in the number of industrial facilities treating their own waste materials (which was not categorised before).

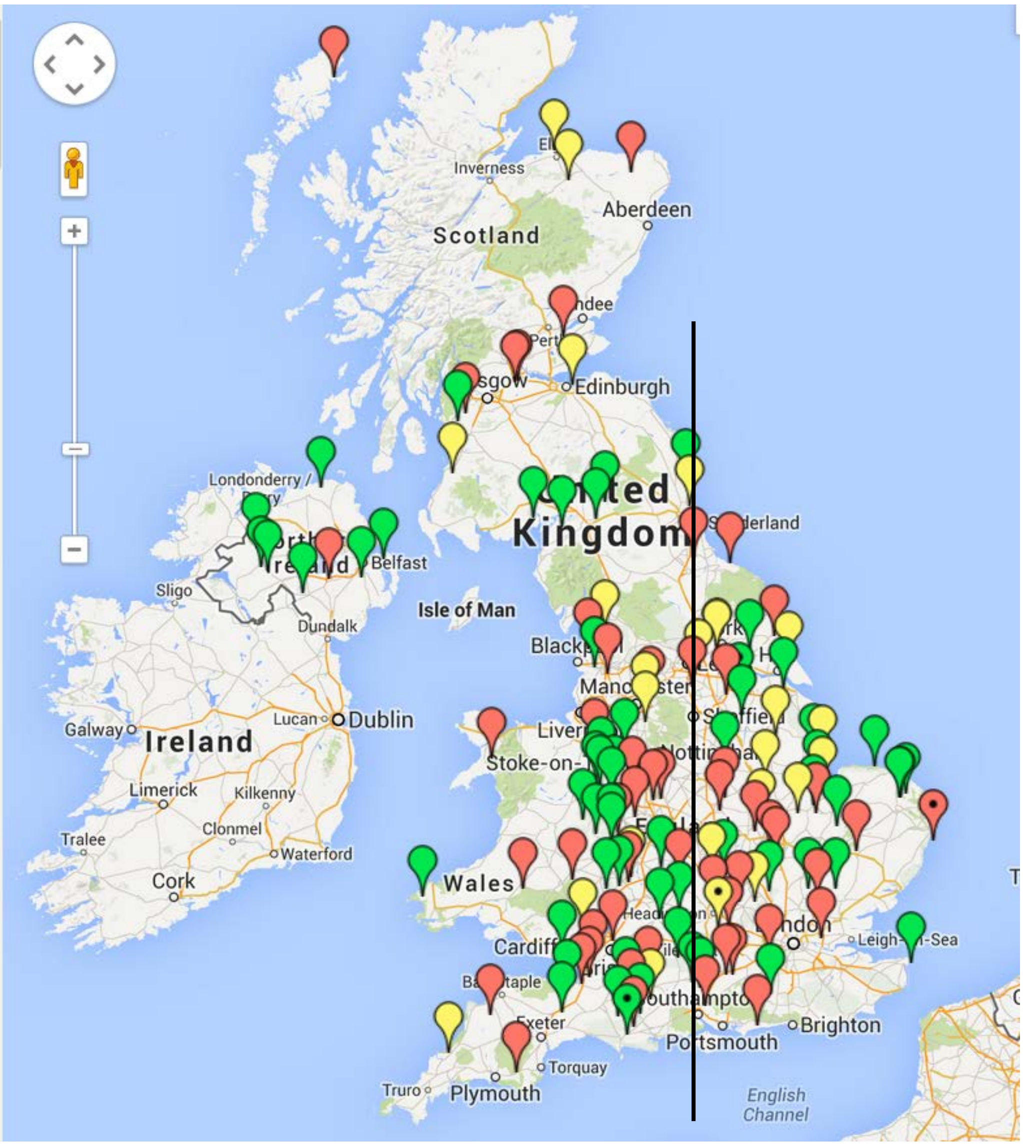


Figure 4-2 AD map (137 sites) in 2014. Source: The Official Information Portal on Anaerobic Digestion (accessed 21 June 2014)
Notes: Green flag = farm facility; red flag = community or food-waste facility; yellow flag = AD facility based at industrial site; flag with black dot = injecting biomethane to the grid; black northing line = divide between the 'East' and West' descriptions used in this thesis.

4.3.2 Questionnaire

The challenge here was in designing a questionnaire (see Appendix 2) that captured enough of the data required, yet was not so extensive that it took up too much of interviewees' time or failed to hold their interest.

There were considerable gaps in the literature (Jones, 2010; Redman, 2010; Black and Veatch, 2010; Mistry *et al.,* 2011a and b) in terms of details of the type and costs of equipment relating to the different feedstock types. Neither did these studies provide information on the specification for building a digester, nor what was included within the costs – for example, did the total include the cost of grid connection or site preparation? This was essential in calculating not only the costs of building the facility, but also the embodied energy of the capital equipment. With considerable variability in feedstock and technology used in the AD sector, the questionnaire was designed to capture as much of this as possible.

With input from a technology provider and one of the case study managers, a list of the most significant equipment (see Appendix 2) required to construct a facility was compiled for the questionnaire. This represented the majority of materials required for building an AD facility, and was used in the calculations discussed in Chapter 5. It was thought best to omit the finer details relating to building specification, as it would be unlikely that many facility operators would know this; instead, this information would need to come from the technology provider, which indeed it did (Mulliner, 2012; Griffin, 2013).

Key output data were chosen to help validate the input data, and to help understand if expected gas and energy outputs were similar to observed data, or to ascertain where there might be differences from the literature or inefficiencies in the system or model design.

Annual operational costs were requested from interviewees due to the expected wide variability created by differing capital and labour requirements across the various feedstock types. A small section on financing was also requested, yet this was not completed by any of the case studies. Other data related to the parasitic energy requirements of the process; gate fees received; the quantity of water used; and if the waste heat generated from the CHP genset was used other than in meeting the parasitic heat requirements of the system. The research was also interested in the barriers to the uptake of the technology, and therefore the remaining questions focused on any difficulties the technology operator may have experienced during the planning application, construction and commissioning phases.

The only AD outputs requested by the questionnaire were the quantity of kW_e generated per annum and the quantity of heat (kW_{th}) used per annum. The reason for this was twofold. First, no real rapport could feasibly be established from a telephone conversation; therefore, at the initial data-gathering interview, it was essential to build trust in order to gain access to commercially sensitive information (whilst this was not expected at the interview itself, it was hoped that interviewees might provide feedback on the model outputs). Second, it was vital to ensure that the model was built with no prior expectation of outputs, enabling the majority of the model parameters and databases to be tested during the validation process for each case study, and allowing for differences or anomalies to be identified more easily.

A revised questionnaire (see Appendix 2) was designed for the final case study (although it was hoped at the time that more facilities in the East of England would be forthcoming). This incorporated considerably more detail on the case study's existing agricultural and AD businesses; the data tables relating to the feedstock were removed, since these were never answered, but there was still a requirement for information relating to the more exotic and less-used feedstock types. Greater detail was requested for the digester and some of the peripheral capital too.

4.3.3 Interviews

The questionnaire was emailed (where possible) to each case study prior to the interview. This gave the interviewee an opportunity to assess the information required and locate any data not to hand. The interviews were completed region by region, with an overnight stay in each one. The facilities were widespread and rural in location, as might be expected, so personal transport was required to reach these sites. The interviewees gave their time freely.

4.4 THE CASE STUDIES

The summary of each interview is set out below for the individual case studies. However, interviewees' comments relating to their experiences have been collated and generalised in Section 4.5 (below), in order to maintain anonymity.

With respect to some of the terminology used within the descriptions, where the distance travelled by the feedstock or digestate is zero, it is assumed that these are either endogenous to the farm or used on the farm, and therefore not imported/exported. The size of the farm was provided by the interviewee.

Three case studies (1, 2 and 13) offered additional output data at the interview, providing greater detail of the capital costs, biogas and methane yields. These data proved particularly useful in distinguishing the different costs associated with differing feedstock types. The data were also invaluable when establishing gas yields for some of the more exotic feedstock types for which no data had been found, including fruits and certain abattoir waste materials. The data also highlighted the benefits of co-digestion (Callaghan *et al*., 1999; Callaghan *et al.*, 2002; Giuliano *et al*., 2012), when the ADEE model underestimated gas yields (before modification) at sites that co-digested materials (see Sections 2.5.4 and 3.3.5.4).

However, one of the case studies (7) had a novel mid-digestion separation unit (since the DM content of the material digested was less than 5 per cent). This enabled the digestion tank to be considerably smaller than would normally be required of a digester receiving this volume of feedstock.

On several occasions, the interviewee was either was unable to provide finer details or was not willing to make information available. However, visiting the company's website, or that of their technology supplier, proved extremely useful in such cases. Technology suppliers were particularly keen to publish quite a lot of information as case study examples of their own, since this acted as a marketing tool in what was then a new industry.

Case study 1		
Variable	**Value**	
Area of operation	West	
Year commissioned	2010	
Farm-based	Yes	
Land area	100 ha	
Total capital costs	£3,955,000	
Annual operational costs	£546,200	
Digester size	3,000 m^3	
Operating temperature	38 °C	
Fuel use	CHP	
Waste heat used	50%+	
Generator size	498 kW (*L)	
Generation efficiency	38%	
Pasteurisation unit	Yes	
Main compensation method	Feed-in Tariffs	
Feedstock	**Quantity (t)**	**Av. distance (miles)**
Dairy trade effluent	3290	0
Baking waste	81	15
Local leftovers	475	10
Source-separated food waste (from two sources)	6,500 + 2,000	35 + 125 respectively
Waste material from herd (head of livestock)	200 dairy cows plus followers	

- The business diversified some decades ago, establishing a creamery. The milk demand at the creamery now exceeds the farm's milk output.
- The farm currently supplies only 30% (approx.) of the creamery's demand.
- There is insufficient on-farm feedstock from livestock wastes or available land to meet the high energy demand of the creamery.
- The business successfully obtained a WRAP Environmental Transformation Fund (ETF) grant.
- The business makes full use of the heat generated from the CHP generator. With specialist equipment, the exhaust gases are lowered from 600 °C at 7 bar to 200 °C, or the equivalent of 420 kWh_{th}. The heat is used for feedstock pasteurisation and maintaining the digester's temperature; but the majority of the waste heat is used within the processes at the creamery, representing a considerable benefit in both environmental and economic terms.

L=limited

Case study 2		
Variable	**Value**	
Area of operation	East	
Year commissioned	2009	
Farm-based	Yes	
Land area	230 ha	
Total capital costs	£865,000	
Annual operational costs	£55,000	
Digester size	800 m^3	
Operating temperature	37 °C	
Fuel use	CHP	
Waste heat used	50%+	
Generator size	170 kW	
Generation efficiency	37.5%	
Pasteurisation unit	No	
Main compensation method	Feed-in-Tariffs	
Feedstock	**Quantity (t)**	**Av. distance (miles)**
Dairy whey permeate	360	0
Cow slurry	1,836	0
Farmyard manure (FYM)	175	0
Maize silage	1,976	0
Fodder beet	320	0
Waste material from herd (head of livestock)	~125 dairy cows plus followers	

- The business diversified some years ago, establishing a creamery.
- The farm operations are closely monitored for energy consumption and sustainability.
- This AD facility was developed through a drive for greater sustainability. The farmer also found that it provided a solution to the changing legislation relating to slurry and manure management in NVZs.
- The heat generated by the CHP engines is utilised on site, in the farmhouse and creamery. At the time of writing, plans were also in place for the installation of a new, micro-community heating system for three neighbouring cottages.

Case study 3

Variable	Value	
Area of operation	East	
Year commissioned	2011	
Farm-based	Yes	
Land area	120 ha	
Total capital costs	£5,780,000	
Annual operational costs	£1,040,000	
Digester size	2300 m^3 + 4300 m^3	
Operating temperature	38 °C	
Fuel use	CHP	
Waste heat used	Digester only	
Generator size	1400 kW	
Generation efficiency	42%	
Pasteurisation unit	No	
Main compensation method	Feed-in Tariffs	
Feedstock	**Quantity (t)**	**Av. distance (miles)**
Maize silage	22,000	7
Grass clover silage	4,000	10

- The landowner has leased a portion of his land to a technology provider. The landowner is contracted to run the digester on a day-to-day basis, as well as being responsible for sourcing the feedstock for the digester. Since there is not enough land for the AD facility to be self-sufficient, a number of subcontracts with local farmers have been struck to grow the crops for the facility.
- Based on an average yield of 45 $t.ha^{-1}$, this digester requires approximately 578 ha (≡1428 acres) of land each year. Accounting for x4 crop rotation cycle, this equates to over 23 km^2 of land over a four-year period.

- There are now three AD facilities within 6 miles of each other in this area, treating 86,000 t of crop-only feedstock. At approximately 45 tonnes per hectare, that requires an annual land area of 1,911 ha (76 km^2 on a x4 crop rotation).

Case study 4		
Variable	**Value**	
Area of operation	East	
Year commissioned	2009	
Farm-based	Yes	
Land area	10 ha	
Total capital costs	£1,000,000	
Annual operational costs	~£45,000	
Digester size	1800 m^3	
Operating temperature	37.5 °C	
Fuel use	CHP	
Waste heat used	50%+	
Generator size	160 kW	
Generation efficiency	38%	
Pasteurisation unit	No	
Main compensation method	ROCs	
Feedstock	**Quantity (t)**	**Av. distance (miles)**
Fruit and vegetable waste	6,000	30
Baking waste	520	10

- This was a home-made AD digester based on a horticultural farm.
- The horticultural business has a high heat load, supplied by four gas turbines, two of which receive gas from the AD facility. The business also has a 1 MW biomass boiler, which supplements their heat requirements in the winter.
- The digester is not a traditional CSTR, but is made up of six 350 m^3 individual batch-type digesters.
- The feedstock posed a modelling problem, since it varied from one week to another. The majority of the feedstock was fruit, with some vegetable waste (overall <3% DM content) from a London market. This was occasionally accompanied by a small amount of baking waste.
- The business was going through a transition and assessing ways to meet the high energy requirements of its horticultural business. At the time of the interview, they were researching the feasibility of moving to a thermophilic process that would enable them to treat larger quantities of materials, and to generate more energy from their other turbines that currently use piped gas, without expanding their current digesters. Alternatively, they were looking to update their entire system in order to manage the additional feedstock.
- The main restrictions to expansion are: the limited area of their own land on which to spread the digestate (24 acres of arable land); and their location in a small hamlet, where residents would most likely object to an increase in traffic as a result of increased feedstock and digestate.

Case study 5		
Variable	**Value**	
Area of operation	West	
Year commissioned	2008	
Farm-based	Yes	
Land area	500 ha	
Total capital costs	£965,000	
Annual operational costs	£217,000	
Digester size	3,600 m^3	
Operating temperature	38 °C	
Fuel use	CHP	
Waste heat used	Digester only	
Generator size	360 kW	
Generation efficiency	38%	
Pasteurisation unit	No	
Main compensation method	ROCs	
Feedstock	**Quantity (t)**	**Av. distance (miles)**
Cow slurry	4,000	0
Poultry excrement	1,100	3
FYM	750	0
Maize silage	730	3
Grass clover silage	730	0
Spring barley (whole crop) silage	730	0
Apple pomace	3,400	10
Waste material from herd (head of livestock)	Two dairy herds totalling 600 head	

- The AD facility has been in operation for over eight years.
- The farmer used some existing capital to reduce development costs, removing the need for a large digestate holding tank.
- Waste heat from the CHP generators is used to meet the digester's parasitic load. The AD facility is too remote for the heat to be used economically elsewhere.
- A grant was received from DEFRA under the bioenergy capital grant scheme.

Case study 6		
Variable	**Value**	
Area of operation	West	
Year commissioned	2010	
Farm-based	Yes	
Land area	>6000 ha	
Total capital costs	£ not provided	
Annual operational costs	£ not provided	
Digester size	5500 m^3	
Operating temperature	38 °C	
Fuel use	CHP	
Waste heat used	~5%	
Generator size	498 kW (*L)	
Generation efficiency	41%	
Pasteurisation unit	No	
Main compensation method	Feed-in Tariffs	
Feedstock	**Quantity (t)**	**Av. distance (miles)**
Dairy slurry inc. fodder remains	2,000	3
Dairy cow slurry	10,000	0
FYM	2,600	0
Grass silage	5,840	1
Maize silage	1,460	3
Fodder beet	730	3
Waste material from herd (head of livestock)	Two dairy cow herds totalling 750 head	

- The CHP generator is restricted to 498 kW, to comply with the FIT band and maximise profits.
- Spare capacity has been built into the design of the digester to allow for additional energy generation, should they decide to add a further generator (up to 500 kW).
- Their aim is to extend the renewable generating capacity of the estate, utilising more of the waste heat generated by piping the additional gas produced to another part of the estate with a large energy requirement for both electricity and heat, improving the productivity of the AD facility.
- Currently, they produce more gas than they require and need to flare off excess gas to remain within the boundaries of the 500 kW generation limit.

L=limited

Case study 7		
Variable	**Value**	
Area of operation	West	
Year commissioned	2011	
Farm-based	No	
Land area	0 ha	
Total capital costs	£1,736,200	
Annual operational costs	£ not provided	
Digester size	1,000 m^3	
Operating temperature	36 °C mesophilic	
Fuel use	CHP	
Waste heat used	Digester only	
Generator size	190 kW	
Generation efficiency	38%	
Pasteurisation unit	No	
Main compensation method	Feed-in Tariffs	
Feedstock	**Quantity (t)**	**Av. distance (miles)**
Dairy whey permeate	10,850	10
Dairy trade effluent	29,900	0

- An industrial digester based at a creamery.
- The digester incorporates a novel mid-treatment separation system, as the feedstock only has 4% DM content. This separation system allows the liquid to be separated after 5 days and removed to the sewers, whilst the solid DM content is retained and digested for a further 40 days.
- The system is designed to process up to 70,000 t of dairy effluent and creamery waste per annum. At the time of the interview they were processing ~40,700 tonnes.
- The business was assessing the feasibility of using the waste CHP heat at the creamery.
- The creamery processes in excess of 30 M litres of milk per annum. The AD unit was installed to treat the waste effluent of the creamery, which was costing the business £180,000 per annum in discharge fees to the sewerage system. This cost has been reduced to £75,000 per annum, since the AD process enables the chemical oxygen demand (COD) of the effluent to be reduced from 25,000 mgCOD.l^{-1} to 250 mgCOD.l^{-1}.
- The company received a £1.74 M grant from the ETF, delivered by WRAP through the Anaerobic Digestion Demonstration Programme.

Case study 8		
Variable	**Value**	
Area of operation	West	
Year commissioned	2011	
Farm-based	Yes	
Land area	Not provided	
Total capital costs	£1,700,000	
Annual operational costs	£85,000	
Digester size	4,300 m^3	
Operating temperature	38 °C mesophilic	
Fuel use	CHP	
Waste heat used	Digester only	
Generator size	498 kW (*L)	
Generation efficiency	39%	
Pasteurisation unit	No	
Main compensation method	Feed-in Tariffs	
Feedstock	**Quantity (t)**	**Av. distance (miles)**
Maize silage	4,000	3
Cow slurry	1,000	3
Poultry excrement	2,000	3
Sugar beet silage	1,000	0
Potatoes	1,000	0
On-farm maize silage	3,000	0

- When visited, this AD facility had only just started commissioning their plant, with the first few hundred tonnes of feedstock.
- Significant additional excess capacity has been built into the digester so that an additional 800 kW CHP generator could be added within 12 months of commissioning, bringing the total generating capacity up to 1,400 kW.
- The facility was an interesting design; whilst looking like a conventional CSTR digester from the outside, it was in fact a semi-plug-flow system, which would look a little like a doughnut from above, if open to the elements. This design enables different feedstock types to be added to the system at different points along the process, enabling the feedstock type to enter the system at the optimum point to achieve its correct hydraulic retention period.

L=limited

Case study 9		
Variable	**Value**	
Area of operation	West	
Year commissioned	1989	
Farm-based	Yes	
Land area	65 ha	
Total capital costs	£65,000	
Annual operational costs	£5,000	
Digester size	105 m^3	
Operating temperature	37 °C mesophilic	
Fuel use	Boiler	
Waste heat used	100%	
Generator size	No electrical generation	
Generation efficiency	n/a %	
Pasteurisation unit	No	
Main compensation method	No compensation applicable	
Feedstock	**Quantity (t)**	**Av. distance (miles)**
Cow slurry	1,900	0
Waste material from herd (head of livestock)	120 dairy cows + followers	

- The business had recently expanded its dairy herd from 90 head.
- They had purchased their first digester (105 m^3) in 1989, under the Ministry of Agriculture, Fisheries and Food (MAFF) farm improvement scheme.
- The MAFF scheme was intended to provide an incentive for both energy generation and nutrient management. It arose out of the Iran oil crisis of the early 1980s.
- The 105 m^3 digester was installed to provide energy to the dairy and the farmhouse. Some of the gas is burnt in a boiler to provide hot water to wash down the dairy and surrounding area, and the rest is used to heat the farmhouse, a couple of outbuildings and private greenhouses.
- The business had recently purchased a second digester (120 m^3 capacity) to complement the first.
- The digestate is used on their fields. They had consistently observed improved grass yields over the years, improving self-sufficiency for their herd.

Case study 10		
Variable	**Value**	
Area of operation	West	
Year commissioned	2009	
Farm-based	Yes	
Land area	445 ha	
Total capital costs	£700,000	
Annual operational costs	£ not provided	
Digester size	1,600 m^3	
Operating temperature	38 °C mesophilic	
Fuel use	CHP	
Waste heat used	Digester only	
Generator size	160 kW	
Generation efficiency	37%	
Pasteurisation unit	No	
Main compensation method	Feed-in Tariffs	
Feedstock	**Quantity (t)**	**Av. distance (miles)**
Cow slurry	8,000	0
Poultry manure	1,460	3
FYM	830	0
Waste material from herd (head of livestock)	350 dairy cows plus followers	

- This farmer has diversified and provides a farm consultancy business also, providing a web-based information facility.
- A further herd of 300 dairy cows is kept on an adjoining farm, just over one mile from the AD facility. They plan to transport the slurry up to the site in the future.
- The business had recently established itself as an AD technology provider. Their aim is to promote the use of small-scale, sustainable energy generation, waste management and nutrient management in such a way that fits in with the existing farming practices of the host farm.
- Their digestate is kept in uncovered lagoons.

Case study 11		
Variable	**Value**	
Area of operation	West	
Year commissioned	2011	
Farm-based	Yes	
Land area	305 ha	
Total capital costs	£850,000	
Annual operational costs	£45,000	
Digester size	550 m^3	
Operating temperature	38 °C mesophilic	
Fuel use	CHP + boiler	
Waste heat used	50%+	
Generator size	50 kW_e + 70 kW_{th}	
Generation efficiency	33%	
Pasteurisation unit	No	
Main compensation method	Feed-in Tariffs	
Feedstock	**Quantity (t)**	**Av. distance (miles)**
Dairy cow slurry	6,965	0
Pig slurry	260	0
Waste (whole crop) silage	200	0
FYM	585	0
Waste material from herd (head of livestock)	250 dairy cows plus followers	
	100+ sows	

- This system was built as an educational demonstration tool and was not designed for the outputs of the farm activities or the energy demands of the college.
- The facility operates two different systems, with two small, farm-sized digesters: a 450 m^3 CSTR digester and a 100 m^3 plug-flow system.
- The farmland is used to grow crops for animal feed, including maize, grass, wheat and barley.
- The system was 100% funded by the North West Development Agency and Rural Development Programme for England, and therefore only qualifies for ROCs. The methane is combusted in two ways: in a 70 kW boiler, to heat water that is used around the dairy unit and parts of the college; and in a 50 kW CHP engine, generating energy that provides 15% of the college’s electricity requirements.
- A change in farming practices to all-year housing of dairy cattle means they now have more slurries and manures than their digesters can handle.

Case study 12		
Variable	**Value**	
Area of operation	West	
Year commissioned	2011	
Farm-based	Yes	
Land area	553 ha	
Total capital costs	£3,700,000	
Annual operational costs	£ not provided	
Digester size	3,500 m^3	
Operating temperature	38 °C mesophilic	
Fuel use	CHP	
Waste heat used	Digester only	
Generator size	498 kW (*L)	
Generation efficiency	39%	
Pasteurisation unit	Yes	
Main compensation method	Feed-in Tariffs	
Feedstock	**Quantity (t)**	**Av. distance (miles)**
Source-separated food waste	8,500	15
Dairy cow slurry	11,000	0
FYM	1,100	0
Pig slurry	5,000	0
Waste material from herd (head of livestock)	400 dairy cows plus followers	
	230 sows plus weaners and finishers	
	7,500 free-range laying hens	

- This facility was built on the site of a large agricultural educational college that had a strong research base, in addition to its extensive farming activities.
- The facility has developed as a commercial entity in its own right, and is financially viable independently of the other college and farming activities.
- Food waste is collected from local towns.
- Electrical energy generated meets 75% of the college's daytime requirements.
- Energy is exported to the grid at night and during holiday periods.
- There were plans to connect the CHP engine to the college's heating system to utilise that as well, however; the AD facility was over a quarter of a mile from the college and costs were prohibitive.

****L=limited**

Case study 13		
Variable	**Value**	
Area of operation	East	
Year commissioned	2006	
Farm-based	Yes	
Land area	324 ha	
Total capital costs	£1,505,000 + £520,000	
Annual operational costs	£305,175	
Digester size	2500 m^3	
Operating temperature	38 °C mesophilic	
Fuel use	CHP	
Waste heat used	Digester only	
Generator size	600 kW	
Generation efficiency	42.7%	
Pasteurisation unit	Yes	
Main compensation method	ROCs	
Feedstock	**Quantity (t)**	**Av. distance (m)**
Pig slurry	2,100	0
Abattoir dissolved air floatation (DAF) slurry	4,965	3
Cattle stomach content	1,265	3
Fish DAF slurry	2,085	30
Bakery waste	300	30
Yeast by-products	2,735	80
Waste material from herd (head of livestock)	280 sows plus weaners and finishers	

- The business has been diversified for a long time and has been involved in agricultural contracting and farming for four generations. The farm received abattoir waste materials for many years before the decision was taken to build an AD facility.
- This AD facility was operational in 2006.
- Additional expenditure of £520,000 had been required recently to replace the CHP generator.
- Legislation changed in 2009, when EU Article 13: EC1069/2009 required that category 2 and 3 biowaste materials would require further treatment before they could be spread to land. This was the main driver for the business to set up an AD facility, in order to fulfil their existing contracts.

4.5 INTERVIEWEE COMMENTS

The comments below represent a consolidation of those made in the original series of interviews, along with a few of my own observations made during this process. They have been separated into four main themes: planning and start-up, transportation, regulation and policy, and operations.

4.5.1 Planning and start-up

To most interviewees, this was one of the most stressful aspects of the project, particularly for the pioneers for whom there were few previous, endogenous case studies from whom they could gain knowledge or advice from the point of view of planning, regulation and construction. Technology was brought in from abroad, mainly due to the considerable experience already gained on the Continent. But gaining planning permission often took a considerable length of time (in excess of two years for two case studies), which meant that feasibility studies quickly became out-of-date as exchange rates changed. As knowledge of the technology became more available, encouraged by the government's AD Strategy and Action Plan (DEFRA, 2011c), companies were engaging with the various stakeholders right from the outset, helping to speed up the process. This enabled users to reduce the planning period to just under a year.

The end-users of the technology (farmers and waste managers) were not the only stakeholders who had little or no knowledge of the technology. Few involved with the planning or regulatory authorities knew how to regulate or permit development. Initially, there were no guidelines, specific policies or regulations relating to AD. Therefore, each new facility was treated very much on an ad hoc basis, with planning and regulatory interpretation and decision-making differing across the UK. Often, the level of planning, regulation and permitting requirements was subject to the knowledge and experience of the regulatory authority in which the facility was proposed. Uncertainty was reduced and uniformity introduced once again through the AD Strategy and Action Plan (DEFRA, 2011c). However, apart from one case study, which experienced significant problems due to local opposition (due to the close proximity of the planned facility to a housing estate), all had relatively swift and positive experiences. One did not seek or obtain planning permission as it was piggy-backed on the back of a much larger project that was occurring simultaneously.

Grid connection was another issue relating to the planning of an AD facility. Due to the remote nature of most of these sites, the distribution networks often advised that they would have to connect to the grid considerable distances from where they were operating. Connection charges for the case studies ranged considerably, from £50,000 to £750,000. One case study had its connection incorrectly modelled by the distribution network, which meant that unless they paid more than £500,000 for their connection, they would be restricted to 75 per cent of their planned electrical output. This had a significant impact on the potential financial viability of the project. In the end, they did proceed, and were eventually able to increase their output to the full design capacity at their same connection site.

The final issue reported related to those facilities treating municipal waste from various councils. Businesses had found that the process of bidding for feedstock was secretive and demanding. They suggested that the councils were either unprepared or unable to form contracts within a reasonable time frame that enabled the facility to gain funding. In addition, these facilities were unable to gain long-term contracts like the waste management firms, and in many cases the longest contract that was awarded to them was three years (although in most cases it was less).

This had considerable knock-on effects for the AD facility, in terms of obtaining low interest-rate financing, or indeed any financing at all. These companies relied heavily on gate fees in order to pay for the additional cost of equipment that they had to install to comply with the treatment of this type of material. One of the case studies also reported that they were often only able to secure very poor quality (highly contaminated) feedstock and very rarely received half the value of the gate fee.

4.5.2 Transportation

Several sites had transport restrictions imposed on them during the planning application process, not only to improve roads and signs, but also to restrict transport to and from the site in specific directions and at certain times of the day, and two case studies were only allowed to use certain roads to access their site.

4.5.3 Regulation and policy

Nearly all the case studies saw changes to regulation and policy as their main future concern, be it in the way they were funded, the regulation of their operations or the disposal of the digestate. Competition from future AD facilities built was also a primary concern, due partly to the increased competition for feedstock that this would represent. In the past, this was mainly due to the way in which AD was funded after the introduction of the FIT scheme. This provided improved remuneration over that which could be achieved through the ROC compensatory scheme, resulting in an uneven playing field, in which the newer facilities were able to receive lower-value biowaste feedstock, since they were receiving more for the energy that they generated.

For those who were compensated through the ROCs, the demise of this scheme was of considerable concern. The new scheme had not been announced when the interviews took place; however, all the potential schemes were thought to be overly complex and required expensive professional advice in order to understand and manage them.

4.5.4 Operations

Many, if not all of the AD facilities had experienced problems with the equipment that had been supplied to them. Most of these problems were specific to pumps and valves that were simply not sufficiently robust. Many of the early AD operators underestimated the corrosive nature of the material that they were treating, or indeed of the process itself. Certain feedstock types were considerably more caustic than others (pig and poultry manures, for example).

Eight of the 13 case studies did not use and did not plan to use any of the heat generated by the CHP genset, other than to maintain digester temperature. Nearly all of them had some kind of heat load, around the farm or with immediate neighbours, which could have utilised the waste heat. However, because they would not be compensated for constructing the infrastructure to make use of this heat, they had not planned for its utilisation. Those who did use the waste heat were using as much of the heat energy as they could without jeopardising the efficiency of the CHP genset. One had plans to extend the heat use to include neighbouring farm cottages, but only if they were successful in gaining a government grant, since whilst the distance was less than 200 yards, the costs at the time were prohibitive.

Three of the case studies reported that their CHP gensets were unreliable. Whilst they had purchased reconditioned, second-hand gensets from the manufacturers, these had failed before their warrantees had expired. They were able to have them replaced or mended, but they were not compensated for the loss in income they experienced whilst their gensets were non-operational.

One of the larger AD facilities found out after they had built their facility that the scoping study had made incorrect assumptions for the nutrient requirements of their farmland. They were importing a significant quantity of feedstock material, which meant that they were unable to spread their digestate to land and had to export approximately 80 per cent of it. This came at a great cost, in that local farmers were uncertain of its properties or abilities. The AD facility ended up paying for all of the transport costs and soil testing of the receiving land –

approximately £20,000 per month. However, the benefits were clear and the facility has been able to sell on its digestate after 12 months of testing. The other facilities had very good reports from the use of their digestate, reporting that it had enabled them to reduce their reliability on mineral fertiliser by up to 70 per cent.

Some of the facilities had experienced some kind of significant plant failure during operation; injuries were common; and one facility had an essential valve freeze, causing methane losses to the atmosphere for over 12 hours. In February 2013, one of the sites again suffered failure in one of its pumps, causing several thousand cubic metres of digestate to spill over land for more than 36 hours. This could have caused a significant pollution issue had it not been for the immediate involvement of the EA and the Fire Brigade. The clean-up took several weeks to complete. In the early stages, the EA was pumping significant quantities of hydrogen peroxide into the local stream, to maintain levels of oxygen within the water and therefore preserve aquatic life and minimise the environmental impact. There was very little information about the cause of this failure, but such incidents provide good examples of the risks associated with the management of an AD facility.

Other issues encountered were when a facility tried to use alternative feedstock types to those for which they were designed. One facility, suffering a crop failure, decided to supplement the digester with beet. However, they failed to realise the importance of cleaning the beet thoroughly before preparing it for the digester. Whilst they were concerned that the soil around the beet might cause the digester size to reduce over time, they had installed measures that would enable the safe and continual removal of this material. However, what they had not accounted for were the stones that were also attached to the feedstock. These caused significant (and expensive) damage to the macerator, pumps and digester feeder.

The final issues related to a lack of understanding of the biochemical process, including the degree of recirculation of the digestate liquor, which in one case caused ‘foaming’, due to high concentrations of ammonia; and a change in livestock husbandry practices which increased the levels of DM content, which also led to foaming, due to increased levels of ammonia. In the latter case, the increasing ammonia levels were not noticed early enough, causing the digester to ‘sour’ (fail completely). This is a significant problem, as it is often impossible to restart the biological process, and the only thing left to do is to remove all the feedstock present in the digester and start the process from scratch. It can then take many months before the facility is running at full capacity once more and generating an income.

4.6 COMMENT AND REFLECTION

Over half of the case studies visited had significant additional capacity available in their systems. This created difficulties in modelling the case studies, since the digester sizes did not match the quantity of feedstock currently used. Over a quarter of the case studies had designed the additional capacity into their systems, whilst the remainder had difficulties securing feedstock. This demonstrated two things: first, that many were trialling the technology before fully committing funds to additional generators, giving over more of their own land to growing crops for their digester, or contracting other farmers to grow crops on their behalf; second, some facilities had difficulties in securing long-term contracts for existing or new feedstock sources.

The questionnaire was designed for collecting details of CAPEX and OPEX. These were overly detailed and the majority of the interviewees were unable to provide the data, for one reason or another. Not one interviewee provided information on how the facility was funded, which in the end was gathered from professional financial advisors within the industry. However, on occasion, some of the finer details and specifications were not known or were unavailable; in such cases, visiting the companies' websites or those of their technology suppliers proved invaluable in filling the gaps.

In hindsight, the questionnaire should have included more of the operational and design data specific to the feedstock, digestate and AD facility itself. Greater emphasis should have been placed on some of the operational procedures, rather than on the detail of finance. It would also have been useful to have acquired more detail on their existing business and farming activities, in order to assess how case studies expected the new energy-generating operations to fit into their existing activities. Farm size was not always obtained and had to be gathered from websites, if available, or through further communication, where possible. This was important in verifying the yields achieved from on-farm activities, the distance the feedstock travelled within the farm, and the land available to receive the digestate before any excess needed to be exported.

With regard to the questions relating to operators' experiences, these should have been completed separately at a later date, when the questions could have been more structured, and certain questions less open. However, the questionnaire was designed so that the interviewee was given licence to offer as broad a description as possible of their experience of developing and operating an AD facility. Additionally, people tend to be more comfortable communicating face to face, and interviewees may not have been willing to spend more time answering further questions at a later date.

In general, those who were prepared to be interviewed were happy to talk about their experiences, both good and bad. Few, however, were happy to impart CAPEX or OPEX information. One case study refused to offer any information relating to CAPEX or OPEX, but was happy to provide other information; whilst another provided CAPEX information that did not make economic sense when modelled. When comparing the data provided by this case study to that of other researchers produced for a government project two years later, the CAPEX varied considerably. These data were therefore treated with extreme caution and are highlighted when discussed in the validation chapter (see Chapter 6).

In summary, judging from the comments made during these interviews with the case study operators and other stakeholders within the industry, it is still an immature industry, and one that suffers from a lack of overall openness and from poor communication both within the sector and among those wishing to enter it. The ADEE model was built (see Chapter 5) in order to better understand what might be the cause of these barriers. The model was used to provide different scenarios (see Section 3.6) of how the technology might be developed and deployed across England in order to achieve its potential as an energy generator, GHG mitigation technology and waste management process.

Chapter 5: Model

'All the human and animal manure which the world wastes, if returned to the land, instead of being thrown into the sea, would suffice to nourish the world.'

Victor Hugo (1802–1885) – *Les Misérables*

5.1 INTRODUCTION

This chapter explains how the methods discussed in Chapter 3 were employed to explore the multifaceted role of AD across three regions in England. To achieve this, a number of calculations were brought together that could evaluate both the environmental and the economic cost benefits of the technology, thereby answering the research aims and objectives. The Anaerobic Digestion Environmental and Economic (ADEE) model was developed using a modular approach in MS Excel.

The model needed to provide data that enabled the research questions to be answered. The main function of the model, therefore, was to provide data, based on a mix of feedstock types and quantities across a number of scenarios that enabled the following research objectives to be answered:

- What is the quantity of energy and GHG emissions embedded within the materials used in constructing this capital equipment?
- If purpose-grown crops are used, how much energy is required during the various farming activities needed to grow them?
- What are the indirect energy requirements (and associated GHG emissions) from the manufacture of controlling sprays and fertilisers included in the life cycle?
- How much energy (and GHG emissions) is required/produced in transporting the feedstock to and digestate from the treatment facility?
- How much mineral fertiliser would be required to replace the nutrients available in the digestate?
- What is the offset in energy required and emissions produced from the manufacture of a similar quantity of mineral fertiliser?
- What is the net quantity of energy (both heat and electricity) generated from the process?
- What are the net (positive (emission) or negative (saving)) GHG emissions from all the various associated processes?

- What are the capital costs and operational costs attached with performing the processes described above?
- What other financial costs and benefits are associated with the processes (but not falling within the definition of CAPEX or OPEX) described above?

In answering these questions, the ADEE model, when scaled up, is able to assess which method of deployment (or scenario) can generate the greatest quantity of energy and mitigate the greatest quantity of GHG gases, and to inform the net energy and GHG emissions of each scenario, assessing if the technology has a positive or negative effect on the environment.

Chapter 2 demonstrated that there have been many approaches to the assessment of AD. Some focused on typical dairy or arable farms with available on-farm feedstock types (Jones, 2010; Köttner *et al*., 2008; Hughes, 2011), whilst others assessed the treatment of specific feedstock types in specific scenarios – such as centralised (community) off-farm AD units (Mistry *et al*., 2011a and b). It was thought that these approaches were restrictive, since they did not consider the co-digestion of biowaste materials in a farm setting. Many had assessed the efficacy of co-digestion (see Section 2.5.4); however, only Banks *et al.* (2011) assessed the wider benefits of co-digestion of biowaste with cattle slurry on a scale greater than a single site. Three case studies used in this research were already co-digesting various crops and on-farm waste materials with off-farm waste materials, demonstrating its feasibility and the flexibility of the technology to perform multifunctional roles.

The ADEE model provides outputs based on the inputs (whatever they may be) for a single digester. The model outputs may be scaled up to produce figures that would represent a region's requirements, based on the available feedstock and the outputs from the configuration(s) of an individual (or many) AD facility size(s). Section 5.2 discusses the information and data required for the model to calculate its results, whilst Section 5.3 sets out the main calculations used across the five core modules of the model that produce the results required to answer the research objectives.

5.2 DATA ENTRY

The ADEE model is able to produce results from just a few key data inputs, including the type and quantity of feedstock, with the model assumptions filling in the rest of the detail. However, a number of other data could be input to improve the accuracy of specific single-site AD facilities. The main information required can be divided into four sections: feedstock, transport, economic and process.

- The feedstock section only requires the type, quantity and value of feedstock to be treated.
- The transport section requires the distance travelled and the average tonnes hauled at any one time. The model calculates fuel consumption for distances travelled during the collection of municipal waste (see Section 5.3.1), based on the assumptions from a report by WYG (2012); whilst transport from all farming activities is discussed in Sections 5.3.2.2 and 5.3.2.3.
- The economic section requires only the interest rate, tax rate, inflation rate, discount rate, lifespan of the project, mechanism for remuneration (FITs, ROCs or RHI) and the number of years of financing. All capital and operational costs are calculated by the model – these can be overridden if required. These all influence the calculation of the IRR, NPV and levelised cost of energy for an AD investment project.
- Finally, the process section requires detail of operating temperature, geographical location (providing regional ambient soil and air temperatures), CHP genset electrical efficiency, other energy sources, number of digesters (otherwise assumed one), use for the biogas, if pasteurisation is required and if the digestate is to be separated into its solid and liquid derivatives.

From the input of this information, all calculations can be made subject to the following two assumptions relating to finance and emissions:

It is assumed that the financial costs of growing imported crops are included within the purchase price. All environmental costs, both on- and off-farm feedstock types, are calculated by the model for crops specifically grown for the AD facility. All economic and environmental costs for municipal, commercial and industrial waste are calculated from collection at source.

The following set of emission data and conversion factors (see Table 5-1) relating to transport and energy consumption have been taken from various DEFRA publications, in particular from the *Digest of United Kingdom Energy Statistics* (DUKES) (DECC, 2013a). Other sources not mentioned in the text can be found in Appendix 3, Tables A1.5 and A1.7. Since most agricultural establishments are very remote, it was assumed that they are located off the gas-grid system, and therefore are forced to use heating oil (kerosene) as the fuel of choice for heating the barns, dairy, farmhouse and other buildings, including activities that require the heating of water. The model offsets the GHG emissions associated with these activities, using the waste heat from the AD facility. The energy requirements for dairy cattle husbandry are calculated by the model on a per capita basis of 325 $kW.cow^{-1}.a^{-1}$ (as provided by Bilsborrow *et al*., 2010). The model also calculates the parasitic load of the AD facility (see Section 5.3.3.3), including a separator for the digestate (if selected); should the waste heat be exported, the economic and financial benefits are calculated (see Section 5.3.4); and if sufficient excess electricity is produced to allowing for the export of electricity, the environmental and economic benefits are also calculated (see Section 5.3.4).

Table 5-1 GHG conversion factors of the UK general electricity mix, diesel and natural gas

Emission parameter	Energy source and value				
Kg CO_{2eq} per unit	General electricity mix (per kWh)	Diesel (per litre)	Burning oil (kerosene) (per litre)	Biomethane (per kg)	Natural gas (per m^3)
Total CO_2	0.59368	3.2413	3.0714	1.3282	2.2422
CO_2	0.52114	2.6569	2.5319		2.0280
CH_4	0.00025	0.0009	0.0055		0.0030
NOx	0.00323	0.0191	0.0069		0.0012
Total direct	0.52462	2.6769	2.5443	0.0052	2.0322
Total indirect	0.06906	0.5644	0.5271	1.3230	0.2100

Adapted from: DEFRA (2012b), Annex 1, Table 1b; Annex 3, Table 3c; and Annex 9, Table 9b

Where no complete emission data had been provided (see Table 5-1), or where certain expected emissions had been assumed from within the scope of this research (i.e. CH_4 emissions from landfill or N_2O emissions from slurry pits etc.), the GHG conversion factors displayed in Table 5-2 were used to allow all the GHG emissions to be expressed as CO_{2eq}. Carbon dioxide equivalent (CO_{2eq}) is a universal unit of measurement that allows the global warming potential of different GHGs to be compared.

Table 5-2 GHG conversion factors

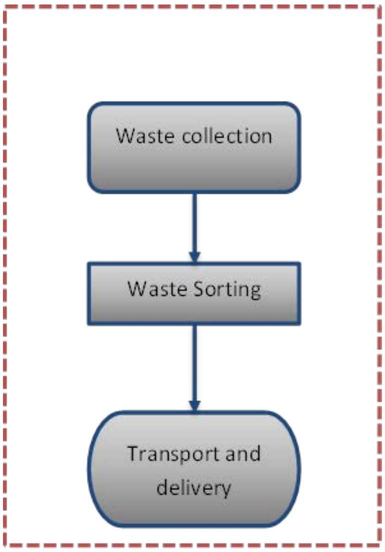
	Conversion factor
CO_2	1
CH_4	21
N_20	310
SF_6	23,900
Multiply to obtain CO_{2eq} value	

Source: DEFRA (2012b: 18, Table 5a)

5.3 MODULE CALCULATIONS

In order to facilitate a logical discussion of the calculations, assumptions and reasons behind the model's construction, and along the AD life cycle from inputs to outputs (i.e. the mechanics of the ADEE model displayed in Figure 3-3), the five component parts, or modules, were divided up. Each of the next five sections describes an individual module of the ADEE model and the various calculations made within it. These elaborate or help to contextualise some of the previous discussion.

5.3.1 Module 1: Biowaste and livestock-waste-material feedstock types



The ADEE model captures all non-farm activities (see Section 3.3.3.5) relating to feedstock destined for the AD facility (see Figure 5-1), such as the collection and delivery of biowaste materials and the processing of municipal biowaste materials, assuming that such materials are sent through an MRF. The model only accepts quantities of feedstock in multiples of one tonne. All transport fuel consumption calculations are broken down to the quantities of litres of fuel used for each tonne of feedstock. Delivery from multiple sources is possible for municipal waste.

Figure 5-1 Biowaste and livestock-waste-material feedstock pathway, Module 1

This section of the ADEE model also calculates the quantity of cow slurries and manures from the number of head of cattle present on the farm. On-farm pig and poultry slurries and manures, in addition to all off-farm livestock slurries and manures, are not calculated using the number of head in a herd, but the gross weight, like all other feedstock types. The transport of these livestock materials is treated in the same way as other feedstock types and is discussed in the sections that follow.

5.3.1.1 Livestock feedstock types

The model calculates the quantity of expected slurry and manure produced by the cattle. There are slight differences in quantities collected between beef and dairy cattle, as a result of their husbandry; therefore, beef or dairy needs to be defined at the input stage, along with the number of head of animal and the duration (in weeks) the animals are expected to be housed. The model calculates the quantity of slurry and manure produced weekly, based on DEFRA (2010a) RB209 data. It is assumed that of the total quantity of excreta produced, 92.5 per cent will be classified as pure slurry, whilst the remaining 7.5 per cent will have some straw and/or feed mixed in and will be classified as manure (Davies, 2013). There are no per capita calculations for the other livestock (pigs and poultry), as these are based on the quantity input (tonnes), since small changes in the number of head do not have a large impact on digester size.

The number of cattle and the period for which they are housed can have a significant impact on the digester size, and therefore on capital costs and the additional quantity of supplementary feedstock required to co-treat these on-farm wastes. For example, every additional cow to a dairy herd produces approximately 11 t of collectable excreta (if housed for 20 weeks per annum – as in the South), or approximately 23 t of collectable excreta (if housed for 44 weeks per annum – as part of an intensive farming herd).

This section of the model also includes calculations for the offset of GHG emissions from the energy use at a dairy, where a digester on a dairy farm is being modelled. Details of the background to this were discussed in Section 3.3.5.8.

5.3.1.2 Biowaste calculations

Transport distances of feedstock and digestate to and from the AD facility were provided in miles during the interviews; these were converted to kilometres during calculation (1 mile:1.609 km), along with any other data presented in miles rather than kilometres.

The quantity of fuel used per annum is calculated from the number of journeys required to move the total tonnage of materials, on the assumption that the refuse truck has a fuel economy of 4.5 mpg (WRAP, 2010b). Having quantified the diesel requirement (l), this is then multiplied by the emission factors (see Table 5-1) to calculate the CO_{2eq} emissions produced (see Eqn 5-1). To calculate the quantity of energy used, Eqn 5-2 is used.

Eqn 5-1 GHG emissions from feedstock transport $$kg\ CO_2e = \sum L \cdot \frac{gCO_{2eq}/L\ diesel}{1000}$$

Eqn 5-2 Energy used in feedstock transport $$GJ = \sum L \cdot \frac{MJ/L\ diesel}{1000}$$

Where: L = total litres of diesel used from all sources in this section; 3.2413 $KgCO_{2eq}.L^{-1}$ = CO_{2eq} emission conversion factor; 35.86 $MJ.L^{-1}$ = energy conversion factor.

To provide a simple calculation of the impacts of the food-waste feedstock through an MRF, the quantity (t) of municipal household kitchen waste feedstock is multiplied by the electricity (1.6 $kWh.t^{-1}$) and diesel (0.36 $l.t^{-1}$) coefficients (Powell, 2011), and then multiplied by the relevant GHG conversion coefficients (DEFRA, 2012b) set out in Table 5-1. To calculate the impact on the economics of the model, the quantity of diesel is multiplied against the current diesel value.

5.3.1.3 Emissions from landfill

It is well documented that organic materials ferment in landfill sites and emit methane (see Section 1.4.2). If biowaste is a chosen feedstock, the ADEE model assumes that the alternative treatment would have been landfill. The model therefore calculates the offset emissions from diverting the material from landfill.

Literature (Gregory *et al.*, 2003) suggests that 10 per cent of methane (and other gases) escapes through fissures in landfill-site caps. The model also assumes there is net 1.5 per cent leakage (and flaring) of methane from AD facilities across the process; subtracting this 1.5 per cent from the 10 per cent methane leakage from landfill, a net 8.5 per cent avoidance in methane emissions (E^S) is calculated (see Eqn 5-3), based on the expected methane yield from the diverted material treated at the AD facility. Other avoided emissions calculations from various related activities are dealt with in the next section.

Eqn 5-3 $$\boldsymbol{E^s = \sum biowaste\ methane\ yield \times 0.085}$$

5.3.2 Module 2: Farm-material feedstock types

This module is quite complex and requires a lot of data relating to the type and number of feedstock types selected. It works identically for materials produced either for on-farm (at the site of the digester) feedstock types or for off-farm feedstock types, except for the additional transport costs calculated in getting the feedstock from a remote site. The various activities are broken down below.

The type of feedstock input will influence the AD facility in terms of the capital required and the cost of that capital. The model can account for single feedstock-type digesters, as well as for co-digestion of several different materials.

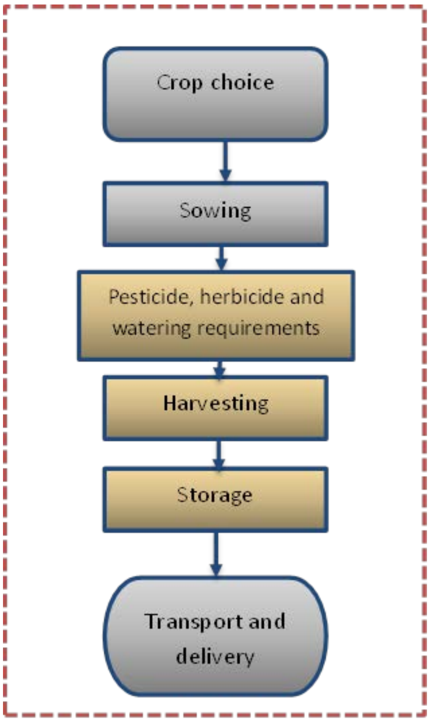


Figure 5-2 Modelling of purpose-grown crops, Module 2

In reality, the type of on-farm feedstock types digested will depend on the type of farm; assuming that all supplementary feedstock types are local, the choice will be governed by soil type, climate and other factors. The greatest influence will be their economic viability, in terms of expected yield from the land, coupled with the expected energy yield from the feedstock type. This could be anything from on-farm waste materials such as animal manures and slurries (see Section 5.3.1.1) or unsold crops, to purpose-grown crops (see Section 5.3.2.1) intended for the digester.

The model is unable to account for the different farming practices, particularly in animal husbandry. Feeding practices can have a significant impact on the animal's quantity of excreta and its characteristics. The duration for which the livestock are housed needs to be selected, as this is dependent on location and herd size. The model calculates the expected quantity of excreta (DEFRA, 2010a) from the number of head of on-farm cattle selected and the time housed.

Transport costs for off-farm materials (both environmental and economic) are calculated (in the same way as in Section 5.3.1.2) both to and from (as digestate) the facility. On-farm farming activities are calculated separately (see Section 5.3.2.1), as are on-farm transport costs (see Section 5.3.2.2). Other activities are accounted for by the model, particularly the offset of energy use in the dairy, and the offset of GHG emissions from the use of digestate, and the indirect GHG emissions from the use of crop-protection sprays (for both, see Section 5.3.2.3).

5.3.2.1 Farming activities for purpose-grown crops

With reference to Section 3.3.5.9 regarding the different crop-growing farming activities, data for fuel consumption were gathered from a number of sources (see Table 3-6). However, this research calculated and used fuel consumption figures based on the collection of the typical fuel consumption data of different horse-power-sized tractors used in the UK, from several well-known manufacturers, taking the average fuel consumption per hour. The average time taken per hectare for each crop was calculated using Nix's (2012) expected contractor work rates, thereby providing an estimate of the fuel consumption per hectare of crop. The energy and emissions calculations are shown below (see Eqns 5-4 and 5-5).

Eqn 5-4 Energy requirement for field activities $= \sum \textit{\textbf{field operations}} \times \textit{\textbf{fuel consumption}} \times \textit{\textbf{area}} \times \textit{\textbf{MJ}}$

Eqn 5-5 GHG emissions from field activities $= \sum \textit{\textbf{field operations}} \times \textit{\textbf{fuel consumption}} \times \textit{\textbf{area}} \times \textit{\textbf{CO}}_{\textit{\textbf{2eq}}}$

The area required for growing the feedstock is calculated using the expected yield per hectare divided by the quantity (t) of feedstock used. Therefore, the costs of all crop-growing farming activities can be calculated for both on-farm and off-farm crops. Transport calculations for off-farm transport to the AD facility can be input if known for a single source, or an average distance can be input if a number of suppliers are used. Since greater information is provided for individual on-farm AD facilities, further calculations regarding the transport of feedstock can be achieved as described below.

5.3.2.2 On-farm transport

All farming activities are measured in kilometres. The average distance from field to farm building is calculated using Eqn 5-6.

Eqn 5-6 Average on-farm transport distance = $\left(\frac{\frac{a}{0.7}\times 10000}{\pi}\right) \Big/ \sqrt{2}$

Where: a = the number of hectares of the farm divided by the estimated percentage of usable area (after woodland, roads and buildings), then converted to acres. For simplicity, the farm is deemed to be circular, with the main farmhouse and other buildings at its centre. It assumes that one-third of the farm area is unusable, due to roads, paths, hedges, buildings, and so on. An average distance to the field is then calculated accordingly.

The area required to grow crops is calculated using expected crop yields published by Nix (2012). Whilst modelling the scenarios, the average regional farm size relative to the herd size being modelled (see Appendix 3) was used; without this, the model could underestimate the size of the farm by not taking into account the areas of the farm not associated with activities connected with the AD facility (e.g. crops sold to the market). For off-farm crop-material feedstock types, the model calculates all the activities used within the field. The model also calculates transport from farm to AD facility, but cannot calculate the transportation costs from field to farm gate, since the model is not informed of the size or number of different farms supplying the AD facility. This was not deemed to be significant in the overall modelling of an AD facility. However, collectively, within the scenario of crop-only digesters, this could be significant.

5.3.2.3 Fertilisers and sprays

The quantity of nutrient removed is assumed to be the quantity required by the crop during growth. The values are those displayed in DEFRA's RB209 *Fertiliser Manual* (DEFRA, 2010a).

The *Fertiliser Manual* also sets out the recommended quantity of nitrogen, phosphorus and potassium that can be applied to land, dependent on the type of soils, the quantities of nutrient already present in the soil, the estimated annual rainfall in area and the expected nutrient requirement of the crop to be planted. These parameters are used in calculating the soil nitrogen supply (SNS) and other soil index values used in the ADEE model. Phosphorus (P) and potassium (K) are relatively stable and are not transformed during the process, but there are some minimal losses (volatilisation) of nitrogen (N) during the process, and potentially greater losses during digestate storage and application to land (see Sections 2.5.1 and 2.6.1).

The calculation for the quantity of fertilisers (NPK) required (see Eqn 5-7), and therefore the use of the digestate, is based on two assumptions:

- The calculation is based on the same quantity and type of crop being grown (therefore same area of land) again, within the normal rotation in another part of the farm.
- Calculations of nutrients required are capped by the soil index value (DEFRA, 2010a) specified for that land (default to soil index value of one for N, P and K) and crop requirement.

Eqn 5-7 Quantity of digestate used ***= soil index value for nutrient - nutrient value in digestate***

Since the nutrients are not separated from the digestate, the quantity of digestate that can be spread to land is limited by the nutrient that fulfils the land requirement first. Nitrogen was often the most common limiting factor, but in some cases phosphorus was also a limiting factor. When large quantities of biowaste were digested, potassium could potentially become the limiting factor. There is little literature on the toxicity of potassium in terms of animal health. Potassium is ubiquitous in soils and is only known to be toxic to cattle at ultra-high concentrations (Finch, 2012). The ADEE model therefore allows for up to 150 $kg.ha^{-1}$ over-application of potassium (based on the potassium soil index value for the crop being grown for AD), allowing the limiting factor to be either phosphorus or nitrogen. All the calculations relating to the quantity of digestate that is required for land are based on the crop that is grown for the digester (effectively replenishing what was taken from the soil) from land with an assumed soil index value of one.

There is a considerable quantity of data and variables (see Appendix 3) used within the farming module, in addition to the data obtained for the feedstock mentioned above. Data were collected on GHG emissions from the manufacture of NPK fertilisers and crop sprays, as well as the energy required in making them, along with GHG emission and energy requirements from manufacturing herbicides, fungicides and insecticides (see Table 5-3).

The quantity of fertiliser or spray (kg/ha) is provided by Nix (2012); DEFRA's RB209 (2010a) provided details of the fertiliser requirement, dependent on the crop grown, and the soil type, based on SNS, phosphate and potash (potassium) indices. Farm activity requirements for the different crops were provided by Salter (2011) and updated by Finch (2012) in an email exchange. This is multiplied by the requirement per hectare per crop.

Table 5-3 Energy and GHG emissions from fertiliser production (per kg)

Parameter	(MJ kg^{-1})	CO_2 (kg/kg)	CH_4 (kg/kg)	N_20 (kg/kg)	Total CO_{2eq} (kg/kg)	Total CO_{2eq} (kg/kg) sprays
NH_4NO_3	40.6	5.877	0.0028	0.0364	6.6954	
P_2O_5	15.8	2.287	0.0011	0.0142	2.6056	
K_2O	9.3	1.346	0.0006	0.0083	1.5337	**Inc. 15% allowance for an excipient**
Herbicides (a.i.)	264.0	38.217	0.0183	0.2369	43.5366	50.07
Fungicides (a.i.)	168.0	24.320	0.0117	0.1507	27.7051	31.86
Insecticides (a.i.)	214.0	30.979	0.0149	0.1920	35.2910	40.58

Adapted from: CROPGEN (2004b)

Note: a.i. = active ingredients

The manufacture of fungicides, herbicides and insecticides was accounted for in the model, using equal thirds (see Eqn 5-8) of each from the average values and costs from Nix's farm guide book (2012), based on the a.i. in CROPGEN's D25 (2004b) life-cycle report of energy requirement (α) and CO_{2eq} emissions (ε). An additional 15 per cent for GHG emissions was added to allow for the manufacture of the chemical excipient of the a.i. Both these equations can be represented as follows, with (ε) being substituted for (α) in the energy calculation:

Eqn 5-8 $$\left(\frac{1.15\times\varepsilon_h}{3}\times\frac{1.15\times\varepsilon_i}{3}\times\frac{1.15\times\varepsilon_f}{3}\right)\times n$$

Where: ε_h = emission factor from herbicide manufacture; ε_i = emission factor from insecticide manufacture; ε_f = emission factor from fungicide manufacture; and n = number of times a crop is sprayed.

The value of the digestate is calculated from its constituent parts (NPK), less the value from on-farm livestock, which would have been applied to land if a digester were not present. The quantity of NPK is calculated by the ADEE model using values in DEFRA (2010a; see also Appendix 3, Table A1.8), multiplied by the average cost per kilogram in 2012 (Nix, 2012), represented in Appendix 3, Table A1.2.

These figures are used in calculating the financial savings from using the digestate in replacement of mineral fertilisers and establishing the energy requirement and GHG emissions from the manufacture of sprays and mineral fertilisers.

5.3.3 Module 3: The digester and other capital requirement calculations

As illustrated in Figure 5-3 (below), this module is central in that it calculates the inherent energy and GHG emissions associated with the building materials used in the capital equipment. The module includes the database for all the feedstock types, and the materials used in constructing the digester, buffer tanks, pasteurisation units, digestate holding tanks and silage clamps. There is also a basic calculation for the inherent energy of the CHP genset.

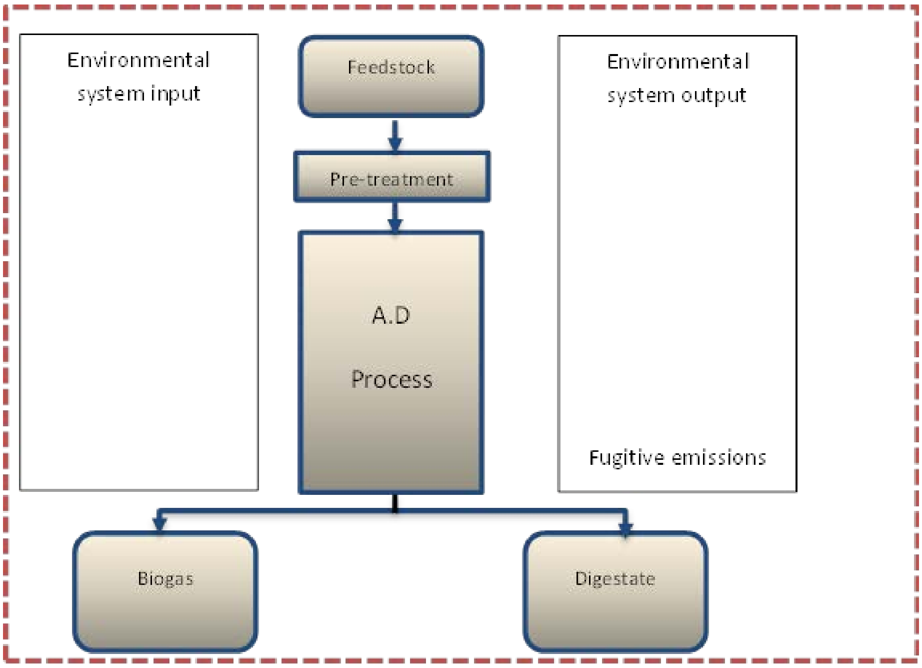


Figure 5-3 The central process of the model, Module 3

The model assumes that feedstock is added to the digester equally throughout the year. This represents one of the most challenging aspects of modelling AD, since the reality is that on-farm feedstock materials are seasonal, and therefore there are differing digester-size and operational requirements over the year. Crops, for example, are not available whilst growing, and slurries or manures are not available in the same quantities whilst the livestock are in the fields during summer months. In terms of capital equipment, the design is based on the 'peak period' of digestion, with the facility operating at its maximum capacity. Normally, a facility manager will seek exogenous materials if his own feedstock is likely to run out, so that the bacterial cultures within the digester are kept alive and the facility generates energy, and therefore an income.

This could make the late spring/early summer period a good time to 'slow' down the digester for maintenance and renewals. Stopping the process is not often a reasonable proposition, as it takes a significant period of time to get the digester up to full working capacity, since it takes time for bacterial colonies to establish themselves. Therefore, the system can only be slowed down to a level which enables the CHP gensets to operate at their minimum level (unless the gas is to be flared, which is literally burning money). The temporal change in feedstock types needs to be gradual, and as the liquid feedstock (slurries) becomes scarce in the summer, greater quantities of water need to be added.

The AD facility configuration is dependent on the feedstock types that the facility is designed for. Additional technology would be required for root crops that may have stones and soil attached to them. Soil causes the digester to silt up, reducing its capacity, whilst stones can destroy augers, pumps and other mechanical devices used in the process. Technologies used to mitigate these contaminants have consequences for the financial viability of the treatment facility.

The most significant financial impact on the AD facility design is for the use of one particular feedstock type (food waste). In general, a large reception building is required to receive the waste, in addition to other technologies, such as pasteurisation units and decontamination units (to separate out the contaminants, such as plastic bags, cutlery, tin cans). These alone create additional expenses of around £633,500 for a digester treating approximately 15,000 t of waste per annum (case study 1). Licences, additional labour and biohazards also need to be considered when treating this feedstock type.

The size of the capital equipment required is governed by several parameters. Technology users wish to keep their costs to a minimum and therefore seek to reduce the size of the capital equipment. This can be achieved in a number of ways, including the use of catalysts or pre-treatment methods that speed up the release of biogas from the substrate and allow an increase in throughput-reducing costs. These parameters are outside the scope of this research and they are not used in the ADEE model.

There still remain a number of variables that influence the capacity requirement of an AD facility, however, even without the considerations mentioned above. These include temperature, water requirement and the retention time needed by the substrate.

5.3.3.1 The effects of temperature on performance and digester size

Temperature plays a crucial role in process optimisation and defining digester size. The longer the period of digestion, the larger the volume of digester required. From an economic point of view, the larger the digester, the greater the cost, which can mean the difference between viability or not.

Dependent on the temperature range chosen – mesophilic in this research – the economic trade-off will be to achieve the greatest gas yield possible, all the while keeping capital and operational costs down, whilst not creating the potential for pollution issues post-digestion. Abedeen (2010), reproducing Reynolds and Richards' (1996) graph on the effects of temperature on the digestion of biodegradable solids in municipal waste water sludge (see Figure 5-4), and Ward *et al*. (2008) suggested that 36 °C is the optimal temperature for the anaerobes to operate on sewerage sludge, within the mesophilic range.

Nearly all of the case studies advised that their operating temperature was between 37 °C and 39 °C. This may be a result of different substrates being digested or biology present that pushes the temperature curve up to where the metabolic activity is optimised.

- The apex of the curve represents the time required to digest 90% of degradable (volatile) solids in primary sludge as a function of digestion temperature.
- Mesophilic range extends up to about 42.2 °C.
- Thermophilic range starts above 38 °C.
- Optimal mesophilic temperature is around 36 °C.

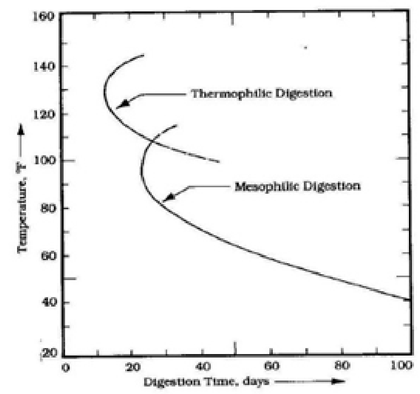


Figure 5-4 Digestion time (days) versus temperature. Adapted from: Abedeen (2010)

5.3.3.2 The interaction between water use, digester volume and hydraulic retention time

The water required within the process, hydraulic retention time (HRT), temperature and digester tank size are all inextricably linked. The quantity of feedstock used, in addition to the quantity of water required and the duration that the feedstock remains in the digester, are combined in calculating the size of digester required to treat that specific combination of feedstock types over the year.

The model uses the following simple equation to calculate digester size:

Eqn 5-9 $$\boldsymbol{Digester\ volume} = \frac{\boldsymbol{TS\ m^3.a^{-1} + H_2O\ m^3.a^{-1}}}{\boldsymbol{365}} \times \boldsymbol{HRT(d)}$$

Where: TS = total solids (t) per annum; HRT = hydraulic retention time (days); 1 t H_2O = 1 m^3; and 1 t feedstock ~ 1 m^3.

However, whilst the quantity of TS (or FM) is known, the additional water required and HRT need to be calculated. The addition of water has two aims: first, to reduce the DM content to a level that is mechanically manageable; and second, to help manage the chemical processes of the system, in particular, to ensure that ammonia levels, which build up naturally in the digester, stay below 3,000 $mgNH_4^+.l^{-1}$ (Köttner *et al*., 2008). If this concentration is exceeded, it can quickly cause the process to become inhibited, and eventually leads to a risk of failure of the biological system. It is impossible to model this latter water requirement, since it is a natural build-up of ammonia that will be feedstock-led and digester-specific and may vary temporally, as feedstock quantities change throughout the seasons. This can only be assessed through physical measurement.

To a degree, this management is completed by ensuring that the quantity of VS (those compounds of the feedstock converted to biogas) is kept within certain limits. The ADEE model calculates the parameters that ensure that the addition of VS does not exceed 4 $kg.m^{-3}.d^{-1}$ (Banks *et al*. 2011); this is calculated within Eqn 5-15. Research has shown that instability in the digester can arise with increasing rates of VS (Banks and Zhang, 2010). If this becomes too great, it can cause instability in the biological system (Callaghan *et al*., 2002), potentially overloading and 'souring' the digester, effectively killing the active bacteria. Instability in the biological system can also lead to the partial breakdown in the feedstock VS and biogas emissions from the digestate storage tank (Comino *et al*., 2010) if not covered. There are some exceptions to this, but a high degree of management skill and close monitoring of the system are required to remove this uncertainty.

The quantity of VS is partially controlled with the addition of liquid, which could also include: digestate, farmyard washings, collected rainfall, dairy washings or water. Recycling of digestate has its implications, as this involves recycling the ammonia present in the digestate solution, which could inhibit the digestion process. Therefore, the digestate can only be recycled a couple of times (dependent on the feedstock being digested) before an alternative is required.

5.3.3.2.1 Water requirement

The total DM content of the feedstock per cubic metre per day is important in terms of the overall mechanics of the process enabling the substrate to be moved through the system. In general, for a mesophilic CSTR, the total DM content is unlikely to exceed 19 per cent; however, the results calculated for case study 3 showed that they operated with a DM of 20.2 per cent. Generally, the average DM content is approximately 12 per cent or less, due to the impact of the DM content on the efficiency of the pumps moving the substrate around the system, and indeed their ability to do so if this is allowed to get too high.

The ADEE model sets a maximum target DM content of 14 per cent. Should the total DM content of the feedstock exceed this value, the model makes the following calculation:

Eqn 5-10
$$\boldsymbol{Water\ requirement\ (t)} = \left(\frac{(\boldsymbol{\theta} - \mathbf{0.14})}{\mathbf{0.14}} \times \boldsymbol{D_{dm}}\right) \times \mathbf{0.35}$$

Where θ = percentage DM content of the feedstock added; D_{dm} = average DM content of the digester, calculated by adding the DM content of the digestate to the DM content of feedstock, divided by two.

The aim is to achieve a suitably low DM content that can be pumped round the system, without increasing the size of the digester so much that costs become prohibitive. The water requirement can be reduced to a certain degree through recirculation of the liquor from the digestate. This recirculation can only occur a number of times until the build-up in ammonia (NH_4^+) becomes too great and starts to inhibit the digestion process. As previously mentioned, NH_4^+ concentration should be kept below 3,000 $mgNH_4^+.l^{-1}$.

The percentage of DM content is found first; this is subtracted from the target rate of 14 per cent, then multiplied by the total feedstock mass to provide the quantity (t) of water required to be added. The model assumes that one-third of the water requirement can be offset by recycling the digestate liquor.

5.3.3.2.2 Hydraulic retention time

The HRT (days) is a function of the mean cell residence time (solids retention time, θ_s) of the organic material in the digester (Abedeen, 2010). The mean residence time can be expressed as follows:

Eqn 5-11
$$\boldsymbol{\theta_c} = \frac{\boldsymbol{X}}{\boldsymbol{\Delta X}}$$

Where θc = mean cell residence time (d); X = kg DM in digester; ΔX = kg DM produced in the digester.

However, since the number of new cells placed in the digester per day is negligible in comparison to the number of cells already resident in the digester, the mean cell residence time is equal to the HRT, assuming that the digester is completely mixed. For design consideration, Abedeen (2010) suggests that θ_c^{design} is much longer than θ_c^{min} – usually 2.5 times longer. However, using the formula against the case studies and comparative research, the 2.5 multiplier was found to cause an excessive overestimation of the digester size required, when compared to the case studies from this and other research. This could be because Abedeen's (2010) research related more specifically to sewerage sludge, and not a combination of materials with differing DM and VS content. Therefore, a more representative figure that related to this research's case studies, the HRT, was increased by 14 days (see Eqn 5-12). In reality, the additional days are dependent on the manufacturer's design and the specific operating conditions designed for that facility – for example, using certain catalysts, process enhancers and operating temperature.

Eqn 5-12 $$\boldsymbol{HRT = \left(\frac{tVS.a^{-1} \times 1000}{tFMm^3.a^{-1} + H_2Om^3.a^{-1}}\right) \Big/ 4 + 14}$$

Where VS.a^{-1} = VS added per annum; $H_2O.a^{-1}$ = amount of water added per annum; and tFM.a^{-1} = amount of FM added per annum (assuming 1 t =1 m^3).

Eqn 5-12 is a combination of two equations (Eqns 5-13 and 5-14) used for calculating the HRT and volume of the digester; it is interchangeable with Eqn 5.15. Eqn 5-13 sets the organic loading rate (OLR) so it does not exceed 4 kgVS.m^{-3}.d^{-1} (denoted by x), the theoretical beneficial maximum (Banks *et. al.*, 2008). Eqn 5-15 is a rearrangement of Eqns 5-13 and 5-14, and is used to calculate the digester volume in order to determine the number of days.

Eqn 5-13 $$\boldsymbol{OLR(x) = \frac{\frac{tVS \times 1000}{365}}{\frac{tFMm^3 + H_2Om^3}{365}} = kgVS.m^3.d^{-1}}$$

Where: $x \leq 4$.

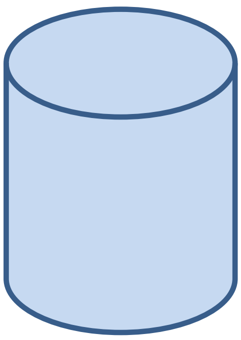
Eqn 5-14 $$\boldsymbol{Volume = \frac{tFMm^3 + H_2Om^3}{365} \times HRT}$$

Eqn 5-15 $$\boldsymbol{Therefore\ HRT = \left(\frac{tVS \times 1000}{tFMm^3 + H_2Om^3}\right) \Big/ 4 + 14}$$

5.3.3.3 Digester construction, embodied energy data and process energy requirements

Anaerobic digesters can be constructed from many different materials. Some of the older, small, on-farm digesters were built of insulated fibreglass. This research assumes that anaerobic digesters are constructed from either steel or reinforced concrete. The foundations and bases are always constructed of reinforced concrete. The construction of the digestate storage tanks and silage clamps are discussed in Sections 5.3.3.5 and 5.3.3.6 respectively. Either concrete or steel construction for the digester can be chosen, but the other capital structures are automatically defaulted to concrete construction.

Section 5.3.3.2 described the calculation for the minimum working digester volume required (Eqn 5-13), based on the expected feedstock and water input needed for the process. For simplicity, and since CSTR is the most commonly used tank reactor in the UK, the digester is assumed to be of cylindrical shape (see Figure 5-5).



Area of floor (square and 15% bigger) = $r^2 \times 1.15$

Area of the sides = $2\pi rh$

Walls = (π × diameter × 250 mm) × h

Roof = πr^2 × 200 mm (concrete only)

The steel roof includes 100 mm of rock-wool insulation

Figure 5-5 Digester statistics

The calculation for the digester size is that of a simple cylinder, based on a diameter:height ratio of 2:1 for a concrete digester and 3:1 for a steel-based digester. However, in reality, depending on the overall size of the digester and local planning regulations (height restrictions, etc.), a number of ratios are possible.

Quantities and volumes of materials (see Table 5-4) for the digester and digestate holding tank were calculated based on statistics provided by Mulliner (2012). The quantities of materials required for the silage clamps were based on the Bock clamp construction method of aggregate 'sandwiched' between two concrete walls, as used by one of the case studies. These figures were compared with one other technology provider's data (Future Biogas; Griffin, 2013). The averages of these two figures were used in the ADEE model, displayed below (see Table 5-4).

Table 5-4 Construction assumptions for digester, silage clamp and holding tank

Parameter		Value
Walls and roof		
Steel inner layer		6 mm thick
Insulation		100 mm thick
Steel outer layer		3 mm thick
Glass coating		0.3 mm thick
Walls (concrete)		250 mm thick
Roof (assume flat cylinder)		250 mm thick (concrete)
Facing steel		0.7 mm thick
Insulation (rock wool)		Density 23–200 kg/m^3 17.3 MJ/kg
Floor		250 m thick and square
Total floor area includes		Calculated area +15%
Steel reinforcing		
Roof (300 mm thick)		2 layers of mesh at 100 mm centres
All rods		12 mm diameter
Walls – horizontal		20 rods.m^{-2} (height × circumference: area of wall)
Walls – vertical		20 rods.m^{-2} (height × circumference: area of wall)
Silage clamps		
Based on Bock silage clamp system		www.bock-uk.com/cms/front_content.php?idcat=39
2 area sizes (depending on the quantity of silage stored)		<5000 t = 30 m (L) × 10 m (W) OR >5000 t = 75 m (L) × 30 m (W)
Bulk density of stored material		1.5 t/m^3
Clamp height		3 m
Concrete walls		12.5 mm thick
Steel reinforcing		2 layers of mesh at 100 mm centres
Area required		Operating area +10%
Digestate storage		
General		Covered, ¾ buried and square
Storage requirement		6 months
Walls and floor		As for digester, 250 mm thick (concrete)

Source: Mulliner (2012)

To identify the quantities of different materials used in the construction of the digester, first, the volume of materials demanded is calculated, using the equations in Figure 5-5 (based on the material qualities and digester dimensions – see Table 5-4). To identify the quantity of concrete (t), the volume calculated previously is multiplied by the specific material densities (see Table 5-5). This work does not provide a complete analysis of all the materials used in an AD treatment facility – only the materials of greatest mass. A full analysis and calculation of all materials used is outside the scope of this research and would also differ from one designer/manufacturer to another, since each takes a very different approach to the design and specification of their AD systems.

Having ascertained the quantity of materials used, the inherent energy of this material can be calculated by multiplying these quantities by the respective embodied energy value of the material in question. This information is used to calculate the embodied energy utilised in making these materials (see Table 5-5).

The thermal coefficients of the materials employed in calculating the thermal efficiency of the digester (and therefore the amount of heat loss and energy required to heat the digester) are also displayed below (see Table 5-5), and are applied in conjunction with Eqns 5-16 and 5-17.

Table 5-5 Embodied energy and material densities of materials used in digesters, silage clamps and pasteurisers

Parameter	Embodied energy GJ/t	Material density t/m^3	Source
Concrete	1.1	2.3	Hammond and Jones, 2008
Reinforcing steel	24.6	7.8	
Sheet steel (galvanised)	39.0	8.0	
Stainless steel	56.7	7.9	
Insulation (rock wool)	16.8	0.2	
Glass coating of steel	23.5	2.5	
Thermal properties of material used			
Construction materials	Thermal conductivity (W.m^{-1}.°C^{-1})		
Concrete	1.9		Hammond and Jones, 2008
Steel	45.0		
Rock wool	0.033		

The expected electrical energy requirements (see Table 5-6) of different digester types (Berglund and Borjesson, 2006) have been set in this model against digester sizes, as follows:

a) small farm digester with required volume less than 1,000 m^3

b) digester with required volume greater than 1,000 m^3, but may or may not be receiving up to 3,000 t.pa^{-1} municipal or C&I food waste

c) large AD facility with required volume in excess of 1,000 m^3 and treating more than 3,000 t.pa^{-1} of municipal or C&I food waste.

This was to model the treatment of small quantities of pre-pasteurised imported materials in on-farm situations, such as within the hub-and-pod concept.

Table 5-6 Average electrical energy requirements for different-sized digesters

MJ/t FM	Farm size/type
33	a) Farm
50	b) Average
66	c) Centralised (community)

Source: Berglund and Borjesson (2006)

The energy requirement for maintaining the digester's temperature (see Eqn 5-15) is based on calculations discussed in CROPGEN (2004a). Coefficients of heat transfer were taken from Hammond and Jones (2008), and average monthly soil and air temperatures (between January 1931 and June 2012) were obtained from the Met Office website. Met Office data collection sites of Durham, Lowestoft, Ross-on-Wye and Southampton were taken to represent North, East, West and South, and an average of these combined figures was used to represent a national average, the fifth option.

Combining the equations used to calculate the heat loss from the digester (see Eqn 5-16) and raise the temperature of the feedstock to the operating temperature (see Eqn 5-17) calculates the heat demand of the digester. Used in conjunction with the data above, provided by Berglund and Borjesson (2006), this completes the calculation for the overall parasitic energy requirement of an AD facility.

Eqn 5-16 $$hl = UA\Delta T$$ (Salter and Banks, 2009)

Where hl = heat loss (kJ s^{-1}); U = coefficient of heat transfer (W m^{-2}. °C); A = surface area (m^2); and ΔT = change in temperature across the surface in question (°C).

Eqn 5-17 $$q = CQ\Delta T$$ (Salter and Banks, 2009)

Where q = heat required to raise the feedstock to operating temperature (kJ.S^{-1}); C = specific heat of the feedstock (kJ.kg^{-1}.°C); Q = quantity of feedstock added; and ΔT = temperature difference.

5.3.3.4 Required CHP genset size and inherent energy calculations

The engine's electricity-generating capacity requirement (see Eqn 5-18) is a function of the expected gas yields from the feedstock over the year being close to that of the observed data, converted at the energy density value for methane, 9.888 kWh.m^{-3}; this total is then multiplied by the electricity conversion coefficient for that engine, giving the total annual electricity generated. The total annual electrical energy produced is then divided by the number of operating hours per annum (8,040 hrs), which calculates the genset requirement for that scenario.

Eqn 5-18 $$\text{Genset capacity} = \frac{(\boldsymbol{y} \times \boldsymbol{d_m})\boldsymbol{E_e}}{\boldsymbol{t}}$$

Where y = methane yield (m^3); d_m = energy density of methane; Ee = electricity conversion efficiency coefficient of that CHP genset; and t = time (hrs per annum).

The CHP genset's electrical energy generation capacity is used to determine the embodied energy of the genset. This is based on the genset's mass, which is based on the Jenbacher GS series engines (see Table 5-7). The embodied energy coefficient for the genset is based on the galvanised steel value (see Table 5-5). For simplicity, for gensets with electrical energy-generating capacities of <250 kW, a mass of 4,900 kg is used; for gensets with electrical energy-generating capacities of >250 <1,000 kW, 9,000 kg is used; and for gensets with electrical energy generating capacities of >1,000 kW, 14,000 kg is used. The pipework used around the facility is also calculated approximately, using the genset mass size. It was assumed that a similar quantity of stainless steel would be required for pipework around the site. Similarly, the embodied energy coefficient for the pipework is based on the stainless steel value (see Table 5-5).

Table 5-7 Jenbacher GS series engines

Generating capacity (kW_e)	Weight (kg)	Model
250–330	4,900	J208 GS
500	8,000	J312 GS
	8,800	J316 GS
1,063	10,500	J320 GS
800	10,900	J412 GS
	13,100	J416 GS
1,500	14,600	J420 GS

Adapted from: Clarke Energy (2013)

5.3.3.5 Digestate storage size and inherent energy calculations

The digestate storage tanks are considered to be of concrete construction in a similar way to the digester, but without the use of insulating material. Between the digester and the storage tank, they have combined storage capacity for six months' digestate.

5.3.3.6 Silage clamp size and inherent energy calculations

The calculation of the required silage clamp volume assumes that all crops will be ensiled and need storage. The volume of the silage clamp required is calculated based on a bulk density of 1.5 $t.m^{-3}$, or a requirement of 3.2 $t.m^2$ for maize and 2.5 $t.m^2$ for grass silage. The clamp side-height is fixed at 3 m, but allowing the feedstock height to rise to 4 m away from the sides. There are two basic sizes, dependent on the quantity of feedstock to be housed; either 30 m (L) × 10 m (W) for smaller clamps, or 75 m (L) × 30 m (W) for larger clamps. The base is assumed to be 0.2 m thick and the walls 0.1 m thick, in-filled with aggregate from the construction phase to form robust wall structures.

5.3.4 Module 4: Biogas treatment options

There are many possible uses of the methane-rich biogas, including: the combustion in a boiler for the generation of heat; the combustion in a CHP genset for heat and electricity generation; the upgrade for conversion to transport fuel; the upgrade for injection into the gas-grid system; and the production of hydrogen for use in fuel cells.

The production of hydrogen and the upgrade of biogas to transport fuel are not within the scope of this research. The model is able to calculate the environmental and economic costs associated with upgrade for injection into the gas-grid system; but the main analysis in this research focuses on the use of the gas in generating heat and electricity from a CHP genset.

The useful energy content of the biogas is provided by the methane. Since this is produced either from waste materials or from purpose-grown crops, it is deemed to have a neutral GHG effect. However, the quality of any energy-generating system can be defined by the energy return on energy invested. The greater the net return, the greater the return on both the resource used and the environmental benefit. Some end-products have more intensive energy processes than others, and it is those aspects that are investigated. Which final energy pathway is chosen is an economic decision, defined by policy incentives, geographical location and scale.

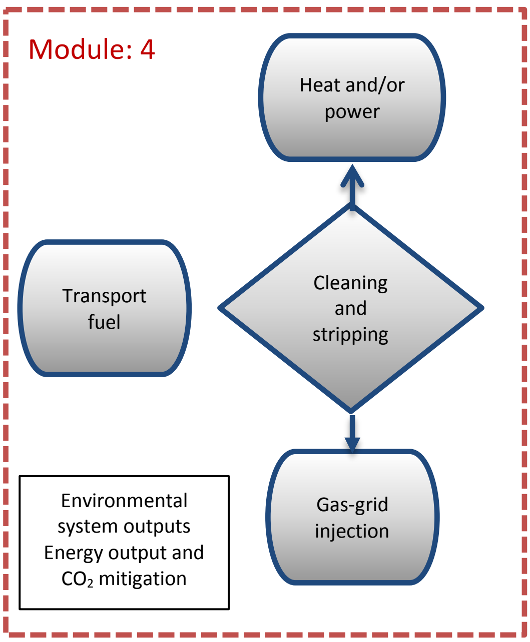


Figure 5-6 Biogas treatment options, Module 4

The calculation for gas upgrade to grid can be made in two ways. Both methods use the same energy requirement coefficient (see Table 5-8) for the upgrade process; however, the energy source for the upgrade process and the parasitic energy requirements of the AD facility can be chosen either from grid sources (gas and/or electricity) or from the installation of a small CHP genset, using part of the biogas produced from the AD process. The model calculates the quantity of parasitic heat and electricity required by the facility, and calculates the smallest CHP unit required. If heat energy is the greater requirement, any additional electricity not required on site is sold to the grid.

The experience and data for gas upgrade to grid is very limited. Neither the Adnams brewery, Suffolk, nor the Didcott sewerage works, Oxford, was operating when interviews were requested in 2011. Three others have subsequently been built (Rainbarrow Farm, Dorchester; ReFood, Widnes; Vulcan Renewables, Doncaster), but these facilities were built outside the time frame of this research, and there were few details available on the various websites, particularly relating to financial costs. These are expected to be in excess of the cost of a CHP genset; however, for the purposes of this research, the financial costs of the gas-upgrade equipment were deemed to be equal to those of a CHP genset.

Table 5-8 Energy required to upgrade gas for injection to the grid

Energy required for gas upgrading*			
0.3–0.67	kWh/m^3 biogas		
3–6	~ % energy in upgraded gas		
Energy required for compression*			
0.3	kWh/m^3 to 250 bar		
Values previously used here:			
Upgrading	1.8	MJ/m^3 biogas	0.5 x 3.6
Compression	1.08	MJ/m^3 gas compressed	0.3 x 3.6
Superseded by the following energy consumption delivering to grid at 9.5 bar (or less)†			
0.2	kWh/m^3 upgraded and compression up to 400 Nm^3/hr (0.72 MJm^{-3})		
0.25	kWh/m^3 upgraded and compression up to 700 Nm^3/hr (0.90 MJm^{-3})		

Adapted from: *Salter and Banks (2009); †Steentje (2012)

Predominantly, module 4 of the ADEE model calculates the financial rewards from the use of the biogas produced (Eqn 5.19). The model converts the quantity of biogas produced into energy in terms of MJ or kWh. Methane has an energy content of 35.6 MJm^{-3} or 9.88826 kWh^{-1}m^{-3}. The volume of biogas/methane is spread equally over the operating period of the year, which is assumed to be 8,040 hrs. If the period of generation were less than this, then a higher-rated engine would be required, if the facility could not store the gas or was not to burn the profits; similarly, if the period of generation were to be longer, a smaller, potentially less expensive CHP unit would be required. This could take the facility into a lower FIT bracket (if on the cusp of two FIT brackets), enabling the facility to gain higher rewards from producing the same amount of energy. In each case, the quantities of biogas and methane are calculated for their energy content and financial value.

Eqn 5-19 Energy value of gas $= y.d_m.E_e.FIT$ ***or*** $y.d_m.E_e.RHI$

Where: y = volume; d_m = energy density of methane; E_e = energy conversion factor; FIT = appropriate current Feed-in Tariff; and RHI = appropriate current Renewable Heat Incentive tariff. All conversion factors, FIT and RHI values can be found in Appendix 3.

The parasitic energy of the digester and gas-upgrade equipment is calculated by the volumes of gas multiplied by the working energy demand of the equipment. The methane used to generate this energy is deducted from the total methane produced if provided by the on-site CHP genset; however, if the energy is provided by grid electricity or fuel oil, the environmental and economic costs are calculated accordingly and included in the net output figures. The engine efficiency can be set within the range of 34 to 49 per cent, but at a default of 39 per cent. Older CHP gensets will be at the lower level, and currently, the most efficient electrical conversion gensets operate at about 42 per cent efficiency. Some of the technology providers have talked of using Organic Rankine Cycle (ORC) engines, which could generate up to 10 per cent additional electricity; however, these are expensive and not tested in this sector. The remainder is waste or unusable energy.

To calculate the quantity of energy and GHG emissions saved by the AD facility, existing heat and electricity sources are required – for example, if heat is obtained from gas, fuel oil or electricity. For this research, the source for electricity is always assumed to be the CHP unit or the national grid. For heat energy, it is assumed that the waste heat from the CHP unit is used to maintain the parasitic load of the digester and pasteuriser, unless gas upgrade is chosen with no CHP genset on site, in which case fuel oil is assumed to be the source for maintaining the digester temperature when required and grid electricity is used.

5.3.5 Module 5: Digestate transport and options

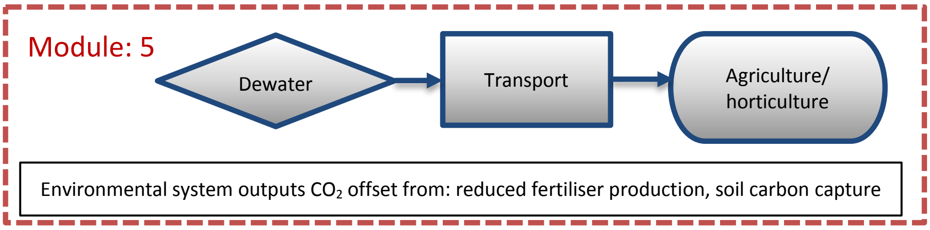


Figure 5-7 Conceptual model, Module 5

The few options for the digestate depend on its end use, the amount of available land at the facility and where it will be used. Some larger farms are able to pump the digestate out to the fields, where it can be spread in the normal way, but without the requirement to move the digestate long distances across the farm. Sites that have very little land to spread the digestate to have two options to minimise storage costs (with a third for the waste management industry): first, to export it to neighbouring farms; or second, to dewater the digestate (the solid 'cake' fraction is higher in phosphates and has a more stable nitrogen content, enabling it to be spread to land at any time of year) and, in a covered vessel, store the nitrogen-rich supernatant for later application to land. The third option is to dry out the digestate and incinerate it with energy recovery, which destroys the nutrients present. This research assumed that the AD operator would wish to utilise the digestate, which has nutrient value, and spread it to land. Therefore, there is no option for disposal (i.e. incineration). The research was completed based on the single option to dewater the digestate, separating the digestate solid residue from the liquid fraction. However, the benefits – fewer storage requirements, application of the solid fractions for longer periods of the year and reduced transport costs – would need to be balanced against the additional cost of purchasing the separating and spreading/pumping machinery, the ongoing maintenance and energy costs. A belt press was chosen because whilst it was not the quickest, the volume reduction was good and the energy requirement was low (see Table 5-9).

5.3.5.1 Digestate separation

There were few data available on digestate separation through the case studies, since few operated them. Their use is dependent on many variables, including existing farming practices, local environmental conditions and, in particular, whether land is sited within an NVZ.

There are many different methods of separating the solid and liquid fractions of digestate (see Table 5-9). The model does not allow the operator to choose one method over another, and this would only be of value in choosing technology for a specific digester. In assessing which technology to use in the model, that which provided the greatest reduction volume, with the least energy demand, whilst having a reasonable working capacity, was chosen. Of the five methods described below, the belt press and decanter centrifuge offered the best trade-off between the three criteria. Based on the data available (see Table 5-9), the belt-press separation technique was chosen for the model.

Table 5-9 Separation efficiencies and energy requirements of five different separation techniques

Separation type	DM	N	P	K	Volume reduction	Specific energy	Flow rate	Specific energy	Working capacity		
	%	%	%	%	%	kWh/m^3	m^3/h	MJ/m^3	kWh/m^3	t/hr	t/a
belt press	56	32	29	27	29	0.70	3.3	2.52	2.20	8 max	up to 50/-
decanter centrifuge	61	30	65	13	25	3.70	10.0	13.32	1.50	2 max	up to 16/-
screw press	45	17	20	12	15	1.30	11.0	4.68	42.5	5 max	up to 50/-
sieve centrifuge	33	18	15	21	17	4.50	3.70	16.20	5.5	10k l.h^{-1}	15/-
sieve drum	41	18	18	17	18	1.00	14.0	3.60			

Adapted from: Lukehurst et al. (2010); Salter (2011); Møller et al. (2000)

The belt-press data were used in this research. This technology appeared to have one of the higher volume reduction rates, yet required the least amount of energy. The data (see Table 5-9) were used, in combination with the quantities of digestate produced from the process, to calculate the energy used, and GHG emissions if the separation process was included in the scenario.

5.4 OUTPUTS

The purpose of the model is to provide outputs which can be used at several different levels in the assessment of AD. The model provides data on a single-site basis, providing environmental and economic data based on the type and quantity of feedstock. The model summary page (see Figure 5-8), contains eight main summary boxes. Four smaller boxes highlight some of the operations measured as part of the overall life cycle of AD, including:

- energy requirement of the dairy (if dairy cattle are modelled) and a digester separator
- electricity requirement of the dairy (if dairy cattle are modelled) and a digestate separator
- OLR of the model-run.

The first main box (see Figure 5-8, top left) provides a summary of the feedstock type used, the land requirements on- and off-farm for crops grown specifically for the AD facility, some facility statistics and gas yields from the process. Following the small box displaying the energy use by a dairy unit and digestate separator (if relevant) are two boxes (Digestate and nutrient values and Diesel use); these relate to the nutrient values present in the digestate and diesel used across all the different activities modelled within the life cycle. They are used within the environmental and economic calculations.

5.4.1 Environmental outputs

There are three environmental summary boxes in Figure 5-8 (Energy balance, Annual process emissions, and Offset emissions); these separate the figures that are used in calculating the following:

- the net energy balance of the system
- the direct and indirect GHG emissions associated with all the activities related to AD
- the saved GHG emissions, which are calculated from using the commodities that AD displaces, such as:
  - electricity from the grid network
  - heat from fuel oil
  - mineral fertilisers

  and GHG emissions captured and utilised from materials otherwise left to discharge them into the atmosphere, including:

  - methane escape from untreated slurries and manures
  - methane escape from biowaste sent to landfill.

The energy used in the various areas of operation and construction is combined, including the energy required to construct the main structures of the AD facility (the embodied energy). This total value is divided over the entire lifespan of the project. The inherent gross energy value of the total quantity of methane produced by the digestion process is then subtracted from the annual embodied energy value. This is the sum of embodied energy values of the various major structures (see Section 5.3.3.3) divided by the number of years of the project lifetime. This provides the net annual energy balance (GJ/annum) of the system. The inherent energy value of the capital structure (see Section 5.3.3.3) is also converted to GHG emissions equivalents, using the appropriate embodied energy factors (see Table 5-5) and the appropriate conversion factors (see Appendix 3, Table A1.6), having converted joules to watt-hours, using the conversion factor 0.27778 (see Appendix 3, Table A1.7), providing an annual net CO_{2eq} emissions figure that is added to the other annual emissions (attributable to its various operations), so that these emissions are allocated correctly too. These outputs all help to measure the environmental strength of an AD investment project.

5.4.2 Economic outputs

The final box (see Figure 5-8, Financials) sets out the economic summary for the model-run, including capital and operational expenditure, expected income from electricity and heat sales or sale of methane to the gas grid, income from gate fees (if applicable) and the value of the digestate (either from sale, if exported, or offset from the purchase of mineral fertilisers).

A profit-and-loss value is provided, but this is arbitrary (dependent on accountants), so is not used. An IRR is provided, as well as the NPV at 20 years (the project lifespan), calculated with a discount rate of 12 per cent (see Section 3.4.1.2). The model also calculates the average ROCE (sometimes used as measure of investment) and the levelised cost of capital (not shown in Figure 5-8). These are all used in assessing the financial viability of an AD investment project.

These output data could be used in a number of ways – for example, as a guide to individual farmers/businesses wishing to appraise a particular project for its environmental and economic benefits; by local planning departments, to assess if a particular project meets the environmental targets set out by current planning regulations; or by policymakers wishing to be informed of the efficacy of current incentives and assessing what might be required to achieve their goals, either current or future.

SUMMARY

PROCESS REQUIREMENTS		
Total MuniCommInd waste inputs	0.00	tonnes
Total livestock waste inputs	0.00	tonnes
Total crop inputs	0.00	tonnes
OFF-farm land requirement	0.00	ha
ON-farm land requirement	0.00	ha
Digester loading	0.00	$tFM/m^3/day$
Digester capacity requirement	#DIV/0!	m^3
Retention time	#DIV/0!	days
Biogas produced	0.00	m^3a^{-1}
Methane produced	0.00	m^3a^{-1}
CHP electricity produced	0.00	GJ
	0.00	MWh
Generator required	0.00	kW
CHP heat produced	0.00	GJ
Methane upgraded & compressed	0.00	m^3
Energy value of methane injected	0.00	GJ
	0.00	MWh equivalent
Method of compensation	FiTs	

ON-FARM ELECTRICITY USE (GJ)	GJ	Source
Dairy electricity	0.00	CHP
Separator electricity	#DIV/0!	CHP

DIGESTATE AND NUTRIENT VALUES	N - Nitrogen (kg)	P_2O_5 - Phosphate (kg)	K_2O - Potassium (kg)
Digestate			
On-farm (Total)	0.00	0.00	0.00
Imported (Total)	0.00	0.00	0.00
Nutrient available percentage	0.40	0.60	0.90
(Mineral fertiliser saving) or TOTAL	**0.00**	**0.00**	**0.00**
Nutrient availability per tonne FM	0.00	0.00	0.00
On-farm requirement			
Quantity (t) of digestate produced	**#DIV/0!**		**#DIV/0! t of digestate used on**
Digestate required for crops	0.00	0.00	0.00
Used from digestate	#DIV/0!	#DIV/0!	#DIV/0!
Quantity exported	#DIV/0!	#DIV/0!	#DIV/0!
ON-farm **requirement** or **surplus added**	#DIV/0!	#DIV/0!	#DIV/0!
Off-farm requirement			
Crop requirement	0.00	0.00	0.00
Used from digestate	0.00	0.00	0.00
OFF-farm **requirement** or **surplus added**	**0.00**	**0.00**	**0.00**
Quantity of digestate exported (t)	**#DIV/0!**		**#DIV/0! Value per tonne**

Assumes unused ON-farm digestate is used on suppliers OFF-farm first

DIESEL USE	Litres	GJ	Value (£)
C & D of MuniCommInd waste to centre	0.00	0.00	£0.00
OFF-farm-waste and crops to centre	0.00	0.00	£0.00
OFF-farm crops production	0.00	0.00	£0.00
ON-farm crop production	0.00	0.00	£0.00
ON-farm digestate use	#DIV/0!	#DIV/0!	#DIV/0!
Export of digestate (gate to gate)	#DIV/0!	#DIV/0!	#DIV/0!

Organic loading rate of the digester #DIV/0! **OM $kg.m^{-3}.d^{-1}$**

ENERGY BALANCE per year	On-farm		Off-farm	
Crop production fuel direct	0.00	GJ	0.00	GJ
Crop production fuel indirect	0.00	GJ	0.00	GJ
Transport fuel for waste - direct	0.00	GJ		
Transport fuel for waste - indirect	0.00	GJ		
Sprays manufacturer	0.00	GJ	0.00	GJ
Required fertiliser manufacturer	#DIV/0!	GJ	0.00	GJ
Digestate transport and application - direct	#DIV/0!	GJ	#DIV/0!	GJ
Digestate transport and application -	#DIV/0!	GJ	#DIV/0!	GJ
Digester required parasitic electricity	#DIV/0!	GJ		
Digester required parasitic heat	#DIV/0!	GJ		
Required dairy electricity	0.00	GJ		
Required separator electricity	#DIV/0!	GJ		
			Source	
Imported fuel for on-site heat requirement	0.00	GJ		
Imported electricity for plant from grid	0.00	GJ		
Buffer tank	0.00	GJ/a		
Digestate storage tank embodied energy	#DIV/0!	GJ/a		
Digester embodied	#DIV/0!	GJ/a		
Approx. engine embodied	19.50	GJ/a		
Pasteuriser heat requirement	#DIV/0!	GJ		
Pasteuriser embodied	#DIV/0!	GJ/a		
Silage clamps embodied	0.00	GJ/a		
Biogas use	**CHP**			
Energy in CH_4 produced	0.00	GJ		
Electricity generated	0.00	GJ	0.00	MWh
Heat generated	0.00	GJ		
Exportable electricity	#DIV/0!	GJ		
	#DIV/0!	MWh		
Exportable heat	0.00	GJ		
	0.00	MWh		
Energy content in upgraded CH_4	0.00	GJ		
Energy IN	#DIV/0!	GJ/a		
Energy OUT	0.00	GJ/a		
Energy balance	**#DIV/0!**	**GJ/a**		

ASSUMPTIONS

Av. distance to digestate recipient - 4 miles
Digestate taken in 10 t loads
The price is obtained for digestate exported
?MWe is "sold" to the farm @10p kWh
?% of heat generated is "sold" to the ? @4.5p kWh

Electricity for separator #DIV/0! kWh_e

ANNUAL PROCESS EMISSIONS from fossil fuel sources		
Diesel used in ALL crop production & digestate removal	#DIV/0!	kg CO_2e
Diesel fuel used in waste transport	0.00	kg CO_2e
Herbicides, pesticides & other sprays manufactured	0.00	kg CO_2e
Emissions from OFF-farm fertiliser production	0.00	kg CO_2e
Imported electricity for AD		kg CO_2e
Imported electricity for separator		kg CO_2e
Imported electricity for gas upgrade to grid		kg CO_2e
Emissions from ON-farm fertiliser production (if shortfall)	#DIV/0!	kg CO_2e
Imported heat for AD		kg CO_2e
Imported heat for pasteuriser		kg CO_2e
Emissions from leakage and flaring	0.00	kg CO_2e
Annual allocation of emissions from the embodied structure	#DIV/0!	kg CO_2e
Annual emissions from **uncovered** digestate storage tank	0.00	kg CO_2e
Total emissions	#DIV/0!	kg CO_2e

OFFSET EMISSIONS		
Emissions if electricity had been generated from UK grid mix	0.00	kg CO_2e
Emissions saved from equiv. grid electricity generated	#DIV/0!	kg CO_2e
Emissions saved from utilising the heat generated	0.00	kg CO_2e
Emissions saved from gas upgrade equivalent		kg CO_2e
Emissions saved from fertiliser production (digestate use)	#DIV/0!	kg CO_2e
Emissions saved from slurry that remains untreated	0.00	kg CO_2e
Emissions saved from methane escape from landfill	0.00	kg CO_2e
TOTAL EMISSIONS SAVED FROM ANAEROBIC DIGESTION	#DIV/0!	kg CO_2e
Emissions per MWhe generated	#DIV/0!	**kg CO_2e/MWhe**
Emissions per tonne of feedstock treated	#DIV/0!	**kgCO_2e/t**
Emissions from production per MWh exported (CHP only)	#DIV/0!	kgCO_2eq/MWhe
NET emissions per MJ of CH_4 produced	#DIV/0!	Kg CO_2eq/MJ
NET emissions/MWh of electricity **exported** (CHP and CHP+upgrac	#DIV/0!	Kg CO_2eq/MWhe
NET emissions per kWh of CH_4 upgraded		Kg CO_2eq/MJ

FINANCIALS			
Total capital expenditure		#DIV/0!	
Income from electricity		#DIV/0!	
Income from heat	£	-	
Income from gas grid injection	£	-	
Income from digestate (value)	£	-	
Total gate fees	£	-	
Total income		#DIV/0!	
Direct fuel use			
Used in farming activities	£	-	
Digestate disposal diesel		#DIV/0!	
Cost of ON-farm sprays	£	-	
Collection			
Other costs		#DIV/0!	**Payback within**
Total costs		#DIV/0!	**(yrs)**
Profit/loss		~~#DIV/0!~~	#N/A
Internal rate of return		#VALUE!	at 20 years
Net present value (12% discount rate)		#DIV/0!	at 20 years
Costs per GJ CH4 produced		#DIV/0!	
Profit/loss per tonne digested		#DIV/0!	£/t
Av. return on capital		#DIV/0!	

Electricity for dairy 0.00 kW_e

Figure 5-8 The ADEE model summary output page

5.5 REFLECTIONS

Whilst Microsoft Excel 2010 is considerably more stable than previous editions, the program is still susceptible to unforeseen corruption, which was experienced on a number of occasions. Using a program such as MS Excel has certain benefits over using an 'off-the-shelf' black-box packages which provide results from the input of data, but does not necessarily state how these results were achieved.

The biggest issue was deciding when to start programming and when to stop collecting data. In hindsight, collecting all data first would have been preferable, since one would know how the data would be presented, which itself would have made it easier to organise the data in the program. Collecting data halfway through the programming of the model required re-programming many of the numerous calculations. This could be problematic and caused delays, and could also lead to errors in programming code, which in turn took considerable time to find and adjust. Breaking down the model into modules did allow for a certain degree of flexibility in the programming (for updating and modification), and also made the process easier when following calculations requiring a number of steps.

Understanding the limitations of the software being used and what impact that might have as research developed also played a considerable part in programming. It was not until towards the end of developing the model and researching the subject that it became evident that the programming was inadequate, as it would not allow the swift repetition of model-runs and, consequently, would delay the completion of this research. Therefore, some Visual Basic for Applications needed to be learnt in order to install a script allowing for iterative calculations (over 5,000 in total, in the end).

Modelling both the environmental and the economic aspects of AD has been challenging. To the best of the author's knowledge, there is no single bespoke software package that enables the analysis of both of these aspects for AD. Therefore, MS Excel 2010 has provided a good platform from which to embark on research of this nature. However, MS Excel does have its limitations, and it is possible that other, higher-level computer programs, such as Matlab or GAMS, might have proved to be more flexible, particularly in allowing for optimisation, economic or Monte Carlo analysis of AD, which might have accelerated the modelling process and allowed for greater investigation. The multidisciplinary nature of this research was also extremely challenging, in terms of the understanding and calculations required in achieving these results.

Chapter 6: Model validation

'Nobody is qualified to become a statesman who is entirely ignorant of the problem of wheat.'

Socrates (died 399 BC)

6.1 INTRODUCTION

Validating the model program is essential if the results from the scenario modelling are to be accurate and credible. The program was based on the modelling of single digesters; therefore, the outputs had to simulate the outputs from real-life AD facilities. To achieve this, four key model output results and numerous case studies (both from this research and from other research) were used. The four key model outputs were:

- digester size (see Section 6.2.1)
- biogas and methane yield (see Section 6.2.2)
- CHP genset capacity (see Section 6.2.3)
- capital expenditure (see Section 6.2.4).

There are considerable difficulties in modelling AD. First, the feedstock used by the case studies often changed during the year, for a number of reasons. Where possible, historical data were obtained to help remove this uncertainty; however, a number of the case studies used were only in their first or second year of operation and were unable to provide a complete year's dataset. There are a number of environmental conditions that influence the inherent energy of a feedstock, particularly crops grown specifically for energy. The inherent energy can change from one year to another, depending on the sugars present in the harvested crop. These can alter according to the quantity of sunshine or rainfall that occurs during the growing season, and can also vary from field to field, as different nutrients in the soil can influence growth.

Inside the digester, micro-organisms are responsible for the digestion process and the production of biogas. Internal environmental conditions can have a significant influence on the efficiency of this process (see Section 2.1). Finally, other factors, such as the fugitive gas emissions across the AD facility (see Section 5.3.1.3), as well as electrical energy conversion efficiency, have a bearing on the output figures. It was believed that if the ADEE model could reproduce the biogas and methane outputs of a real-life facility or case studies from either this research or other research, within 10 per cent tolerance margins, when accounting for the potential inherent energy differences within the feedstock types, the AD design and operating permutations, then the model had been successful.

From the economic perspective, operational costs, if provided, only represent the costs for one year and are difficult to model over the lifetime of the investment project. Allowing for inflation within the programming does go some way to reducing the uncertainty in the output figures; however, it was outside the scope of this research to model externalities, such as different types of inflation, commodity price fluctuations, and so on, across the lifetime of the project. Sensitivity analysis was completed on a number of variables (see Section 7.4); however, the results of this analysis only demonstrate the impact of changing the value of these variables at a point in time. Therefore, validation of the economics of AD focused on the capital costs.

Capital costs modelled were the total investment costs that an investor might be expected to outlay – that is, a feasibility study, professional fees, groundworks, grid connection and commissioning costs; the model also assumes that all new capital infrastructure is required. Modelling some of the case studies was particularly challenging, since some facilities required additional technology (those accepting biowaste materials), whilst others were able to utilise existing capital, such as silage clamps or existing slurry tanks converted to act as digestate holding tanks. Many used their own labour at some point in order to reduce construction costs. These differences highlight the varied capital requirements in setting up an AD facility, when accounting for existing infrastructure, proposed feedstock types to be treated and the general local physical environment in which the facility is sited.

Since many of the input data were derived from the case studies and few output data figures (CAPEX, digester and engine sizes) were supplied by them, further validation of the ADEE model was required. Therefore, three different capital-cost regression models from two other research groups (Mistry *et al.*, 2011a and Jones, 2010) were compared with the model outputs of this research's case studies (see Section 6.3). Where enough data were available from the case studies in Köttner *et al*. (2008) and Redman (2010), their results were compared with those of the ADEE model as well.

Finally, discussion is provided on the difficulties of comparing the life-cycle outputs against other research, particularly when the scope of modelling can be different between different research groups. The ADEE model outputs could only be compared directly with other research when sufficient data were provided in those publications. The ADEE model was used to model the findings of three other research groups (Banks *et al.*, 2011; Styles *et al*., 2013; Evangelisti *et al*., 2014) and the results were compared (see Section 6.3); two of these showed favourable comparisons with the ADEE model.

6.2 VARIABLES USED IN THE VALIDATION PROCESS

This section outlines the validation process against the chosen model-output variables. Each subsection highlights the importance of the output variable chosen and then explains the process by which the variable is validated against external data. The importance of this validation process was not to validate the databases used (as mentioned above, variability can occur from year to year), but to ensure that the calculations within the model program produced results that are comparable to other research. Only some of the data discussed in this chapter are represented in tables and graphs; a complete dataset of the input and output data of this part of the validation process can be found in Appendix 5.

6.2.1 Digester size

The digester capacity is an important variable within the model. It provides a proxy of the expected materials to be digested. The digester capacity is a function of the interplay between feedstock's DM content, HRT and the addition of any water required (see Section 5.3.3.2). Calculations for embodied energy and capital costs are also based on the digester capacity.

Validating the digester capacity did incur several problems, as some of the case studies had certain design anomalies that made an accurate calculation difficult. Six of the 13 case studies had 'built in' additional capacity to their systems, allowing for future business expansion; and other difficulties occurred in estimating the quantity of liquid required, or the HRT of the case studies' systems. The variation in digester sizes is observed in Figure 6-1, with many of the data points falling below the regression line, as the additional capacity moves the data point (towards the right) along the *x* axis. The regression model is still able to explain 79 per cent of the observed data.

It was thought that the case study 3 (red) and case study 7 (mauve) data points (see Figure 6-1) were having a significant impact on the regression model. The red data point had very little impact when removed from the model (after the mauve data point had been removed); however, the mauve data point had a significant impact on the regression model. The novel process utilised by case study 7 enables them to employ a digester approximately one-third of the volume that should be required, without the mid-term separation system that was unique to this particular AD digester design. Removing this data point improved the regression model's r^2 value to 0.87 from the value displayed in Figure 6-1.

It is possible to infer from Figure 6-1 some of the trade-offs the plant designers and owners have made (e.g. many of the data points lie below the regression line, which may be explained by the 'built-in' additional capacity for future expansion), and thereby to see some of the knock-on effects of these compromises. On-farm digesters are often used as nutrient stores as well as digesters; therefore, their HRT can be longer, improving the quantity of gas yielded from the substrate. Additional feedstock always carries a cost for farmers; therefore, they often try to restrict themselves to self-supporting levels of feedstock. In contrast, many waste management facilities prioritise a greater throughput of feedstock in order to maximise their revenue from gate fees (Harrison, 2013). They achieve this by constructing smaller digesters than required and reducing the HRT. This has the effect of lowered gas yields, since the retention time is too short and the feedstock is only partially (~80 per cent) digested. This was not the case with the two case studies that operated on-farm digesters taking municipal waste, but this may have been due to their inability to secure feedstock rather than their desire not to increase throughput.

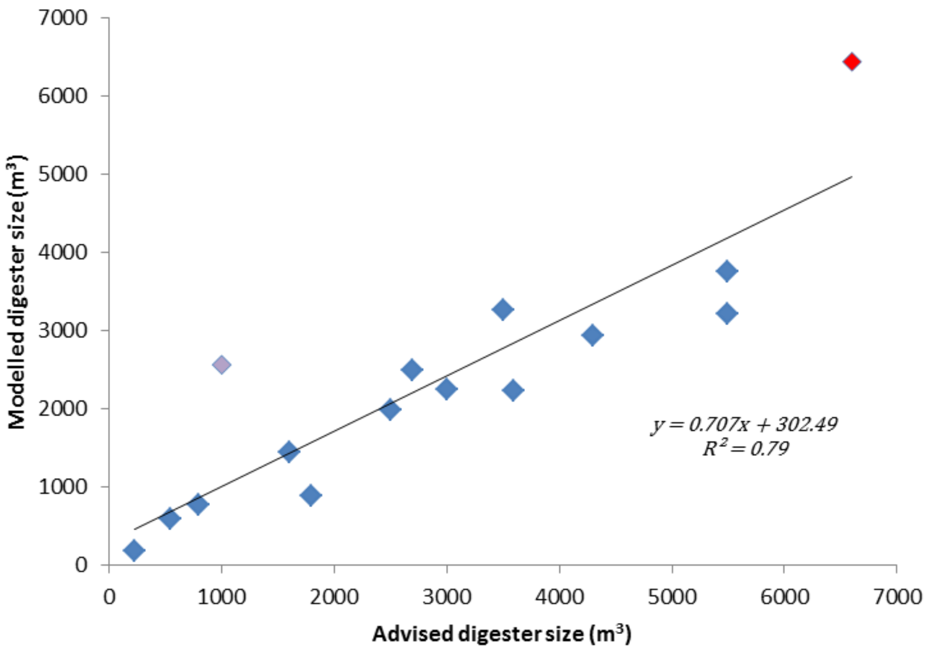


Figure 6-1 Modelled digester size against case study data

6.2.2 Gas outputs

The gas yields were important, since they provided feedback on the yield from the feedstock used, and provided the basis for the onward modelling of the CHP requirement (see Section

6.2.3), the energy generated and the financial reward from the sale of the energy. Case studies 1, 2 and 11 provided biogas and methane output; case studies 1, 2, 3, 5 and 13 also provided feedback on a comparison of the ADEE model's outputs against their own data, stating that this research's calculations were within 10 per cent or less of their own figures. Five case studies were unable to provide any feedback, and the final case study stated that they were in the process of completely changing their operation, due to significant changes to their feedstock types, and were unable to provide data. Therefore, all these data needed to be treated with some caution.

The biogas and methane yields are both a function of the feedstock used in the digester; in addition to this, operating procedure can have a significant impact on expected yield, as mentioned above. These data act as a feedback mechanism on the efficiency of the system to generate energy from the substrates used. However, since there is considerable variability among similar feedstock types (energy content in kitchen waste varies nationally and seasonally) and among generically described feedstock (there are currently in excess of 50 different varieties of maize available (NAIB, 2013)), it is very difficult to obtain an accurate, long-term, temporal picture. Also, many of the gas yield data for the different feedstock types (see Appendix 3: Table A1.8) are either out of date or represented the theoretical maximum at the time. There were no data available for the expected gas yield values for a number of feedstock types used by case studies 4, 7 and 13 – such as abattoir DAF, fish DAF, mixed fruit waste, or mixed dairy permeate/waste. However, these were kindly provided by the facility managers.

Finally, the first model-runs did not account for the uplift associated with co-digestion of certain feedstock types (see Section 2.5.4), but case study data did show that the gas yield was greater than that expected from the sum of the individual feedstock-type yields, which led to the investigation into co-digestion and the decision to uplift gas yield.

Case study 3, the red data point (see Figure 6-2a) is having an impact on the regression model, increasing the gradient of the regression line. By removing this data point, the regression equation is $y = 0.8924x + 129917$ with an r^2 value of 0.93, demonstrating that the difference is significant. However, this modelling does need to be treated with caution for several reasons. Inherent energy for what seem to be similar feedstock types (i.e. maize) do vary considerably, as does the biowaste feedstock, which could differ through the seasons as diet changes. Similarly, biowaste from C&I sources will also vary, depending on the products being manufactured and the particular waste treatment methods chosen. Lastly, the interviews took place over two weeks in March and April 2012. Only three case studies had more than three years' operating experience, three had two complete years' operating experience, and two had only one year's complete operating experience. The remaining five had been operating for less than one year and were not in a position to provide the required data, even if they had been prepared to do so. The electrical energy generated ($kw.a^{-1}$) has a direct relationship to the biogas generated. Six case studies provided confirmation of their annual electrical generation, which is displayed against the modelled data (see Figure 6-2b). Again, the results are very good, and removing the sixth (red) point (case study 3) to assess its influence on the regression model reduces the r^2 value to 0.9634, suggesting that there is an influence, but that it is not strong.

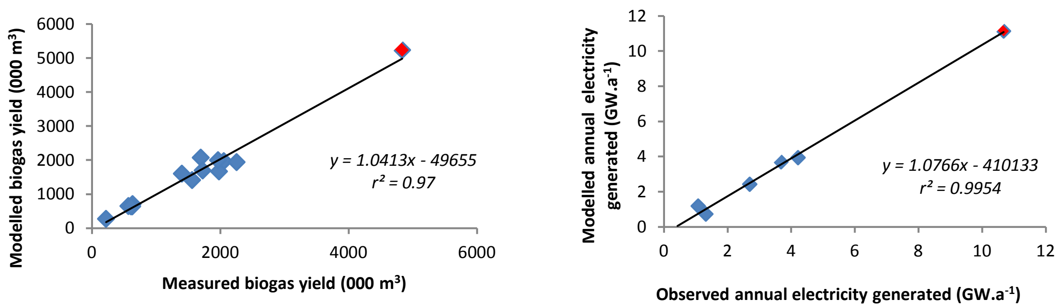


Figure 6-2a and b Modelled biogas yields and electricity generation against observed data

6.2.3 Combined heat and power genset size

Section 5.3.3.4 explains the close relationship between the methane yield and the expected CHP genset generating capacity. The installed capacity is often different to the actual generating capacity of an AD facility because CHP gensets are not built to output specification; rather, the genset is chosen carefully in order to deal with the maximum expected output from the digester. Therefore, modelling is not based on the maximum capacity of the genset, but on the average expected electrical power per hour over one year (assumed to be 8,040 hrs). Three facilities had restricted their genset's generating capacity to take advantage of receiving a higher FIT. These facilities also had the capability to expand their operations, if required, with the existing digester, either by removing the restriction (subject to notification) or by purchasing an additional or larger CHP genset.

The validation of the CHP genset (see Figure 6-3) is important for two reasons. First, it provides a proxy for the efficiency of the digester in converting the organic material into methane to drive the genset. Second, where no gas yields had been provided, but the genset size was known, the genset output was able to validate the methane yield of the digester, since the energy content of methane is constant (9.889 $kWh.m^{-3}$).

The model was accurate in predicting the genset size 98 per cent of the time (see Figure 6-3), converting the energy inherent in the feedstock into energy and making comparisons against the case study outputs. There was concern that the data point to the far right, being a case study generating considerably more electrical power than any of the other case studies, was influencing the regression model. If this data point is removed, the new regression model is $y = 0.9666x + 4.4501$ (r^2 = 0.9655), demonstrating that the impact was small, being less than 2 per cent of predictive occurrences.

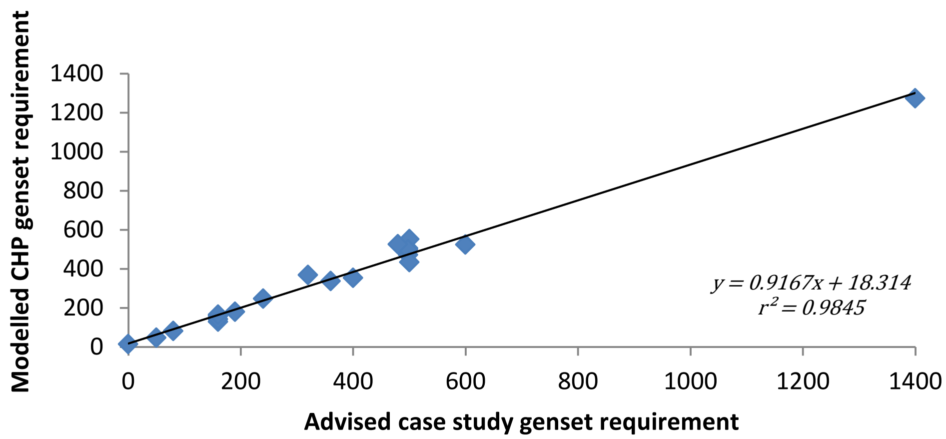


Figure 6-3 CHP genset size modelled against case study data

6.2.4 Modelling capital expenditure of anaerobic digestion

Deciding to invest in an AD facility requires careful consideration, since the investment value is considerable. CAPEX estimation is essential for those wishing to decide if the investment, based on the feedstock available, is viable; or, from the point of view of a policymaker, the amount of subsidy (if warranted) that is required. This section first assesses the ADEE model's efficacy in modelling CAPEX, followed by a general discussion of the capital costs of AD, a specific assessment of the use of regression models to estimate costs, and a comparison of the ADEE model against other research. The ADEE model calculates all CAPEX from the input of only a few key variables discussed earlier (see Section 5.2).

AD capital and operational costs vary considerably, dependent on scale, quantity and type of feedstock treated, as well as the quality of materials and design across the manufacturer spectrum. Technology costs also vary widely, which is a function of the juvenile state of the UK AD technology market at the time of writing (Black and Veatch, 2010), with much of the technology being sourced from Europe, particularly Germany and Austria (Redman, 2010). For this reason, CAPEX is extremely uncertain. Costs may reduce as the market matures; however, this will be dependent on government incentives remaining strong and consistent.

Individual digesters are unique, since they are rarely set up by the same technology provider or have the same feedstock, construction and operational procedures. Each slight change in these variables adds a slight variation to the AD facility. This, in turn, increases the uncertainty in accurately calculating capital costs for AD. Some have generated capital cost curves based on their observations and calculations (Jones, 2010; Mistry *et al*., 2011a; Black and Veatch, 2010), but there still remains considerable variation in both approach and results.

Another issue encountered is the detail of what is included in the total cost quoted – that is, the inclusion or exclusion of consultants' costs, feasibility costs, planning, grid connection and groundwork. These are site-specific and not something a technology provider can predict. The cost of grid connection can often vary significantly, depending on the capacity of the digester and the site's proximity to the nearest acceptable substation. Five of the data points used in this research were provided by a technology provider who did not provide examples, including site groundwork preparation costs or grid connection costs; therefore, some fixed costs were input in their place, based on the data provided by the case studies.

A comparison of CAPEX modelled against the observed values provided by the case studies (see Figure 6-4) showed that the model accounts for 77 per cent of the observed data. This value compared favourably with the two regression models (type 1 AD facilities: $r^2 = 0.9244$; and type 2 AD facilities: $r^2 = 0.5521$) developed by Mistry *et al*. (2011a), discussed in Section 2.3.2, but highlighted the uncertainties in modelling the capital costs of AD when the variety of different feedstock types has a significant impact on the type and cost of equipment required to treat them.

The two green data points (see Figure 6-4), represent the two digesters taking municipal kitchen waste (case studies 1 and 12). These two AD facilities have large reception halls and a range of other additional equipment for de-packaging and decontaminating the feedstock prior to digestion. These two data points, whilst not outliers, do have the effect of increasing the slope of the regression line; however, this is probably counteracted by the red data point.

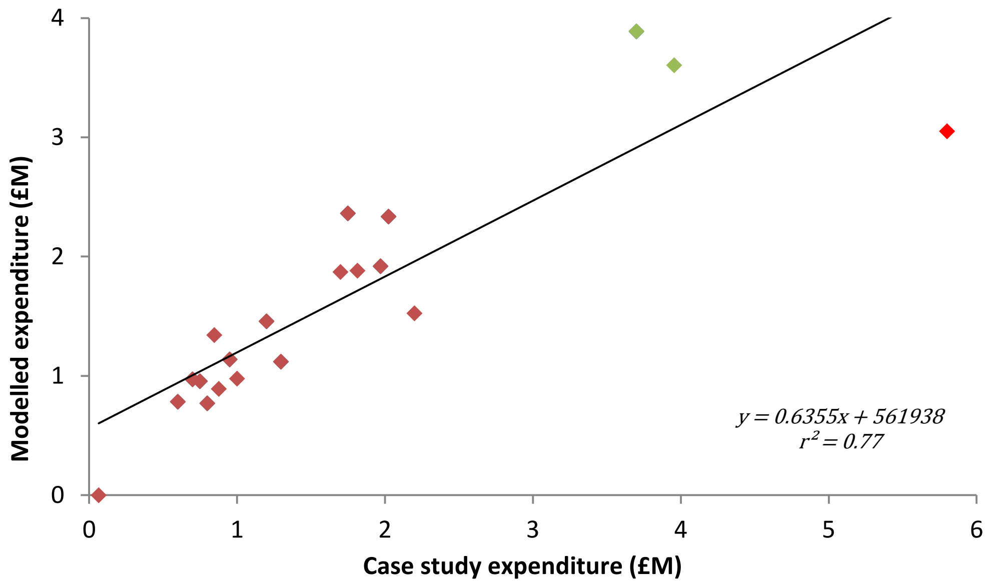


Figure 6-4 Modelled capital expenditure against data provided by the case studies

This red data point, which represents case study 3, warranted some caution within this analysis. The results from modelling this particular case study made no financial sense. Based on data provided, it was surprising that this project proceeded in the first place, since the model showed that it would never make a profit or return a positive NPV by the project end. It was difficult to understand the exceptionally high costs provided by the owner when comparing its CAPEX with other case studies. It was thought that these costs may have included interest payment costs to the business, but despite several requests for clarification, this was not confirmed by the owner.

This caution was reinforced when the same case study was represented in a recent DEFRA publication (Styles *et al.*, 2013). Here, the case study informed the research investigators that the capital expenditure was £4 M (not £5.7 M). There was also a slightly different mix of feedstock types than those provided three years previously. The effect of this case study on this research's CAPEX regression model was considerable; its amendment to the lower figure removed much of the downward 'force' created by this anomaly. This change improves the regression model to explain 92 per cent of the data (see Figure 6-5) modelled by the ADEE model against measured data, when compared to the regression ADEE model (see Figure 6-4) with the original figures. This demonstrates the power that these data had on the original regression model, and the accuracy of the ADEE model in modelling the expected CAPEX in a number of different scenarios.

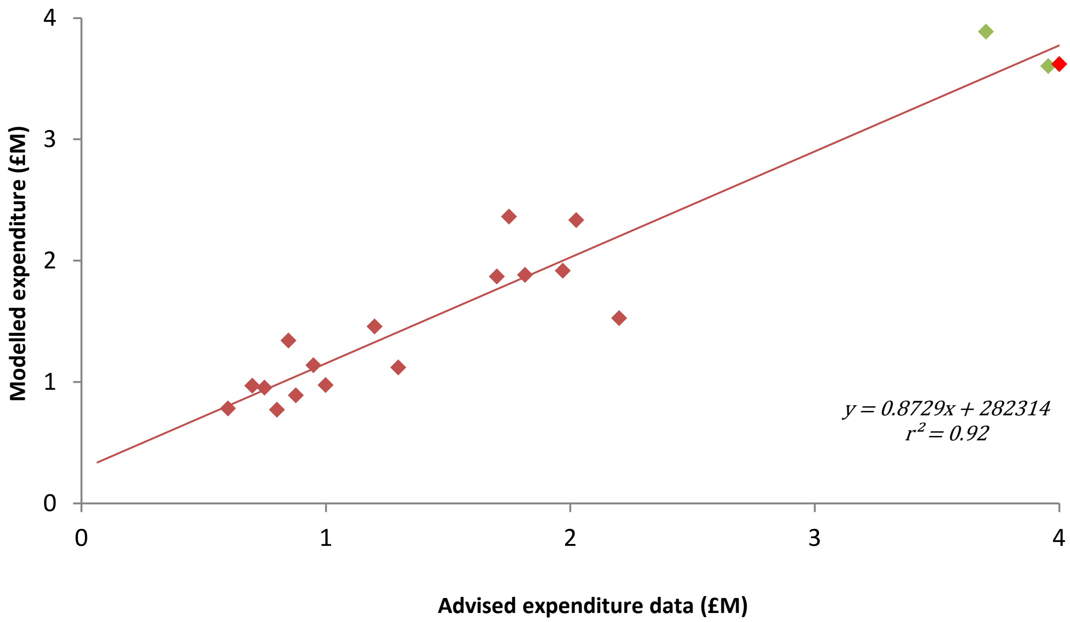


Figure 6-5 Modelled expenditure against data provided by the case studies (amended)

Capital and operational costs are a function of feedstock type and, as such, they fix the timescale of the model to a single snapshot, since modelling can only account for feedstock stated to be treated over a 12-month period; any mid-term alterations cannot be included. Whilst, in reality, a degree of flexibility is possible between some of the different feedstock types, certain feedstock types require additional capital equipment to ensure the efficient treatment of the different feedstock types and/or compliance with health and safety regulations. Some of the difficulties attributed to changing feedstock types were highlighted by a number of the case studies, which incurred complications when trying alternative feedstock types. For example, one facility wished to include fodder beet in its feedstock mix (which was predominantly slurry and grass silage). Being a root crop, the beet arrived at the facility covered in soil and stones. This caused problems with the macerator, the pumps and the working volume of the digester (clogging up the system with soil and breaking the pumps).

The ADEE model is not a temporal model that provides outputs from market changes to feedstock prices over the year, or indeed over multiple years, and therefore it does not take into account any mid-term modifications made to an individual system. Inflation can be fixed in the ADEE model at the beginning of the project period, but, as with the other parameters, this is not adjustable over the project period, since the outputs only provide a snapshot in time.

6.3 COMPARING THE ADEE MODEL AGAINST OTHER RESEARCH

Few documents were found that provided information on the costs required to assess the economic viability of AD. The Official Information Portal on Anaerobic Digestion states that figures from seven project developers asked (by Renewables East) to provide indicative CAPEX costs for a facility similar to Biogen Greenfinch's facility near Bedford ranged between £2 M and £4.4 M, depending on their assumptions. Reports by Jones (2010) and Mistry *et al.* (2011a and b), provided more detail.

6.3.1 Calculating capital costs using alternative methods

Due to the complexities of capital requirements, which are dependant on feedstock types and certain economies of scale, capital costs are difficult to ascertain. Redman (2010) suggested capital costs of between £2,500 and £6,000 per kilowatt of installed electricity-generating capacity, with an average of approximately £4,000. British Biogen (now Biogen) quoted between £3,000 and £7,000 per kilowatt of installed electricity-generating capacity (in Jones, 2010), as the technology was more expensive in the UK than overseas. Jones (2010) quoted between £4,000 and £8,000 per kilowatt for AD facilities of installed electricity-generating capacity of between 500 kW and 50 kW respectively. This research observed costs of considerably greater variation, between £2,353 and £16,000 per kilowatt of installed electricity-generating capacity (see Figure 6-6). The highest figure represented an educational facility, which had been set up to demonstrate many aspects of AD, rather than being configured for commercial purposes, and which was fully funded by the government. The average value, representative of the case studies in this research without this outlier, was just over £5,979 per kilowatt of installed electricity-generating capacity.

6.3.2 Calculating capital costs per kilowatt of installed capacity using regression analysis

One of the case studies was unable to be included in this analysis, since it did not generate electricity. The two regression models (see Figure 6-6) represent the total observed facility costs per kW of installed capacity based on all the case studies (the red regression line). There were four outlying case studies, which were removed (the blue regression line) to assess their influence on the first regression model (red line). These are represented by the blue data point, the two green data points and the top red data point.

The two green data points represent the AD facilities classed as 'community' facilities (receiving significant quantities of municipal waste). Whilst both have been built on agricultural land (or based on farms), one only accepts municipal, commercial and industrial food wastes; the other accepts municipal waste, along with some of its on-farm wastes and other agricultural materials. Both these facilities have made considerable additional investments (compared to facilities not receiving biowaste materials) in order to treat these feedstock types received. The blue marker (bottom left) represents an AD facility built with 100 per cent government funding under the ETF, and incorporating expensive novel technology. The final case study removed represented the largest AD facility used in this thesis (the red data point). As discussed earlier (see Section 6.2.4), the data from this case study needed to be treated with some caution. The impact on the regression model in removing these four data points is significant (see Figure 6-6). Adding back the (red) data point only, but using the figure stated in Styles *et al.* (2013), provided a regression equation of $y = 2567.2x + 419003$, with an r^2 value of 0.95, demonstrating the influence that this data point has on the regression equation.

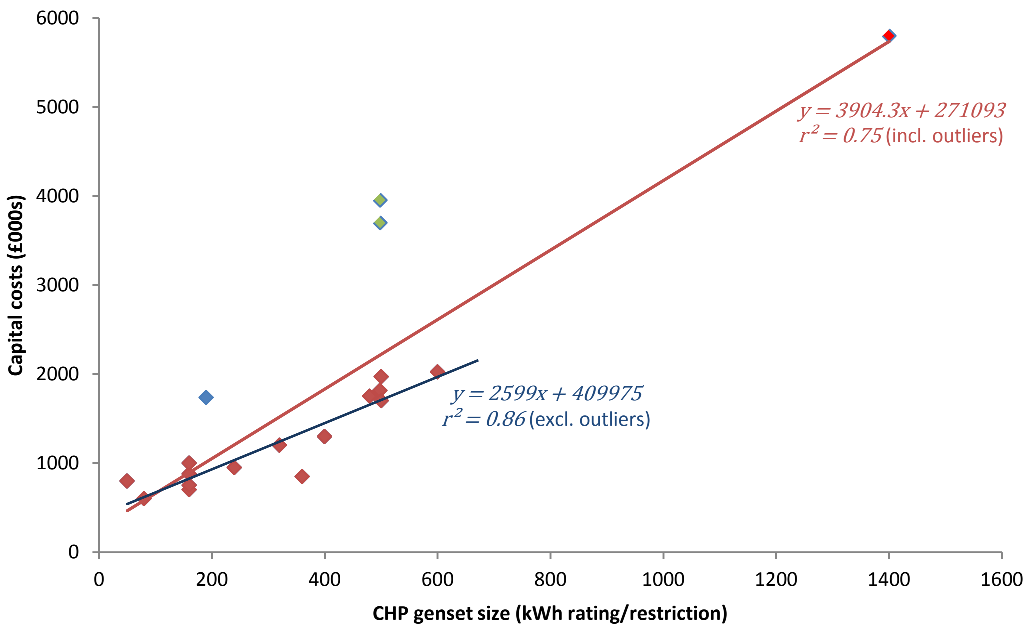


Figure 6-6 Total costs per kWh engine capacity from advised data

The general point made here is that regardless of the data being observed or modelled (see Figure 6-7), it is very difficult to accurately predict the capital costs of AD using a regression model. The influence of the different feedstock materials on the capital requirement is significant, increasing the variation from the mean.

Therefore, using a model that can account for certain types of feedstock (including/excluding biowaste feedstock materials) can help to improve the accuracy of predicting capital costs for many more different permutations of AD treatment facilities (see Figure 6-5). When visualising these modelled results in a graph, a regression model can be produced (see Figure 6-7), based on the lower capital cost value for the last (red) data point. The blue data point is still having a powerful influence on the regression model; if this data point were removed, the new regression model has an r^2 value of 0.94 (y=2459.4x + 657,700).

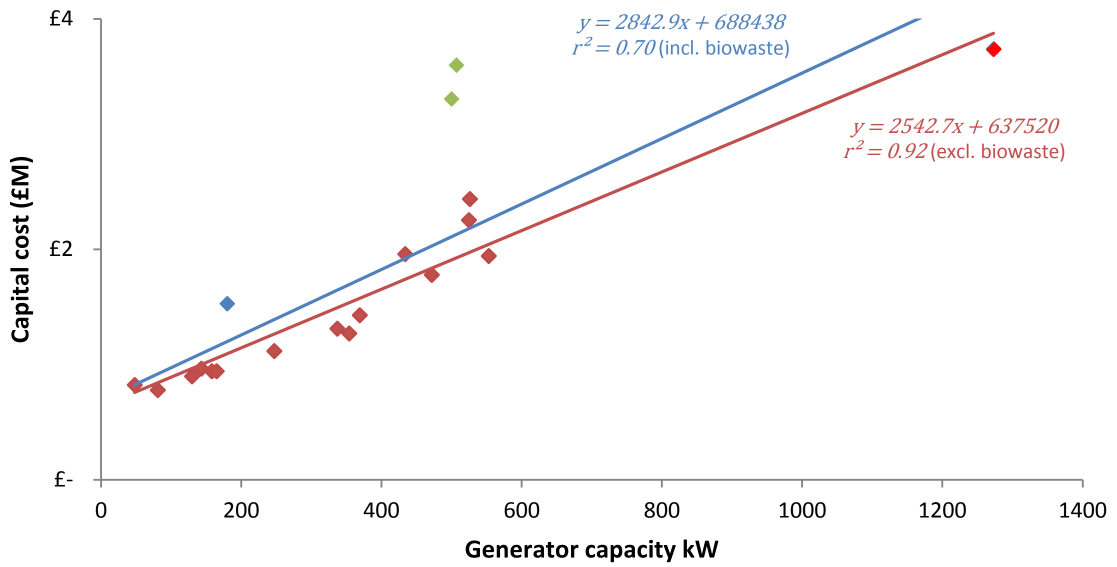


Figure 6-7 Capital cost per kW of generated capacity predicted by the ADEE model

6.3.2.1 Comparing the ADEE model against four AD regression models

Using case study data, the ADEE model's capital cost calculations were compared against three regression models from two other research group studies, and against the regression model generated above from the ADEE model results. Both this research and that of Jones (2010) calculated costs based on installed capacity, whilst the two regression models from Mistry *et al*. (2011a) used the number of tonnes treated.

[1] AD capital costs = 3557 × installed capacity (kW) + £221,041 Jones (2010)

[2] AD capital costs = 116 × feedstock (t) + £2,000,000 option/type 1 Mistry *et al.* (2011a)

[3] AD capital costs = 79.5 × feedstock (t) + £516,000 option/type 2 Mistry *et al.* (2011a)

[4] AD capital costs = 2459.4 × installed capacity (kW) + £657,700 ADEE regression model

Both [1] and [3] were based on farm feedstock types, treating little or no biowaste materials; [2] represented the Mistry *et al.* (2011a) type 1 formula, specific to the high use of municipal household food waste. The results of using these four formulae are compared against the advised data provided in the case study interviews (see Figure 6-8). Five individual case studies (shown as red circles on Figure 6-8) are discussed below.

- Case study 1 is shown to be accurately modelled by the ADEE model and Mistry *et al.* (2011a). An extra £400,000 included by the site operator was for a specialist digestate drying facility, which many new facilities would not include. However, the drying facility was a key condition to receiving funds for the AD facility, which was paid for, in part, by the ETF (hence the underestimation by both models). All the other models underestimate the capital costs, since they do not account for the additional equipment required in treating biowaste material.
- Case study 5 was a difficult one to model, since the owner made use of his own labour when constructing his facility and also some of the existing capital. However, reporting to Jones (2010), the operator did mention that it would have cost in excess of £1.1 M, bringing it more in line with the modelled figures. All but Mistry *et al.* (2011a), option 1, made a good estimation of capital costs for this site.
- Case study 7 was underestimated by Jones (2010) and the ADEE model (and regression model), since this case study made use of novel technology and was one of the first AD facilities built. Mistry *et al.*'s (2011a) regression model methods overestimated this case study, since their calculations are based on tonnage of throughput, which in this case is very high.
- Case study 10 was overestimated by all the models, although by how much or if at all is hard to tell, since no detail of the connection costs and groundworks costs were provided.
- Case study 12 was underestimated by the ADEE regression model, Jones (2010) and Mistry *et al.* (2011a), option 2, since none of these can account for the additional capital required for treating biowaste materials. Mistry *et al*. (2011a), option 1, overestimates this case study by 34 per cent; this was probably due to the inclusion of a high quantity of low-energy on-farm waste materials, which skewed the calculation. The ADEE model overestimated costs by 5 per cent. Finally, all models overestimated the CAPEX provided for the last five case studies, 16–20. These case studies were provided by one of the technology providers who did not include estimates for grid connection or groundwork costs, which would have added a few hundred thousand

pounds to the cost of construction and may have brought the CAPEX in line with the ADEE model and Jones (2010).

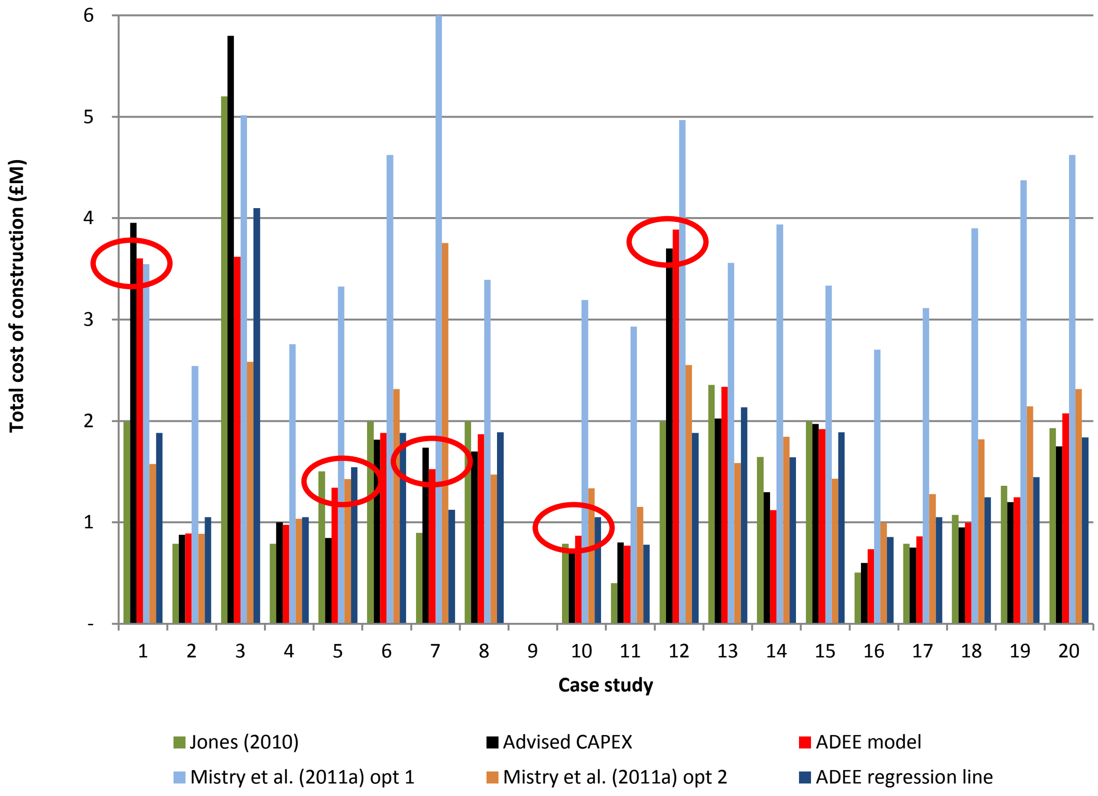


Figure 6-8 The comparison of three cost calculations against the advised case study costs in this research

Finally, comment is necessary on the modelling of case study 3, which all models underestimated. Some caution was applied to this case study's outputs (see Section 6.2.4). However, using the information provided in Styles *et al.* (2013) (CAPEX of £4 M), the observed costs fall more in line with both the ADEE model and the ADEE regression model, with Jones (2010) and Mistry *et al*. (2011a), option 1, overestimating, and Mistry *et al.* (2011a), option 2, underestimating costs. In fairness, Mistry *et al.* (2011a), option 1, can only really be compared with case studies 1 and 12, since these two are the only case studies that fall within the categorisation of option 1, whilst all other case studies should be comparable to Mistry *et al.* (2011a), option 2.

Both methods of calculating total capital cost (£/kW and £/t) have their strengths and weaknesses; however, the method adopted by Mistry *et al*. (2011a), using the quantity of feedstock, consistently overestimates CAPEX across all feedstock types. This may be the reason why they underestimated the potential for AD in England and Wales. Jones (2010) was accurate for the farm-only based feedstock, which it was designed for, and understandably underestimated sites receiving food waste. Since the ADEE model accounted for feedstock type as well as capacity, it was more flexible in estimating a greater number of digester types.

The discussion above highlights the difficulties or uncertainties in using regression models to calculate CAPEX costs for a technology, such as AD, which utilises a number of different feedstock types, and has different capital and technology requirements, dependent on the substrates being treated – in particular, where municipal wastes are concerned (reception building, pasteuriser, decontamination equipment, filters, etc.). This affects the associated capital costs, which a regression model is unable to take into account. This demonstrates that regression analysis may not be the best method in modelling the capital costs of AD when seeking to calculate all possible different scenarios associated with the AD process, although two simple regression models may be used (as in Mistry *et al.*, 2011a). A more complex model, such as the ADEE model, which takes into account the different capital requirements of the feedstock types in its calculations, may be the preferred option when modelling a wide range of different feedstock types.

Not all research has used regression models to calculate the capital costs of AD, and the next section seeks to compare the ADEE model's outputs with the case studies from two research projects that do not appear to have used a regression model in calculating costs.

6.3.2.2 Comparing the ADEE model against research with no apparent regression models

Section 6.3.2.1 compared the ADEE model with four different regression models calculating the capital costs for case studies used in this thesis. This section seeks to compare the calculation efficacy of the ADEE model using the case studies used in third-party research. Few published papers or reports provide enough information for the ADEE model to produce comparable results. However, two other research projects provided sufficient data (both in terms of inputs and outputs) against which to compare the outputs from the ADEE model. Neither of these research projects stated that they had used or published details of regression models in their analysis.

Köttner *et al.* (2008) were invited to assess the possibilities of building eight facilities in Cornwall. Enough input information was provided to compare eight of their case studies used for analysis in a range of rural scenarios with the ADEE model outputs. The CAPEX and OPEX of Köttner *et al.*'s research were difficult to assess, primarily due to the change in the value of money, ROCs being the sole method of compensation, and the limited number of technology providers in the UK at the time. However, the impact of the introduction of FITs can be seen by the increased profitability of many of the scenarios shown and by a reduction in the payback period (see Table 6-1); although in three case studies this has been masked by the high capital costs of smaller AD facilities calculated using the ADEE model.

There are a number of output differences between the ADEE model and that produced by Köttner *et al.* (2008) (see Table 6-1): whilst there are significant differences between the biogas yields of each model, the methane yield is comparative for Köttner *et al.*'s case studies 1 to 6, whilst 7 and 8 are substantially different. Closer inspection of the detail showed that the expected biogas yields for many of the feedstock types were greater in the ADEE model, leading to the conclusion that different feedstock databases had been used by this research.

One of the main differences between the ADEE model and Köttner *et al.*'s (2008) model relates to the HRT assumptions. The calculations by Köttner *et al.* (2008) had a significantly greater HRT than the ADEE model. This has clear implications for the capital requirements, increasing capacity and costs to the owners (although this research's cost calculations were greater than Köttner *et al.*'s (2008). This may have been the result of different materials and design techniques, and inflation). The difference between the HRT calculated by the two models across Köttner *et al.*'s (2008) case studies ranged from a few days up to double the retention time modelled by the ADEE model, over 130 days (although this latter case study was designed with a secondary unheated digester that this model would have treated as a covered digestate holding tank, from which residual gas could be collected). In the latter instance, some of this additional capacity was due to the presence of a secondary digester being used effectively as a storage facility for the digestate over the winter period, thereby removing the need to construct separate storage facilities. For example, Köttner *et al.*'s (2008) case study 3 is of particular interest here, recommending a heated primary digester (1,854 m^3) with 69 day HRT, followed by an unheated secondary digester (2,994 m^3), which acts as a digestate storage facility as well. Since this research assumed that digestate storage is covered (effectively, a second unheated digester tank, from which residual gas could be collected), it is assumed that in this case the model would calculate the capital requirement, materials and costs appropriately.

The capital costs are different for many reasons. First, the time value of money: inflation means that most things now cost approximately 30 per cent more than at the beginning of the twenty-first century. Second, the detailed descriptions available in Köttner *et al.* (2008) discuss the capital already available at the site, to act either as feedstock or digestate storage, thereby reducing outlay in some areas. Finally, the financial outputs were difficult to compare, as FITs were not in existence then, only ROCs. However, remodelling these scenarios including FITs still did not mean that there was an improvement in the financial viability of all. Whilst three of the case studies modelled showed annual profits, not one returned a positive NPV with a discount rate of 12 per cent and, as such, none of these case studies would be built based on the modelled parameters (see Appendix 5, Table 1.19).

Table 6-1 Comparison of outputs between the ADEE model and Köttner et al. (2008)

	KOTTNER 1	ADEE 1	KOTTNER 2	ADEE 2	KOTTNER 3	ADEE 3	KOTTNER 4	ADEE 4
Annual outputs								
Engine requirement (kW)	50	57	400	415	190	166	92	107
Biogas produced (m^3)	249460.00	285810.00	1677686.00	1729221.00	628745	726747.00	382615.00	471456.00
Methane produced (m^3)	132806.00	140460.00	918206.00	896899.00	340151	345824.00	210998.00	228,547.00
Electricity produced (MW)	436.93	486.00	3507.00	3339.00	1298	1335.00	803.90	861.00
Heat produced (MW)	641.00	583.00	3994.00	3848.00	1502	1435.00	930.50	948.50
Income from electricity (£)	£57,020.00	£87,337.00	£461,295.00	£603,564.00	£169,043.00	£259,633.00	£104,093.00	£162,194.00
Income from heat (£)	£6,599.00	£7,869.00	£5,616.00	£16,498.00	£44,032.00	£45,207.84	£0.00	£2,134.00
Total income (£)	£69,854.00	£101,539.00	£505,889.00	£684,040.00	£240,056.00	£333,879.00	£112,702.00	£181,084.00
Total expenditure excl. grants (£)	£506,921.00	£754,500.00	£1,364,085.00	£1,930,000.00	£953,176.00	£945,500.00	£470,054.00	£879,500.00
Total OPEX (£)	£119,219.00	£182,311.00	£476,692.00	£599,542.00	£271,430.00	£271,833.00	£134,511.00	£221,602.00
Retention time (d)	80	56	75	64	123	68	69	48
Digester size (m^3)	1186	450	3707	2440	1854	1167	1854	908
Payback (yrs)	>44	-	11	5	26	6	32	11
Annual profit/(loss)	-£49,364.00	-£78,638.62	£29,198.00	£155,044.51	-£31,374	-£4,745.54	-£21,809.00	-£80,098.04

Table 6-1 cont.

Annual outputs	KOTTNER 5	ADEE 5	KOTTNER 6	ADEE 6	KOTTNER 7	ADEE 7	KOTTNER 8	ADEE 8
Engine requirement (kW)	167	173	185	192	75	68	650	965
Biogas produced (m^3)	705025.00	814564.00	742908.00	769808.00	229613.00	336586.00	2632887.00	3777258.00
Methane produced (m^3)	388739.00	379301.00	427925.00	419177.00	127435.22	161195.00	1474083.00	2062878.00
Electricity produced (MW)	1461.70	1390.00	1617.60	1594.00	416.00	613.00	5689.90	7762.00
Heat produced (MW)	1780.40	1550.00	1951.30	1743.60	619.00	600.00	6942.90	8432.50
Income from electricity (£)	£190,111.00	£268,660.00	£211,326.00	£274,604.00	£54,142.00	£100,693.00	£738,415.00	£1,029,553.00
Income from heat (£)	£6,739.00	£6,977.00	£28,717.00	£53,975.00	£234.00	£3,163.00	£128,292.00	£132,812.00
Total income (£)	£204,791.00	£256,962.00	£258,272.00	£340,170.00	£59,129.00	£121,833.00	£1,009,906.00	£1,349,455.00
Total expenditure excl. grants (£)	£822,122.00	£1,252,500.00	£876,590.00	£1,273,500.00	£464,489.00	£828,500.00	£3,157,036.00	£3,988,000.00
Total OPEX (£)	£164,064.00	£273,476.00	£208,678.00	£279,937.00	£106,331.00	£197,586.00	£934,214.00	£945,441.00
Retention time (d)	53	40	41	32	64	45	44	48
Digester size (m^3)	2669	2060	2669	1846	1186	744	5338	5817
Payback (yrs)	8	10	8	5	>40	15	10	5
Annual profit/(loss)	£40,727.00	£6,281.91	£49,594.00	£66,836.48	-£47,202.00	-£100,225.79	£75,692.00	£300,351.79

The ADEE model was also examined against the case studies provided in Redman (2010), noted as NNFCC (see Table 6-2). In this study, Redman used three case studies based in the UK, two Danish case studies, and a case study based on a typical German AD facility. There was enough detail provided by Redman (2010) to provide a comparison in capital costs between four of these case studies (see Table 6-2). Redman converted the currency costs to GBP, which this research took and recalculated to 2013 values, using a historic inflation calculator (from www.thisismoney.co.uk). The financial outputs are difficult to compare, since the European market is more mature than the UK market and capital costs are lower (Jones, 2010). Having run the data through the ADEE model, it showed that the ADEE model overestimated the modelled HRT for Redman's case studies 1 and 2, and, as a result, overestimated digester volume, which, in turn may, explain the increase in capital costs modelled. However, case study 1, which is an English facility treating a considerable quantity of municipal waste, may be under pressure to provide a quick throughput of this feedstock type, so that it is able to take advantage of the gate fees per tonne of waste received (although if the facility operates at a higher digester temperature or uses catalysts to accelerate the process, for example, this would not be the case). Case study 2 only treats cattle slurries, which would only be available for part of the year, whilst the animals are housed over winter, and milked or in the farmyard throughout the rest of the year. The digester would therefore only be operative for this part of the year. The facility is 21 years old, received a 50 per cent support grant from the government, and only provides a small income to the farm when in operation.

The ADEE model is not designed for modelling small AD facilities, mainly due to the expensive materials used within the modelling parameters. Smaller AD facilities might be more adept at using cheaper, lighter materials that also require less groundwork preparation, such as the insulated fibreglass used in the small AD facilities built in the 1980s and 1990s. Many of the small AD facilities in this country do not produce enough biogas to facilitate the purchase of a CHP genset, and instead opt to burn the fuel directly in boilers. The ADEE model also assumes that all new capital equipment is required, rather than utilising existing capital, such as turning slurry stores into anaerobic digesters, as some have done.

Table 6-2 A comparison of outputs from case studies provided by the NNFCC and the ADEE model

Variable	NNFCC 1	ADEE 1	NNFCC 2	ADEE 2	NNFCC 3 EU	ADEE 3	NNFCC 4 EU	ADEE 4
Heifer & steer slurry/Dairy cow slurry			Dairy cow slurry	Dairy cow slurry	Dairy cow slurry	Dairy cow slurry		
Number of cows			220	220	450	450		
No. of weeks housed			24	24	28	28		
Quantity of pig manure (t)	12000	12000					8950	8950
Quantity of grass silage (t)					4000	4000		
Grass silage value (£)					22	22		
Quantity of maize silage (t)					4500	4500	730	730
Maize silage value (£)					30	30	30	30
Quantity of municipal waste (t)	30000	30000						
Municipal waste distance (miles)	35	35					50	50
Municipal waste value (£)	30	30					30	30
Glycerine (t)							1825	1825
Export of digestate (miles)	10	10	4	4	4	4	4	
Engine electrical efficiency	39.0%	39.0%	35.0%	35.0%	39.0%	39.0%	39.0%	39.0%
FIT up to 250 kWh	ROCs	15.16	ROCs	15.16	ROCs	15.16	ROCs	15.16
FIT 251 kWh–500 kWh	ROCs	14.02	ROCs	14.02	ROCs	14.02	ROCs	14.02
FIT > 500 kWh	ROCs	9.24	ROCs	9.24	ROCs	9.24	ROCs	9.24
RHI for < 200 kWh	ROCs	7.1	ROCs	7.1	ROCs	7.1	ROCs	7.1
Annual outputs								
Engine requirement (kW)	>1000	1531		27	300	475	500	557
Biogas produced (m^3)		4943211.00		124726.00	1740000	2010756.00	1825000.00	1854947.00

Table 6-2 cont.

Variable	NNFCC 1	ADEE 1	NNFCC 2	ADEE 2	NNFCC 3 EU	ADEE 3	NNFCC 4 EU	ADEE 4
Methane produced (m^3)		3237766.00		57370.00		1003652.00		1176977.00
Electricity produced (MW)	No	12310.30	77.00	218.13		3816.00		4475.00
Income from electricity (£)	Provided	£1,686,552.00		£38,551.00	£494,000.00	£679,273.00	£324,000.00	£620,960.00
Income from heat (£)	No heat use	£59,558.00			£27,800.00	£129,234.00		
Total income (£)		£2,814,605.00		£38,551.00	£565,000.00	£855,837.00	£324,000.00	£620,960.00
Total expenditure excl. grants (£)		£5,459,000.00	£233,000.00	£694,500.00	£1,000,000.00	£1,996,000.00	£1,212,650.00	£1,578,000.00
Total OPEX (£)		£1,109,580.00		£133,825.00	£435,000.00	£628,524.00	£310,000.00	£482,378.00
Retention time (d)	30	52	20	39	55	57	70	54
Digester size (m^3)	4400	6383	300	335	2800	3094	3000	1618
Payback (yrs)		3				5	7	5
Annual profit/(loss)		£1,735,065.00		-£93,078.12	£130,000.00	£238,225.65	£100,000.00	£36,564.59

6.4 LIFE-CYCLE VALIDATION

Comparing the outputs from different LCA research can be problematic. Quite often, the scope of the research between different research groups is very different and is dependent on the resources and time available to researchers, including the software packages used, the availability of data to complete the research (Ekvall, 1999; Ekvall *et al*., 2007) and the audience at which the research is aimed. This research's focus was on GHG emissions only and therefore did not represent a full LCA (see Section 3.3). It did, however, follow as complete a life-cycle scope as possible, encompassing all the main direct and indirect activities associated with AD. The ADEE model did not account for emissions from LUC or iLUC, since the main aim of this research was to produce a set of scenarios that did not impact significantly on existing farming activities. Where the modelling of LUC and iLUC would have been beneficial in this research was in modelling scenarios three and four (see Section 3.6.3), or in comparing outputs with research that also included LUC (Styles *et al.,* 2013). A comparison of the LCA output data of this research against the outputs of other research is discussed below.

In modelling the case studies for this research, net carbon savings per MW generated were measured in each of the model-runs. These GHG savings ranged considerably, from 384 $kgCO_{2eq}.MW^{-1}$ to 1237 $kgCO_{2eq}.MW^{-1}$ (mean of 806 $kgCO_{2eq}.MW^{-1}$). Styles *et al*. (2013) reported CO_{2eq} changes associated with AD, from a net saving of 1380 $kgCO_{2eq}.MW^{-1}$ for co-digesting pig slurries with food waste, to a net emission of 340 $kgCO_{2eq}.MW^{-1}$ (positive emission) for the digestion of a monoculture of maize – the influence of iLUC was excluded in these calculations.

Evangelisti *et al*. (2014) calculated a carbon saving of 2,300 tCO_{2eq} from treating 25,574 t of food waste in southeast London, equivalent to a net saving of 65 $kgCO_{2eq}.tFeedstock^{-1}$. This compares to the figures modelled by the ADEE model, which showed a potential net saving of 261.45 $kgCO_{2eq}.tFeedstock^{-1}$ (6686 tCO_{2eq} total), with over 50 per cent of emission savings derived from the offset of emissions from removing the organic matter from landfill. There are many differences in the assumptions made between this research and that of Evangelisti *et al*. (2014); and the calculations behind the US GaBi LCA program are not known.

Finally, when comparing the co-digestion of cattle slurry with food waste in four different scenarios, Banks *et al*. (2011) reported net savings of between 777 $kgCO_{2eq}.MW^{-1}$ and 824 $kgCO_{2eq}.MW^{-1}$. A specific comparison was made against scenario 3 in Banks *et al.* (2011). The quantity and type of feedstock used in this scenario were simply input into and run through the ADEE model. The carbon saving calculated by Banks *et al.* (2011) was

777.32 $kgCO_{2eq}.MW^{-1}$, compared to the ADEE model's calculation of 808.02 $kgCO_{2eq}.MW^{-1}$ (a difference of less than 4 per cent).

The life-cycle modelling of the ADEE model compares strongly against the research of Banks *et al*. (2011) and Styles *et al*. (2013). However, the comparison against Evangelisti *et al*. (2014) was weaker, perhaps as a result of the number of different assumptions made throughout Evangelisti *et al.*'s work, such as electrical conversion efficiency of the CHP genset, the inherent energy of the feedstock and the percentage of fugitive gas emissions from the system.

6.5 SUMMARY

In summary, the ADEE model performs effectively against the life-cycle and economic outputs of other research. The key indicators of the model's efficacy stand up very well against the data provided by this research's case studies. The digester size calculations are indicative 79 per cent of the time, rising to 87 per cent when removing the case study with novel separation technology. Similarly, the gas yields (particularly methane), as measured by the CHP genset size, provide excellent indicative results 98 per cent of the time. This is enforced by the modelling against data provided in Köttner *et al*. (2008) (see Table 6-1). In turn, this should mean that the income derived from electricity generation should be similarly accurate, assuming that the electrical conversion efficiency of the CHP genset is correct.

When comparing the modelled GHG emissions from the ADEE model with Banks *et al.* (2011) and Styles *et al.* (2013), the results appear to be within the tolerances set by this research. However, it is difficult to assess where the differences may lie when comparing data with others' research, unless the work being compared is completely transparent in the methods used, providing enough key indicators of the main assumptions and calculations employed. Unless there is a clear breakdown of the scope of the research and the values of emissions calculated, it is not possible to fully understand where the differences may lie in the results.

This chapter has revealed some of the difficulties in modelling AD using generic calculations, and has gone some way towards offering a robust alternative. The ADEE model provides an accurate method of assessing the environmental and economic costs and benefits of constructing and operating an AD facility in a number of different scenarios.

The energetic value of feedstock and the emissions from the digestate are probably the two areas that provide the greatest uncertainty in modelling AD systems, and therefore the greatest degree of variability in comparison with other work. These two factors have the greatest influence on the economic and environmental performance of AD systems.

Chapter 7: Refining scenario two (hub-and-pod) and sensitivity analysis

'If you're using first-class land for biofuels, then you're competing with the growing of food. And so you're actually spiking food prices by moving energy production into agriculture.'

Bill Gates (1955–)

7.1 INTRODUCTION

This research seeks to assess the multifunctional role of AD in England: to identify what are the roles of AD (energy generation, waste management and carbon mitigation), and seek how best the technology might be deployed to maximise these different roles whilst having the least impact on existing land use and farming activities – that is, the aims and objectives of this research (see Section 2.8). This research also seeks to assess if current government policy might facilitate this.

To help achieve these aims, a computer program was built (Chapter 5) and validated against third-party data (Chapter 6). The validation demonstrated that the program is able to model the environmental and economic cost benefits of the technology under a range of different scenarios. The general approach used in this research to achieve the research goals was discussed in Section 3.7, which included a description of how the outputs from the optimised model-runs were used in calculating the regional results for scenarios one, three and four. Put simply, the transition from optimised model-run to regional results was a matter of dividing the total available feedstock in the region under investigation by the amount treated at a single optimised AD facility (model-run), to obtain the total number of facilities required in that region using that method of deployment. The environmental and economic model-run outputs were then multiplied by the expected number of AD facilities in that region.

However, with the inclusion of livestock waste materials, the approach became slightly more complex, and a number of additional analytical steps and procedures were required to assess scenario two. These were completed under the umbrella of a hybrid approach (see Section 7.1.1) and were as follows:

1. Defining feedstock into static and mobile feedstock types (see Section 7.1.2).

2. Analysis of:

    i. national livestock farm sizes (see Section 7.1.3)
    ii. national household waste (see Section 3.7.1.1)
    iii. other biowaste of the three chosen English regions (see Section 3.7.1.3).

3. The national cattle and pig herds were put into different herd-size categories and a mean herd size was calculated for each one (see Section 7.1.3.1).

4. Completing a number of model-runs to establish what minimum quantity of a single mobile feedstock type could treat each of the mean herd-size categories within a financially viable context, based on current government incentives (see Section 7.2.2).

5. Completing a number of model-runs to establish what minimum quantities of multiple mobile feedstock types could treat each of the mean herd-size categories within a financially viable context, based on current government incentives (see Section 7.2.4.3).

6. Completing regional analysis on the quantities of mobile feedstock types that are available to treat the existing static feedstock types. Small adjustments to the feedstock quantities were needed to account for different herd-size means and also the different availability of mobile feedstock types (see Section 7.3).

Lastly, a sensitivity analysis of several economic and environmental variables was completed. This altered certain parameters fixed during the initial analysis, but which could have a bearing on the environmental or economic credentials of the model-run that was to be used to represent the regional-level scenario outputs (see Section 7.4).

7.1.1 A hybrid approach to analysing anaerobic digestion

The two-stage analysis approach adopted is similar to that found in economic analyses (Hourcade, 2006). The first stage was to assess how a series of single-digester scenarios could be developed that treated the less economically viable static feedstock types with the supplement of the more economically viable mobile feedstock types. The aim at this stage was to assess the minimum quantity of single supplement feedstock types and the minimum quantity of additional multiple feedstock types that were required to ensure that livestock waste materials could be treated in an economically viable context. The second stage was to analyse the total feedstock available in each of the chosen regions, and then, using the optimal model-runs produced, based on the analysis completed in the first stage, to establish the greatest quantity of slurries and manures that could be treated using the hub-and-pod concept.

7.1.1.1 Bottom-up approach

Each model-run represents a single permutation of a fictitious AD facility treating a specific quantity of feedstock or mix of feedstock types within a number of set conditions. A series of optimal environmental model-runs were established, using both national and regional data that formed the basis of typical farm sizes. These outputs were also required to be economically viable; therefore, the model-run was economically optimised when the IRR was equal to or slightly in excess of the 12 per cent hurdle rate (see Section 3.4.1.3) set and the model-run achieved a positive NPV.

7.1.1.2 Top-down approach

Having developed a series of scenarios that were diverse in their feedstock use, yet remained financially robust against potential reasonable future stresses, each of the three regions needed to be analysed to assess the distribution and quantities of available feedstock (livestock waste materials (see Sections 7.1.3.1 and 7.3.2) and biowaste materials (see Section 3.7.1)).

Having estimated the total biowaste feedstock available in a region, a simple ratio was calculated between two types of poultry waste (the other non-crop, high-energy feedstock type) and biowaste feedstock, followed by an estimation of how best to distribute these two waste feedstock types and the two purpose-grown crops (maize and grass), to supplement the digestion of the low-energy slurries and manures. This was with the aim of maximising the quantity of energy generated and GHG emissions mitigated.

Having already established the availability of biowaste in each of the regions (see Section 3.7.1), to evaluate scenario two fully, the quantification and distribution of livestock waste materials in each region needed to be completed. There was also a requirement to separate the feedstock into two categories for the purposes of this scenario, for reasons discussed in the next section.

7.1.2 Categorising feedstock into two clear types

To strengthen the analysis of scenario two and, in particular, the treatment of the 'less appealing', low-energy, low income-generating feedstock types, all feedstock types were divided into two categories (static and mobile), based on their inherent energy-density values, and therefore their financial value as a commodity. For example, mobile types tended to be higher-energy, higher-value feedstock types, such as waste produced from food-processing, commercial premises and households, as well as crops grown specifically for AD. In contrast, static feedstock types were predominantly the low-DM, low-energy, low-value, farm-based feedstocks – essentially, cattle and pig slurries and manures. These are expensive to transport any great distance, are not viable to treat alone, unless in very large quantities, but constitute an environmental concern to policymakers in terms of GHG emissions and potential nutrient pollution to watercourses.

Clearly, not all feedstock types are equal in terms of their inherent energy value or their financial value. Some feedstock types, such as biowaste materials from the food industry and domestic households, have an economic benefit to the AD treatment facility because the facility receives a gate fee (of between £25 and £70 per tonne); however, this feedstock type also has good energy yields. On the other hand, glycerol, a by-product of ethanol production, has an economic cost to the AD facility of up to £200 per tonne, because of its significant methane yields and therefore income-generating properties to the AD facility. Crops and crop residues have differing values to the AD industry in terms of their inherent energy content and financial value, either as a cost to grow or, more importantly, as the cost of purchase (or loss in revenue from sale) on the commodities market.

To the contrary, slurries and manures potentially have the lowest (inherent energy and economic) value to the AD industry. These materials have already been digested, and therefore the greater portion of the inherent energy value from the original material has been assimilated by the animal. As a consequence, slurries and manures from cattle and pigs form the basis of the first category (static feedstock types), which has little or no value for transportation. However, poultry manures were excluded from this group, since both their DM content and inherent energy value are high enough to place them in the second category (mobile feedstock types). It is the low-energy slurry and manure materials that are the most difficult to encourage people to treat. To this end, few businesses would pay for the transport of these materials to be digested for so little (financial) gain.

Transport is a significant cost, both environmentally (Larson *et al*., 2009; Tunesi, 2011; Capponi *et al*., 2012) and financially. Miles (2013) reported that, according to the latest HGCA UK grain haulage survey, average haulage costs had increased by 8 per cent over the previous 12 months. Not only is there a requirement in the AD process for accessible feedstock to be delivered, but the resulting digestate also needs to be managed in a responsible manner. The digestate is a valuable product that is high in plant-available nutrients. It might be possible for smaller facilities to utilise all the digestate produced on their own land; but for larger facilities, importing large quantities of feedstock, it is likely that all or part of the digestate will need to be transported off-site, depending on the area of land owned. Transportation of digestate off-site has additional costs, since under certain circumstances EA waste licences are required. The aim, therefore, was to minimise the quantity of feedstock being transported, as well as the distance travelled, for good business practice as well as to improve environmental benefits.

To summarise, placing different feedstock types into one of two categories provided a focus at two levels. First, the categorisation allowed a natural base for mobile feedstock types to be delivered to the static feedstock types. Second, it provided the cornerstone for a potential distribution pattern of AD that helped to build the picture of how the technology could be developed in England. Having categorised the feedstock types, the next stage was to evaluate the distribution patterns of the static feedstock types at a national and regional level, and to develop a series of financially viable model-runs, using these feedstock types alone or in combination with other feedstock types.

7.1.3 Investigating the distribution of feedstock at the national scale

Before starting to model different scenarios of AD in England or its regions, analysis of the available feedstock types in England needed to be completed. Crops grown specifically for AD did not require analysis: if these crops could be grown in a region, then they would be cultivated depending on the economic benefit of doing so, rather than utilising the land to grow crops for food. Therefore, analysis focused on the on-farm waste material feedstock types (limited by the number of livestock in each region and individual farming practices); and on the off-farm, feedstock-limited biowaste materials (limited by what is generated by households and by the food-processing, retail and waste management sectors).

At this point, it was possible to start assessing how much of a particular supplementary feedstock type was required to treat the static feedstock in a financially viable context. The static feedstock types are addressed first, followed by the biowaste materials.

7.1.3.1 Analysing national livestock farm data

The aim of analysing the livestock across England (see Table 7-1) was to establish the quantity of slurries and manures produced by the animals. These waste streams are a source of GHG emissions and a concern for other air and water pollution. These feedstock types can be treated by AD, providing a source of renewable energy and an income to the farmer.

Table 7-1 Livestock statistics for beef and dairy cattle and pigs in England

Region	Dairy cattle			Beef cattle			Pigs		
	No. of holdings	Number of dairy cattle	Farmed area (ha)	No. of holdings	Number of cattle	Farmed area (ha)	No. of holdings	Number of pigs	Farmed area (ha)
North East	366	14825	62359	2035	277471	389676	216	89056	24729
North West & Merseyside	3096	273258	330202	6682	952846	658735	670	138284	43723
Yorkshire & the Humber	1530	91279	158404	5115	566376	522166	1262	1222505	111454
East Midlands	1298	80628	143780	4190	510715	444506	715	344131	60121
West Midlands	2236	169071	218520	6137	763851	514327	879	188840	53320
Eastern	488	20477	73332	2072	209877	289168	989	1032016	92545
South East (incl. London)	1070	74481	171640	3911	443232	488120	1039	204756	83902
South West	5031	434428	591627	12692	1797018	1196659	2019	386529	136780
England	**15115**	**1158447**	**1749864**	**42834**	**5521386**	**4503357**	**7789**	**3606117**	**606574**

Adapted from: DEFRA June 2010 Census of Agriculture and Horticulture (DEFRA, 2013a)

However, only basic observations can be made from this information:

- There were 15,115 dairy herds in England.
- The average dairy-herd size was 76 head on an average farm of 116 ha.
- It is not possible to state how the 1,158,447 dairy cattle are distributed across the 15,115 farms.

If the average of these national or regional figures had been used to form the basis of the initial model-run analysis (see Table 7-2), the data would have been relatively meaningless, in that it does not provide an accurate distribution pattern of herd sizes across the dairy, beef and pig populations, either nationally or regionally. What it did highlight was that there is a considerable variation in stock levels between the different English regions against the national mean.

Table 7-2 National mean herd sizes compared to the mean herd sizes of three English regions

	Dairy cattle		Beef cattle		Pigs	
Mean herd size and farm area	**Herd size**	**Area (ha)**	**Herd size**	**Area (ha)**	**Herd size**	**Area (ha)**
East of England	42	150	101	140	1044	94
South West	86	117	141	94	191	68
West Midlands	76	98	125	84	215	61
England	77	116	129	105	463	78

Adapted from: DEFRA June 2010 Census of Agriculture and Horticulture (DEFRA, 2013a)

The regional mean herd size compared to the national mean is exaggerated further for beef and pig herds. With the help of DEFRA (2013a), the national livestock statistics were subdivided into a number of size categories (see Appendix 3, Tables A1.11a–e); this enabled a more detailed picture to be built of the distribution patterns of livestock (dairy and beef cattle, pigs, layers and broilers) across England. Further detail was not possible since DEFRA was concerned that individual herds might be identified. The averages of the new herd-size categories (see Table 3.10) formed the basis of later analysis for developing the different national and regional baseline scenarios that this research focuses on.

Had this research taken the average herd size for beef cattle, dairy cattle and pigs in England, model-run calculations would have been based on 129, 77 and 463 animals per herd, respectively. However, this does not really tell us about the distribution of herds, and therefore the distribution of manures and slurries produced across the country. In addition to the spatial differences that help to define the distribution of manures and slurries, there are also differences in the husbandry of these animals, depending on a region's climate and growing period. Smaller herds are left out longer in the fields, thereby reducing the quantity of waste products collected during housing and milking periods.

The reason why this research sought to find a more detailed distribution pattern was because initial investigations showed that there were not enough supporting (mobile) feedstock types for all the static feedstock types without impacting on existing farming activities, or without creating a situation in which growing crops specifically for energy generation would compete with growing crops for food. Similarly, initial investigations, including outputs from the model, had already revealed that AD facilities based on smaller herd sizes were not economically viable (Köttner *et al*., 2008) without the support of considerable quantities of high-energy feedstock types. Therefore, some form of prioritisation needed to be ascertained.

By splitting up the herd sizes into smaller ranges and using the mean values of these ranges for analysis, it was possible to assess if there were differences in the economic and environmental benefits (or costs) across the whole livestock community, and, if necessary, to prioritise those farm sizes that provided the greatest environmental and economic benefits to achieve government targets.

Table 7-3 Defined national ranges and averages of static (primary) feedstock types

Beef and dairy herd size categories	Mean cattle no. (head) of each category	Mean dairy no. (head) of each category	Pig herd size category	Mean pig no. (head) of each category
700 +	900	870	1000+	2653
500–699	580	570	500–999	731
350–499	410	400	300–499	392
200–349	260	250		
100–199	140	140		

Adapted from: DEFRA June 2010 Census of Agriculture and Horticulture (DEFRA, 2013a)

Defining herd sizes, DEFRA (2013a) states that ‘dairy cows are defined as female dairy cows over two years old with offspring’, but offspring are not included. Of the 15,115 dairy holdings in England, only 20 fell into the highest range category (700+ dairy cows), whilst 10,391 holdings fell into the lowest range category (1–99 dairy cows), which had an average of 27 cows per holding. There were 3,369 holdings in the next lowest range category (100–199 dairy cows), which was the minimum that this research held to be financially feasible.

DEFRA does not have a definition of beef cattle herd size, assuming that all other cattle not dairy cows are beef cattle. Herd sizes therefore include all followers or offspring. Of the 42,834 beef cattle holdings in England in 2010, 594 holdings fell into the highest category range. However, there were in excess of 25,000 beef cattle holdings in the lowest category range, with an average holding of just 37 cows (not financially viable). The next lowest herd-size category (100–199) had in excess of 8,500 herds that this research thought to be potentially viable.

For convenience in defining herd sizes for model-runs, means from the national categorised ranges were used to form the basis of the different model-runs for analysis. Tables A1.11a–e in Appendix 3 display national livestock data, with the mean values of the different livestock herd-size categories calculated and defined (see Table 7-3). The lowest herd-size category (1–99 head) was removed from future analysis at this stage, since these herds were thought to be financially unviable and therefore fell outside the scope of the ADEE model.

The other livestock in this feedstock category are pigs. Pigs produce considerably less excreta than cattle, and data on pigs are more difficult to analyse than for cattle and dairy herds, because litters are so much bigger and animal husbandry more varied, both regionally and nationally. Cattle and dairy are essentially the same animals, but this classification alone helps to distinguish herd size and provides an indication of animal age (required when using RB209 (DEFRA, 2010a), which distinguishes excreta quantities in terms of animal age). This is not the case with swine herds. DEFRA does not distinguish between pigs over their life cycle.

7.2 THE MODELLING PARAMETERS AND PROCESS

Before discussing how the model-runs were developed, it is important to state that a number of variables were fixed at this stage. These relate principally to the:

- value of the different feedstock types modelled (as either a cost or a benefit to the facility)
- financial environment in which the model-runs are tested
- compensation value received from generating the energy (FITs, ROCs or RHIs).

Two approaches were adopted: a bottom-up approach (discussed in the rest of Section 7.2), which sought to assess the viability of AD from a series of individual AD model-runs; followed by a top-down approach, which assessed the potential available feedstock in a region, and then used the optimised model-runs from the bottom-up approach to help assess the scenario analysis at the regional level (see Section 7.3).

7.2.1 Model variables fixed in the primary phase of model-run analysis

A number of economic and system assumptions needed to be made to establish the national baseline model-runs to which alterations could be made (i.e. regional air and soil temperature), for the regional analysis and so that sensitivity analysis could be completed (see Section 7.4). To this end, a set of common variables were fixed (see Table 7-4), which represented the baseline assumptions used throughout this research. Whilst modelling scenario two, three variables, marked with an asterisk (see Table 7-4), needed to be overridden to stop the model from calculating specific capital costs that would have been included if the hub-and-pod concept was not being modelled, as in scenario one – capital such as large reception buildings incorporating de-packaging and macerating equipment and other equipment normally necessary for treating biowaste material on-site. Since these activities occur off-site (centrally, in the hub), these costs are not incurred by the AD facility owner.

The aim of the hub-and-pod concept is to allow for the delivery of contained, biologically safe biowaste feedstock directly to a contained vessel within the AD treatment facility. Essentially, this means that less capital infrastructure and labour are required at the AD facility, since the majority of the pre-processing is completed off-site.

The pre-processing removes the need for the treatment facility to perform the de-packaging and de-contamination that would normally be required. Even source-segregated biowaste can be contaminated with plastics, cutlery, toys, and so on, which could damage an AD facility or its process. As a result of off-site pre-processing, groundwork costs at the AD facility are reduced, since the working area required is smaller; wheel-washing facilities are not necessary; the odour management required when operating a reception building is removed; and the size of the reception building is significantly reduced. However, not all technology can be omitted. ABPR regulations state that the digestate must still be pasteurised before leaving the facility and being sent to land (DEFRA, 2013c), even though the material received by the 'pod' will have been pasteurised by the 'hub' before leaving that facility.

Since a third party would be treating the waste material at the pod, this service carries a charge. Therefore, the gate fee normally received at the AD facility is reduced to a baseline of £20 per tonne of waste received, as opposed to what might be £80 per tonne for non-source-separated waste, the current Landfill Allowance Trading Scheme (LATS) value.

Table 7-4 Variables fixed whilst developing the baseline model-runs

Variable	Value
Number of weeks animals housed	Herd size and region dependent
Poultry layers' manure value	£10
Poultry broilers' manure value	£10
Grass silage value	£20
Maize silage value	£30
Biowaste value	£20
Retention period (days)	Modelled
Engine electrical efficiency	39%
Discount rate	12%
Pasteuriser used	Post
Separation unit used	Yes
Hours of generation per annum	8040
Cost of diesel fuel	£1.40
Regional temperature	UK average
Reception building*	£0
Capital-cost reduction value*	£183,500
Tax rate	17%
Inflation rate	2.5%
Interest rate over base	5.5%
Percentage of debt	80%
Total labour costs*	£15,000
% heat utilised in addition to the digester's parasitic load	10%
FIT <250 kWh	15.16p
FIT 251 kWh–500 kWh	14.02p
FIT >500 kWh	9.24p
RHI <200kWh	7.10p

The variables were fixed when biowaste was used in the model.

Having discussed the assumptions made during the development of this scenario, the next phase of analysis was to establish the minimum quantity of each supplementary mobile feedstock (see Section 7.2.2) required to establish a financially viable AD facility, according to the baseline variables (see Table 7-4). To begin with, the national mean herd size (source of static feedstock types) for each of the categorised ranges (see Table 7-3) was combined with a number of different single feedstock types, to determine the minimum supplementary feedstock required in order to establish a viable AD facility. The assessment of scenario two was completed under two overarching restrictions:

- First, that the optimised model-runs selected, whilst being financially robust, were also restricted by the quantity of high-energy, high-value feedstock treated at the facility. The aim was to treat as much of the on-farm livestock waste as possible.
- Second, the quantity of crops grown specifically for AD use was minimised. This was to limit the impact on existing farming activities.

These restrictions were made because a central objective of this research is to provide a set of model-runs that complement the existing farming system; that seek to treat the low-energy, low-value, on-farm waste material and not to impact on land use for growing food; and that minimise environmental impacts from LUC or iLUC respectively.

7.2.2 Calculating the minimum quantities of single supplementary feedstock types required

To establish the financial viability of treating livestock-based AD treatment facilities, additional feedstock types are required to supplement the slurries and manures. This enables the facility to generate enough energy to ensure its financial sustainability. To establish the level of additional supporting feedstock required, five mobile feedstock types were modelled in increasing quantities until financial viability was established. The mobile feedstock types chosen were:

- poultry waste – broiler hens (55.85 per cent DM content)
- poultry waste – layer hens (28.6 per cent DM content), separately defined
- biowaste
- grass silage
- maize silage.

These were chosen for their energy-generating capacity and potential GHG mitigation qualities. The two crops chosen were considered to have the least impact on existing farming activities (depending on the region), and, more importantly, should not compete with land use for food. The first three feedstock types are waste materials that have reasonably high energy, and, if left untreated, could pose an environmental concern. The final two are already established AD feedstock types. These were also chosen since they are crops already grown in the three study regions selected, and would fit in with regional farming activities. In the West, excess or underutilised pastureland could be used; whilst in the East, maize could act as a break crop to the existing farm-crop rotation, thereby not impacting too greatly on existing farming activities. However, this could create potentially difficult economic decisions, such as the requirement for new technology or labour, as well as the fact that their previous break crop might be a valuable product that could compete with maize in the medium- to long-term.

Maize does have some negative environmental impacts associated with it, specifically, high water demand and soil erosion (Finke *et al.*, 1999). However, these can be lessened to a degree by good farming practices. There are, of course, many other crops that can be used in AD facilities, some of which can be seen in this research's case studies, and considerably more in the literature (e.g. Amon *et al*., 2007a; Babel *et al.*, 2009; Köttner *et al.,* 2008). These may have a greater influence on the crop cycle of a farm and would most certainly impact its profitability. The digester, however, could provide a suitable alternative to the farmer, should he not achieve an acceptable price for his crops at market.

The first step in ascertaining the viability of an AD facility was to determine the quantity of additional (mobile) feedstock required to achieve this. The different quantities of single feedstock types (see Table 7-5) were modelled incrementally until viability was achieved.

Table 7-5 Quantities of mobile supplementary feedstock types incrementally added (t.a^{-1})

Model-run number	Poultry – layers	Poultry – broilers	Grass silage	Maize silage	Biowaste
1	0	0	0	0	0
2	750	750	1500	1500	1000
3	1000	1000	2000	2000	2000
4	2000	2000	3000	3000	3000
5	3000	3000	4000	4000	4000
6	4000	4000	5000	5000	5000
7	5000	5000	7500	7500	7500
8	10000	7500	10000	10000	10000

7.2.3 Model-run decision process

Each of the supplementary feedstock type quantities (see Table 7-5) were modelled against each mean livestock herd size (see Table 7-3) until the minimum quantity of supplementary feedstock established the financial viability of the model-run. This section briefly outlines the decision process behind accepting or declining the different model-runs.

The hurdle rate set for financial viability was an IRR of 12 per cent, with a positive NPV (see Chapter 3). Any model-run with an IRR of less than 12 per cent or, more often than not, greater than 16 per cent, was discarded, unless there were no alternatives. This ensured that only enough land for energy production was utilised and energy crops were not promoted over food crops. The aim was not to match the feedstock requirement to attain an IRR of 12 per cent, but to find the feedstock mix that was as close as possible to attaining an IRR of 12 per cent with a positive NPV. Few model-runs provided IRRs of exactly 12 per cent, but the next highest value was chosen, as the NPV was stronger. In several instances, when measuring the financial viability of adding increasing quantities of a single mobile feedstock, no model-run provided either an IRR value of 12 per cent or more, or an IRR of 12 per cent or more with a positive NPV value simultaneously.

Other decision criteria under consideration included the engine-size requirement and the quantity of CO_{2eq} saved across the model-run. The engine size was considered in order to establish if a model-run's expected energy output matched a known manufactured engine size. This would help to ensure the efficiency and longevity of the CHP genset. Emphasis was also placed on the quantity of CO_{2eq} saved in the model-run, but since the quantity of CO_{2eq} saved was always a positive value (see Figures 7-1 ($CO_{2eq}.MW^{-1}$) and 7-2 ($CO_{2eq}.t^{-1}$)), this was not prioritised at this stage. These two figures represent the mean carbon savings across all the different model-runs for beef, dairy and pig mean categories. The model-run numbers represent the same model-run numbers displayed in Table 7-5.

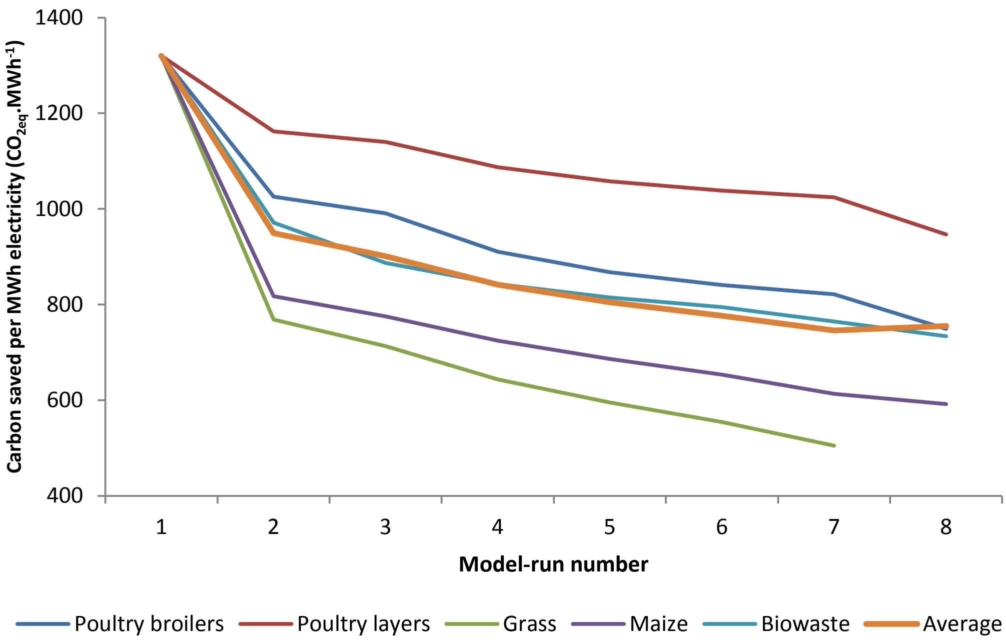


Figure 7-1 Mean carbon savings per MWh of electricity generated

There is a gradual decline in the quantity of carbon saved per MWe generated, as other factors (e.g. farming activities and other transport GHG emissions) increase. Biowaste saves the most significant quantities of GHG emissions, but tails off more rapidly as the increased imported material needs to be exported again, since there is not enough land on site to spread the digestate to. Grass remains the inferior performer, having the least inherent energy and therefore not generating as much energy as the other feedstock types modelled here per additional tonne. The other side to the GHG performance of grass is that the farming of grass is quite energy-intensive, in terms of the farm activities and fertilisers and sprays required to maintain the grass, offsetting the benefits provided through the generation of renewable energy.

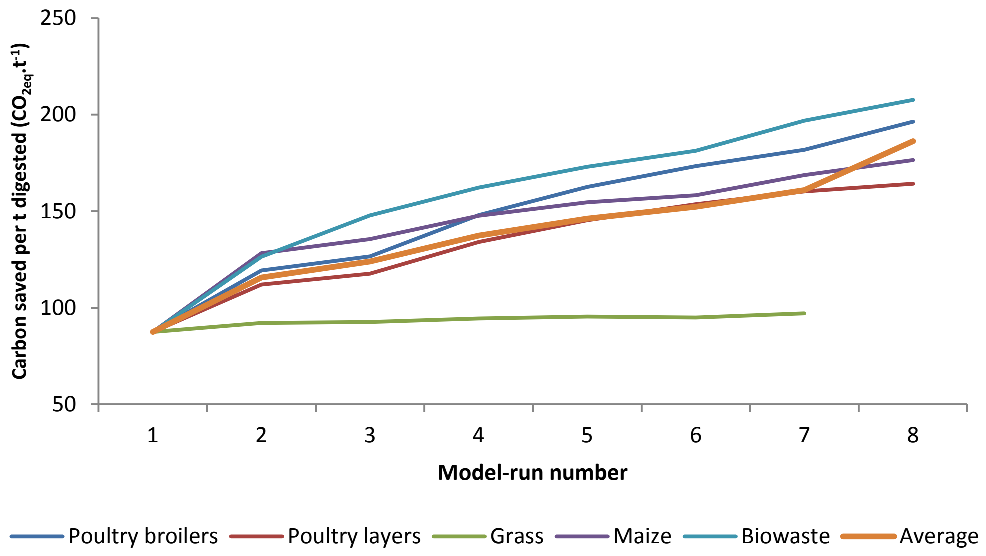


Figure 7-2 Mean carbon savings per tonne of material digested

The only analyses that can be interpolated from Figures 7-1 and 7-2 are that, in terms of energy generated, the greatest quantity of GHG saved is when manures and slurries are treated alone (yet these generate the least energy); and that GHG abatement increases with every additional tonne treated by AD, as would be expected from renewable sources.

7.2.4 Selecting the optimal model-runs

This next section explains how the model-runs were developed: first, by combining single static feedstock types with single mobile feedstock types, to understand the economic and environmental impacts these combinations might have; and second, by combining single static feedstock types with multiple mobile feedstock types. A classification system was devised to name each of the model-runs, using a series of letters and numbers to distinguish between the different model-runs (see Appendix 4). This process is explained in greater detail below. In addition to the economic and environmental cost–benefits measure, the model also calculates the area of land required to cultivate the crop feedstock types grown specifically for AD (grass and maize) for single AD facilities, enabling the impact on land use requirements at a regional scale to be assessed.

7.2.4.1 Single feedstock type model-runs

To explain the process more clearly, an example of modelling one static feedstock type (dairy cattle) against the combination of one mobile feedstock type (grass silage) is displayed below (see Figure 7-3). This represented 35 iterations of the model (i.e. seven iterations for each of the five mean dairy herd-sizes represented).

Dairy (head)	Grass silage	Model-run no.
	0	1
870	1500	2
570	2000	3
400	3000	4
250	4000	5
140	5000	6
	7500	7

Figure 7-3 Combining dairy feedstock type with grass silage feedstock type

This process was completed for each of the mobile feedstock types against each of the static feedstock types (dairy cattle, beef cattle and pig herds), in excess of 500 iterations. In addition to these single mobile feedstock model-runs, 35 additional mixed mobile feedstock model-runs were completed, for reasons that will be explained later (see Section 7.2.4.3). This established a series of model-runs that treated the on-farm slurries and manures with the minimum quantity of mobile feedstock required to meet the financial hurdle rate that classified the AD facility as financially viable.

The object was not to maximise the profits of any individual AD facility, but to ensure that the modelled facility added value to the existing business, was financially sustainable and did not significantly impact on existing farming activities, either on-site or locally. The goal was to ensure that there were sufficient mobile feedstock types available (locally) to treat as much of the static feedstock type in that area as possible.

An example of model results from one mean herd-size category (870 dairy cows) against the addition of different quantities of grass is displayed in Figure 7-4 (below). Each model-run's results are displayed vertically above the model-run number. The scale on the left axis is logarithmic, displaying the data (total GHG emissions saved, electricity generated, total income, NPV and payback period) that are not given as a percentage, which appear on the right axis (IRR).

These six separate indicators were chosen at this stage to aid the decision of model-run viability (see Figure 7-4, legend). In assessing the question of 'How much grass is required to economically treat slurries and manures from 870 dairy cattle?' the following observations were made from the seven model-runs made (see Figure 7-4):

- Total emissions saved ranged from 2,199 $t.a^{-1}$ (model-run 1) to 3,097 $t.a^{-1}$ (model-run 7).
- Annual income ranged from £359,000 to £706,000 (model-run 6 providing the greatest income).
- No payback period exceeded 10 years.
- Electricity generated ranged from 2,042 $MWh.a^{-1}$ to 4,646 $MWh.a^{-1}$.
- IRR ranged from 0% to 11%.
- No model-run returned a positive NPV for grass feedstock.

This example was chosen for two reasons. First, and mainly, to demonstrate the process by which model-runs were assessed in terms of their environmental and economic attributes, and how the decision process was completed in choosing which model-run was used at the next stage of analysis; and second, to demonstrate the difficulties in modelling AD.

Dealing with the latter first, the summary above highlights the uneconomical status of treating slurries with grass using the ADEE model, since no model-run (or AD facility with that particular feedstock mix) would have been built in real life, as no model-run had a positive NPV.

This suggests that no scenario using dairy slurry and grass is financially viable. Using the ADEE regression model (see Section 6.3.2.1), the capital expenditure calculated for model-run 6 was £1,845,590 (and not £2,259,000, as produced by the ADEE model here). This would return a positive NPV for this model-run. This does not mean that the ADEE regression model is more accurate than the ADEE model; however, it does highlight an anomaly that occurs when using the model, particularly with single feedstock systems. To explain, the ADEE model has a 'trigger point' at 400 kW installed capacity. If the model calculates that the model-run would require a CHP engine of 400 kW capacity or more, then the model assumes that a higher-capacity CHP genset is required, with larger peripheral equipment. It is this change that increases the CAPEX significantly. There is a large increase in generating capacity between model-runs 5 and 6, 387 kW and 483 kW respectively. This would require an additional £100,000 cost in the genset alone, before the cost of increasing the physical capacities of the pipes, pumps and other equipment required. However, in real life, an alternative CHP genset manufacturer could be found that would bridge this gap at a lower cost. It is only at trigger points such as this that caution is required when using the ADEE model.

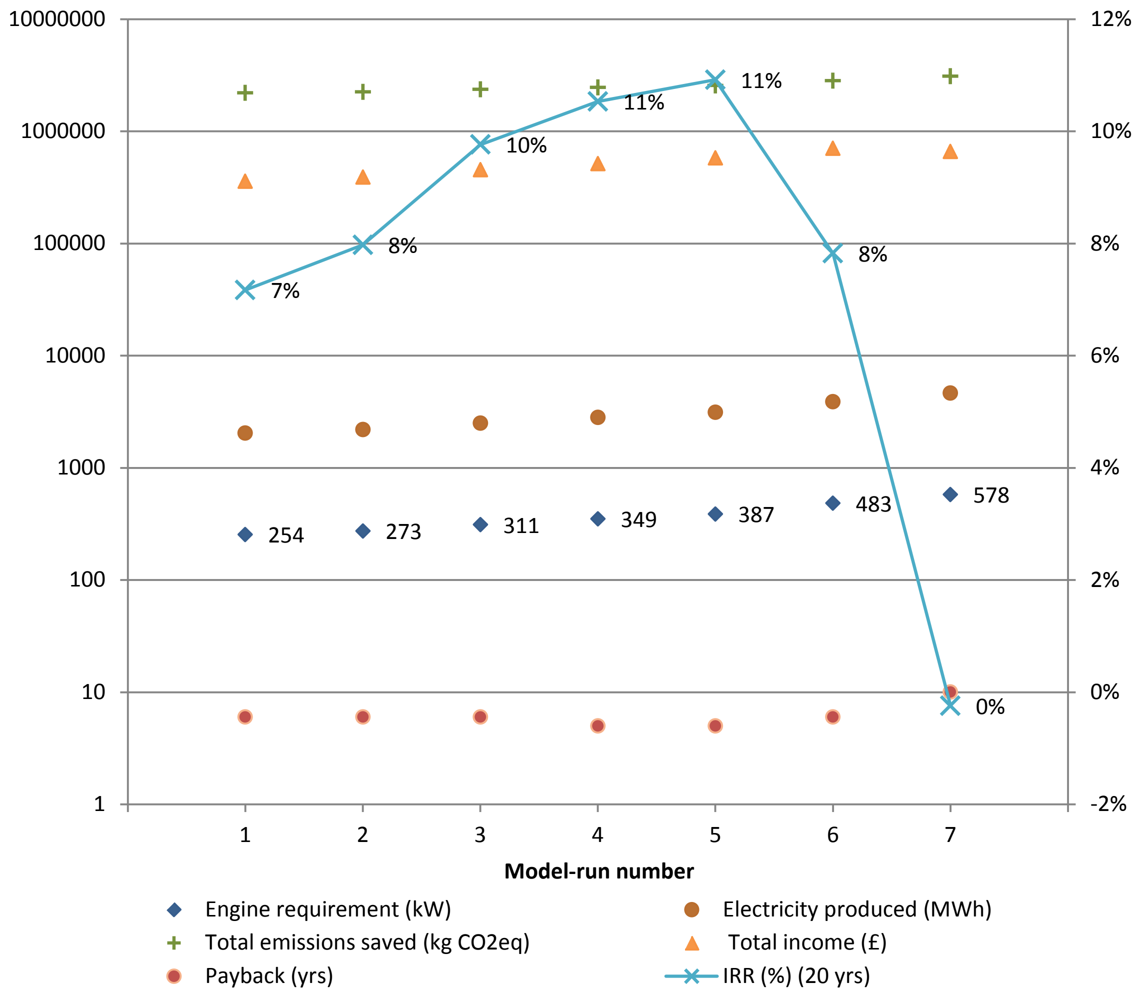


Figure 7-4 Summary of results from seven model-runs based on a dairy herd of 870 head modelled against a single mobile feedstock type (grass silage)

In the example of supplementing slurry with grass silage, the IRR of model-run 7 reduced considerably as it reached the trigger point discussed above. Likewise, the increase in feedstock allowed the model-run to generate enough energy to ‘push it’ over the DECC FIT tipping point, into the top (lowest-paying per MWh) bracket, reducing the income per tonne of feedstock. This does not invalidate the model, but highlights a weakness that needed to be considered when modelling the different scenarios of this thesis.

Returning to the decision process and the worked example (see Figure 7-4), the first assessment is to make sure that the hurdle rate is achieved – that is, the amount of return required by the investor per annum, set at 12 per cent. The next assessment criteria asks if the investment adds value to shareholder capital, and if, at the end of the investment project, the investor has a positive financial gain, qualified in present-day values (NPV). Lastly, but with no less weight, the environmental qualities are assessed in terms of the net GHG savings achieved. Total GHG savings were chosen over GHG savings per MW generated or GHG savings per tonne treated: the former ($kgCO_{2eq}.MW^{-1}$) reduces as energy generated increases. Since the addition of feedstock with high inherent energy generates considerably more energy than the baseline slurry only, this is not a good measure of GHG savings mitigated; the latter ($kgCO_{2eq}.t^{-1}$) measure is also unreliable in that increased GHG emission savings would be expected, as more feedstock generates greater quantities of energy and offsets more energy from mineral fertiliser manufacture, as more digestate is produced.

In this example, model-run 5 was chosen to move to the next stage of analysis. However, this model-run still did not achieve the economic criteria for financial viability and is therefore treated with caution. Further investigation (such as finding out if a tipping point had just been exceeded) might have shown that model-run 6 was more suitable and would have been chosen over model-run 5, since it achieved 300 t CO_{2eq} greater savings per annum. Further investigation was ruled out for reasons that will be made apparent in Section 7.2.4.2.1.

This process was completed for the category means of each of the three static feedstock types against each of the varying quantities of the five mobile feedstock types – a total of 552 model-runs, until a complete set of model-runs was built that met the criteria set (approximately 62 model-runs). The results of this are discussed below.

7.2.4.2 Model-run results: the addition of single feedstock types

Some of the chosen model-runs were the only model-runs that fitted all the accepted criteria, particularly when modelling grass silage. This was primarily due to grass having the least inherent energy value of the mobile feedstock types. When mixing grass with pig slurry, none of the model-runs was financially viable.

However, a pattern soon became clear of typical quantities of each mobile feedstock type required to treat the static feedstock within the economic criteria (see Table 7-6). These quantities were typical across the whole range of category means of cattle, dairy and pig farms. With regard to the model-runs co-digesting slurries with grass, very few model-runs met the financial viability criteria.

Table 7-6 Minimum mobile feedstock required to meet financial viability

	Poultry – layers	Poultry – broilers	Grass silage	Maize silage	Biowaste
Beef 900	3000	4000	5000	4000	3000
Dairy 870	3000	3000	5000	4000	3000
Pigs 1000+	3000	4000	7500	4000	3000

But what does this mean? According to DEFRA (2013a), there are 65,738 livestock holdings of dairy, beef and pigs across England (see Appendix 3, Tables A1.11a, b and c). Removing the lowest herd-size category of each farm type would leave a total of 24,935 holdings. Treating these remaining holdings with biowaste alone would require approximately 74,805,000 t, approximately five times more than is currently produced in the UK. So, biowaste alone will have little impact on treating the static feedstock in England. However, this waste stream does have the ability to supplement in excess of 5,300 AD facilities if the total currently produced (16 Mt) were to be divided equally (3,000 t per AD facility).

In the next section, we look at the other mobile feedstock types being used in this research (maize and grass), and ask how much land would be required if one of these single feedstock types were used to supplement the static livestock feedstock, and what would be the impact on the existing farm business.

7.2.4.2.1 Land requirement

This section investigates how much land is required to treat the slurries and manures of the average herd in England, and how many of these herds (on-farm waste materials) can be treated with the supplement of a single feedstock type within the financially viable context presented by this work.

Assuming that the average national yield for grass and maize is 45 t per hectare, each viable facility would require approximately 112 ha of grass or 89 ha of maize. The average farm size in the largest beef cattle category (900 head of beef cattle) is approximately 420 ha (see Appendix 3, Table A1.11b), and the average size of the smallest farm size (in this study), with 140 head of beef cattle, is approximately 120 ha. There is also considerable regional variation (see Appendix 3, Table A1.13a, b and c). Using these single mobile feedstock types alone would significantly impact on the existing farming activities of an on-farm AD facility and the surrounding area.

Nationally, there are only 20 dairy farms across England and 594 beef cattle farms that fit into the largest farm herd-size categories. If the slurries and manures were treated on these farms alone, this would require a total of 68,768 ha grass or 54,646 ha maize, using the quantities of single supplementary feedstock types displayed in Table 7-6. The initial model-runs showed that increasing quantities of mobile feedstock types were required as herd sizes reduced, to maintain financial viability. However, for the sake of making this point, if the quantities of mobile feedstock were the same as those shown in Table 7-6 (above), and were used to treat the slurries and manures from the 17,533 viable beef cattle herds, excluding the smallest (unviable) farm-size category (of which there are 25,301 beef cattle herds alone), then 2,833,712 ha grass or 2,251,789 ha maize would be required across England. This would still not account for 4,724 of the 15,115 dairy herds and more than 1,600 pig herds thought viable if supplementary feedstock were available.

To put this into context, according to the Farm Business Survey's last report (RBR, 2013), for 2011/12, the total area of agricultural holdings for the East of England is 1,308,809 ha, of which 987,275 ha were used for growing crops and 230,103 ha for grass/rough grazing land. Therefore, to treat only the 17,533 beef cattle holdings that were deemed to be financially viable would require an area almost one and a half times the size of the East of England's total agricultural area. This alone would have a significant impact on farming activities across England and would also impact heavily on prices for UK food produce.

Of the 550-plus model-runs based on national livestock data, seven model-runs using grass or maize silage may have provided different results in terms of feedstock required to make a facility viable, by restricting the engine output to less than 250 kWh. This would have brought the model-run within the lowest FIT rate (see Table 7-4) and might have qualified the model-run for viability. However, in all of these model-runs, the result was to move the mobile feedstock requirement down to the next quantity level (i.e. from a requirement of 4,000 $t.a^{-1}$ to 3,000 $t.a^{-1}$). Since this was still thought to cause disruption to the existing farm business, an alternative solution was sought.

It is clear that not much of the static feedstock available in England or the three chosen regions could be treated solely by single mobile feedstock types without seriously impacting on crop rotations or crops for food. Farmers deal with risks and uncertainties from many different internal and external forces, including the possibility of crop failure through disease and risks from climate change; large commodity market fluctuations, causing price uncertainty, also have an important role in agricultural decision-making. Therefore, good business and farming practices suggest that a mixture of feedstock types would be appropriate to minimise the effects of these potential threats to existing activities and to safeguard the viability of the new AD facility.

The next step was to assess if a mixture in the mobile feedstock types used in a model-run would result in a reduction of the burden on land required for an AD facility, minimising the impact of AD on land for food or biodiversity, whilst maintaining financial viability and protecting the business from the impacts of crop failure.

7.2.4.3 Multiple feedstock type model-runs

It was clear that should the on-farm waste materials be the focus of AD, then the quantity of single supplement feedstock types was insufficient to treat all the on-farm materials without impacting on existing farm activities or competing with food production. In fact, it is apparent that it is impossible to treat all the on-farm waste feedstock types with capital costs at their current levels. A new, pragmatic approach was adopted to assess a number of possible combinations of quantities of mobile feedstock types against the static feedstock types. Again, the aim was to achieve the same economic viability set out in Section 7.2.3.

For the purposes of this research, poultry waste from layers and from broilers were treated as two different feedstock types, as their physical and chemical properties are slightly different, due to their different animal husbandry. Effectively, they have different DM content, and different biogas- and methane-generating potentials, and produce digestate of differing quality as well. Whilst they are strictly the same animal species, only either layer manure or broiler manure could be chosen as part of a model-run mix (i.e. not in combination with each other).

The procedure for model-run development was similar to that described in Section 7.2.4, but with a significant increase in the number of combinations of mixed feedstock for each category mean of static feedstock. The number of model-runs was reduced significantly by the few initial trial model-runs, completed with the single feedstock model-runs mentioned above, which helped to narrow down the different potential combinations. However, each of the mean categories of the static feedstock types needed to be tested against a number of different combinations of the mobile feedstock types (see Figure 7-5), in order to establish a new set of model-runs that were again financially viable.

	Poultry – layers or broilers	Grass silage	Maize silage	Biowaste
Beef cattle	500	750	500	750
	600	1000	750	1000
Dairy cattle	750	1250	1000	1250
	800	1500	1250	1500
	1000		1500	2000
Pigs	1250			
	1500			

Figure 7-5 Quantities of single feedstock types mixed in different ratios for model-run analysis

To illustrate the modelling process again, some of the model-runs are used in defining the multiple feedstock model-run for a particular herd-size category (e.g. herd of 560 dairy cows). Table 7-7 displays the feedstock type variables altered in assessing which combination might be most suited (environmentally and economically) to supplementing the slurry and manure produced by 560 dairy cows. Table 7-7 explores some of the combinations being tested (of the quantities of crops specifically grown for AD, poultry manure and biowaste to supplement the static feedstock types), to strike a balance between carbon mitigation, energy generation and land use.

Similarly to the single supplementary feedstock additions, all other variables (see Table 7-4) and feedstock values (see Table 7.7) were fixed. At this stage, the quantities of supplementary feedstock types were being assessed to attain the minimum threshold (12 per cent IRR) for a financially viable model-run; the aim was not to assess what the effects might be on a model-run of externalities such as changes to the inflation rate, interest rate and other costs/benefits, such as transport costs and the value of feedstock (reducing for those feedstock types that attract a gate fee; or increasing for those feedstock types for which a fee (or cost) is already payable/attributable). These factors are outside the influence of the facility operator, but their influence on the viability of the AD facility needs to be calculated in order to properly appraise the project and to establish if the investment is likely to proceed.

The low quantities of the different supplementary feedstock types are displayed below (see Table 7.4). Of particular note is the small quantity of biowaste materials used. Under normal operational requirements, these configurations would not be economically viable, due to all the additional capital required to treat this material on-site. However, adopting the hub-and-pod concept allows for these smaller quantities to be brought safely into the farm environment, enabling the treatment of livestock waste materials economically.

Table 7-7 Variables used in the model-runs for a dairy herd of 560 cows

Variable	Model-run no.					
	D560Mix 1	D560Mix 2	D560Mix 3	D560Mix 4	D560Mix 5	D560Mix 6
Feedstock type	Dairy cow slurry					
Head of animals	560	560	560	560	560	560
No. of weeks housed	44	44	44	44	44	44
Quantity of layer manure (t)	500	500	500	0	0	0
Value of layer manure (£)	10	10	10	0	0	0
Quantity of broiler manure (t)	0	0	0	500	500	500
Value of broiler manure (£)	0	0	0	10	10	10
Quantity of grass silage (t)	500	750	1250	500	750	1250
Grass silage value (£)	20	20	20	20	20	20
Quantity of maize silage (t)	1250	750	500	1250	750	500
Maize silage value (£)	30	30	30	30	30	30
Quantity of biowaste (t)	2250	2250	2250	2250	2250	2250
Biowaste value (£)	20	20	20	20	20	20

The results from these particular model-runs are displayed below (Figure 7-6). They show that the approximate inherent energy content established in single feedstock type model-runs have been translated to the mixed feedstock type model-runs here. Unsurprisingly, this is a result of the majority of income being received from the sale of energy. Effectively, the model has calculated the minimum energy (or income) required to maintain a financially viable AD facility, based on the quantity of supplementary feedstock needed to treat a given amount of static feedstock.

All model-runs have positive NPVs between £238,000 and £480,000, and total GHG savings of between 2,180,000 $kgCO_{2eq}.a^{-1}$ and 2,429,110 $kgCO_{2eq}.a^{-1}$. However, the IRR varies between the different model-runs. It is represented in Figure 7-6 (below) by the right-hand scale. The natural choice, looking at the results figure, would be model-runs 1 and 4, as these provide the greatest IRR and NPV values, as well as the greatest GHG emission reduction. However, the aim of this research is not to maximise the profits of individual digesters, but to ensure that as much static feedstock as possible can be treated with the least quantity of supplementary feedstock. Therefore, model-runs 2 and 5 were chosen as the viable model-runs for scenario analysis. These model-runs require 250 t less feedstock, or 6 ha less land, than model-runs 1 and 4, with IRRs in excess of 15 per cent.

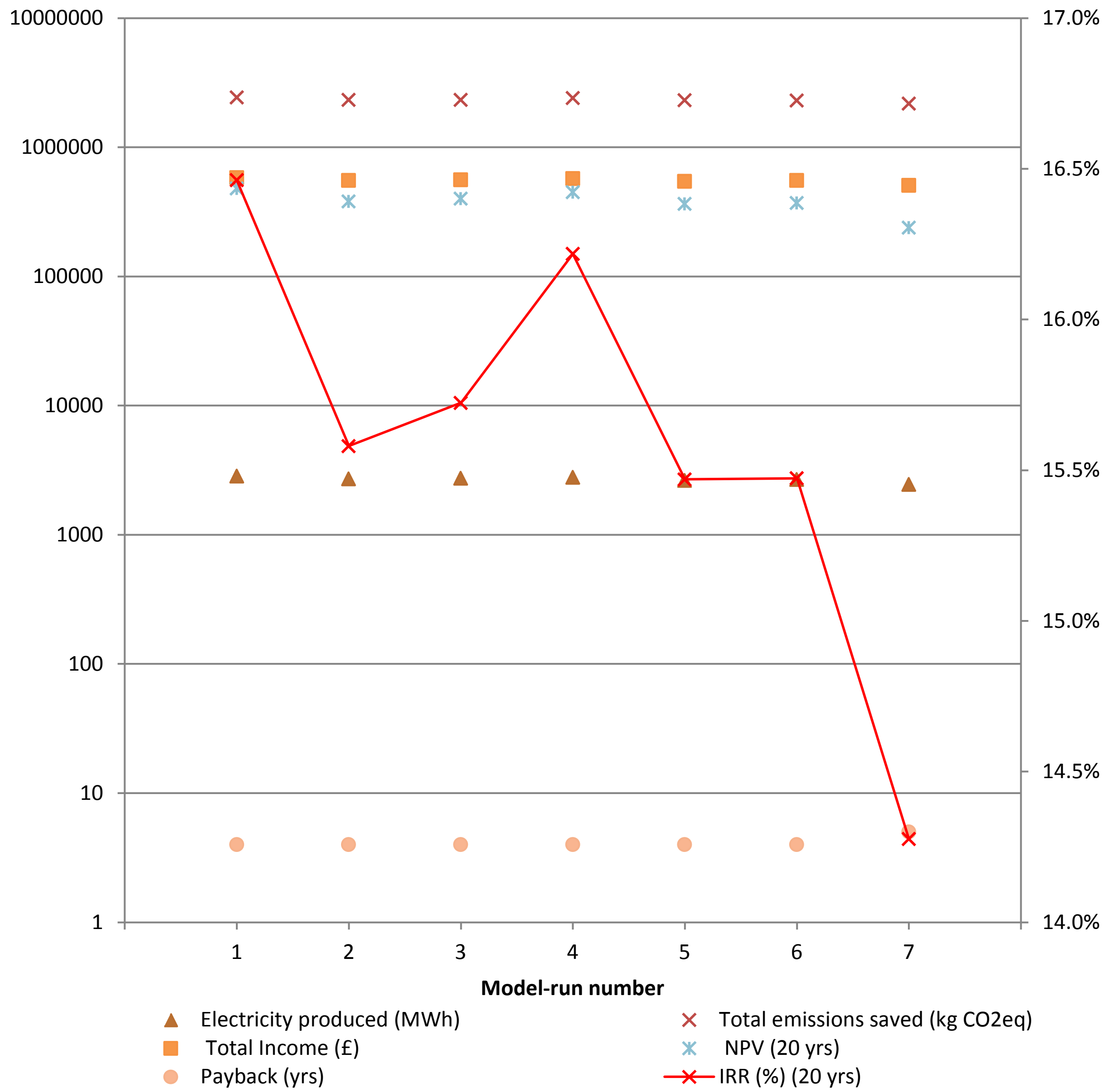


Figure 7-6 Seven national model-runs, based on a dairy herd of 560 cows, with the feedstock mixes displayed in Table 7-7

At the end of this stage, a series of environmentally and financially robust national model-runs had been developed for each of the 12 herd-size category means (excluding the smallest two pig herd sizes; see Table 7-8), and these were put forward to the regional analysis. However, analysis of available static feedstock in the three regions (see Table 7-8) highlighted the challenges in assessing the use of this technology at regional level when using national data (see Table 7-8). Initial investigations showed that some of the chosen national feedstock mixes would not meet the financial requirements proposed at the respective regional level. There were several reasons for this, the main two being:

- The mean herd sizes differed across the regions, particularly at the intensive farming level. This caused subtle differences in the requirements for mobile feedstock types that altered capital requirements, energy outputs and therefore financial viability.

- As suspected, the quantity of mobile feedstock types was considerably less, proportionally, than the quantity of static feedstock types, and these proportions differed across the three chosen regions. This meant that there were not enough mobile feedstock types to treat all the static feedstock types without the extensive use of crops grown specifically for AD. Feedstock mixes needed to be altered to take regional differences into account, so that as many of the static feedstock types as possible were treated within each region, whilst maintaining the overarching restrictions (see Section 7.2.1, last paragraph).

Therefore, a set of region-specific model-runs were developed for each of the three regions. The next section explains that only minor changes were required to the existing set of model-runs, as a result of the region-specific limitations. This represents the end of the bottom-up analysis mentioned at the start of this chapter; the top-down approach is described next.

7.3 REGIONAL MODEL-RUNS

Essentially, at this point, a series of individual AD facility scenarios had been developed that showed how, with the addition of a small quantity of supplementary mobile feedstock types, manures and slurries could be treated at different scales across England within a financially viable context. This section describes how the individual scenarios or model-runs developed in Section 7.2 were modified due to regional variations in herd sizes, and how the final model-runs were used to produce results necessary to answer the research objectives.

These regional variations were caused by different distribution patterns of livestock across the three regions, in addition to differing quantities of biowaste available. The impacts on the regional modelling are discussed next and explain why subtle changes needed to be made to the national model-runs to ensure that the scenario analysis remained robust.

7.3.1 Quantifying the mobile feedstock types in the three regions

These feedstock types included all poultry manure waste, crops grown specifically for the AD facility and biowaste. The quantity of available fowl manures (see Appendix 3, Tables A1.15a, b and c; A1.16a, b and c) was calculated from flock sizes provided by DEFRA (2013a), multiplied by the excreta values provided by DEFRA (2010a).

The quantities of different types of biowaste for each region were calculated, discussed (see Section 3.7.1) and presented in Table 3-9. Lastly, the land available for maize and grass, the two crops chosen for this study, specifically grown for energy generation, were only limited (in reality) by the quantity of available agricultural land in a region. However, for the purposes of this research, the aim was to minimise the use of agricultural land.

These data were used in conjunction with the regional livestock data provided by DEFRA (2013a), discussed in the next section, to produce the total available feedstock in the three chosen regions (as summarised in Tables 7-9, 7-10 and 7-11 below).

7.3.2 Changes in regional herd-size distribution

Quantities of mobile feedstock types developed from national mean herd-size categories (see Table 7-5) were placed in their regional mean herd-size categories and the model was run. However, results showed that many of the model-runs were no longer financially viable. Analysis of herd sizes at the regional level showed variations significant enough to cause these changes from the national means in some categories (see Appendix 3, Tables A1.12a, b and c; A1.13a, b and c; A1.14a, b and c).

It was apparent from an initial model-run that even small changes in herd-size numbers impacted on the financial viability of many of the model-runs, because of the additional capital requirements.

The negative impact occurred where there was an increase in mean livestock numbers from the national mean value. Each additional cow produces approximately 0.4 t (~0.4 m^3) extra slurry per week, or approximately 10 m^3 per cow (not including yard washings) per annum. It was previously established that the treatment of slurries and manures alone is not viable (within the scope of this research), and that supplementary mobile feedstock types are required to ensure financial viability. Small increases in the number of cattle can quickly impact on financial viability, as larger AD tanks are required, and possibly other capital too.

The issue did not arise often; however, there were several differences – for instance, the average herd size for the largest beef cattle category changes from 870 head nationally to 1,130 in the East of England (see Table 7-8). This would require a minimum increase in digester capacity of approximately 450 m^3, or approximately £50,000 investment costs. A more detailed look at the static feedstock distribution needed to be completed, in addition to a detailed assessment of the availability of the mobile feedstock types limited in quantity (poultry waste and biowaste), as opposed to those that can be grown on demand and are limited only by availability of land or competition with crops for food.

The top five (of six) herd-size categories for dairy and beef cattle and the top four (of six) herd-size categories for pigs (see Table 7-8) represented 79 per cent, 74 per cent and 75 per cent of the total regional dairy cattle populations; 85 per cent, 79 per cent and 82 per cent of the total regional beef cattle populations; and 92 per cent, 97 per cent and 93 per cent of the total regional pig populations of the South West, East of England and West Midlands respectively. Treating all of this static feedstock material, without some degree of impact on the existing activities of the agricultural community, as previously demonstrated (see Section 7.2.4.2.1), would pose a considerable challenge.

Table 7-8 Mean herd sizes of defined categories for three English regions

	Mean herd sizes for each defined category			
Dairy herd size categories	**National**	**South West of England**	**East of England**	**West Midlands**
700+	870	870	0	0
500–699	570	575	0	565
350–499	400	412	365	460
200–349	250	255	245	260
100–199	140	140	140	140
Beef herd size categories	**National**	**South West of England**	**East of England**	**West Midlands**
700+	900	985	1130	895
500–699	580	580	570	585
350–499	410	415	415	410
200–349	260	265	260	265
100–199	140	145	140	145
Pig herd size categories	**National**	**South West of England**	**East of England**	**West Midlands**
1000+	2653	2560	2630	2200
500–999	731	725	753	745
300–499	392	400	400	400
150–299	221	206	216	218

Whilst assessing the distribution of the static feedstock types for the three chosen regions, it was deemed prudent to quantify the available biowaste and other classified mobile feedstock types in each region, in order to ascertain how much of the static feedstock could be treated without impacting too greatly on the normal farming activities of a region or its neighbours. The next section describes how this was completed.

7.3.3 Total available non-crop regional feedstock

The regional differences in livestock numbers and available feedstock types become apparent immediately: the East of England has by far the greater pig and poultry farming community; whilst the South West of England houses the largest beef and dairy herds by several hundred thousand.

Indeed, the scale of treating the static feedstock types with the potentially available mobile feedstock types is clearly challenging. The livestock waste is the expected waste collected whilst the cattle are present in the farmyard or housed over the winter period and whilst being milked (dairy herds only). The length of time the animals are housed depends on many factors, including the size of the herd (intensity of production) and a farmer’s individual animal husbandry practices; but for the smaller herds, the predominant factors are the weather pattern of the region and any annual changes in weather patterns. It is clear from the regional data displayed below (Tables 7-9, 7-10 and 7-11) that not all the static feedstock types could be treated by the non-crop feedstock types available in that region alone, and that some assistance would be needed from crops specifically grown for generating energy.

The East of England represents the best opportunity to treat the majority of its static feedstock (3,026,348 t), due to the high proportion of poultry and biowaste (2,227,419 t) available to the static feedstock.

Table 7-9 Available non-crop feedstock types in the East of England

EAST OF ENGLAND				
	Numbers	Total excreta production	As slurry (92.5%)	As manure (7.5%)
Dairy cows	20,477	190,925	176,606	12,028
Beef cattle	209,877	1,163,557	1,076,291	73,304
Pigs	1,032,016	1,671,866	1,546,476	105,328
Poultry – layers	4,144,257	163,118		
Poultry – broilers	20,294,696	453,789		
HH, C&I + biowaste		1,610,512		
	TOTAL	**5,253,768**		

Note: An approximate split between the slurries and manures produced is shown on the right of each table. It is assumed that of the total quantity of excreta produced, 92.5% will be classified as pure slurry, whilst the remaining 7.5% will have straw and some feed mixed in and will be classified as manure (Davies, 2013). Other livestock, pigs and poultry etc. is based on the quantity input, since the model does not make the same calculation.

The South West of England, on the contrary, produces significantly greater quantities of static feedstock types (11,636,606 t) than mobile feedstock types (1,968,549 t). This does not mean that there is no potential for AD in the South West of England, as will be demonstrated in Sections 8.2 and 8.3; however, it does suggest that there are fewer opportunities to mitigate the on-farm GHG emissions, due to the sheer number of livestock herds in the region.

Table 7-10 Available non-crop feedstock types in the South West of England

South West of England				
	Numbers	Total excreta production	As slurry (92.5%)	As manure (7.5%)
Dairy cows	434,428	3,182,620	2,943,923	200,505
Beef cattle	1,797,018	7,827,809	7,240,724	493,152
Pigs	386,529	626,177	579,214	39,449
Poultry – layers	6,936,374	273,016		
Poultry – broilers	11,470,001	256,469		
HH, C&I + biowaste		1,439,064		
	TOTAL	**13,605,155**		

A similar challenge exists in the West Midlands, with 5,286,961 t of static feedstock being produced in comparison to 2,020,251 t of mobile feedstock types. However, there is still considerable potential for AD to play an important role in both of these regions, in terms of waste management, GHG mitigation and energy generation.

Table 7-11 Available non-crop feedstock types in the West Midlands

West Midlands				
	Numbers	Total excreta production	As slurry (92.5%)	As manure (7.5%)
Dairy cows	169,071	1,351,218	1,249,877	85,127
Beef cattle	763,851	3,629,822	3,357,585	228,679
Pigs	188,840	305,921	282,977	19,273
Poultry – layers	5,060,393	199,177		
Poultry – broilers	12,438,166	278,117		
HH, C&I + biowaste		1,542,957		
	TOTAL	**7,307,212**		

Some of the final regional model-run feedstock configurations were governed, to a degree, by the available quantities of mobile feedstock in the region. This did not mean that these new model-runs were any less robust than the model-runs developed previously, but that small changes to the various quantities of feedstock, particularly the reduction in biowaste materials, would require an increase in the use of crops, would introduce pressure on using land to grow food and would challenge the financial viability of the AD facility. The baseline model-runs had fixed parameters (see Table 7-4) and were tested rigorously against externalities during the sensitivity analysis, discussed next.

Tables A1.20, A1.21 and A1.22 (see Appendix 5) set out the final mix of feedstock types (blue columns) used in modelling scenario two, the hub-and-pod concept. Each mean herd-size category was divided in two, in order that half the number of herds were treated with poultry layer waste and the other half with poultry broiler waste material.

7.4 SENSITIVITY ANALYSIS

Sensitivity analysis was completed on a number of variables against the final set of baseline regional model-runs. The aim was to assess how changes to these variables impacted on the financial viability and environmental robustness of the model-run, and therefore the scenarios as a whole.

The variables scrutinised, and the changes made to them (see Table 7-12), were predominantly to test the model-runs under different types of financial stress. Other variables changed, which also had a financial implication, were predominantly altered to examine a model-run's environmental credentials. They relate to distance travelled for feedstock and digestate, the percentage of heat exported, and the impact on carbon emissions (from transport) and carbon savings (from the increase in use of energy generated).

Only a few sensitivity model-runs included multiple changes made to the model. These related mainly to certain operating conditions, particularly whilst applying or testing the robustness of the hub-and-pod concept. It was not within the scope of this research to challenge every potential external impact. The results of the sensitivity analysis are discussed below.

The following sections discuss the average impact from altering the variables (see Table 7-12) on regional model-runs for the East of England, calculated from the aggregated outputs from each herd-size categories (see Table 7-8). The rationale behind choosing just one region to complete the sensitivity analysis was that the changes made in a sensitivity analysis are not region-specific, but would have equal weight across England. For example, changes to inflation, interest rates and FIT values would be national in their effect, since they are set by central government.

The exception to this rationale occurred when altering feedstock values. Here, discussion is provided on the impacts to feedstock price changes for each of the regions, as the feedstock mix for the different mean herd-size categories was different across each region. Feedstock values, particularly those traded on the national or international market, would also be relatively homogeneous across the country; however, the gate fee received for biowaste material varies considerably, and is dependent on the distance the material needs to travel and the quality of material that is received – for example, biowaste material that is highly contaminated and has not been separated at source commands a higher value than material that is more pure, free from metal, plastics and the like. Twenty-six different variables (see Table 7-12) were tested individually to assess the impact they had on the environmental and economic performance of AD.

The sensitivity model-runs were completed on the regional model-runs for the East of England. They are based on biowaste materials being received on-site that have first been processed at a central hub. This negated the requirement for a large reception hall and other ancillary equipment, and removed £450,000 costs for the reception building and a further £158,500 for the decontaminating equipment that would have been required. This is the approximate cost of equipment needed to treat up to around 15,000 t biowaste per annum, or an AD facility with a 500 kWe CHP genset.

Analysis and comparisons were made against the two other regions, since they had slightly different mixes in feedstock due to the different availabilities across the three regions. These are highlighted where there were significant differences in outputs to those of the East of England. These relate to the economic viability rather then the environmental GHG emissions savings, since the latter are a function of the quantity of feedstock used and the energy generated.

Table 7-12 Changes to variables made during sensitivity analysis

Variable	Original value	Value 2	Value 3	Value 4	Value 5
Layer manure value	£10	£0	£5	£15	
Broiler manure value	£10	£0	£5	£15	
Grass silage value	£20	£16	£18	£22	£24
Maize silage value	£30	£27	£33	£36	
Biowaste value	£20	-£10	£0	£30	
Biowaste import distance (miles)	10	5	15	25	50
Digestate export distance (miles)	4	8	12	25	
Engine electrical efficiency	39%	35%	37%	41%	
Discount rate	12%	8%	10%	15%	
Hours of generation per annum	This has no effect on the quantity of energy generated. It might affect the FIT applicable to the facility or provide a longer downtime for maintenance.				
Cost of diesel fuel	£1.40	£1.20	£1.60	£1.80	
Region	UK average	Region-dependent			
Reception building*	£0	£450,000			
Grant value*	£0	£158,500			
Tax rate	17%	19%	22%	25%	
Inflation rate	2.5%	3.5%	4.5%	5.5%	
Interest rate over base (0.5%)	5.5%	4%	7.5%	9%	
Percentage of debt	80%	60%	70%		
Total labour costs*	£15,000	£25,000			
% heat utilised external to the AD process	10%	0%	20%	30%	
FIT <250 kWh	15.16p	14.40p	13.68p	13.00p	
FIT 251–500 kWh	14.02p	13.32p	12.85p	11.99p	
FIT >500 kWh	9.24p	8.78p	8.43p	8.02p	
RHI <200 kWh	7.10p	9.10p	8.70p	7.10p	
No heat or digestate value	The removal of the financial value of the heat and digestate				
All capital costs for biowaste treatment	In addition to the £450k cost for reception hall and peripherals, the reinstatement of the £158k capital costs and higher staff costs as above.				

Note: * The capital costs are removed and labour costs fixed when modelling the hub-and-pod concept.

7.4.1 Changes to feedstock value

All changes to feedstock values impact heavily on the NPV on the different model-runs for the East of England (see Figure 7-7), based on a discount rate of 12 per cent; however, no model-run with an increase in the cost of poultry waste, grass and maize silage caused a project to be unviable, since the NPV does not drop below £165,000 (poultry layer manure, £15 per tonne).

To the contrary, changing the value of biowaste feedstock has a significant impact on NPV. As the value of the gate fee to the treatment facility falls, the NPV falls proportionately. The NPV of a project turns negative before the value of biowaste reaches zero. Therefore, it would be highly unlikely if any facility, based on this concept and the parameters set, would be built if it could not secure long-term biowaste feedstock with a gate fee of less than £7.00.

In the West Midlands, a biowaste value of £10 turns the NPV of two of the model-runs negative, and two more have NPVs that are too low to encourage an investment project like this to proceed, based on a 12 per cent discount rate. With a zero value, only one model-run would proceed to development; the others would fail at the feasibility stage. In the South West of England, as there is so little biowaste material available to treat the significantly large quantity of static feedstock types, the results are even more pronounced. Potentially, no model-runs would proceed below the £20 per tonne value of biowaste, *certeris paribus*. This makes the South West particularly vulnerable to small changes in feedstock prices and economic externalities.

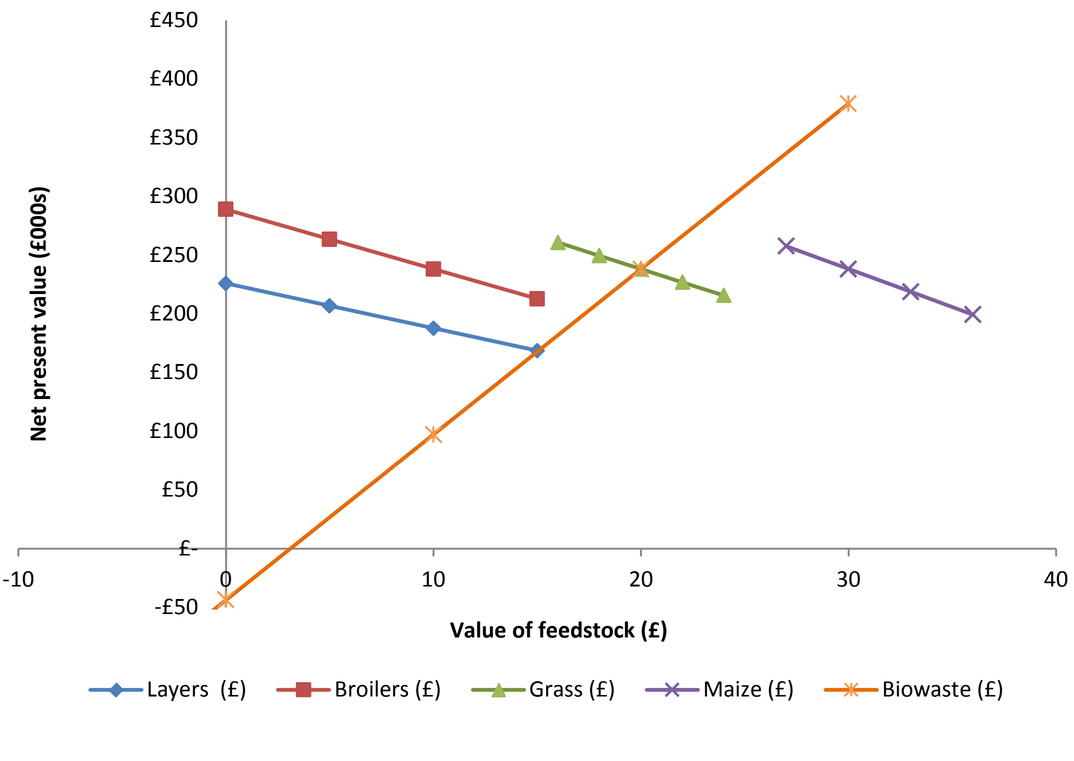


Figure 7-7 Impacts on average NPV as the cost of feedstock changes

This demonstrates the importance of the income stream of this feedstock type, as well as the energy content. It would also mean that should this type of conceptual model be adopted across England, the facilities would need to be protected from market forces to ensure that there was a minimum value of biowaste materials.

Three model-runs in the South West were particularly vulnerable to the high prices in chicken manure (broiler and layer) and maize, whilst only one model-run in the West Midlands returned a negative NPV with the high value of chicken layer litter.

7.4.2 Changes in biowaste feedstock transport distances

The transport of biowaste materials was modelled at five different distances (5, 10, 15, 25 and 50 miles) from an MRF to the AD facility. The collection of the biowaste to an MRF was fixed (see Section 5.3.1) and had no impact on the IRR or NPV of the model-runs. The impact on the annual GHG emissions was also small for these model-runs (see Figure 7-8). This was thought to be due to the small quantity of biowaste feedstock utilised within each model-run, and the relatively small distances travelled. However, if these emissions were aggregated across the whole region, or whilst assessing extremely large individual municipal facilities of 80,000 t or more (which would require a large catchment area to service such a large quantity), this would have a greater impact on GHG savings at regional or national level when calculating transport emissions, both in terms of the distance from where the feedstock originates and the distance to where the digestate needs to be exported.

The total GHG emissions saved ($kgCO_{2eq}.MWh^{-1}$ or $kgCO_{2eq}.t^{-1}$) by altering the distance travelled by the feedstock is shown below (see Figure 7-8). An increase in the distance travelled from 5 miles to 50 miles has the effect of increasing GHG emissions by approximately 4 $kgCO_{2e}.MW^{-1}$, or 0.9 $kgCO_{2e}.t^{-1}$ treated, or 20,700 $MgCO_{2eq}.a^{-1}$, if moving the full 23 Mt available across England the additional distance.

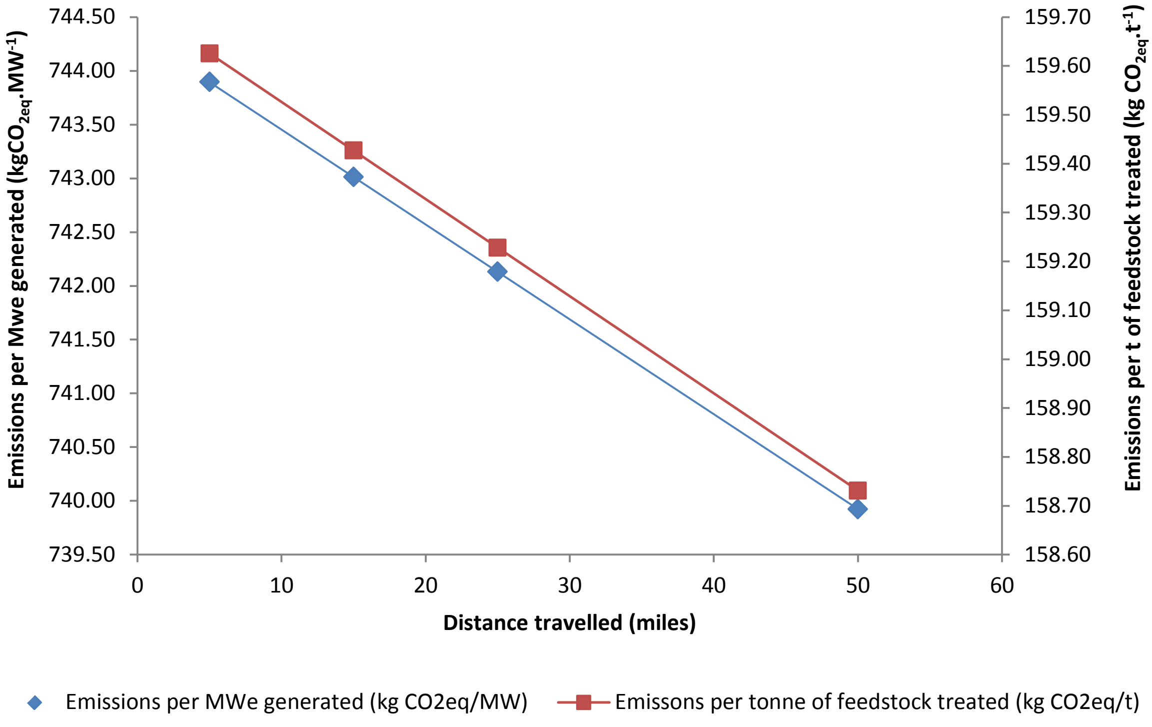


Figure 7-8 Average (total) GHG emissions saved as biowaste travel distance increases

The greatest impact occurs if significant quantities of feedstock travel long distances, which is more the case when supplying large central digesters that require a wide catchment area. If this business model is considered, the impact is magnified by the requirement to export the digestate material long distances to find land that would not be over-burdened by the nutrient-rich material.

7.4.3 Changes in digestate transport distances

Similar to the transport of feedstock, the GHG emission trends for transporting digestate are linear. However, since it is assumed that agricultural vehicles (tractors) would be responsible for the transport of the digestate off-site, and that these vehicles are less fuel-efficient than large bulk carriers or trucks, there is a greater decline in GHG savings as the digestate travels further (see Figure 7-9). This is highlighted by the increase in slope as distance increases.

An increase in distance travelled by the digestate from 8 miles to 25 miles increases GHG emissions by approximately 13 $kgCO_{2eq}.MW^{-1}$, or 2.75 $kgCO_{2eq}.t^{-1}$ feedstock treated. In terms of $kgCO_{2eq}.t^{-1}$, the transport is different. Material received at the facility is assumed to be delivered by a truck with fuel consumption of 4.5 mpg, whilst the digestate is removed with a tractor with fuel consumption of 3.2 mpg.

In terms of economic impact, it is assumed that the AD facility operator will be responsible for the transport costs of removing the digestate from the facility. All but the longest distances remain viable in the West Midlands; at the 25-mile export distance, seven of the 11 scenario model-runs fail to remain financially viable, based on the 12 per cent discount rate. At the 25-mile export distance, one facility in the East of England and six in the South West fail to be viable. It is important that the vast majority of digestate can be spread to the farmer's own land, or land available as close to the facility as possible, when considering constructing an AD facility and maintaining its continued financial viability.

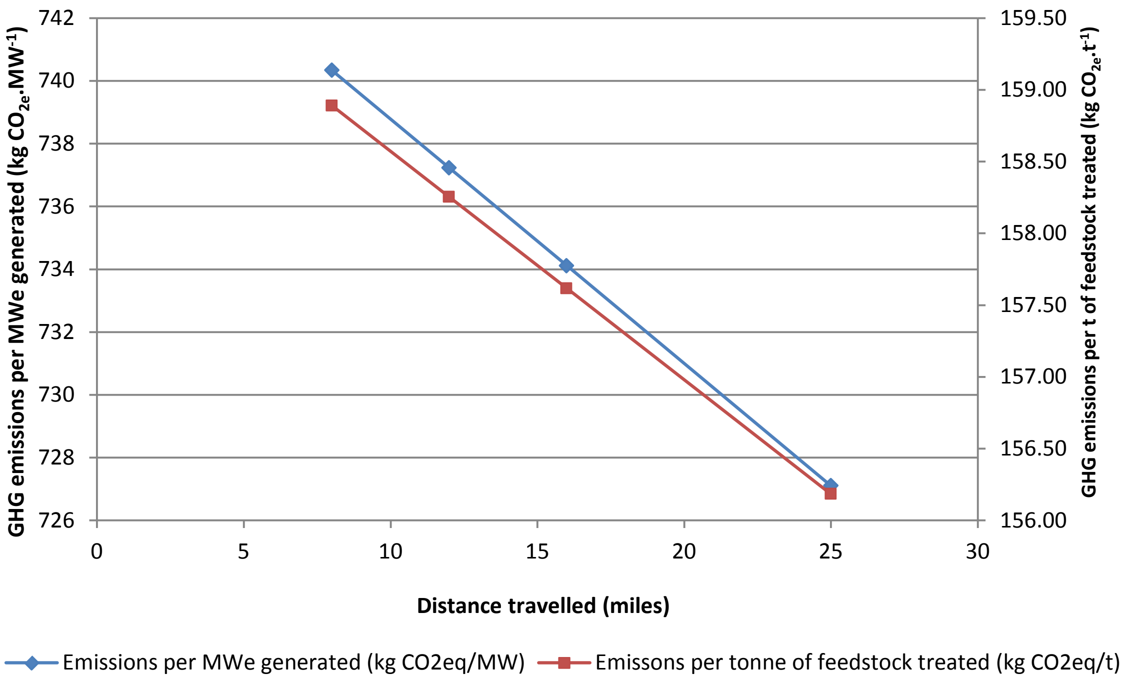


Figure 7-9 Average (total) GHG emissions saved as digestate travel distance changes

The implications of this regionally or nationally would most likely be seen only if large central digesters were predominantly built. If a system of local treatment facilities was set up, in which the quantity of digestate produced could be spread on the facility's farm land, with only small amounts transported locally, the impact from transport would be reduced.

7.4.4 Changes to electrical-generating efficiency

Improved generating efficiency only occurs when purchasing a CHP genset that is more efficient than another. Reduced generating efficiency occurs when there is not enough biogas to fuel the genset at its optimal level, causing stress to the engine. At some point, the engine will stall and fail to generate energy.

In terms of modelling the electrical conversion efficiency of one CHP genset over another, the impact on model-runs can be considerable, as regards their financial viability. The average IRR changed from 14 per cent to 16 per cent when an engine's efficiency rose from 35 per cent to 41 per cent (see Figure 7-10). The same efficiency changes observed a 62 per cent increase in NPV. One model-run was the complete reverse (NPV £130,775.10 to -£1,719,062.67), which was explained by the trigger point being met (400 kW engine) in the model, when a larger and more expensive engine is selected, causing a drop in the financial outputs. It is probably this trigger point that is responsible for the some of the observations below, particularly in model-runs C140 and D245 (FIT trigger point), and P753 (generating trigger point).

The model is unable to distinguish between engine conversion efficiency and engine requirement based on the number of annual operating hours. This kind of impact has already been discussed and is an anomaly to be aware of when using the ADEE model. Two model-runs that had negative NPVs at 35 per cent engine efficiency had in excess of sixfold increases in NPV at 41 per cent engine efficiency. However, there remains a strong caveat that the model does not account for any increase in costs from an increase in efficiency (i.e. the model assumes that all CHP gensets of a particular generating capacity range are of equal value, regardless of their conversion efficiency rating). Baseline model-run costs were based on known gensets that operated at 39 per cent electrical energy efficiency.

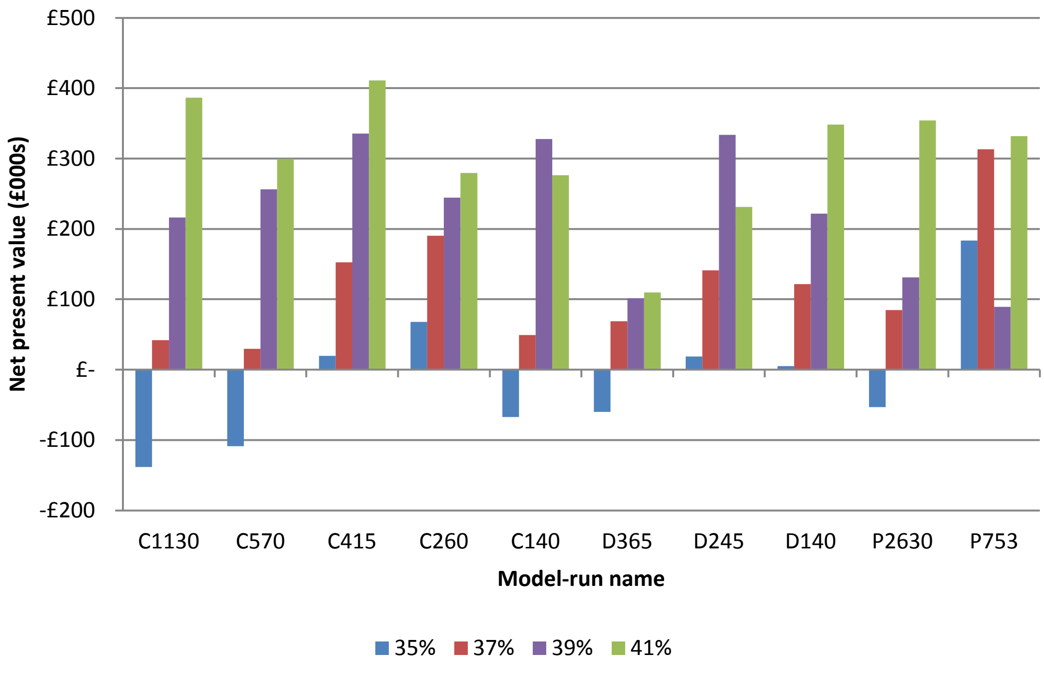


Figure 7-10 Impact on NPV as CHP genset electrical conversion efficiency changes

In terms of the environmental impacts from increased conversion efficiency, as might be expected, the quantity of GHG mitigation (saved) per MWh generated decreased (since only the quantity of energy generated has increased, but the quantity of GHGs mitigated has remained the same), whilst GHG mitigation per tonne of material digested increased (as the quantity of GHG emissions mitigated from renewable energy increases from the same quantity of material treated).

7.4.5 Changes to transport fuel costs

Transport costs had relatively little impact on the NPV. The majority of transport costs occur for biowaste during collection to the MRF. When growing crops specifically for energy, the various different farming activities in growing these crops incur the greatest fuel use. However, the greatest use of fuel is for the export of digestate (if that is required), particularly in large, centralised biowaste AD facilities, or when a large quantity of feedstock is imported to the treatment facility and there is little available land to which to spread the digestate.

7.4.6 Changes to the discount rate

Changing the discount rate only affects the NPV of the model-run (or project). The discount rate is the rate of return (or interest rate) required from future cash flows at present-day values for the investment made. Therefore, the lower the discount rate, the greater the present-day value of the investment at the end of the project term (see Figure 7-11). A change in this variable only demonstrates that if the investor is prepared to accept a lower return for his investment, the value of the project is greater at the end of its lifetime. The way in which the discount is calculated is described in Section 3.4.1.2.

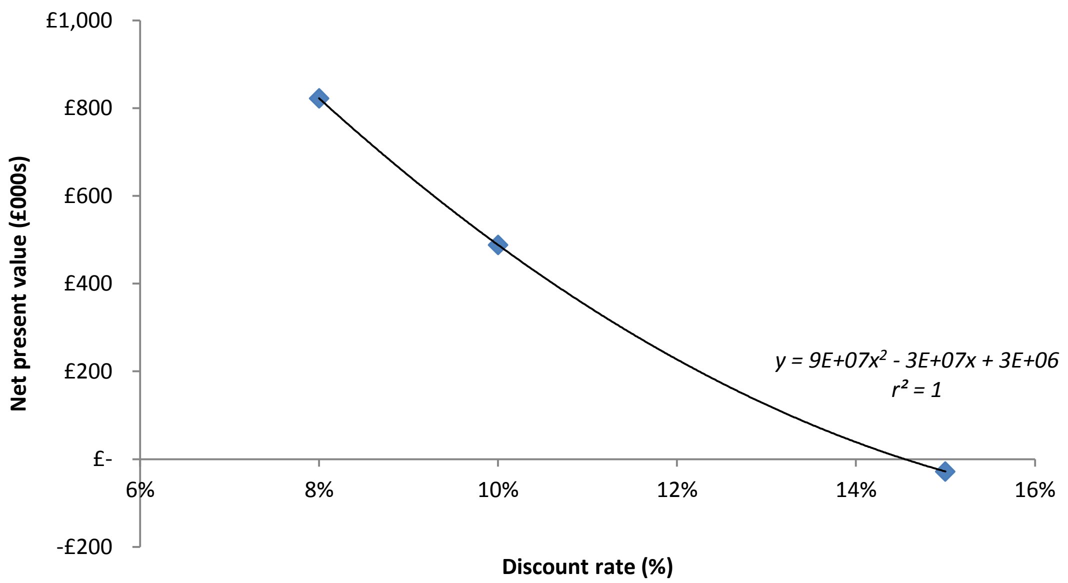


Figure 7-11 Impact on NPV as a result of changes to the discount rate of a given investment project (model-run)

Mistry *et al*. (2011a) chose to use a discount rate of 15 per cent for AD facilities accepting 85 per cent or more biowaste material, but only a positive discount rate (i.e. >0 per cent) for all other AD facility types. However, it was felt that this was optimistic. Farmers are businessmen and understand the value of risk; when using consultants, they would be advised of the kind of return on their investment that should be required – hence the use of a 12 per cent discount rate. The graph above (see Figure 7-11) demonstrates that in requiring a return of 15 per cent, the hub-and-pod configuration would not occur in England, since the NPV turns negative at about 14.5 per cent (discount rate); however, at 12 per cent, support for this kind of investment would potentially be very strong within the agricultural community.

Without getting into current macroeconomic policy, it could be argued that the discount rate should be either higher or lower. An investment fund manager would require more return from his capital, stating that not only are the risks of the technology high, but that the economic background and potential changes to FITs are too great to accept a low discount rate. Conversely, with interests rates so low, and with potential deflationary pressures currently in the background, a technology user-investor might say that the opportunity to obtain funds at the lowest historical long-term interest rates, and to achieve even an 8 per cent net return, would be very attractive. This leaves considerable latitude in the argument over which discount rate is correct or reasonable.

7.4.7 Changes to tax, interest and inflation rates

Tax and interest rates had a contrasting effect to the inflation rate on the model-runs (see Figure 7-12). The impact of increasing inflation had a significant positive effect on NPV. This is a result of the FIT being index-linked. History shows that wage inflation does not keep up with the RPI to which the FIT is tracked. At the time of writing, deflationary pressures in the economy, accentuated by the Bank of England printing money and maintaining low interest rates, is creating underlying inflation in some sectors of the economy, whilst having a negative impact on overall current inflation measured by the RPI. Whilst the average impact from a change to either the interest rate or the tax rate is significant (64 per cent reduction for a 5 per cent increase in the interest rate, and 49 per cent reduction for a 6 per cent increase in the tax rate), smaller changes to the inflation rate (2 per cent increase) have a far greater impact on the average NPV of the project (96 per cent increase). This is a result of the FIT being index-linked.

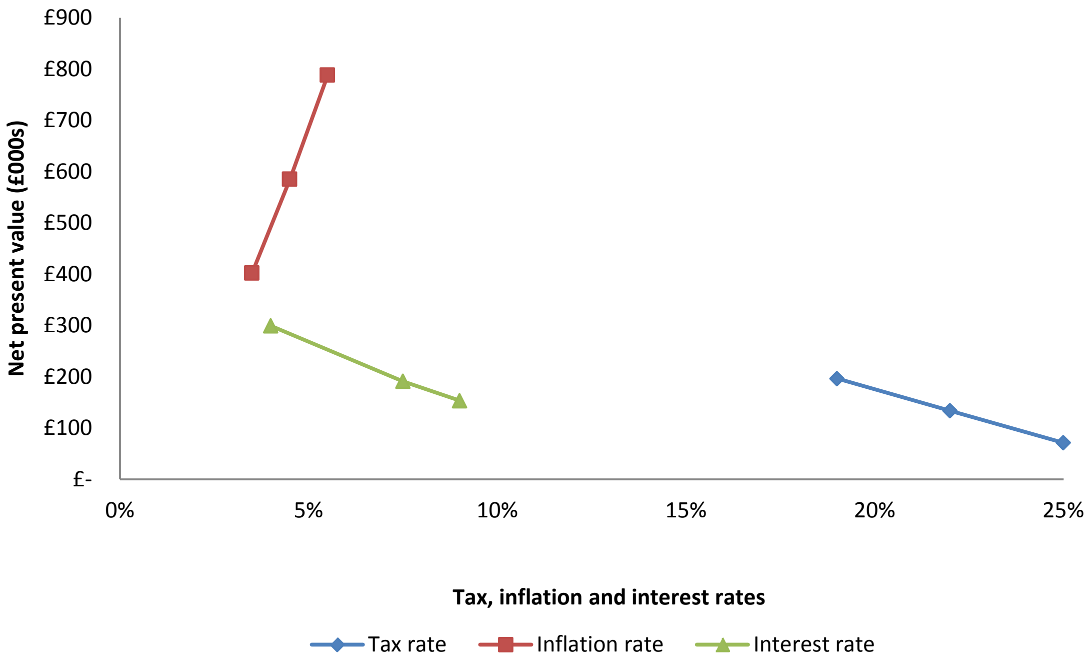


Figure 7-12 Impacts on NPV following changes to tax, interest and inflation rates

The current economic environment (2010–14), with interest rates at their historical lowest and inflation rates slowly rising, coupled with index-linked returns from renewable investments, should have provided the ideal platform for significant interest and investment in AD in the UK. Interest in AD new builds is high (in the 12 months to August 2013, planning had been granted for over 200 AD facilities; DEFRA, 2013e); however, this does not seem to be translating into new build projects. This may be a result of projects not being able to gain funding, or that in April (2014) the government confirmed the start of the FIT degression for the lowest two FIT brackets when the current target point is achieved.

7.4.8 Changes to the quantity of heat utilised on site or exported

When designing the AD facility, many AD users do not consider using the 'waste' heat generated by the CHP genset beyond offsetting the heat requirement of the digester to ensure the biota are kept at the optimal temperature. However, utilising the excess heat over and above the parasitic requirement of the digester has a significant impact on both GHG mitigation (see Figure 7-13) and income.

One of the case studies had a significant local heat-load which they took advantage of. The heat energy produced from the CHP genset was recycled several times, so that, in theory, they were using in excess of 100 per cent of the usable heat generated. In reality, it is only possible to utilise approximately 80 per cent of the total heat generated by the CHP genset, before it influences the efficiency of the engine; but if the usable heat has been captured from the genset, it can be used in several processes. All the regional baseline model-runs utilise 10 per cent of the heat produced, over and above the digester and peripheral capital requirements. The effects of not using that 10 per cent are discussed in Section 7.4.10 below.

The amount of available waste heat is proportional to the size of the CHP genset. A smaller genset will have a smaller (<100 kW) heat output, and most of this will be required to heat the AD process. Larger facilities (>250 kW) will have more available heat, and a genset of approximately 500 kW can have a significant impact on the heat-load of commercial installations, potentially saving thousands of tonnes of GHG emissions and thousands of pounds per annum – should there be a local requirement.

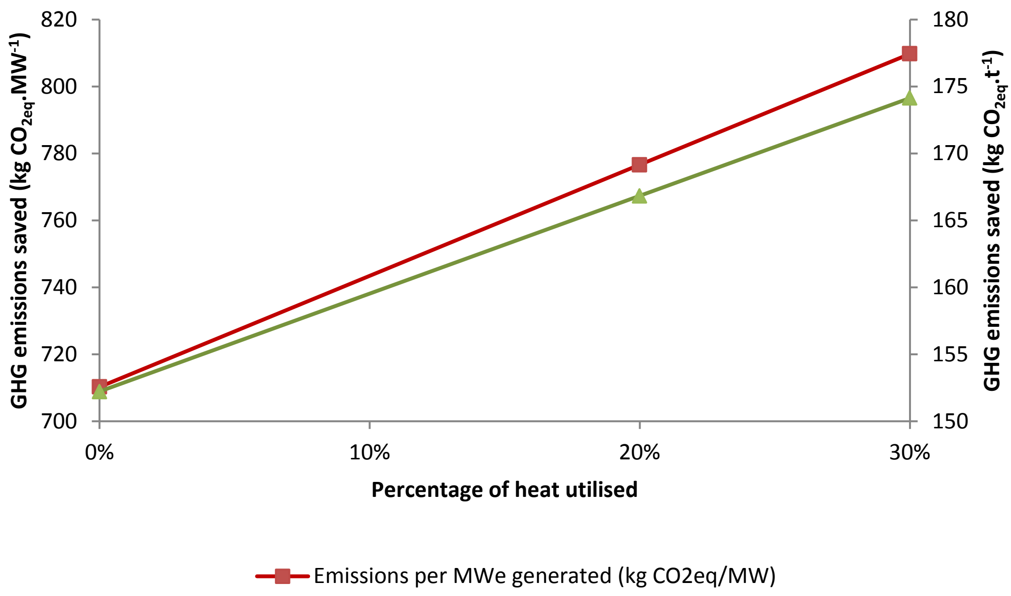


Figure 7-13 Impacts on average GHG emissions saved in utilising waste heat from CHP engines

Economically (see Figure 7-14), the benefit of using just 30 per cent of the waste heat generated (as opposed to no heat at all) increased the NPV of the project by approximately 100 per cent, on average (from £207,886.37 to £419,965.42). It also improved GHG savings by approximately 100 kg $CO_{2eq}.MWh^{-1}$, or 22 kg $CO_{2eq}.t^{-1}$ treated, equivalent to roughly 14 per cent improvement from a zero baseline. This research has assumed that an individual end-user of the technology has utilised 10 per cent of the waste heat energy, either for washing down the farmyard and dairy units, or for heating the farmhouse and other buildings where it would be cost-effective.

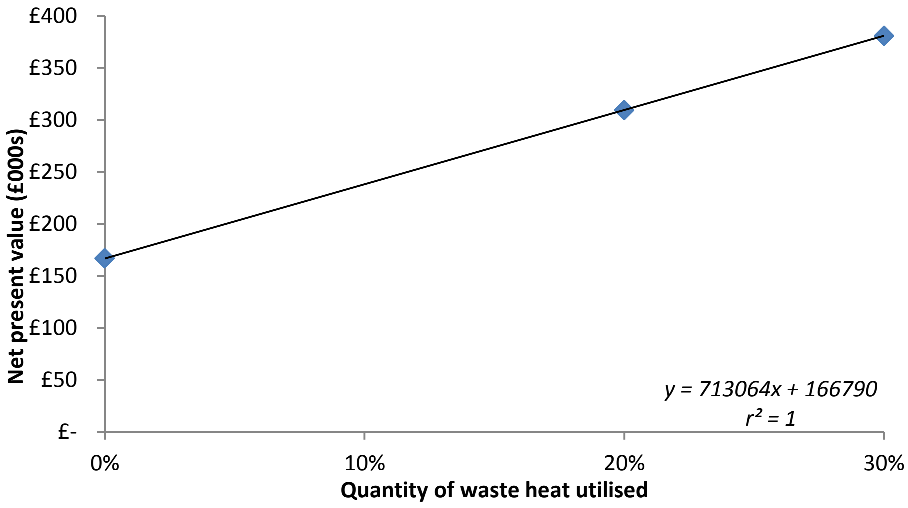


Figure 7-14 The impact on the mean NPV of using greater quantities of heat from the CHP genset

7.4.9 Changes to the Feed-in Tariff

There will be many future changes to the incentives provided to renewable energy generation, including AD. The government has confirmed that, effective from April 2014, when the generating capacity trigger point is achieved at some point this year, a 20 per cent reduction (known as degression) in the FIT of the two lowest categories will be implemented on new projects. This type of change is frequently embedded within policy when supporting new technologies, as it is assumed that the cost of technology reduces as demand increases and a number of new suppliers enter a market. Policy review periods are often put in place to ensure that the timing and magnitude of the change is correct.

The impact of these tariff changes on the model-runs (see Figure 7-15) demonstrates that a number of model-runs remain viable. Closer analysis shows that when the first degression occurs, no further AD facilities would be built treating the highest two and the lowest beef cattle herd-size categories, or the highest dairy and pig herd-size categories. Only the lowest pig herd-size category is likely to go ahead when the second round of FIT degression comes into effect. This essentially means the end of mid-sized AD facilities being built in England with the hub-and-pod configuration. Discussion of the impacts caused by this FIT plan continues in Section 8.5.

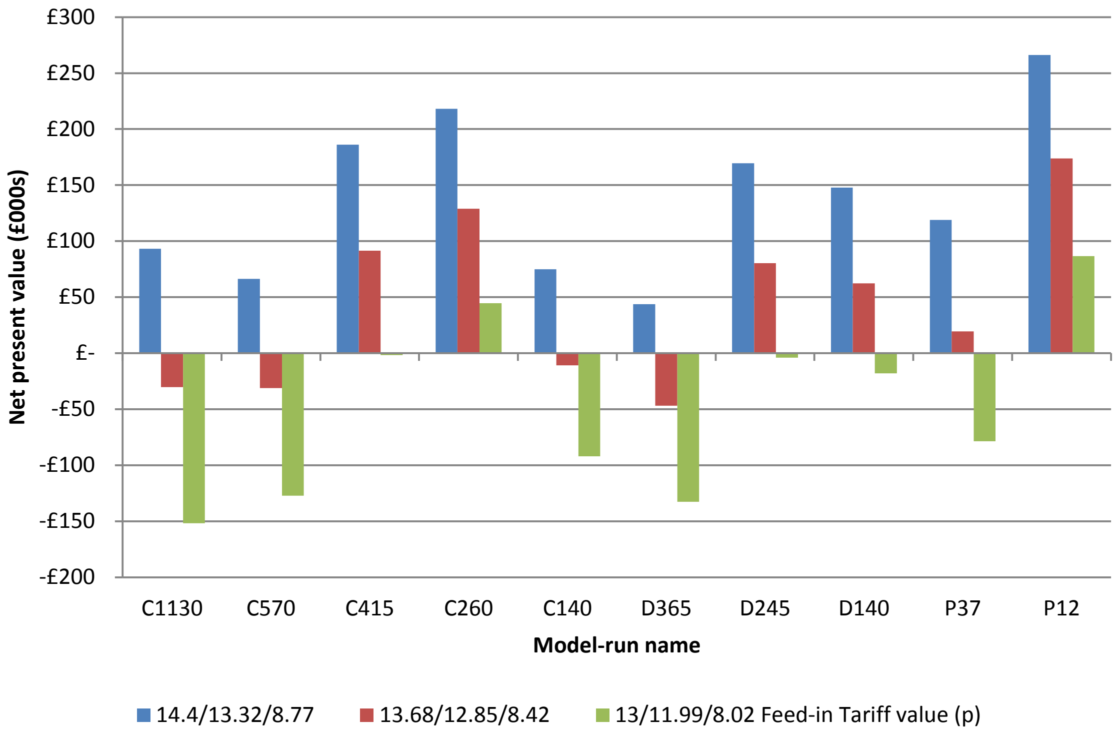


Figure 7-15 The impact on NPV of the Feed-in Tariff degression

7.4.10 Removing the value of heat and digestate, or hub-and-pod benefits

Currently, external investors (including banks lending finance) do not account for the value of heat and digestate within their financial appraisal, since it does not provide an income stream, but merely offsets costs to the existing business. This will differ if the heat is sold to local businesses or houses, and if the digestate is sold on. Financial lenders are cautious when they feel they are lending for efficiency gains rather than purely adding value. Lenders would also be cautious about the value of the digestate, since the mix of feedstock can change throughout the year. This could impact on the nutrient quality of the digestate, and therefore its nutrient value to others. Other decision criteria might include the manner in which the investor has been advised to structure or secure the debt, but this detail is outside the scope of this research.

This research has assumed that debt is internalised and held within the existing agricultural business. Therefore, it should be reasonable to include the value of heat and digestate in the project appraisal, as both impact on the existing bottom line of overall business profitability. This can be achieved by offsetting such business costs as energy to heat buildings, dairies and grain dryers, or the purchase of fertilisers.

The introduction of the hub-and-pod concept allows for the treatment of large quantities of low-energy waste feedstock types, without impacting on the overall farming strategy of land use for food. In removing the requirement to install expensive specialist treatment equipment and facilities on site, but to 'share' these costs with other 'pods', the AD facilities are provided with an opportunity to reduce their on-farm GHG emissions, generate a valuable local heat and electrical energy source, and find a mechanism by which they can manage their on-farm nutrient bank. Without this conceptual model, additional on-farm treatment facilities are required, and on-farm waste feedstock requires a considerable increase in supplementary feedstock types to become viable.

The impacts on the NPV (discount rate of 12 per cent) of removing the value of heat and digestate or the hub-and-pod benefits are considerable (see Figure 7-16). Of the baseline model-runs – that is the original optimised financially viable model-run developed in Section 7.3 (blue columns in Figure 7-16, below) – not one remains viable when either benefit is removed. Whilst the impact of removing the value of heat and digestate is serious, these facilities might become viable with larger quantities of feedstock used. The impact is far less significant than the additional capital required to treat this quantity of feedstock. No model-run would advance to the planning stage, since there would be no chance of economic viability at these levels. Any AD facilities developed would not include the treatment of their on-farm waste materials, since they would take up volume that could be used by high energy- and income-yielding feedstock types.

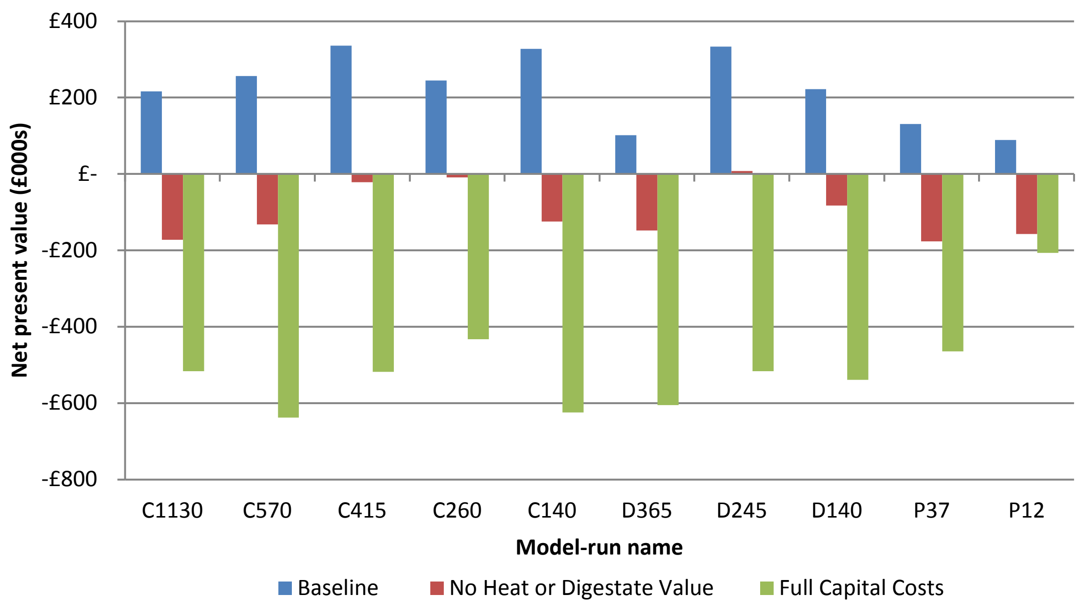


Figure 7-16 The impact on the NPV of withdrawing the value of heat and digestate (red column), or the infrastructural benefits provided by the hub-and-pod concept (green column)

7.5 DISCUSSION

Several points can be made from the analyses in this chapter:

- Under the current incentive schemes (January 2014), AD is financially viable in England across a number of different model-runs.
- The environmental benefits of using crops grown specifically for energy reduces more sharply as the quantity required increases (see Figure 7-1), compared to other feedstock types.
- Relatively small changes in herd-size numbers can have a significant impact on financial viability or, more importantly, the quantity of supplementary feedstock required (see Section 7.3.2).
- Grass is not the best possible option as a single supplementary feedstock type and should be mixed with other crops, as significantly more grass (t) is required than maize (see Table 7.6).
- The inclusion of single crops (specifically grown for energy) requires a minimum of 4,000 t (100 ha) of maize in most model-runs, and considerably more grass – impacting on existing farming activities (see Section 7.2.4.2.1).
- The quantities of available mobile feedstock in all regions is not sufficient to supplement all the cattle and pig slurries and manure in those regions (see Tables 7-9, 7-10 and 7-11)
- Whilst the impact of distance on an individual facility from GHG emissions from the transport of feedstock and digestate does not appear to be significant because of the small quantities involved (see Figures 7-8 and 7-9), the combined impact at a regional or national scale could be.
- Investing in the most efficient energy conversion engines has a significant impact on the financial viability of an AD facility (see Figure 7-10)

These analyses have also demonstrated the importance of using and including heat energy and digestate in the feasibility calculations, and have highlighted the case for developing on-farm AD. There are fundamental benefits to the environmental argument of providing an on-farm heat source, particularly if there are other local heat loads from residential or commercial sources (dairy or greenhouses, etc.). Economically, both have value to the overall business that should not be ignored when assessing the viability of investing in AD. This assessment does depend on the circumstances of the farm set-up and how the finance is to be funded. If the investment project is kept on the overall farm balance sheet, then the offsetting value of heat and digestate use should be accounted for, as this improves the profitability of the overall business (see Figure 7-16). Including these two items when funding the project off the balance sheet (i.e. as a separately funded business to the main farming business) would require that both heat utilisation and digestate would be sold to the farm and suitable long-term contracts set up, in order to satisfy the funding bodies.

7.6 SUMMARY

This chapter has discussed how a series of model-runs was developed from the co-digestion of single mobile feedstock types with static feedstock types. It has demonstrated that the use of single supplementary crop feedstock types would significantly impact on existing agricultural land use and activities (see Section 7.2.4.3). Therefore an alternative method was sought that enabled the treatment of large quantities of low-energy feedstock types with a mix of both crops grown specifically for AD and other on-farm waste feedstock types and biowaste (scenario two, the hub-and-pod concept).

The results suggest that adopting the hub-and-pod concept may help achieve support for treatment of a greater quantity of low-energy feedstock types than would be possible from supplementing this low-energy feedstock with one or more crops. Slight changes to the quantities of different supplementary feedstock were required when investigating at the regional level, due to the variance in mean herd sizes from national to regional levels. Further alterations were required when accounting for the available feedstock in the regions (see Appendix 5: the blue columns of Tables A1.20, A1.21 and A1.22). The final model-runs were then tested against a number of variables that could affect the viability of these model-runs. Sensitivity analysis highlighted potential areas of vulnerability using the hub-and-pod conceptual model; in particular, demonstrating that significant quantities of energy and GHG mitigation would not be possible without the benefits that such infrastructure it provides. The other two main points that should be made are that when considering financing an AD project, including the value for heat and digestate is important, but if they are included, the appropriate siting of the facility should be carefully assessed.

Returning to the thesis objectives (see Section 2.8), one of the central aims was to minimise the impact of land use for energy generation over land use for food production. It has already been demonstrated that using single-crop feedstock types (see Section 7.2.4.2.1) in treating on-farm livestock waste materials has a significant impact on existing agricultural activities, either on- or off-farm. It is clear that not all the on-farm waste materials can be treated viably with other on-farm waste materials or biowaste materials alone, and therefore a proportion of crops grown specifically for AD must be used. Even then, only a fraction of the total livestock waste materials can be treated to generate energy using AD. The hub-and-pod concept does allow for more of these feedstock types to be co-digested with fewer crop materials when combining pre-treated waste materials on-site. Prima facie, the hub-and-pod concept seems to provide the optimal solution for maximising energy and GHG mitigation, whilst having the least impact on existing farm activities.

Chapter 8: Results and discussion of regional and scenario analysis

'Most of us spend the first six days of each week sowing wild oats; then we go to church on Sunday and pray for a crop failure.'

Fred Allen (1894–1956)

8.1 INTRODUCTION

This thesis sought to address six overarching objectives:

- characterise and quantify the main available feedstock types available in England
- investigate the best method to maximise energy generation and GHG mitigation within an economically viable context
- understand how AD could be developed in order to maximise the mitigation of GHGs
- identify how to maximise net energy generation utilising AD technology
- assess how AD could be deployed in order to maximise energy generation and GHG mitigation, without having a negative impact on food production
- compare the economic and environmental efficacy of AD against other renewable energy technologies.

The first two objectives were achieved in earlier chapters. In Section 7.1.2, feedstock was grouped into either mobile or static feedstock types, to define those feedstock types that were practicably and economically transportable and those that were not. In order to quantify and assess the distribution of the static (livestock) feedstock types, further categorisation was required, based on the size of herd or flock from which they derived. Whilst this did not provide a geographical location of origin, it did permit analysis of the distribution pattern expected in an area – in this case, an English region.

The second objective, relating to economic viability, was dealt with by the decision processes throughout the modelling process and explained in Section 7.2.3, which states that only those model-run results that achieved an IRR of 12 per cent or more and a positive NPV at 20 years were represented in the regional scenario runs, ensuring that the final outputs were all based on economically viable AD facilities.

The remainder of this chapter sets out the results of the different scenarios posed in Section 3.6 and addresses the remaining four objectives. The results of the different scenarios are discussed next, in Section 8.2. The objectives relating to carbon mitigation, energy generation and land use are answered in Section 8.3. A short discussion follows on the impact that the government’s degression strategy on FIT values will have in shaping the deployment of AD, and therefore the technology’s ability to achieve its potential. DEFRA’s AD Strategy and Action Plan is revisited after being put in place three years ago, and a brief assessment is made on how the hub-and-pod system could impact on DEFRA’s expectations, as well as other research groups’ projections.

Finally, a comparison is made of the environmental and economic efficacy of AD against a number of other energy-generating technologies (see Sections 8.5 to 8.8), with the aim of achieving the last objective of this thesis. First, a comparison is made of the amount of space required to generate energy; second, a comparison is made between the ability of different energy-generating technologies to mitigate carbon. The last two indicators compare the levelised cost of generating energy and mitigating GHG emissions over the lifespan of different technologies with AD.

This research has shown that a number of ‘trade-offs’ are required if one or other objective becomes the primary goal. Four scenarios were developed (see Section 3.6) reflecting four principal methods of deploying the technology in England, depending on the goals that were set to be achieved. The aim of developing these four scenarios was to assess which one offered the best solution to the objectives posed by this thesis.

8.2 RESULTS: UTILISING ANAEROBIC DIGESTION IN THREE ENGLISH REGIONS

Chapter 3 set out the method and criteria for developing scenarios one, three and four, whilst Chapter 7 examined how the ADEE model was used to establish a set of economically viable AD facilities for scenario two, again based on current incentive schemes, but with a focus on treating livestock (static) feedstock types across all the different mean livestock herd-size categories. This approach provided the basis for the hub-and-pod scenario. The regions were analysed for their feedstock availability and this section sets out these results, as well as those of the other three scenarios measured.

The results are presented here in two sections. First, a brief introduction to each scenario is given, with the results, followed by a brief discussion. This highlights not only the differences between the scenarios, but also the differences across the three regions, and helps to distinguish the benefits of the different scenarios. Second, four common metrics (cost of mitigating carbon, annual GHG emissions saved, land requirement and quantity of energy generated per annum) are extracted, analysed and discussed individually, providing a more detailed and specific comparison. The method of calculating these common metrics is shown in Table 8.1.

Table 8-1 Common metrics used in analysing the four scenarios

	PARAMETER	REFERENCE	
1	CHP genset required (kW)	Section 5.3.3.4	Per facility
2	Electricity output per site ($MWh.a^{-1}$)	Section 5.3.3.4	
3	GHG savings per site ($tCO_{2eq}.a^{-1}$)	Section 5.4.1	
4	Area of land required per facility (ha)	Section 5.3.2.1	
i	Installed capacity (MW)	1 x ii	Per region
ii	No. of AD facilities required	Section 3.7	
iii	MWhe generated per annum	2 x ii	
iv	Average cost of GHG emissions mitigated (£.t $CO_{2eq}.a^{-1}$)	Section 8.3.1	
v	Total area of agricultural land required in the region	4 x ii	

8.2.1 Scenario one: biowaste only

This scenario is discussed first, being the only scenario that was limited by the quantity of feedstock available in a region or in England as a whole. There is almost ten times more livestock waste produced on farms annually than anthropogenic biowaste; and crops grown specifically for energy are only restricted by the availability of land, competition for food or government policy.

Analyses were completed using the methods discussed in Section 3.7.2. Outputs (CHP genset size, electrical output, GHG emissions (savings) and land required) from the optimal model-run were used in calculating the total potential for each region, assuming that 100 per cent of the biowaste was available for treatment through the AD system in the region (see Table 3-9).

This total quantity of 'available' biowaste in the region was divided by the quantity treated at each facility (in this case, 40,000 t), to establish the number of AD facilities required to digest the total quantity of waste in each region (see Table 8-2). The total energy and GHG emissions savings were then calculated by multiplying the individual facility outputs by the number of facilities required in the region being analysed. To calculate the average cost of GHG emissions savings, the total quantity of GHG savings in a region were divided by the total calculated payment from FITs for producing the quantity of energy generated. Finally, the installed capacity was calculated by dividing the total quantity of energy generated by the number of hours of generation in one year, which for the purposes of this research was 8,040 hours.

Table 8-2 Scenario one results, based on single-size centralised biowaste-only AD facilities

Parameter	East of England	South West of England	West Midlands	
40,000 t facility with 25-mile feedstock catchment & 25-mile export of digestate to land				Per facility
CHP genset required (kW)	**2195**			
Electricity output per site ($MWh.a^{-1}$)	**17,647**			
GHG savings per site ($tCO_{2eq}.a^{-1}$)	**11,553.5**			
Area of land required per facility (ha)	**~2**			
Total regional available feedstock (tonnes) (theoretical maximum)	**1,610,512**	**1,439,064**	**1,542,957**	Regional results
Installed capacity (MW)	**88**	**74**	**80**	
No. of AD facilities required	**40**	**36**	**39**	
MWhe generated per annum	**705,880**	**635,292**	**688,233**	
GHG mitigated per annum ($tCO_{2eq}.a^{-1}$)	**462,140**	**415,926**	**450,587**	
Average cost of GHG emissions mitigated ($£.tCO_{2eq}^{-1}.a^{-1}$)	**145**	**145**	**145**	
Total area of agricultural land required in the region	**n/a**			

8.2.1.1 Discussion

A number of model-runs were made before deciding which should represent scenario one (see Section 3.7.2). These basically changed feedstock quantities and distances travelled by feedstock and digestate. Many of the model-runs completed for this scenario resulted in highly positive financial returns, with IRRs ranging from 11 per cent to 49 per cent, and NPVs ranging between £918,000 and £31 M. Only one model-run, treating the smallest quantity of feedstock assessed and receiving no gate fee, had an IRR of less than 10 per cent and negative NPV. All except the smallest AD configuration had payback periods of less than five years; and even the model-run that was treating the least quantity of biowaste had a payback period of seven years, suggesting that the facility was viable, but that the expectation of a 12 per cent discount rate was excessive. Larger facilities still have IRRs and high positive NPVs when the gate fee is removed entirely. However, for simplicity, only one model-run (facility scenario) is used in assessing the performance of scenario one (shown in Table 8-2), representing a catchment of approximately 200,000 homes (based on each household generating 200 kg kitchen waste per annum – see Section 3.7.2).

Many of the AD facilities most recently or currently being constructed in England fall within this scenario category and have been established at the larger end of the scale, where returns are considerable and payback periods less than two years. There are no incentives for the operator to produce (PAS110) digestate that could be used as a valuable fertiliser, thereby further offsetting GHG emissions from the production of mineral fertilisers. Some facilities are even assessing if it is possible to incinerate the digestate, thereby destroying the closed-loop recycling of organic waste materials.

A number of these facilities have been constructed by the waste management industry, which is already incentivised through the LATS to reduce biowaste material being sent to landfill (thereby reducing GHG emissions by proxy). If treating their biowaste by AD, they are essentially being paid twice for removing biowaste from landfill, or reducing GHG emissions (through LATS and FITs). Whilst gate fees are high (up to £82.t^{-1}), there is an incentive to put greater quantities of feedstock through the AD process, rather than optimising the methane yield for energy generation. This has led to digesters being constructed that are smaller than required, operating at lower-than-required retention times. This maximises profits, by directly reducing capital and operational costs. This could potentially lead to an increase in GHG emissions, since the facilities are only designed to collect 80 per cent biogas; therefore, the feedstock is still generating methane (or has the potential to) when leaving the digester (Harrison, 2013), should the remaining gases not be collected.

This implies that a market failure has developed, stopping the release of this biowaste material outside the waste management industry and restricting utilisation of the greatest benefit from this resource. For example, reports from one case study noted that they were unable to enter into any long-term agreements with either the waste management companies or waste disposal authorities, and when contracts were made, only a small proportion of the gate fee was received. This may be unique to this site, or it could be ubiquitous across the industry. (Further investigation is outside the scope of this research.) However, it does lead to inefficiencies within the system and misallocation of resources, as materials are kept within the waste industry, which benefits from and can control (higher) gate fees as well as profit from the FIT.

More generally, financing has also proved difficult for many wishing to invest in AD, and the lack of feedstock or long-term contracts has been cited as a barrier to securing long-term debt

(DEFRA, 2013e). There could be many reasons for this, including the current inherent problems found in the financial sector.

8.2.2 Scenario two: the hub-and-pod concept

The hub-and-pod concept offers an alternative method of treating biowaste materials, but with the specific aim of supplementing on-farm livestock waste materials along with other supplementary feedstock types (see Section 3.7.2). The aim is to bring financial viability to the treatment of feedstock types with low inherent-energy qualities, and to provide a reasonable income by which to repay the expensive capital equipment costs. This was the most complicated exercise and necessitated a specific chapter (see Chapter 7) to describe the methods, procedures and decision process in assessing this scenario.

Even after all the analysis leading up to the optimal model-runs, further changes were made dictated by the available feedstock in the region. The final feedstock mixes and model-run results for each herd-size category (see Table 7-8) are displayed in Appendix 5, Tables A1.20, A1.21, A1.22. It is these data that were used in producing the scenario results for each region displayed in Tables 8-3, 8-4 and 8-5 below.

These latter tables demonstrate how challenging it proved to treat all the static feedstock without impacting on other farming activities, particularly in the South West (see Table 8-4), where it only the treatment of 12 per cent of beef and 34 per cent of dairy cattle populations' slurries and manures was possible; and in the West Midlands (see Table 8-5), where treatment of 33 per cent of beef and 34 per cent of dairy cattle populations' slurries and manures was achieved. The livestock population in these two regions was far greater than could be supported by supplementary feedstock types, without impacting on other regional farming activities by using crops grown specifically for AD. On the contrary, the East of England (see Table 8-3) has a much smaller livestock population and is able to treat a much greater quantity of on-farm livestock waste materials, without impacting on other farming activities (57 per cent beef and 74 per cent dairy cattle populations' slurries and manures).

The quantities of feedstock treated, energy generated and GHG mitigated in this scenario were expected to be greater than from scenario one, since additional feedstock types were being digested, enabling greater production of methane. It was also thought unlikely that the AD facilities would be as large as those developed in the other scenarios, unless cooperatives were formed by farmers wishing to pool their livestock slurries and manures across short distances (not assessed in these scenarios). It was expected, however, that the overall regional benefits would be greater in terms of quantities of energy generated and GHG emissions mitigated, and this was in fact what was demonstrated (see Tables 8-3, 8-4 and 8-5). All other regional calculations were completed as discussed above.

Table 8-3 Scenario two results: hub-and-pod results for the East of England

Static feedstock	Mean GHG saving per site $kg.MWh^{-1}$	Mean $MWh.a^{-1}$ generated per site	% of population's slurries and manures
Beef cattle herds	796	2,454	57
Dairy cattle herds	701	2,033	74
Pig herds	711	2,224	93
Installed capacity (MW)			**247**
No. of AD facilities required			**808**
MWh generated per annum (MWh)			**1,982,981**
GHG mitigated per annum ($tCO_{2eq}.a^{-1}$)			**1,423,342**
Total area of agricultural land required (ha)			**39,932**
Average cost of GHG emissions mitigated ($£.tCO_{2eq}^{-1}.a^{-1}$)			**199**

Table 8-4 Scenario two results: hub-and-pod results for the South West of England

Static feedstock	Mean GHG saving per site $kg.MWh^{-1}$	Mean $MWh.a^{-1}$ generated per site	% of population's slurries and manures
Beef cattle herds	911	2,862	12
Dairy cattle herds	833	2,533	34
Pig herds	737	1,949	71
Installed capacity (MW)			**227**
No. of AD facilities required			**809**
MWh generated per annum (MWh)			**1,827,196**
GHG mitigated per annum ($tCO_{2eq}.a^{-1}$)			**1,456,324**
Total area of agricultural land required (ha)			**32,007**
Average cost of GHG emissions mitigated ($£.tCO_{2eq}^{-1}.a^{-1}$)			**183**

Table 8-5 Scenario two results: hub-and-pod results for the West Midlands

Static feedstock	Mean GHG saving per site $kg.MWh^{-1}$	Mean $MWh.a^{-1}$ generated per site	% of population's slurries and manures
Beef cattle herds	830	2,470	33
Dairy cattle herds	806	2,387	34
Pig herds	718	2,104	69
Installed capacity (MW)			**204**
No. of AD facilities required			**722**
MWh generated per annum (MWh)			**1,643,898**
GHG mitigated per annum ($tCO_{2eq}.a^{-1}$)			**1,192,444**
Total area of agricultural land required (ha)			**26,363**
Average cost of GHG emissions mitigated (£.$tCO_{2eq}^{-1}.a^{-1}$)			**198**

8.2.2.1 Discussion

The impact of the hub-and-pod system is clearly significant. Mistry *et al.* (2011a) assessed that the maximum number of AD facilities across the UK would be only 855. In addition, they calculated that combining food waste and agricultural feedstock types could mitigate between 3 $MtCO_{2eq}.a^{-1}$ and 5 $MtCO_{2eq}.a^{-1}$ in total. However, this research has shown that using the hub-and-pod method allows the higher-energy feedstock type materials to treat a significant quantity of on-farm waste materials. The potential capacity in the South West alone (809 facilities) almost matches the national total calculated by Mistry *et al.* (2011a). Using the hub-and-pod concept, the total GHG saving across the three modelled regions exceeds 4.07 $MtCO_{2eq}.a^{-1}$ (three-quarters of the national total calculated by Mistry *et al*. (2011a)).

Comparisons between the results of scenarios one and two were difficult because of the vast differences in feedstock used and the quantities of energy generated and carbon mitigated as a result. In addition, scenario two required land for growing crops, whilst scenario one did not. Scenarios three and four also required land for growing crops; consequently, a better measure for comparison was needed, so that scenarios three and four could be compared against each other and with scenario two. The research followed the systematic LCA techniques (see Section 3.3); hence, to enable an accurate appraisal between the different scenarios, the functional unit was energy generated per region. The optimum value per region was set by the scenario two outputs. Therefore, scenarios three and four were scaled appropriately so that each generated similar quantities of energy per annum to scenario two in each of the regions, allowing for their other environmental attributes to be compared. Scenario one was the only scenario restricted by the quantity of available feedstock, which meant that similar upscaling was not practicable.

8.2.3 Scenario three: crop-only facilities

There was a degree of uncertainty in the modelling of crop-only AD facilities, due to doubts about their modelled financial viability. This was essentially a result of the data provided by case study 3, which this scenario is based on. As explained in Section 6.2.4, their data needed to be treated with caution. It is this caution that brings a degree of uncertainty to this scenario, as was highlighted by a series of model-runs that were completed on different feedstock mixes and quantities, to assess the viability of a crop-only facility. Very few had double-digit IRR values and none had positive NPV at 20 years, even though most returned six-figure profit values and average ROCE in excess of 15 per cent. However, these last two financial measures were not used in the overall financial appraisal of the model-runs (facility scenarios), for reasons expressed in Section 3.4. The size of facility falls into the highest FIT category (or lowest remuneration value), which is one of the main reasons why fewer facilities are required to generate the same quantity of energy when compared to scenario two. However, this type of facility is particularly vulnerable to environmental events, such as poor or failed harvests, which increase feedstock costs and also impact on food costs.

In this scenario (see Table 8-6), in order to calculate the number of AD facilities required, the total energy generated from scenario two (e.g. 247 MW for the East of England) was divided by the energy output from the optimised model-run using crop-only feedstock types (1.337 MW). Having calculated the number of facilities required (185 facilities for the East of England), this number was multiplied by the figures for the following data at the single site: electrical energy output and GHG emissions savings, allowing for the calculation of the total GHG emissions mitigated; the land required to grow the crops; and the approximate cost of mitigation in that region.

Table 8-6 Scenario three results: outputs based on a crop-only AD facility

Parameter	East of England	South West of England	West Midlands	
Inputs				Per facility
18,000 t maize (whole crop) silage				
4,000 t grass silage				
4,000 t spring barley (whole crop) silage				
Outputs				
CHP genset requirement (kW)	**1337**			
Electrical output per site ($MWh.a^{-1}$)	**10753**			
GHG savings per site ($tCO_{2eq}.a^{-1}$)	**5,802.6**			
Area of agricultural land required per facility (ha)	**622 (av. 45 $t.ha^{-1}$)**			
Installed capacity (MW)	**247**	**227**	**204**	Regional results
No. of AD facilities required	**185**	**170**	**153**	
MWhe generated per annum (MWh)	**1,989,305**	**1,828,010**	**1,645,209**	
GHG mitigated per annum ($t\ CO_{2eq}.a^{-1}$)	**1,073,481**	**986,442**	**887,798**	
Total area of agricultural land required in the region (ha)	**115,070**	**105,740**	**95,166**	
Average cost of GHG emissions mitigated ($£.t\ CO_{2eq}^{-1}.a^{-1}$)	**176**	**176**	**176**	

8.2.3.1 Discussion

These feedstock types have high DM content, which means that a large quantity of liquid is required in the digester to ensure that the substrate can move round the system. This increases capital costs as the size of digester increases. The model is unable to account for any catalysts or feedstock pre-treatments that might help to reduce retention time; or indeed an operator's decision to only partially treat the feedstock to achieve a lower gas yield. However, it was thought that whilst the partial treatment of feedstock may be the situation at large biowaste-only facilities, which receive a gate fee for each tonne of feedstock treated, it is highly unlikely that a facility paying for its feedstock would partially digest this, unless the feedstock was provided at a discount that would compensate for the loss of energy generated, or unless the reduction in the cost of capital (due to the smaller facility size required) over the lifetime of the facility was also sufficient to compensate for the reduced income resulting from incomplete digestion – either of which would bring considerable uncertainty and risk to the operator. The implications of incomplete digestion are wider than just reduced capital expenditure or reduced income. Only partially digesting crop feedstocks can lead to wider environmental impacts, such as more land being required to generate the same quantity of energy as a facility digesting its feedstock completely; and increased risk of the potential of GHG emissions from the undigested material whilst waiting to be spread to land or following application to land, unless managed properly.

A study produced by the National Farmers' Union (NFU) (in Vogel and Hellawell, 2011: 15) estimated that approximately 1,000 AD facilities, generating 500 kW each, from 12,925 t grass, would require 235,000 ha grassland (assuming that an average of 55 $t.ha^{-1}$ could be achieved). Effectively, this would permit an installed capacity of 500 MW across England. The grass yield is higher than that modelled by this research, which assumed that a further 88,100 ha would be required to generate the same amount of energy, not taking into account crop rotation for rotational grassland. The ADEE model also showed that each AD facility would mitigate 1,480 $tCO_{2eq}.a^{-1}$, generate 3,572 $MW.a^{-1}$ and require 323.13 ha of land, thereby saving 1,480,000 $tCO_{2eq}.a^{-1}$ and generating approximately 3.6 $GW.a^{-1}$ nationally. Even though the NFU study was generous with the grass yield per hectare (compared to Nix, 2012), the overall demand on the land is only a small fraction of the total UK cropable area of 6.258 Mha (DEFRA, 2012a: 5).

8.2.4 Scenario four: a combination of scenarios one and three

This last scenario may be representative of what is the current state of AD development in England, a predominance of biowaste-only facilities and crop-only AD facilities, with very few combining both feedstock types or with livestock waste materials.

Again, the aim was to compare the outputs with scenarios two and three; therefore, the total installed electrical capacity was set as for the other two, and the number of facilities required was calculated as follows. The quantity of energy generated from biowaste is restricted by the available feedstock in the region, so the quantity of energy generated from this feedstock was calculated first. This biowaste total (see Table 8-7) was deducted from the total installed capacity calculated in scenario two. The remaining energy supply is generated from crop-only facilities, at the same scale modelled for scenario three. For example, if the total power generation from biowaste was 20 MW, and the total electricity generated in scenario two was 100 MW, the remainder would be made up from crop-only facilities. If these were 4 MW facilities, then 20 additional crop-only facilities would be required to complete the scenario.

Table 8-7 Scenario four results: regional results from a mix of both biowaste-only and crop-only AD facilities

Parameter	East of England	South West of England	West Midlands	
Biowaste-only facility				Per facility
40,000 t facility with 25-mile feedstock catchment & 25-mile export of digestate to land				
CHP genset required (kW)	**2042**			
Electricity output per site ($MWh.a^{-1}$)	**16,414**			
GHG savings per site ($tCO_{2eq}.a^{-1}$)	**10,903.8**			
Area of land required per facility (ha)	**~2**			
Total regional available biowaste feedstock (t) (theoretical maximum)	**1,610,512**	**1,439,064**	**1,542,957**	
Crop-only facility				Per facility
18,000 t maize silage				
4,000 t grass silage				
4,000 t spring barley (whole crop) silage				
CHP genset requirement (kW)	**1337**			
Electrical output per site ($MWh.a^{-1}$)	**10753**			
GHG savings per site ($tCO_{2eq}.a^{-1}$)	**5,802.6**			
Area of agricultural land required per facility (ha)	**622**			
Outputs				
Installed capacity (MW)	**247**	**227**	**204**	Regional results
No. of AD biowaste only and (crop-only) facilities required	**40 (119)**	**36 (111)**	**39 (89)**	
MWhe generated per annum	**1,985,487**	**1,828,875**	**1,645,250**	
GHG mitigated per annum ($tCO_{2eq}.a^{-1}$)	**1,153,339**	**1,060,651**	**967,582**	
Total area of agricultural land (ha) required in the region	**74,018**	**69,042**	**55,358**	
Average cost of GHG emissions mitigated ($£.t\ CO_{2eq}^{-1}.a^{-1}$)	**163**	**164**	**161**	

8.2.4.1 Discussion

The benefits of this scenario begin to emerge as the more favourable option for energy generation and increased environmental benefits, over both scenarios one and three, as the results demonstrate that scenario two is able to generate more energy (than scenario one) and mitigate more carbon and impact less on agricultural land use (than scenarios three and four).

The next four sections analyse four key performance indicators from the different scenarios. They aim to demonstrate why a single metric is insufficient when assessing the costs and benefits of AD. In brief, whilst the cost of mitigating carbon (see Section 8.3.1) is between 10 per cent and 18 per cent lower for the other three scenarios than for scenario two, the quantity of carbon mitigated is significantly less. Scenario four also requires between 72 per cent and 100 per cent more land than that required by scenario two.

8.3 COMPARING THE SCENARIOS AT REGIONAL LEVEL

8.3.1 The annual cost of mitigating carbon

This first measurement assessed the annual cost of mitigating one tonne of carbon (shown in Tables 8-2 to 8-7 above). This is a simple calculation compared to that based on the levelised discounted costs of mitigating carbon (see Table 8-18), discussed later. There is no transparent mechanism in the energy-generating sector which calculates the charge of carbon equivalent emissions or, in the case of some renewable technologies, the cost for saving carbon equivalent emissions. This calculation is based on remuneration from the FIT for generating electricity; so, effectively, if AD were remunerated for saving carbon rather than generating electricity, the costs might look like those in Table 8-8 (which include the value of electricity generated as well).

Using the optimum model-run calculated for each livestock brackets (see Table 7-8), the total income is calculated from the quantity of energy generated, multiplied by the appropriate FIT value, and finally multiplied by the number of farms that were included in that region, dependent on the quantity of available supplementary feedstock. As expected, the costs were lower for all bar the hub-and-pod concept (see Table 8-8); this was a result of all the hub-and-pod AD facilities fitting into the lowest two (or highest-paying) FIT categories, whilst the other scenarios required greater economies of scale to be financially viable.

Most model-runs in scenario two fell into the middle FIT bracket, but with a considerable number of facilities still coming within the highest-paid FIT bracket. For example, analysing the results from modelling the beef cattle herds in the East of England showed that 178 facilities fell into the highest-paid FIT bracket, and 116 facilities treating cattle herds fell into the middle bracket. Currently, FIT rates are £151.60, £140.20 and £92.40 per MW electricity generated. Whilst there is a 52 per cent difference in the number of middle and lowest-paying-FIT farms, this does not translate to a 52 per cent difference in the cost of mitigating carbon (see Table 8-8). Taking the difference between scenarios one and two, there is only a 37 per cent increase in the cost of mitigating one tonne of carbon, highlighting the increase in GHG mitigation for every one megawatt of energy generated.

The influence on the size of facility, and therefore the lower FIT category, ensures that the cost per tonne of carbon or megawatt of energy is always lower. One could conclude that from the point of view of cost to the consumer, the most favourable method of deployment of AD would be scenario one, but this does not inform the consumer of the quantity of GHG mitigated.

Table 8-8 A comparison of average annual costs (£) in mitigating one tonne of carbon

	East of England	South West of England	West Midlands
Scenario one: biowaste only	145	145	145
Scenario two: hub-and-pod	199	183	198
Scenario three: crop-only	176	176	176
Scenario four: mixed	163	164	161

8.3.2 Greenhouse gas mitigation

Upon investigation, scenario one does not perform as well as the other scenarios in terms of the annual quantity of CO_{2eq} mitigated regionally. Scenario one is unable to provide the same carbon savings per annum as any of the other scenarios (see Table 8-9).

This is demonstrated further by hypothesising that the supply of biowaste material would enable the same quantity of energy to be generated as for the other scenarios. If this were true, 113, 104 and 94 biowaste-only facilities would be required in the East of England, West Midlands and South West of England respectively, mitigating 1,305,546 t, 1,201,564 t and 1,086,029 t of carbon equivalents respectively. These figures, respectively, are still 8 per cent, 18 per cent and 9 per cent less than the carbon mitigated through the hub-and-pod concept (see Table 8-9), assuming that the AD facilities were on the same scale as that for scenario one (see Table 8-2).

Clearly, scenario two is the more favourable option if the main aim of AD deployment is to reduce GHG emissions, thereby answering the third objective of this thesis (see Section 8.1).

Table 8-9 A scenario comparison of total GHG (tCO_{2eq}) saved per annum per region

	East of England	South West of England	West Midlands
Scenario one: biowaste only	462,351	392,537	425,248
Scenario two: hub-and-pod	1,423,342	1,456,324	1,192,444
Scenario three: crop only	1,073,481	986,442	887,798
Scenario four: mixed	1,153,339	1,060,651	967,582

8.3.3 Energy generation

In many respects, this next measurement (see Table 8-10) is superfluous, in so far as scenarios two, three and four were deliberately similar, as the set energy generated per region represented the functional unit (energy generated per region). They do differ slightly, so that whole numbers of facilities could be used; however, energy generation for all of the last three scenarios could increase or decrease, depending on the incentive to generate energy over the incentive to produce food or mitigate carbon.

Having used energy generation as the target in this section, answering the fourth objective of the thesis is difficult without assessing the other goals; however, it does demonstrate that if pursuing energy generation, scenario one (or biowaste material only) is not the best choice.

Table 8-10 A scenario comparison of electricity generated per annum (MWh) per region

	East of England	South West of England	West Midlands
Scenario one: biowaste only	705,880	635,292	688,233
Scenario two: hub-and-pod	1,982,981	1,827,196	1,643,898
Scenario three: crop only	1,989,305	1,828,010	1,645,209
Scenario four: mixed	1,985,487	1,828,875	1,645,250

8.3.4 Land use

However, even without measuring these environmental impacts from land-use change, scenario two utilises half as much land as scenario four, or approximately one-third as much land if adopting scenario three (see Table 8-11). Scenario one needs to be mentioned in that there would be negligible impact from any land used to construct the AD facilities, since they take up very little space. If impacts to land use were the sole goal, then scenario one would be chosen. However, if investigating the best method to maximise energy generation and GHG mitigation within an economically viable context (the second objective of this thesis), the answer must remain that scenario one does not achieve this.

Table 8-11 A comparison of the annual land (ha) requirement to support AD in each region for each scenario

	East of England	South West of England	West Midlands
Scenario one: biowaste only	-	-	-
Scenario two: hub-and-pod	39,932	32,007	26,363
Scenario three: crop only	115,070	105,740	95,166
Scenario four: mixed	74,018	69,042	55,358

One of the main concerns of the government is the impact AD might have on land use (DECC, 2012a), in terms of competing for land to grow crops, increasing land rental prices (and, indirectly, food prices) and the possibility of increased CO_{2eq} emissions due to these LUCs. There is considerable pressure on land from man to grow food for both direct and indirect consumption; and to provide space for shelter and work, clothing and warmth. When governments incentivise activities that create distortions in that land use, this can have both financial and environmental impacts (Styles *et al*., 2013; Mezzullo *et al*., 2012), felt locally and further afield. The impacts from both LUC and iLUC are outside the scope of this research, and have not been measured either in terms of GHG emissions changes or other environmental impacts.

The NFU (in Vogel and Hellawell, 2011: 15) stated that there are some 860,000 ha of idle or marginal land that could be used to grow crops specifically for AD. However, much of this land may have been marginalised by development and may not be of the size or shape conducive to modern farming practices used for the type of crops useful to AD. Other land may have soil of poor quality, which would make it equally unsuitable for the intensive growth of nutrient-demanding crops, and better suited for other activities, such as coppicing for woodchip.

8.3.5 Summary of results

In analysing four key performance indicators used across three investigated regions of England, it is apparent that if renewable energy generation were the priority, then scenario one would not be the best method of deployment of AD in England. However, if costs were the focal point, then scenario one would be chosen as the best method, regardless of the quantity of renewable energy it could generate, or indeed the quantity of GHG emissions mitigated. The cost per MWe generated, and therefore GHG mitigated, both reduce as the facility size increases and the FIT value per MWe generated reduces. The marginal costs per MWe were the same for scenarios three and four; however, the quantity of GHG emissions saved were less, due to the increase in agricultural processing, transport costs and the removal of GHG savings from emissions from landfill (scenario three).

To some extent, the costs for scenario two could have been reduced by ensuring that the AD facilities modelled fell within the upper two FIT brackets, by encouraging larger facilities to treat more of the on-farm waste feedstock types. This could be achieved by forming cooperatives between neighbouring livestock farmers, or by increasing the supplementary crop feedstock types at the smaller AD facilities. However, this would have impacted on the quantity of energy generated and the quantity of GHG mitigated.

The results discussed in this section have answered one of the research objectives in relation to maximising GHG savings, and have helped to answer three others (maximising energy generation, impacting on food production as little as possible and, finally, maximising energy generation and GHG savings within an economically viable framework). These last three objectives are more difficult to answer without some degree of trade-off between one or other of the objectives.

Clearly, using biowaste only as a feedstock precludes scenario one from meeting the fourth objective of maximising energy generation, since it is restricted by the quantity of available feedstock. Similarly, scenario three must be precluded from meeting the fifth objective due to its high demand for agricultural land. Scenario two poses the best method of developing AD if mitigating GHG is the main priority; however, since scenario two does use land to grow crops specifically for generating energy, there could be an argument that this could impact upon food production, where scenario one does not because it does not use land at all (other than to site its operations). Yet it could be strongly argued that the quantity of land required under scenario two would not be sufficient to impact on food prices or the existing agricultural practices within a region, particularly when compared to scenarios three and four, and reports such as Vogel and Hellawell (2011).

With GHG mitigation maximised, land-use change minimised and energy generation on parity with scenarios three and four, it can be concluded that scenario two would be the best method of deploying AD across England, thereby achieving the fifth objective of this research.

To answer the remaining objective, AD needs to be compared to a number of other energy-generating technologies. Before this is carried out, there follows a brief discussion relating to the government's forecasting of the potential of AD in the UK, as well as an assessment of the impacts on the AD sector of the government's FIT degression policy.

8.4 DEFRA'S ANAEROBIC DIGESTION STRATEGY AND ACTION PLAN REVISITED

DEFRA (2011c) expressed uncertainty in forecasting the potential of AD, highlighting the difficulties of obtaining planning permission, the granting of an environmental permit and approval under the ABPR as just some of the hurdles that a developer may encounter between applying for planning permission and a facility actually being built. However, DEFRA (2011c) estimated that the potential exists for AD electricity capacity to reach between 3 and 5 TWh by 2020 (with no further comment on the use of the biogas for grid injection or biofuel use). This falls roughly in line with a report by ARUP (2011), which suggested that the maximum electrical capacity for AD would be 5.67 $TWh.a^{-1}$.

Mistry *et al*. (2011a) calculated that should agricultural feedstock types dominate AD deployment, then approximately 5 TWh electricity (mitigating 63,000 $tCO_{2eq}.a^{-1}$) could be achieved nationally; but when utilising all feedstock types, 14 TWh electricity (mitigating in excess of 3 $MtCO_{2eq}.a^{-1}$) would be achieved. How this is achieved is difficult to tell, since Mistry *et al.* (2011a) suggest that there are only two AD facility types (type 1 – food-waste-driven, receiving >15 per cent food and garden waste; and type 2 – agricultural, receiving <15 per cent food and garden waste).

This research has shown that across the three regions studied, a total of 5.45 TWh electricity could be generated per annum (mitigating 4.072 $MtCO_{2eq}$). Taking an average of the three regions, and multiplying the average by the number of regions in England, an estimate of what could be achieved by utilising the hub-and-pod concept would be a total of 14.5 TWh electricity generated per annum (mitigating 10.859 $MtCO_{2eq}$, using 10 per cent of the heat generated). However, this would require considerable direction from central government. Some recommendations towards decarbonising the English energy, agricultural and waste management sectors are discussed in the next section.

The 2012–13 annual report (DEFRA, 2013e) highlighted very few additional barriers from the 2011 report (mentioned above). New research was to be completed at the micro-scale (community AD and localism), and on gas upgrade for transport fuels and injection to the grid. Further support has been offered to the rural community in terms of feasibility study assessments, with particular reference to sustainability and LCA. However, the overall trend is for food waste and other biowaste to be treated at large, centralised facilities, whilst there remains a degree of scepticism over the sustainable viability of on-farm AD facilities. Finally, in reference to finance, DEFRA (2013e) noted that banks continued to struggle to finance AD projects, since debt is outside the reach of many on-farm AD projects that do not project expected high returns. The focus towards large, centralised biowaste treatment facilities is reinforced by the WRAP AD Loan Fund having recently provided funds to a facility being developed to process 53,000 t of biowaste, and the Green Bank only providing funds to similar large, centralised, biowaste-only facilities. DEFRA (2013e) cited a Green Bank report stating that project success related to feedstock selectivity (biowaste), access to land for the digestate, and availability of skilled and knowledgeable personnel, much of which is available in the agricultural sector. What is essential when deciding to build an AD facility is to ensure a secure, long-term agreement of feedstock supply – the first five years of operation as a minimum (to cover the capital payback period), but preferably longer.

8.5 IMPACTS FROM THE FEED-IN TARIFF DEGRESSION POLICY

Currently, there are three FIT categories for AD, determined by the energy-generating capacity of the CHP genset; these are 0–250 kW; 251–500 kW; and 501 kW and above. Under the government's degression policy, the two lowest (energy-generating) bands will have the payment value reduced by 20 per cent to all new entrants to the AD market, as soon as the electricity capacity trigger point is achieved. This trigger point is the level at which the total quantity of electricity generated by all generators within these FIT categories is achieved nationally, although this was to be no earlier than 1 April 2014.

However, the highest FIT category is not affected by this first round of digression, penalising smaller potential energy producers twice over. First, it reduces the attractiveness of investment at these sizes, driving demand towards the larger AD facilities; and as this thesis has demonstrated, big is not always best when generating energy and mitigating carbon using AD. This action will also make it more difficult for the AD technology to mitigate the same level of GHGs from the agricultural sector. Second, this policy will divert high-value feedstock (biowaste material) towards centralised units (scenario one), away from the farming community that requires this feedstock type to supplement the lower-value feedstock types (scenario two).

This could lead to the greater use of crops grown specifically for energy, further reducing the quantity of GHG emissions savings achievable from the agricultural sector in particular. In addition, the demand for crops grown specifically for energy will increasingly place land previously used to grow food crops in competition (potentially raising food prices for UK produce). This could lead to an increase in the potential for environmental change (including increased GHG emissions) from a permanent change in land use. If the agricultural community still requires incentives to grow crops other than for food, the incentives should be separated, so that the greatest quantity of GHG emissions are mitigated first and are linked specifically to the treatment of on-farm livestock waste materials.

The general impact of the degression policy will be that AD does not achieve its potential in terms of the quantity of energy it could generate or the quantity of abated GHG emissions, as less on-farm (GHG-emitting) material is treated, feedstock has to travel further to 'find' an AD treatment facility, and the digestate has to be transported further to 'find' land that can take its valuable nutrients without overloading its soils.

The other impact of the inequality of these changes is that they could lead to financial uncertainty across the sector. Such uncertainty might be increased by changes to German renewable energy remuneration rules, which seek to improve the GHG abatement per euro paid – something that could happen in the UK in the future. To clarify, the German government retrospectively applied FIT qualifying requirements on all AD facilities, should they wish to continue receiving the full FIT value for the electricity they generate (EEG, 2012). It required the AD facilities to utilise at least 40 per cent of the waste heat they generated (in addition to the heat used to maintain the digester temperature), with some AD facility types required to use 60 per cent. Implementing heat use in areas where there is no immediate demand, or where there is significant distance between the source (CHP genset) and the heat-load could prove very costly. The Germans made these changes in a mature market; making similar changes in a market that is only just developing could set the industry back many years.

8.6 ENERGY PER UNIT AREA

Seven different renewable technologies have been compared by MacKay (2012), as regards the quantity of land required to generate one watt of energy. The first observation (see Table 8-12) is that using biomass is not efficient in terms of the quantity of land required to generate significant quantities of energy. Whilst AD is not the least efficient (Highland rainwater), biomass (in all useful forms) is five times less efficient than the next renewable technology (wind energy).

Table 8-12 Land required to generate one watt of energy using different renewable technologies

Technology	$W.m^{-2}$
Wind	2.5
Plants (biomass)	0.5
Solar PV (farms)	5
Tidal pools	3
Tidal streams	8
Rainwater (Highlands)	0.24
Concentrating solar power (equatorial)	15–20

Source: Adapted from David MacKay (2012)

Using the results from the scenarios, various calculations and deductions can be made, including the energy conversion efficiency per unit area of land (see Table 8-13). Using crop-only digesters as a means of generating energy has the lowest energy conversion efficiency rate from land, followed by scenario four, which includes centralised AD facilities, which reduce the land demand. Scenario one only requires the land upon which the facility stands and has to have the best conversion efficiency per square meter; however, of the remaining three other scenarios, which generate at least two and a half times more energy (than scenario one), scenario two offers the most favourable conversion efficiency, providing improvements of between 24 per cent and 54 per cent over those figures calculated for biomass by MacKay (2012).

Table 8-13 Energy generated per square metre ($W.m^{-2}$)

	East of England	South West of England	West Midlands
Scenario one: biowaste only	-	-	-
Scenario two: hub-and-pod	0.62	0.71	0.77
Scenario three: crop only	0.21	0.21	0.21
Scenario four: mixed	0.33	0.33	0.37

The figures displayed above (see Table 8-13) were calculated using electricity produced from a CHP genset with 39 per cent electrical energy conversion efficiency. Only the electricity generated was accounted for, providing a direct comparison with MacKay (2012). Purposely utilising the heat generated from the process would significantly improve the energy conversion efficiency of the figures displayed. Using gas upgrade to grid also improved the expected conversion efficiency (or energy used); however, there is an energy requirement for the upgrading technology.

This first measurement only allows us to compare the conversion efficiencies of biomass from one square metre of land. However, it does provide a sound measure for comparing the different methods of deploying AD, and highlights the inefficiencies of not deploying AD using the hub-and-pod concept. This method of comparison, however, does not provide any additional measure of the costs or benefits of utilising a technology, such as net GHG emissions.

8.7 LIFE-CYCLE ANALYSIS AND GREENHOUSE GAS EMISSIONS

The following discussion relates to GHG emissions calculated and compared during this research. Section 8.7.1 provides a brief discussion of the differences in quantification of emissions from landfill, whilst Section 8.7.2 relates to the total emissions (either emitted or mitigated) from various energy-generating sources. These discussions will show that the ADEE model may underestimate GHG savings compared to the other research estimating emissions from landfill; yet comparison of the final total values produced by this model shows that they are similar to those calculated by the IPCC (2012), suggesting that the ADEE model is providing results within narrow and comparable limits of accuracy.

8.7.1 Greenhouse gas emissions from landfill

DEFRA (2011c) states that every one tonne of food waste diverted from landfill saves 4.2 tCO_{2eq}, but also that only approximately 500 $kgCO_{2eq}$ is avoided for each tonne of food waste treated by AD. Mühle *et al*. (2009) and Jeswani *et al*. (2013) reported significantly different figures of emissions from landfill sites of municipal solid waste, of 175 $kgCO_{2eq}$ and 395 $kgCO_{2eq}$ per tonne of waste respectively. This research calculated (see Eqn 5-3) net GHG emissions savings from landfill to be 162 $kgCO_{2eq}$ (without deducting the leakage from the AD facility shown in the equation). Since the calculations from Mühle *et al*. (2009) and Jeswani *et al*. (2012) are based on landfill of all (MSW) waste, it can only be assumed that the increased emissions arise from other organic materials present in landfill sites, such as paper and certain rubbers, which are outside the scope of this model. The largest difference in expected GHG emissions from landfill sites remains between this research and that of DEFRA (2011c), which may supersede and/or overestimate the emissions calculated by an earlier DEFRA project's outputs, which this research uses (Gregory *et al*., 2003). However, this only strengthens the argument of diverting biowaste from landfill sites to be treated at AD facilities.

8.7.2 A comparison of Greenhouse gas emissions from different energy-generating technologies

A more powerful and useful comparison of a technology's impact on the environment, particularly in terms of its impacts on climate change, is offered by data provided by the Intergovernmental Panel on Climate Change (IPCC). The IPCC (2012) published a table of GHG emissions from a number of energy-generating technologies (see Table 8-14).

The life-cycle GHG emissions for what the IPCC termed 'bio-power' (considered to include the full range of technologies generating energy from biomass) range significantly, but bio-power remains the only technology type that delivers a GHG emissions saving. No other renewable energy technology provides GHG savings. CCS is excluded, since the technology does not generate energy, but removes carbon from the atmosphere or the flue-gases of energy-generating technologies.

Table 8-14 A review of LCA of GHG emissions from electricity generation technologies ($gCO_{2eq}.kW^{-1}$)

Values	Bio-power	Solar		Geothermal energy	Hydro-power	Ocean energy	Wind energy	Nuclear energy	Natural gas	Oil	Coal
		PV	CSP								
Minimum	-633	5	7	6	0	2	2	1	290	510	675
Maximum	75	217	89	79	43	23	81	220	930	1170	1689
CCS min.	-1368								65		98
CCS max.	-594								245		396

Source: Adapted from IPCC (2012: 982)

It is difficult to establish precisely which biomass types were assessed by the IPCC (2012), or indeed which technology conversion type was used to generate energy. Assessing just a few feedstock types and only one energy conversion pathway (CHP) in this research produced quite a range of outputs (see Table 8-15), all of which were negative (i.e. provided GHG savings (in red) rather than net emissions (in black; see Table 8-14)). Whilst the units are different, they are one magnitude different and are therefore directly comparable to the figures in Table 8.14 above.

The greatest GHG savings observed were when treating the largest livestock herds, since they offered the greatest GHG savings from the agricultural sector. When utilising crop-only feedstock types, the least GHG savings were observed, mainly due to a lack of offsetting GHG emissions from biowaste and/or on-farm waste materials, plus the intensive use of agricultural machinery in crop production. The treatment of biowaste also compared less favourably to the hub-and-pod concept as the AD facilities were larger, requiring a large catchment area for the feedstock and higher transport emissions, coupled with a lack of offsetting GHG emissions from agricultural on-farm waste materials.

Table 8-15 GHG emissions based on results of four different scenarios produced in this research ($kgCO_{2eq}.MW^{-1}$)

Scenario	GHG saving per MW generated ($kgCO_{2eq}.MW^{-1}$)		
	Mean	Minimum	Maximum
East of England hub-and-pod	-718	-654	-944
South West of England hub-and-pod	-797	-623	-959
West Midlands hub-and-pod	-727	-626	-906
Biowaste only	-655	-	-
Crop only (16,000 t maize; 6,000 t grass; 6,000 t barley (whole crop) silage)	-540	-	-

Only mean values for biowaste-only and crop-only facilities are displayed, since only facilities of one size were considered within a particular scenario. The GHG emissions from the 'hub' were not included, since it was assumed that a hub would be carbon-neutral or –negative, because it would have an AD facility attached to it that was sufficiently large that the waste heat generated from the CHP genset would be sufficient to power the pasteurisation process. Alternatively, the hub could be sited near an existing energy-generating facility or incinerator, and could make use of the waste heat generated from these sites.

One of the main differences between the LCA assessment conducted by the IPCC and that carried out by this research was that the IPCC included the facility decommissioning in their calculations. There are two reasons why this research did not include decommissioning energy and emission values. First, the project lifetime for this research was restricted to the financial remuneration period governed by FITs, and not the lifespan of the capital equipment, which could vary by up to 50 per cent, depending on its role. It is not certain if there would be funding available for renewable energy generation after this period, or indeed if operating facilities will be able to extend their existing remuneration over the useful lifetime of the facility itself. Second, no literature was found on the decommissioning or recycling of any aspect of AD facilities.

Clearly, the results produced from this research are comparable with the lower-value ranges of the IPCC figures (see Table 8-14), demonstrating that AD is an effective and proven tool in mitigating GHG emissions whilst generating energy. How much energy is generated or GHG mitigated within England will depend on whether these attributes are recognised under current government incentive schemes, and this has yet to be seen. One way in which technologies are appraised by governments is in terms of the expected running costs incurred over the lifetime of a technology at today's values, and therefore how much government support the technology will require over its lifetime. This represents the final method by which technologies are compared in this research.

8.8 THE LEVELISED COSTS OF ENERGY GENERATION AND CARBON MITIGATION

These two measures were first introduced in Section 3.4. A brief reminder of each measure will be followed by the results calculated (discussed in Sections 3.4.7 and 3.4.8) for each scenario, which were then compared with other energy-generating technologies.

8.8.1 The levelised cost of energy generation

The levelised cost of energy represents a method for identifying the price at which electricity must be generated (from a specific source) to provide a break-even value over the lifetime of an energy project, and comparing this against other technologies. DECC (2011b) estimated levelised costs of energy generation for a number of renewable technologies, including AD (see Table 8-16), and compared them with the most favourable, low GHG-emitting, fossil-fuel, energy-generating technology: CCGT.

Table 8-16 Estimated levelised cost ranges (£.MW^{-1}) for electricity technologies from 2010

Technology	Offshore wind	Onshore wind	Solar PV	Dedicated biomass	Biomass co-firing	Biomass conversion	AD < 5MW	CCGT	Nuclear*
Max.	191	127	380	165	110	128	194	79	108
Min.	149	75	202	127	94	106	75	76	90

Source: Adapted from DECC (2011b) and (2013e: Table 6*)

The same calculation was completed on the model-runs of this research to establish the levelised costs of energy generation associated with the four different scenarios (see Table 8-17). The estimated costs using the ADEE model compare well with DECC's figures, but mainly at the top end of their calculations. Only some of the largest biowaste-only facilities produced levelised costs under £100.MW^{-1}. Some of the levelised cost figures (£.MW^{-1}) produced from this research did extend beyond the upper limit estimated by DECC (see Table 8-17). This could be for many reasons, including the underestimation of capital costs by DECC for the smaller AD facilities, or DECC's focus on the generation of some renewable energy at the cheapest cost (larger scale). All the model-runs from scenarios one, three and four fell within the lowest-paying FIT bracket, whilst all of the model-runs developed for scenario two fell within the two highest-paying brackets.

At the other end of the scale, this research did establish its lowest levelised cost for energy (£82.MW^{-1}) in treating biowaste material only at the very largest scale (100,000 t of biowaste or more per annum). However, these facilities also had some of the lowest GHG savings per MW electricity generated (less than 647 $kgCO_{2eq}.MW^{-1}$). Since a significant proportion of these emissions savings are from the offsetting of GHG emissions from landfill gases, and since the waste management industry is already incentivised to reduce GHG from biowaste material (DEFRA, 2005), effectively, the government is paying the same sector twice for the reduction in these GHG emissions. At these large-scale facilities, the payback period can be as little as two years or less; the NPV is in excess of £30 M; and the IRR is 49 per cent. By removing the payment received as a gate fee (set at £20 in this research, rather than the full current LATS value of £80) at these facilities still provides an IRR of 32 per cent, with an NPV in excess of £17 M. Scenario two (biowaste only; see Section 8.2.1) assumed that AD facilities were smaller than that described above.

Table 8-17 The levelised cost of energy generation

	East of England	South West of England	West Midlands
Scenario one: biowaste only	111	111	111
Scenario two: hub-and-pod mean	173	179	175
Max.	199	211	206
Min.	148	143	150
Scenario three: crop only	165	165	165
Scenario four: mixed*	151	153	146

Note: * ***This represents the average cost of the total number of facilities calculated in Table 8.7.***

8.8.2 The levelised cost of carbon mitigation in energy generation

Using a slightly different approach to demonstrate the cost of mitigating 1 tCO_{2eq} to those figures calculated previously (see Table 8-8), the figures in Table 8-18 are calculated using the maximum-value levelised cost of energy (see Table 8-16) and the maximum value of GHG emissions (see Table 8-14). For the ADEE-modelled data, the average of the scenarios based on the regional mean was used (see Tables 8-15 and 8-17) to calculate the cost of mitigating carbon over the project term.

The aim was to compare the cost of mitigating 1 tCO_{2eq} of some renewable energy-generating technologies and traditional energy-generating technologies, such as nuclear and gas, against coal. However, the only levelised cost figures found for coal (DECC, 2013e) were based on the costs of projects starting in 2025, which included CCS, which is not currently operational in the UK. Therefore, the data were normalised against the second most popular energy-generating fossil fuel – CCGT.

Again, this is not an ideal measurement on several levels. First, the costs are based on projected costs, which add a layer of uncertainty. Second, it does not provide a measure of the conversion efficiency, the quantity of energy or CO_{2eq} that is or could be generated/mitigated using a particular technology, or the amount of land required to generate the electricity. Lastly, all of these figures include the value of energy, since the figure used is the cost of energy, and not the cost of carbon. Therefore, to achieve a more accurate figure, the cost of generating electricity needs to be broken down.

Table 8-18 The additional levelised cost of mitigating 1 tCO_{2eq} compared to the levelised cost of mitigating 1 tCO_{2eq} using CCGT

Technology	Cost (£.tCO_{2eq}^{-1} saved)
CCGT	£84.95
Nuclear	£40.85
Offshore wind	£131.92
Standard solar	£422.20
Biomass conversion/Biopower	£57.31
ADEE model AD – scenario one	**£22.08**
ADEE model AD – scenario two	**£56.05**
ADEE model AD – scenario three	**£58.50**
ADEE model AD – scenario four	**£47.35**

In conclusion, after CCGT, nuclear energy remains the most cost-effective method of generating energy and mitigating GHGs. Depending on the method of conversion, utilising biomass could offer the best method of mitigating GHGs. AD (as modelled in this thesis) certainly offers the most effective and cheapest method of GHG mitigation; however, it is not possible to state which of the conversion methods assessed by the IPCC is comparable to AD. Their figures do suggest that, at its worst, biopower could mitigate fewer carbon equivalents than hydropower and ocean energy, and be more comparable to wind energy, concentrated solar power and geothermal energy. The figures provided by this thesis could be improved further (i.e. greater GHG savings) by the increased use of the waste heat from the CHP gensets.

Of the three AD scenarios assessed in this thesis, scenario one is the cheapest method of mitigating carbon (more than half the cost per tonne of carbon mitigated than scenario two, and about half that of nuclear fission). However, scenario one can only generate approximately one-third of the energy generated per annum by scenario two, and can only mitigate about one-third of the GHGs per annum. So, whilst it is cheap, it is not that effective.

8.9 SUMMARY

The central aim of this chapter was to pull together the research and analysis completed in earlier chapters, and to answer the remaining four research objectives.

Section 8.3.2 demonstrated that scenario two would mitigate at least 19, 27 and 19 per cent more GHGs in the West Midlands, the South West and the East of England respectively (compared to the next best, scenario four). Section 8.3.3 showed, that on average, scenario two generated 62 per cent more electricity in each region, when compared to scenario one. In terms of land requirement, scenario one requires very little at all, but when comparing the different scenarios that do utilise land for growing crops specifically for energy, scenario two utilises approximately one-third of the land required by scenario three, or half of the land required by scenario four.

In comparing AD with other energy-generating technologies, AD performs particularly strongly when comparing GHG emissions (savings) per kilowatt hour (see Table 8-14); in terms of comparing the levelised costs, scenario two was comparable to offshore wind and solar, and at a similar cost to ‘dedicated biomass’ (see Table 8-16). However, the scale at which scenario two is deployed essentially means that greater governmental support is required. However, unlike large biomass facilities and scenario three, scenario two has a smaller impact on land for growing food and biodiversity. Scenario one has comparable costs with all except CCGT; however, it is restricted in the quantity of energy it can generate.

This research has shown that AD has an important role to play in helping the government to meet some of its energy and environmental targets. It has demonstrated that in adopting the hub-and-pod concept as a method of deployment for AD, the technology has the best opportunity to maximise its carbon-mitigating and energy-generating potential. This research has demonstrated that AD can not only generate significant quantities of energy, but can also do so without impacting significantly on existing agricultural activities.

There remain, however, a number of barriers related to the deployment of AD using this particular strategy. In particular, bringing hazardous material onto farmland carries considerable risk and uncertainty for the farming, food retail and regulatory sectors. However, farmers had been spreading food waste to land for many years before the foot-and-mouth outbreak changed laws to put a stop to this recycling operation, because of the potential risks associated with transferring exotic diseases across the animal populations and, potentially, to humans. However, the hub-and-pod concept illustrates a method of supplementing low-energy, low-value livestock waste (with their own environmental concerns), using other potentially hazardous biowaste materials, which manages both feedstock types in a safe manner, whilst permitting the valuable recovery of energy and nutrients, in addition to mitigating GHGs across three business sectors.

The biowaste materials are first pasteurised off-site, transported in enclosed tankers and then placed directly into enclosed containers, before the AD process. Following digestion, they are pasteurised for a second time, to ensure that any disease is killed, before being spread to land as a quality (PAS110) fertiliser.

Not promoting the use of AD could deliver a double blow to the rural community, which relies heavily on expensive, off-grid heating fuels, such as fuel oil. Focusing on CHP with significant heat use could provide greater opportunities and a cheaper energy supply for local rural communities, potentially creating a renaissance of sustainable economic activity in these areas.

Mistry *et al*. (2011a) suggested that farmers might accept a lower IRR from their investment decisions (see Section 2.3.2). However, this research shows that only a slight reduction in expected returns could make the investment decision considerably more attractive to both technology users and finance houses. This would mean that the financial integrity of their operation would be deemed to be more robust, and this should allow more farmers seeking funds to gain access to them. A 2 per cent reduction (from 12 per cent to 10 per cent) in the discount rate doubles the NPV at 20 years (see Section 7.4.6). However, farmers are still business people, with a strong understanding of risk, and therefore are unlikely to accept a discount rate below 8 per cent, because of the risks involved in running these facilities and the additional capital required to ensure that pollution from these facilities is minimised (spreading equipment, heat use to outbuildings, income for owner).

The task remains to provide some concluding remarks about this research’s aims (see Section 1.7), to make recommendations from this research’s findings and to suggest possible future work – all discussed in the final chapter.

Chapter 9: Conclusions

'As I looked down, I saw a large river meandering slowly along for miles, passing from one country to another without stopping. I also saw huge forests, extending along several borders. And I watched the extent of one ocean touch the shores of separate continents. Two words leaped to mind as I looked down on all this: commonality and interdependence. We are one world.'

John-David Bartoe, astrophysicist (1944–)

The research undertaken in this thesis was motivated by the environmental and economic challenges provoked by the increasing energy demand and resource competition impacting on the biosphere. In particular, this thesis assesses a single bioenergy conversion technology using life-cycle and economic methods, with the aim of establishing the role that AD may play in England by examining the technology's capacity to generate energy, mitigate GHGs and manage biowaste materials.

To achieve this, a range of studies were undertaken using a number of scientific, social, engineering and geographical techniques. Some of these techniques were novel or had not been used before when assessing AD. The range of techniques adopted in this research to evaluate AD in England, have proved to play an essential role when assessing if bioenergy technologies such as AD truly have sustainable credentials.

Chapter 1 set out some of the environmental and energy challenges that national governments are seeking to address. As part of a suite of measures, bioenergy has been identified as a mechanism that can resolve some of these challenges. Bioenergy is an all-encompassing term for defining energy generated from biomass. It includes a number of conversion technologies, feedstock types and end-uses. Bioenergy has the potential to reduce carbon emissions and has its part to play in helping to improve energy security with DECC (2012a), suggesting that bioenergy could account for up to 12 per cent of the UK energy mix. However, the improper employment of bioenergy also has the power to destroy ecosystems, compete for food grown for man and beast, and be carbon positive — rather than carbon neutral or negative. For bioenergy to fulfil its potential, carbon mitigation and fossil fuel displacement must be proven. AD is one of the bioenergy technologies and was introduced as the technology under investigation.

Chapter 2 identified some of the methods previously employed in assessing AD and identified a number of gaps in the assessment of AD, particularly in determining the environmental and economic function of AD at a regional or national scale. Chapter 3 set out the methods to be employed, highlighting the novel approaches used, such as the employment of a novel computer model combining life-cycle and economic assessments. This approach alone enabled the investigation of what environmental benefits could be achieved under current and future economic constraints.

Chapter 4 highlighted the difficulties and novel approach adopted in this research by including a high number of case studies. The case studies revealed the considerable inherent flexibility of AD. Each case study operated under different conditions, using different feedstock types and mixes at different scales, from a small slurry-only facility not generating any electricity, to a large crop-only facility. However, it was probably some of the other, more innovative operators that were the most interesting as case studies, and more difficult to model.

It is the ability of the technology to treat a diverse range of feedstock types which led to an innovative approach used to establish the capital cost of an AD facility in Chapter 5; this enabled the accurate calculation of both single and co-digestion feedstock facilities, particularly when one of the feedstock types was categorised as a biowaste under ABPR. This was in contrast to existing capital cost appraisal methods (£.kW^{-1} and £.t^{-1}; as compared in Chapter 6), which were shown to have their strengths and weaknesses; however, the method adopted by Mistry *et al*. (2011a), using the quantity of feedstock treated, consistently overestimates CAPEX across all feedstock types, when compared to the data provided by case studies for this research. This may be the reason why Mistry *et al.* underestimated the potential for AD in England and Wales in their research. Jones (2010) accurately modelled CAPEX for the farm-only based feedstock types (which it was designed for), and understandably underestimated sites receiving biowaste.

Chapter 7 demonstrated the importance of establishing a detailed distribution pattern of livestock waste production in England (restricted only by governmental disclosure rules), and a basic distribution of biowaste in the three regions investigated (as few data exist). From these distribution patterns, this research was able to provide a novel evaluation of AD at a regional scale, using a range of AD facility sizes, detailed by an extended life-cyle and economic assessment of treating multiple feedstock types simultaneously.

Chapter 8 explored the regional and scenario results. Two conclusions that can be made when assessing AD are, first, that crop-only AD facilities mitigate the least of all GHG emissions per MW of electricity generated; and second, that it is important (as highlighted by this research) to use several different measures when evaluating bioenergy technologies for their environmental and economic costs or benefits.

9.1 GENERAL DISCUSSION AND CONCLUSIONS

9.1.1 The current role of anaerobic digestion

One of this research's aims was to establish the current primary role of AD in England. Based on the current map of operational facilities in the UK, the role is one of biowaste management. The predominant focus of DEFRA's (2011c) AD Strategy and Action Plan is to ensure the treatment of biowaste generated from the UK's food production, retail and consumer sectors. This falls under scenario one, which neither generates the greatest quantity of energy, nor mitigates the most GHGs of all the scenarios modelled. It is unlikely that support for AD that permitted the quantity of land to be developed for the production of crops grown specifically for AD (as calculated in scenarios three and four) would be maintained, since it could lead to competing forces from food production, as well as the production of other biomass for alternative biomass energy conversion technologies and construction materials.

In effect, the current primary role of AD is waste management that also generates energy and reduces GHGs. Effectively, this means that the waste management companies are receiving double incentives for the reduction of GHG emissions from their sector: a gate fee for the removal of biowaste material being diverted from landfill, and an FIT for the generation of low-carbon energy. There is no incentive for optimising the process to convert waste to energy or to use the digestate material as a fertiliser. The technology falls short of its potential in mitigating GHG emissions from agriculture or fertiliser production and in generating larger quantities of renewable energy. There is also currently no incentive for the increased use of the waste heat from the system. This may change as the government moves towards the upgrade of gas to grid injection. However, it still remains the case, as this research has demonstrated, that a significantly greater quantity of energy could be generated when combining biowaste materials with on-farm waste materials.

There is also the possibility that the technology could fail to achieve its potential of GHG mitigation and energy generation modelled under scenario one, as the waste sector becomes free to construct super-large facilities, able to treat hundreds of thousands of tonnes of biowaste at single sites. This increases the distances travelled by the feedstock and digestate (if used). However, it may be more likely that the digestate is dried and incinerated to generate further energy, thereby removing the closed-loop recycling that AD provides in returning nutrients and carbon back to land.

9.1.2 The potential role of anaerobic digestion

Returning to the discussion in Chapter 1 on UK GHG emissions by sector (see Figure 1-4), the energy-generating, agricultural and waste management sectors collectively emitted approximately 259.4 $MtCO_{2eq}.a^{-1}$ in 2011. Similarly, DECC (2013a: Chapter 5) states that the UK generated 359 TWh in 2013. This research has shown that in three of the eight regions of England, AD could mitigate 4.072 $MtCO_{2eq}$, whilst generating 5.45 TWh electricity per annum using the hub-and-pod method, representing 1.6 per cent and 1.5 per cent of the national figures stated above.

Assuming that the hub-and-pod method of deployment can be achieved nationally, approximately 10.86 $MtCO_{2eq}.a^{-1}$ and 14.53 TWh electricity might be achieved for England alone, not accounting for Scotland, Wales or Northern Ireland. These approximate figures have been established by simply taking the average of the three regions calculated in this research and then multiplying the mean by the eight regions in England. These figures represent approximately 4 per cent of the total electricity generation; a reduction of 4.2 per cent in GHG emissions from the combined agricultural, energy and waste management sectors, based on 2011 UK data (or 20 per cent of GHG emissions from the agricultural sector, if proportioning all the emissions to that sector). This may be seen as an unreasonable calculation to make, but even a relatively large change in the total GHG emissions mitigated or energy generated is likely to produce a relatively small change in the national percentages. This also represents more than 15 per cent of the 15 per cent energy generation target from renewable sources by 2020 (if deployment were achieved by 2020 and the total energy generation remained the same as in 2011).

9.1.3 Not impacting on existing agricultural activities

By deploying the hub-and-pod method in England, considerably more low-energy on-farm waste materials could be treated effectively, aiding the agricultural sector in mitigating more of its GHG emissions. Using biowaste materials as a supplementary feedstock type significantly reduces the requirement for crops grown specifically for energy generation, and provides a valuable income (by way of the gate fee) to the farmer, enabling the financial viability of the facility. There has been considerable drive from the previous Labour government and the current coalition government and its agencies to promote the use of AD (see Chapter 1), sponsoring research (Mistry *et al.,* 2011a and b; Northridge, 2013; Styles *et al.,* 2013) to gain a greater understanding of its processes and assess the potential for AD in the UK. Yet uptake of the technology is relatively low. There remain several concerns about deployment of the technology, particularly in terms of its potential to pollute (Boyd, 2014), and the possible impact on agriculture and food production if increased use of AD were to over-encourage the use of purpose-grown crops within the overall mix of feedstock types. Therefore, further research needs to be completed to examine these uncertainties, and the FIT needs to remain at a level that helps to ensure that the mitigating methods can be paid for by the facility and enforced by the planning authority as part of granting planning for each new facility.

9.1.4 Recommendations for the use of anaerobic digestion within a sustainable low-carbon economy

This research has shown that the technology is complex, and the answers to delivering its potential are no less so. The technology cuts across three business sectors and two governmental departments (three if you include the Treasury). Ensuring that the technology achieves its optimal energy generation and carbon mitigation requires considerable direction, particularly with respect to the agricultural and waste management sectors. Without this, the high-energy feedstock would not be available to safely treat the livestock waste materials. Recommendations for the successful deployment of AD would include:

- putting in place a national source-separating scheme of household food waste on a weekly collection basis (Hogg *et al.*, 2007), to ensure the maximum capture in residential household food waste
- splitting the energy-generating incentive (FIT) from the price of carbon, to allow a more transparent measure and valuation of energy and carbon to ensure that those technologies that provide the greatest environmental benefits are duly compensated
- proscribing the biowaste gate fee for AD facilities receiving more than 3,000 $t.a^{-1}$ (excluding an AD facility clearly acting as the ‘hub’, which should be limited to 20,000 $t.a^{-1}$), to promote the use of biowaste with other feedstock types
- planning should require an AD facility to prove a theoretical minimum carbon saving or a minimum heat use of 10 per cent, in addition to maintaining the digester temperature (or more where there is a clear local heat-load), to promote improved environmental benefits
- planning should require AD facilities to have covered digestate storage tanks to capture ammonia and nitrous oxide emissions
- promoting the use of PAS110 digestate, with recognition within the Entry Level Stewardship and Higher Level Stewardship schemes
- digestate regulations should require the application of digestate to land by injection or trailing hose, to minimise ammonia emissions

- developing a forum and incentives for potential and existing AD users to form cooperatives and find livestock feedstock, and to collaborate in building, owning and running AD facilities and/or hub facilities. This is specifically aimed at the lowest two herd-size brackets (see Appendix 3, Tables A1.12a, b and c; and A1.13a, b and c), although these facilities' farm waste materials could only be supplemented by crops grown specifically for AD. The alternative approach would be to find an affordable route to developing micro-scale on-farm community heating systems.

9.2 FUTURE RESEARCH

A number of conclusions and outcomes from this thesis deserve further investigation.

Further research on crop-only facilities should be completed to reduce the uncertainties that arose from the limited data available for this research.

There are a number of areas in which the primary analyses of environmental impacts from AD need to be researched. One essential aspect of AD that has not been evaluated or quantified in this work is an assessment of the inherent environmental benefits of digestate. Digestate not only returns nutrients to soils, but also carbon. Organic matter, whilst only constituting a small percentage of soils, is an important source of nutrients itself (magnesium, calcium, etc.). Organic matter also plays an essential role in soil structure, stability, water retention (Mannion, 2005) and many other functions of soil (Nortcliff, 2005). It is thought that land degradation may reduce food production by up to 20 per cent if no long-term conservation measures are implemented (FAO, 1984). Bhardwaj *et al*. (2011) concluded in their research that improvements in soil quality corresponded with increased primary production and crop yields. Therefore, by closing the loop of food nutrients and carbon, AD could become part of a conservation process, improving soil quality and sustainable food production. Walsh *et al*. (2012) suggested that the digestate from AD had the potential to sequester carbon in soils, which would further highlight the benefits associated with AD. Some current fieldwork is being completed using digestate, funded by WRAP, but until the results have been analysed over a sustained period and the increase in productivity measured, it will not be possible to quantify the total benefits and/or costs associated with the technology. Once primary research has been completed on the inherent properties and benefits to soil, the agricultural and economic benefits should also be calculated and modelled accordingly.

An assessment of the other five regions should be made to establish a more accurate picture of the GHG mitigation and energy potential of AD in England, as well as the potential costs of not adopting a hub-and-pod method. This may also help to establish the impact of utilising the biowaste generated from England's largest cities, such as London and Birmingham, in certain regions, and may provide insight as to which regions could best utilise this waste stream within reasonable transport boundaries.

Completing an in-depth economic assessment of the impacts of each scenario on the rest of the economy would enable the impact of growing crops specifically for energy to be measured against the impacts of increased employment, generation of renewable energy and carbon mitigation.

Finally, investigation of the alternative options for using biogas, such as its purification and direct injection into the grid system, or use as a transport fuel, might be considered to compare against the results presented in this thesis. Completing a full economic and life-cycle investigation of these different fuel pathways may help to inform policy of the most efficient pathway for the deployment of AD that maximises its carbon mitigation and energy-generating potential.

9.3 CONCLUDING REMARKS

There are still a number of uncertainties associated with AD, including the use of biohazardous materials in an agricultural arena, which is dealt with here by treating the materials off-site; and the potential for fugitive emissions of ammonia and nitrous oxide, which impact on health and global warming respectively. Yet ammonia and nitrous oxide emissions are high from cattle and pig farms without treatment by AD as well; what is important is that a method of treatment is provided, of which AD is one option.

Currently, slurry stores are often not capped and sealed, and spreading these materials to land can often be carried out with inappropriate equipment. Additionally, all of these mitigation measures are expensive, when income in the livestock sector is particularly low. AD provides a solution which offers the farmer a suitable income that could facilitate the purchase of equipment and implementation of mitigating measures required to deal with these materials efficiently.

The question remains why, with the recent level of stimulus in terms of research completed, strategies developed and incentives in place, has there been relatively little uptake of the technology? Could this be due entirely to the current economic environment, or are there other forces at play that are preventing its deployment? So perhaps the question that should be asked is: are the right policies in place to ensure that AD achieves its potential, or is there a dominant policy that is driving AD towards one particular function or role, to the detriment of the benefits derived from its other roles?

This thesis has demonstrated that AD has an important role to play in energy generation (potentially providing 4 per cent of total UK electricity generation; 23 per cent of the target for energy from biomass set by the CCC (see Section 1.3)) and carbon mitigation (potentially 4.2 per cent of the combined 2011 GHG emissions of the agricultural, energy and waste management sectors) in England. The benefits discussed here do not extend to the economic benefits that over 2,339 facilities calculated for the three regions of England investigated, or an estimation in excess of 5,000 potential AD facilities for the whole of England, could bring to the economy, raising our construction and manufacturing base, securing long-term sustainable farming and energy for rural communities, and encouraging businesses to move to rural areas, whilst reducing GHG emissions across the UK.

This thesis has highlighted a number of issues that could occur when either the wrong policies are adopted (FIT degression) or the right regulations not put in place (slurry/digestate management). AD has the potential to compete for land for growing food crops, and could potentially act as a source of GHGs, as well as other polluting gases. Some of these gases are already produced on farms, however, and this research suggests that AD acts as a suitable method of controlling these emissions, whilst providing the farmer with an income that would enable him to put in place appropriate equipment and mitigating measures.

There is a fine line between using biomass for generating energy and for the production of food and building materials. It is hoped that this thesis has contributed some knowledge towards the multifunctioning role that AD could have as a sustainable technology, converting biomass into energy and mitigating GHGs from the agricultural, energy and waste sectors in England. Thornley *et al*. (2009) emphasised the importance of having accurate information relating to the relevant impacts of entire bioenergy systems, so as to support the choices made in relation to the development of new bioenergy capacity. It is hoped that this research has indeed added to that knowledge and will help with these developmental choices.

APPENDIX 1 REGIONS

South West of England

The South West is not only one of the wettest regions in England, but it also has one of the greatest variations in rainfall, with average rainfalls of 1,000 mm in the lowlands and 2,000 mm on higher ground), which impacts on the type of farming activities possible in the region.

The South West has the largest agricultural area of all the government regions, at just below 20 per cent of the total area. This covers a wide range of agricultural environments, with 8 per cent of the region covered by Less Favoured Areas (LFAs), and one-third being designated nationally for their landscape qualities (two National Parks, seven Environmentally Sensitive Areas, 14 Areas of Outstanding Natural Beauty, and just under one-quarter of the Sites of Special Scientific Interest in England.

In contrast to the East of England, Natural England (RBR, 2012c) estimates that over 62 per cent of all farmed land in the South West is managed as part of an agri-environment scheme, with 83 per cent covered under the Entry Level Stewardship – 26 per cent of the national agreements.

The South West is also very important to organic production methods. DEFRA data on organic farms for 2011 suggest that the South West has over 170,000 ha of organic or in-conservation land, which is equal to 10 per cent of its agricultural area (RBR, 2012c). The region is predominantly grassland (63 per cent of the agricultural area), with the majority being over five years old. Nearly one-third of the nation’s cattle and over 20 per cent of its sheep population are reared in the South West, and less intensively so than in other regions, but accordingly, fewer crops are grown, covering just 12 per cent of the area.

However, in contrast to other regions, the South West has a greater proportion of small and very small farms (<20 ha), and fewer large farms (> 100ha) than any other region. This fact alone has a bearing on the use of AD in this region, and points to the region requiring special consideration if farm GHG abatement were to be extended to the smaller farms. The initial appraisal for this region only deals with the larger farms; however, it is the smaller farms, which do not produce large quantities of slurries and manures individually each year, that pose the greatest challenge. Most of these farms have limited cash flow and are not able to raise the funds to build a digester. In fact, the farm business income (RBR, 2012c) for the South West in 2011/12 has a per farm equivalent of 87 per cent of that of the whole of

England, which is mainly due to the region's high percentage of grazing livestock farms, which produce the lowest income of any type of farming.

With regard to dairy farming, however, RBR (2012c) reported (in the Farm Business Survey) an increase in farm business income and fund surpluses, mainly as a result of repaid loans, fewer creditors and improved current account balances for 2011/12. The Farm Business Survey also suggested that there was an improved range of investment, with upgrading of facilities, along with an expansion of herd sizes.

Cattle grazing occurs in two main areas: the LFAs of the higher lands (moors) and lowland areas. Farms in the first category come within the Severely Disadvantaged Areas and Disadvantaged Areas of the South West. The average farmed area is approximately 130 ha, of which one-third are tenanted beef cattle farms. This type of agricultural activity is the smallest of all types in the region; however, it does represent the largest output of the region, at 68 per cent, with 9 per cent of this income being received from various agri-environment schemes. The lowland farmers have smaller farms, averaging only 85 ha, predominantly of grassland. Total farm business incomes for lowland farmers were also the smallest of all farm types. Commentary on pig and poultry farms was unavailable from the Farm Business Survey, since too few farms participated in the survey from this region.

The South West of England is as important to the country as a whole in terms of livestock production as the East of England is to crop production, contributing 24.4 per cent and 10.7 per cent respectively to national output for livestock and crop production (see Table 3.2). However, it is interesting to note that the South West contributes more than 5 per cent less in terms of farming income than the East of England, even though the GVA of each region is similar.

West Midlands

Home to over 5.6 M people, the West Midlands is predominantly a rural shire region of England. However, over half of its population lives in large conurbations, including Birmingham, Coventry and Wolverhampton, the former being the second most populous city in the UK (Eurostat, 2014).

The West Midlands makes a significant contribution to England's overall regional output (see Table 3.2), contributing 10.3 per cent and 12.5 per cent of crop and livestock national income per annum. Of the total population of the region, 1.4 per cent are employed in the agricultural and related sectors. In 2010, 13,689 businesses covered in excess of 915,400 ha (70 per cent of the land in the region); 49 per cent was in arable rotation, set-aside/fallow, or leys, whilst a further 45 per cent was under permanent grass; 9.3 per cent of these farms were less than 5 ha in size. The region accounts for 14.4 per cent of the cattle and sheep in England, but also 15.9 per cent of the total potato crop and 12 per cent of horticultural crops too. Agriculture accounts for 0.87 per cent of the region's GVA and 11.8 per cent of England's total.

The average farm size in this region is 124 ha, as compared to the English average of 149 ha. Tillage was 25 per cent lower in 2011, reflected by a 6 per cent increase in permanent pasture and greater popularity for livestock enterprises in the region. The average farm business in the region was £67,708 (£1,900 above the English average). The average dairy farm size was 112 ha, supporting 128 dairy cows and heifers in milk. This farm size and stocking rate is slightly less than the English average. Whilst there was a 15.6 per cent increase in fixed costs and a similar increase in vet and medicine costs, the farm business income saw a healthy increase, similar to the other regions for this activity.

East of England

The East of England is the second largest agricultural region chosen in this research, and one of the flattest, coolest and driest regions of England (annual rainfall of between 450 and 750 mm). These factors all influence the type of farming activities suitable for this region over the others.

The focus is on combinable crop production in the region due to the region's climate, topography and suitable soil types. Fenland and silt soils in the north permit the production of sugar beet, potatoes and field-scale vegetables. The East of England is by far the greatest contributor (in terms of pounds sterling) to crop outputs of all the English regions, contributing 26 per cent of all income from crop area across England (see Table 3.2). However, it is also an important contributor in terms of livestock outputs (12.3 per cent), particularly pig and poultry, due to the proximity of grain production for feed. There are still large grassland areas in Hertfordshire and in the Norfolk Broads, which are suitable for grazing, and which could be used for growing grass for AD.

APPENDIX 2 QUESTIONNAIRES

BUILDING AND INFRASTRUCTURE	Cost	Notes: e.g. If not required, please explain why not, or reasons for any addition equipment i.e. particular feedstock/process
AD Digester	£	
Separator	£	
Feedstock Storage	£	
Digestate Storage tank	£	
Grid Connection	£	
Start/Backup boiler	£	
Water Connection	£	
Groundwork	£	
Reception building	£	
Silage clamp	£	
Weighbridge	£	
Grease Trap	£	
Wheel Wash	£	
Roadways	£	
Heat-use system costs	£	
Mixing Pit	£	
Project Development	£	
Professional costs	£	
	£	
	£	
Grant Assistance 1/.	£	
2/.	£	
Total AD & Connection	£	
MACHINERY CAPITAL		
CHP Generator	£	
Cables and Pipes	£	
Heat Exchanger	£	
Biogas Scrubber	£	
Fencing	£	
De-packaging	£	
Cleaning Technology	£	
De-gritter	£	
Odour management	£	
Front end loader	£	
Pumps	£	
Shredder	£	
Pasteuriser	£	
	£	
Grant Assistance	£	
Total Machinery Costs	£	

OPERATIONAL COSTS Write-off Period	Years	
Building and Infrastructure		
Machinery Capital		
Annual running costs	**£**	
Labour		
Regular & Casual		
Management		
Plant Costs		
Maintenance		
Of AD Plant		
Of CHP		
Vehicle & Licences		
General Overheads		
General Insurance		
Transport		
Water		
Assurances		
Professional Fees		
Testing Fees		
EA Fees		
Spreading Licences		
Office and Telephone		
Miscellaneous		
Total		
Land Building and Finance		
Rent		
Rates		
Total Fixed Costs		

Finance	
Base Rate	%
Over Base	%
Total Lending Rate	%
Initial capital funded by bank	%
Other forms of finance including owner's capital, shares, etc.	
Finance Term (years)	

Other data	
kW_e output	
kW_h output	
Agricultural Diesel Cost (ppl)	£
Electrical parasitic load (kWh/t input)	
Thermal parasitic load (%)	%
Gate Fee per tonne	£
Cost per m^3 water	£
Quantity of water reqd. p.a. (m^3)	
Applicable compensation mechanism (FITs or ROCs)	
Will RHI be sought	
Heat uses	
No. of f/t equiv. staff per week	

Feedstock	Tonnage	Distance travelled (miles)

QUESTIONNAIRE

START-UP & EQUIPMENT

Did you have any particular issues during planning?

How did you overcome them?

Have you had any particular issues with your machinery and what was it?

BUSINESS MODEL

Do you utilise the heat produced from your engines (CHP)? To what extent? If not, do you have plans to?

Do you currently have spare capacity in your digester? Was this planned?

Has your business model changed at any time? i.e. because of feedstock costs, gate fee reductions or tariff changes? Were there other reasons?

COMPANY POLICY

What were your reasons behind choosing to build an anaerobic digester?

Has it met all the outcomes (energy generation, fertiliser substitution, diversification) you set out to achieve?

What do you do with the digestate?

Did you need to change your farming practices/machinery? Costs?

What is your biggest worry about running the digester now or in the future?

				fertiliser costs replacement kg/ha			Sprays (rough guides to requirements) dependent on season kg/ha				
Sector	**Substrate**	**UK Crop Yields Tonnes/ha**	**Cost per tonne**	**Phosphorus**	**Potash (K_2O)**	**Nitrogen**	**herbicides**	**fungicides**	**insecticides**	**growth regulators**	**other!**
Oils and fats	Linseed oil*										
Oils and fats	Rapeseed oil*										
Oils and fats	Soya Oil										
Oils and fats	Sunflower Oil										
Grain / Seed	Barley grain*										
Grain / Seed	Maize grain; dry										
Grain / Seed	Field bean grain										
Grain / Seed	Grain Peas										
Grain / Seed	Mixed grain										
Grain / Seed	Oat grain*										
Grain / Seed	Rye grain										
Grain / Seed	Soy beans seeds steam-heated										
Grain / Seed	Sunflower seed										
Grain / Seed	Wheat grain*										
Vegetables	Potatoes*										
Vegetables	Sugar beet; fresh*										
Vegetables	Cauliflower										
Vegetables	Fodder beet										
Vegetables	Fodder carrot										
Vegetables	onions										
Vegetables	Molasses (sugar beet)										
Silage	Grass silage										
Silage	Maize Grain Silage (Crimped seed)										
Silage	Maize silage										
Straw/Hay	Barley straw										

Straw/Hay	Clover hay 1st Cut										
Straw/Hay	Meadow Hay										
Straw/Hay	Oat straw										
Straw/Hay	Wholecrop Wheat										
Straw/Hay	Wheat straw*										
Straw/Hay	Barley straw NH3 treated										
Straw/Hay	Barley straw NaOH treated										
Straw/Hay	Oats straw NH3 treated										
Straw/Hay	Wheat straw NaOH treated										
Straw/Hay	Wheat straw NH3 treated										
Fresh Cut	Meadow grass green										
Fresh Cut	Sunflowers green start of flowering										
Liquid Manure / Muck	Cattle Muck; fresh										
Liquid Manure / Muck	Horse excrement										
Liquid Manure / Muck	Dairy cow slurry										
Liquid Manure / Muck	Dairy slurry inc. fodder remains										
Liquid Manure / Muck	FYM										
Liquid Manure / Muck	Pig slurry										
Liquid Manure / Muck	Pig muck										
Liquid Manure / Muck	Poultry excrement										
Liquid Manure / Muck	Sheep muck										

What crops do you grow specifically for the digester? What are the alternative crops you could/would grow?

AMENDED CASE STUDY QUESTIONNAIRE (2013)

BUILDING AND INFRASTRUCTURE	Cost	Notes: e.g. If not required, please explain why not, or reasons for any addition equipment i.e. particular feedstock/process
AD Digester (and number)	£	Size m^3 ( ) CONCRETE STEEL
Separator	£	YES NO
Feedstock Storage	£	Size m^3
Digestate Storage tank	£	Size m^3
Grid Connection	£	Approx. distance from sub-station
Start/Backup boiler	£	
Water Connection	£	
Groundwork	£	
Reception building	£	
Silage clamp	£	Size m^3
Weighbridge	£	YES NO
Roadways	£	
Heat-use system costs	£	
Mixing Pit	£	
Project Development	£	
Professional costs	£	
	£	
	£	
	£	
Total AD & Connection	**£**	
MACHINERY CAPITAL		
CHP Generator	£	
Cables and Pipes	£	
Heat Exchanger	£	
Biogas Scrubber	£	
De-gritter	£	
Odour management	£	
Front end loader	£	
Pumps	£	
Separator	£	
Pasteuriser	£	PRE- POST-
Consumables	£	(such as Ferric chloride)
	£	
Total Machinery Costs	**£**	

Operational Costs		
Write-off Period	**Years**	
Building and Infrastructure	25	
Machinery Capital	10	
Annual running costs	**£**	**hrs**
Labour		
Regular & Casual		
Management		
Plant Costs		
Maintenance		
Of AD Plant		
Of CHP		
Transport		
Water		
Professional Fees		
Testing Fees		
EA Fees		
Spreading Licences		
Subtotal		
Land Building and Finance		
Rent		
Rates		
TOTAL FIXED COSTS		

Other data	
Engine size	
Electrical efficiency	
Temp range of digester	38–40 °C
Is the waste heat use around the farm of nearby businesses? YES NO	
What percentage	%
Where is it used? **(*e.g. farm buildings, grain dryer*)**	
Digester and Pasteuriser	
Previous heat source on-site? CHP OIL GAS	
Hydraulic retention period (d)	
Cost per m^3 water	£
Quantity of water reqd. p.a. (m^3)	
Applicable compensation mechanism (FiTs or ROCs)	
Will RHI be sought?	
Farm size	ha
General soil Index value across farm	
No. of livestock	

Feedstock (please state if off farm with *)	Tonnage	Distance from source (miles)	Cost to Purchase (£/t)	Gate Fee received (£/t)

Finance	
Base Rate	%
Over Base	%
Total Lending Rate	%
Initial capital funded by bank	%
Finance Term (years)	

Other crops grown on farm	Tonnage	Land required (ha)

If you have had your feedstock analysed, please provide the following information for each feedstock type:

feedstock	Dry matter content (TS%)	Volatile solid %	CH_4 yield L/kg VS	Biogas yield L/kg VS	NPK content g/kg (total and available)

QUESTIONNAIRE

START UP & EQUIPMENT

Did you have any particular issues during planning?

How did you overcome them?

Have you had any particular issues with your machinery and what was it?

Did you have issues finding funds (if required), and how did you source them?

BUSINESS MODEL

Do you utilise the heat produced from your engines (CHP)? To what extent? If not, do you have plans to?

Do you currently have spare capacity in your digester? Was this planned?

Has your business model changed at any time? i.e. because of feedstock costs, gate fee reductions or tariff changes? Were there other reasons?

COMPANY POLICY

What were your reasons behind choosing to build an anaerobic digester?

Has it met all the outcomes (energy generation, fertiliser substitution, and diversification) you set out to achieve? Did you achieve the return on investment that you desired?

What do you do with the digestate? If spread to your land, have you seen increased agronomic benefits over and above mineral fertilisers? Do you still require to purchase mineral fertiisers?

Did you need to change your farming practices/machinery? Costs?

What is your biggest worry about running the digester now or in the future?

What crops do you grow specifically for the digester? What are the alternative crops you could/would grow?

CASE STUDY FEEDBACK FORM

17 April 2013

You may remember I visited you about this time last year to request data for my research in anaerobic digestion. Since then I have been busy trying to build a model which would provide several environmental and economic outputs. Based on the information provided by you during my visit I have produced several figures which I hope you may be able to agree with. There may also be some figures (such as GHG emission savings) which you cannot confirm, but you might find them of use in terms of marketing your business etc. if the other numbers agree.

One thing I have learnt over the last 12 months is that dependent on an individual AD business's set-up, feedstock supply and the biological outputs of AD are very dynamic, so I am not expecting an exact answer in terms of 'Yes, we used that amount of feedstock and generated that amount of electricity'. However, if the inputs are radically different, then many of the outputs will also be radically different, so please let me know if it is the input or output which is causing the difference.

I have made several assumptions throughout my model as this has been essential to fill certain information gaps and items which could not be measured. Some of these are generic and embedded in the model and others are case-specific. I have included a few for you to check.

Why am I asking you to help me with this?

The main reason is to help me validate how accurate this model is and make sure the initial time you gave me is not wasted. Please have a look at the information provided below about your individual AD plant and let me know just how close my model is to reality.

This will help me with the next stage of my research, understanding the future role of AD in the UK by building a series of different scenarios based on current and potential future policy and economic conditions and incentives, so your commentary now is essential if my model is to be of use for this next stage. Almost any observation of yours will be very helpful to me.

If there is anything that you would like me to explain for any reason, please do not hesitate to get in contact; in fact, I will endeavour to contact you over the next 2 weeks to have a chat.

I do appreciate that you are very busy, but if you could spare a few minutes it would be much appreciated.

Many thanks.

Best wishes

Robert Tickner
University of East Anglia

	Feedstock	Quantity (t/annum)	Cost £/t
A			
B			
C			
D			
E			

	Assumption		Actual (if different)
1	Average gate fee received for municipal and commercial wastes	£	
2	Average distance from feedstock supplier	4 miles	
3	Soil index value across your farm of:	1	
4	Digestate removed in 10 tonne loads		
5	Nutrients provide digestate with value which is accounted for in outputs dependent on nutrient mix.		
6	Waste heat used or sold/valued at (plus RHI if relevant)	4.5p kWh	
7	Engine's electrical generation efficiency		
8	Number of years' financing		
9	Percentage of external capital received		
10	Required digester size calculated (and advised) m^3		

Outputs	Value	Actual (if different)	Unit
Digester loading rate			$tFM/m^3/day$
Retention time			Days
Biogas produced			m^3/annum
Methane Produced			m^3/annum
Tonnes of Digestate produced Used on-farm Exported off-farm			t/annum t/annum t/annum
Total Capital expenditure	£		£
Total OPEX (fixed costs)	£		£
Income from electricity and heat (respectively)	£e	£h	£
This is based on some electricity used on the farm (see below)at a value of FiT + 10p/kWh			
Gate fee income			£
Internal rate of return (@20 years)	%		%
Net Present Value with 12% discount rate (@ 20 years)			£
Total electricity generated			kWhe/annum
On-site electricity used: parasitic requirement, dairy, separator, farmhouse or other on-site relevant businesses			kWhe/annum
Total GHG emissions from process emissions from the AD plant and those processes directly associated with it			$kgCO_2e$/annum
Total emissions saved from using the AD technology			$kgCO_2e$/annum
Energy Balance of the AD plant incl. crop production, feedstock transport, spray and fertiliser use/production, embodied energy of the digester and associated capital equipment.			GJ/annum

Additional comments:

- 0.0% of heat generated is used at the farm @4.5p/kWh_t for washing down the dairy unit and surroundings
- Expected NPK values of the digestate (N – kg/t: P – kg/t: K – kg/t) value £p per tonne.

APPENDIX 3 MODEL PARAMETERS AND ASSUMPTIONS

Table A1.1 Capital and operational parameters

Parameter	Value (£)		
Digester Engine Size	<400	>400<1000	1000+
Digester costs	£115/m3 (Food waste)		£80/m3 (other)
Secondary Digester(s)	As above		
Silage clamps (calc. by the model)	£50/m^2 + £365/m for walls (4 m tall)		
Reception Hall	450000		
Weighing bridge	25000	25000	25000
Ground works*	125000	275000	750000
Grid Connection	50000	85000	150000
Professional costs*	30000	60000	80000
CHP generator (incl. engineering)	225000	350000	800000
Engineering (civil & mech. not incl. above)	15000	50000	150000
Cables and Pipes	40000	60000	90000
De-packaging equipment		96000	196000
Pasteuriser	95000	180000	280000
Electronic controls	45000	65000	80000
Pumps (15% uplift if higher DM content)	37500	55000	85000
Separator	10000	15000	30000
Digestate holding tank	£60/m^3		
Digester Engine Size	<500	>500<1000	1000+
Labour*	7500	15000	50000
Management	7500	15000	25000
Accounting	1000	2000	3500
Testing Fees*	2500	4500	6000
EA Fees*	2500	5000	12500
Spreading Licences where necessary	£1200 per 50 ha		
Consumables (dependent on feedstock)*	2500	8000	10000
Other business expenses (training, Stationery etc.)	2500	6500	12500
Business rates and rent	12000	35000	50000
Feed-in Tariff applicable per engine size	15.16p.kWh^{-1} (<250kWh)	14.02p.kWh^{-1} (>250<500kWh)	9.24p.kWh^{-1} (>500kWh)
Renewable Heat incentive (RHI)	7.1 p.kWh^{-1}		
Annual operating time	8040hrs (335 days)		
Insurance	>£2M@ £0.65/£100, <£2M@ £0.85/£100		
Capital maintenance	1.5%		
Machinery capital maintenance	£0.01p per kWh		
Lifespan – Buildings	20 years (although this could be up to 10yrs more)		
Lifespan – Machinery	9 years(although this could be up to 6yrs more)		
Interest rate	5.5% over 10yr gilt of 2.5%		
Finance term and loan % of capital cost	10 years 80%		
Inflation	2.5% over term of project		
Digester Size m^3	Based on the retention period x average feedstock rate		
*The treatment of untreated municipal and C&I wastes can triple these figures.			

Table A1.2 Fertiliser and spray assumptions

Sprays, fertilisers and operations for ON-crops not used in the digester and used for example as animal feed etc. are not accounted for in the model.

Average cost, energy and emissions of fertilisers and Sprays

Source: Nix (2012), DEFRA (2010a) and Cropgen (2004b)#*

	Cost (£/kg)	Nutrient availability*	Energy in Production (MJ/kg) #	Emissions $kgCO_2e/kg$ #
Nitrogen N (NH_4^+– N)	£0.99p	40%	40.6	6.695
Phosphates P_2O_5	£0.95p	50%	15.8	2.606
Potash K_20	£0.58p	90%	9.3	1.534
Herbicides active ingredients (a.i.)	£32.10p		264	43.537**
Fungicides (a.i.)	£21.03p		168	27.705**
Insecticides (a.i.)	£17.36p		214	35.291**
			**+15% allowance for the excipient	

Table A1.3 Capital configuration assumptions

	Parameter
Digester	STEEL: Circular with 3:1 diameter: height ratio
	CONCRETE: Circular with 2:1 diameter: height ratio
Pasteuriser	70°C Operating temperature
	Duration 1hr @ above temperature; 2 hrs total
Silage Clamp	$1.5tm^{-3}$ Bulk density of feedstock (or $3.2tm^{-2}$)
	3m wall height (silage raised to 4m on average)
	<5k feedstock, 30Lx10W: >5k feedstock, 75Lx30W
	100mm thick concrete walls laid on aggregate
	250mm thick concrete floor
Digestate Storage	Assumed 6 months storage required
	$1m^3$ is equivalent to 1t digestate
	Wall height is 4m (buried 3m into ground)

Table A1.4 Thickness of materials used to calculate volumes of materials used

Structure	Material	Thickness (m)
wall	Concrete	0.250
	insulation	0.100
Floor	Concrete	0.250
	insulation	0.100
Roof	Concrete	0.200
	insulation	0.100
Miscellaneous	Steel Inner Layer	0.0045
	Steel Outer facing Layer	0.0007
	Glass coating	0.0003
	Steel rebar diameter	0.012

Table A1.5 Energy data

	GWh	%
Coal	102.3	28.1
Oil	4.4	1.2
Gas	171.8	47.2
Nuclear	56.5	15.5
Hydro and other fuels	2.5	0.7
wind	10.2	2.8
Other fuels	13.5	3.7
net imports	2.7	0.7
total	363.9	100

Source: DUKES (2011: Table 56: All generating companies, supplied gross electricity fuel mix)

Table A1.6 Emission factors from UK general electricity mix, diesel and natural gas

Emission parameter	Source and value (KgCO_{2eq} per unit)				
	General Electricity mix (per kWh)	Diesel (per litre)	Burning Oil (Kerosene) Per litre	Biomethane (Per kg)	Natural gas (per m^3)
Total CO_{2eq}	0.59368	3.2413	3.0714	1.3282	2.2422
CO_2	0.52114	2.6569	2.5319		2.0280
CH_4	0.00025	0.0009	0.0055		0.0030
NOx	0.00323	0.0191	0.0069		0.0012
Total Direct	0.52462	2.6769	2.5443	0.0052	2.0322
Total Indirect	0.06906	0.5644	0.5271	1.3230	0.2100

Source: DEFRA (2012: Annex 1, Table 1b; Annex 3, Table 3c; and Annex 9, Table 9b)

Table A1.7 Conversion factors calculated from DUKES (2011)

natural gas energy density	0.7	kg/m^3	Km to miles	0.621371
natural gas	10.3	kwh/m^3	Miles to km	1.609344
natural gas	0.02697	m3/MJ	Gallons to Litre	0.219969
natural gas	37.08	MJ/m^3	Litres to Gallon	4.54609
diesel (volumetric energy density)	35.86	MJ/litre	(diesel to MJ)*	
Net Calorific value of diesel = 42.85GJ/ton		There are 1195l diesel per ton		
MJ to kWh	0.277778			
Methane	35.6	MJ/m^3	9.8888968	$kWh_{eq}CH_4m^3$
kWh to MJ	3.6			

*** DEFRA (2011: p.47, Table 11)**

Table A1.8 A Sample of feedstock substrates used within the model

Substrate	Dry Weight (TS %)	Biogas M^3/t FM	% VS	CH4 L/kg VS	CH_4% of gas	M^3 CH_4 t/FM	Biogas l/kg VS	N (kg/Mg FM)	P (kg/Mg FM)	K (kg/Mg FM)
Non-Farm Inputs										
Leftovers; Rich in fat	19.70%	159.83	92.30%	512.00	58%	93.10	879	8.1	1.3	3.4
Old bread	65.00%	482.06	97.20%	763.00	53%	482.06	763			
Fruit and veg waste	15%	57.00	76%	280.00	56%	31.92	500	5.94	0.48	11.7
Linseed oil	99.90%	1222.55	99.90%	833.00	68%	831.33	1225			
Dairy trade effluent	3.45%	11.95	99.00%	213.50	61%	7.29	350	2.3	2.06	0.64
Farm Waste Products								**Nutrient excreted by housed animals (RB209)**		
Cattle Muck; fresh	27.80%	97.73	83.70%	209	50%	48.63	420.00	5.17	2.24	3.97
Horse excrement	27.80%	97.73	83.70%	209	50%	48.63	420.00	5.17	2.24	3.97
Dairy cow slurry	10.10%	32.56	79.40%	181	45%	14.52	406.00	5.17	2.24	3.97
FYM	27.80%	97.73	83.70%	209	50%	48.63	420.00	6	3.5	8
Pig slurry	5.70%	22.71	72.30%	336	61%	13.85	551.00	6.6	3.5	3.5
Farm products/crops								**Nutrient removal (RB209) kg/t fresh matter**		
beans - grain	87.00%	651.30	96.10%	420	54%	351.15	779.00	41	11	12
grass Fresh	31.30%	136.88	91.30%	268	56%	76.59	479.00	3.8	2.1	7.2
lucerne silage (alfalfa)	30.00%	143.10	90.00%	292	55%	78.84	530.00	5.5	1.5	6.5
maize silage	30.70%	203.76	95.50%	365	53%	107.01	695.00	3.8	1.6	4.5
potatoes (main crop)	22.00%	156.25	93.70%	389	51%	80.19	758.00	3.5	1	5.8
barley whole crop silage	29.80%	160.60	92.60%	375	64%	103.48	582.00	3.5	8.6	11.8
sugar beet - beet	20.00%	140.72	92.70%	388	51%	71.94	759.00	1.8	0.8	1.7
wheat – whole crop	39.60%	195.08	92.60%	298	56%	109.28	532.00	3.5	8.4	10.4

Table A1.9 Feedstock material bulk densities

Material	Bulk density (kgm^{-3})
Food waste[#]	500
Grass silage (24% DM)	675
Grass silage (30% DM)	615
Maize silage (22% DM)	820–850
Maize silage (30% DM)	750–780
Fermented whole crop (40% DM)	450–590*
Straw*	150
Potatoes*	750
Brewers grains	1000–1300
Apple pulp	350–400
Chicken manure (70% DM)	500
Cattle slurry	900
Farmyard manure	900

Adapted from DairyCo (2011); [#]WRAP (2010a); DEFRA (2010a); *Köttner et al. (2008)

Table A1.10 ABPR requirements for composting and biogas plants

System	Minimum temperature	Minimum time	Maximum particle size
Composting (closed reactor)	60 °C	Two days	400 mm
Biogas	57 °C	Five hours	50 mm
Composting (closed reactor) or biogas	70 °C	One hour	50 mm
Composting (housed windrow)	60 °C	Eight days, during which windrow must be turned at least three times at intervals of no less than two days	400 mm

Source: https://www.gov.uk/dealing-with-animal-by-products Accessed 4 June 2013

Table A1.11 a, b and c National livestock data of dairy and beef cattle and pig farms (DEFRA, 2013a)

Numbers of dairy cows and farmed area

Region	1 to 99 dairy cows			100 to 199 dairy cows			200 to 349 dairy cows			350 to 499 dairy cows			500 to 699 dairy cows			700 dairy cows and over			Total Dairy cows		
	Holdings with dairy cows	Number of dairy cows	Farmed area (ha)	Holdings with dairy cows	Number of dairy cows	Farmed area (ha)	Holdings with dairy cows	Number of dairy cows	Farmed area (ha)	Holdings with dairy cows	Number of dairy cows	Farmed area (ha)	Holdings with dairy cows	Number of dairy cows	Farmed area (ha)	Holdings with dairy cows	Number of dairy cows	Farmed area (ha)	Holdings with dairy cows	Number of dairy cows	Farmed area (ha)
North East	304	4 358	49 509	46	6 305	7 809	#	#	#	#	#	#	0	0	0	0	0	0	366	14 825	62 359
North West and Merseyside	1 991	69 507	169 496	790	111 088	98 119	255	63 660	46 144	43	17 554	9 732	#	#	#	#	#	#	3 096	273 258	330 202
Yorkshire and the Humber	1 177	30 527	102 992	256	34 644	36 195	85	21 296	17 062	12	4 812	2 156	0	0	0	0	0	0	1 530	91 279	158 404
East Midlands	966	25 199	84 991	265	36 379	43 630	56	14 224	12 552	#	#	#	#	#	#	#	#	#	1 298	80 628	143 780
West Midlands	1 537	42 470	111 384	495	69 084	64 154	177	45 466	35 864	20	8 131	5 321	7	3 921	1 798	0	0	0	2 236	169 071	218 520
Eastern	398	5 300	40 332	70	9 802	23 619	#	#	#	#	#	#	0	0	0	0	0	0	488	20 477	73 332
South East including London	766	11 134	72 783	193	27 571	52 717	78	20 073	27 067	25	10 520	15 017	#	#	#	#	#	#	1 070	74 481	171 640
South West	3 252	93 291	261 030	1 254	177 350	190 652	401	101 359	89 950	80	33 013	29 771	30	17 235	12 861	14	12 180	7 363	5 031	434 428	591 627
England	**10 391**	**281 785**	**892 516**	**3 369**	**472 224**	**516 894**	**1 085**	**274 369**	**241 955**	**191**	**78 248**	**64 867**	**59**	**34 029**	**22 315**	**20**	**17 793**	**11 317**	**15 115**	**1 158 447**	**1 749 864**
AVERAGE		**27**	**86**		**140**	**153**		**253**	**223**		**410**	**340**		**577**	**378**		**890**	**566**			

Numbers of cattle and farmed area

Region	1 to 99 cattle			100 to 199 cattle			200 to 349 cattle			350 to 499 cattle			500 to 699 cattle			700 cattle and over			Total Beef Cattle		
	Holdings with cattle	Number of cattle	Farmed area (ha)	Holdings with cattle	Number of cattle	Farmed area (ha)	Holdings with cattle	Number of cattle	Farmed area (ha)	Holdings with cattle	Number of cattle	Farmed area (ha)	Holdings with cattle	Number of cattle	Farmed area (ha)	Holdings with cattle	Number of cattle	Farmed area (ha)	Holdings with cattle	Number of cattle	Farmed area (ha)
North East	1 145	47 200	136 987	460	65 372	91 028	277	73 073	79 689	75	30 869	28 854	48	28 227	20 308	30	32 731	32 809	2 035	277 471	389 676
North West and Merseyside	3 561	135 285	233 872	1 466	212 815	166 349	1 039	275 010	132 509	358	148 387	62 067	171	99 457	38 718	87	81 891	25 220	6 682	952 846	658 735
Yorkshire and the Humber	3 306	124 789	238 620	985	140 512	128 783	528	138 783	82 323	166	68 858	40 535	86	49 339	18 748	44	44 095	13 157	5 115	566 376	522 166
East Midlands	2 567	94 750	180 608	812	116 442	101 144	507	133 663	86 095	170	69 822	35 306	82	48 025	24 508	52	48 013	16 845	4 190	510 715	444 506
West Midlands	3 665	134 950	178 980	1 240	178 780	128 295	773	201 834	106 444	242	98 681	43 468	142	82 501	31 754	75	67 105	25 384	6 137	763 851	514 327
Eastern	1 454	45 616	139 174	324	45 292	57 262	178	46 106	47 229	56	23 044	19 850	32	18 198	10 679	28	31 620	14 975	2 072	209 877	289 168
South East including London	2 594	83 214	178 810	631	90 174	101 305	394	103 256	100 021	150	61 363	49 478	81	46 790	28 895	61	58 436	29 609	3 911	443 232	488 120
South West	7 009	265 313	351 456	2 679	386 884	266 635	1 809	475 254	273 865	666	275 751	130 949	312	180 267	81 437	217	213 549	92 318	12 692	1 797 018	1 196 659
England	**25 301**	**931 117**	**1 638 508**	**8 597**	**1 236 271**	**1 040 803**	**5 505**	**1 446 980**	**908 174**	**1 883**	**776 776**	**410 508**	**954**	**552 804**	**255 047**	**594**	**577 440**	**250 318**	**42 834**	**5 521 386**	**4 503 357**
AVERAGE		**37**	**65**		**144**	**121**		**263**	**165**		**413**	**218**		**579**	**267**		**972**	**421**			

Numbers of pigs and farmed area

Region	1 to 74 pigs			75 to 149 pigs			150 to 299 pigs			300 to 499 pigs			500 to 999 pigs			1000 pigs and over			Total Pigs		
	Holdings with pigs	Number of pigs	Farmed area (ha)	Holdings with pigs	Number of pigs	Farmed area (ha)	Holdings with pigs	Number of pigs	Farmed area (ha)	Holdings with pigs	Number of pigs	Farmed area (ha)	Holdings with pigs	Number of pigs	Farmed area (ha)	Holdings with pigs	Number of pigs	Farmed area (ha)	Holdings with pigs	Number of pigs	Farmed area (ha)
North East	137	1 748	15 100	13	1 416	2 051	11	2 295	759	7	2 945	434	18	13 196	2 222	30	67 456	4 163	216	89 056	24 729
North West and Merseyside	508	6 420	36 044	37	4 065	1 546	35	7 327	1 453	20	7 633	967	32	22 585	1 873	38	90 254	1 840	670	138 284	43 723
Yorkshire and the Humber	469	7 674	27 703	63	6 671	3 882	92	21 397	9 486	93	35 901	10 264	186	133 073	17 416	359	1 017 789	42 702	1 262	1 222 505	111 454
East Midlands	464	6 224	33 201	41	4 158	2 184	43	9 925	5 763	21	8 449	2 766	41	30 635	2 832	105	284 741	13 376	715	344 131	60 121
West Midlands	675	8 873	35 875	49	5 020	2 795	35	7 636	1 775	22	8 708	4 313	39	29 027	2 475	59	129 576	6 086	879	188 840	53 320
Eastern	387	5 579	30 288	33	3 490	1 293	53	11 432	4 443	66	26 333	4 769	105	79 094	6 794	345	906 088	44 957	989	1 032 016	92 545
South East including London	829	11 645	56 710	57	5 967	4 262	37	8 311	3 906	29	11 135	2 432	32	23 856	3 969	55	143 843	12 624	1 039	204 756	83 902
South West	1 642	19 879	102 688	103	10 906	6 167	52	10 673	2 867	42	16 634	2 498	72	52 188	10 086	108	276 249	12 474	2 019	386 529	136 780
England	**5 111**	**68 041**	**337 610**	**396**	**41 693**	**24 179**	**358**	**78 995**	**30 452**	**300**	**117 739**	**28 444**	**525**	**383 653**	**47 668**	**1 099**	**2 915 996**	**138 222**	**7 789**	**3 606 117**	**606 574**
AVERAGE		**13**	**66**		**105**	**61**		**221**	**85**		**392**	**95**		**731**	**91**		**2653**	**126**			

Notes: The # marks denote data that have been withheld by DEFRA due to the information in one or more of the regions.

The red figures are the calculated mean head number and farmed area.

Table A1.11 d and e National livestock data of poultry layers and boilers (DEFRA, 2013a)

Numbers of laying and breeding fowl and farmed area

Region	24,999 L&B fowl			25,000 to 49,999 L&B fowl			50,000 to 99,999 L&B fowl			100,000 to 149,999 L&B fowl			150,000+ L&B fowl			Total		
	Holdings with laying and breeding fowl	Number of laying and breeding fowl	Farmed area (ha)	Holdings with laying and breeding fowl	Number of laying and breeding fowl	Farmed area (ha)	Holdings with laying and breeding fowl	Number of laying and breeding fowl	Farmed area (ha)	Holdings with laying and breeding fowl	Number of laying and breeding fowl	Farmed area (ha)	Holdings with laying and breeding fowl	Number of laying and breeding fowl	Farmed area (ha)	Holdings with laying and breeding fowl	Number of laying and breeding fowl	Farmed area (ha)
North East	701	243 080	66 345	#	#	#	#	#	#	#	#	#	0	0	0	707	574 380	66 908
North West and Merseyside	2 013	1 055 373	115 551	23	822 786	1 669	#	#	#	6	693 574	376	#	#	#	2 049	3 306 039	117 737
Yorkshire and the Humber	1 987	1 388 535	118 128	38	1 353 427	3 588	5	372 728	47	#	#	#	#	#	#	2 035	3 872 690	122 353
East Midlands	1 665	1 452 083	94 490	32	1 087 461	2 198	15	1 014 412	1 627	#	#	#	#	#	#	1 723	6 764 099	99 384
West Midlands	2 211	1 264 550	104 558	29	1 021 019	1 261	8	582 773	526	#	#	#	#	#	#	2 256	5 060 393	108 516
Eastern	1 416	1 658 767	90 325	30	1 028 554	2 019	#	#	#	0	0	0	#	#	#	1 456	4 144 257	93 733
South East including London	2 333	958 324	136 320	#	#	#	6	458 085	127	0	0	0	#	#	#	2 359	4 971 341	137 863
South West	4 653	1 953 970	227 824	42	1 463 967	3 284	6	412 288	84	5	592 141	92	6	2 514 008	863	4 712	6 936 374	232 147
England	**16 979**	**9 974 683**	**953 541**	**214**	**7 485 147**	**14 754**	**54**	**3 791 043**	**4 198**	**21**	**2 485 626**	**886**	**29**	**11 893 074**	**5 263**	**17 297**	**35 629 573**	**978 642**
AVERAGE		587	56		34977	69		70204	78		118363	42		410106	181			

Numbers of broilers and farmed area

Region	24,999 broilers			25,000 to 49,999 broilers			50,000 to 99,999 broilers			100,000 to 149,999 broilers			150,000 broilers and over			Total		
	Holdings with broilers	Number of broilers	Farmed area (ha)	Holdings with broilers	Number of broilers	Farmed area (ha)	Holdings with broilers	Number of broilers	Farmed area (ha)	Holdings with broilers	Number of broilers	Farmed area (ha)	Holdings with broilers	Number of broilers	Farmed area (ha)	Holdings with broilers	Number of broilers	Farmed area (ha)
North East	14	40 590	2 304	#	#	#	#	#	#	11	1 261 429	154	#	#	#	34	2 005 797	2 564
North West and Merseyside	28	160 472	1 843	9	353 111	582	15	1 141 870	559	#	#	#	#	#	#	66	4 587 304	3 670
Yorkshire and the Humber	33	206 131	2 105	17	613 340	1 276	10	851 237	791	9	1 146 770	501	23	6 884 967	1 445	92	9 702 445	6 118
East Midlands	38	72 927	2 263	#	#	#	#	#	#	17	2 058 784	536	44	11 337 364	1 062	117	14 696 447	4 428
West Midlands	34	77 187	3 910	14	554 142	854	17	1 276 043	1 865	21	2 621 468	2 412	32	7 909 327	5 013	118	12 438 166	14 054
Eastern	61	170 928	2 801	14	520 757	435	55	4 174 880	1 220	29	3 535 950	237	45	11 892 181	2 826	204	20 294 696	7 519
South East including London	75	72 698	6 399	#	#	#	#	#	#	#	#	#	14	3 161 069	248	95	3 593 173	7 015
South West	220	889 076	12 088	30	1 099 362	1 815	37	2 771 073	1 495	17	2 156 175	1 353	18	4 554 316	1 379	322	11 470 001	18 130
England	**503**	**1 690 011**	**33 714**	**91**	**3 403 134**	**5 528**	**158**	**11 959 135**	**6 403**	**110**	**13 518 829**	**5 507**	**186**	**48 216 921**	**12 347**	**1 048**	**78 788 030**	**63 499**
AVERAGE		3360	67		37397	61		75691	41		122898	50		259231	66			

Notes: The # marks denote data that have been withheld by DEFRA due to the information in one or more of the regions.

The red figures are the calculated mean head number and farmed area.

Table A1.12 a, b and c Dairy herd size by region (DEFRA, 2013a)

West Midlands

	1 to 99 dairy cows			100 to 199 dairy cows			200 to 349 dairy cows			350 to 499 dairy cows			500 to 699 dairy cows			700 dairy cows and over			Total		
Percentage of regional population	25%			41%			27%			5%			2%								
	Holdings with dairy cows	Number of dairy cows	Farmed area (ha)	Holdings with dairy cows	Number of dairy cows	Farmed area (ha)	Holdings with dairy cows	Number of dairy cows	Farmed area (ha)	Holdings with dairy cows	Number of dairy cows	Farmed area (ha)	Holdings with dairy cows	Number of dairy cows	Farmed area (ha)	Holdings with dairy cows	Number of dairy cows	Farmed area (ha)	Holdings with dairy cows	Number of dairy cows	Farmed area (ha)
TOTAL	1 537	42 470	111 384	495	69 084	64 154	177	45 466	35 864	20	8 131	5 321	7	3 921	1 798	0	0	0	2 236	169 071	218 520
AVERAGE		28	72		140	130		260	203		460	266		565	257		-				
With Maize	266		3605	258		5167	110		3928	8		483	5		367	0		0	647		13551
With Arable	584		25705	345		17716	144		11648	12		1210	5		567	0		0	1090		56846
permament Grass	1458		66649	462		31170	170		15413	19		2662	7		590	0		0	2114		116484

East of England

	1 to 99 dairy cows			100 to 199 dairy cows			200 to 349 dairy cows			350 to 499 dairy cows			500 to 699 dairy cows			700 dairy cows and over			Total		
Percentage of regional population	26%			48%			19%			7%			0%								
	Holdings with dairy cows	Number of dairy cows	Farmed area (ha)	Holdings with dairy cows	Number of dairy cows	Farmed area (ha)	Holdings with dairy cows	Number of dairy cows	Farmed area (ha)	Holdings with dairy cows	Number of dairy cows	Farmed area (ha)	Holdings with dairy cows	Number of dairy cows	Farmed area (ha)	Holdings with dairy cows	Number of dairy cows	Farmed area (ha)	Holdings with dairy cows	Number of dairy cows	Farmed area (ha)
TOTAL	398	5 300	40 332	70	9 802	23 619	16	3 920	4 600	4	1 455	2 648	0	0	0	0	0	0	488	20 477	73 332
AVERAGE		14	102		140	340		245	288		365	662		-			-				
With Maize	62		1034	#		#	#		#	#		#	0		0	0		0	136		3965
With Arable	216		18878	66		15075	4		#	4		#	0		0	0		0	301		40148
permament Grass	360		14462	65		4291	4		#	3		#	0		0	0		0	445		20466

South West

	1 to 99 dairy cows			100 to 199 dairy cows			200 to 349 dairy cows			350 to 499 dairy cows			500 to 699 dairy cows			700 dairy cows and over			Total		
Percentage of regional population	21%			41%			23%			8%			4%			3%					
	Holdings with dairy cows	Number of dairy cows	Farmed area (ha)	Holdings with dairy cows	Number of dairy cows	Farmed area (ha)	Holdings with dairy cows	Number of dairy cows	Farmed area (ha)	Holdings with dairy cows	Number of dairy cows	Farmed area (ha)	Holdings with dairy cows	Number of dairy cows	Farmed area (ha)	Holdings with dairy cows	Number of dairy cows	Farmed area (ha)	Holdings with dairy cows	Number of dairy cows	Farmed area (ha)
TOTAL	3 252	93 291	261 030	1 254	177 350	190 652	401	101 359	89950	80	33 013	29771	30	17 235	12861	14	12 180	7363	5 031	434 428	591 627
AVERAGE		30	80		140	155		255	224		412	372		575	429		870	526			
With Maize	597		8724	724		16348	268		9811	48		2891	14		1400	0		0	1659		40257
With Arable	1367		43282	977		48865	338		24815	63		9226	19		#	9		#	2773		133065
permament Grass	3094		155944	1208		90255	378		34783	74		11461	29		4467	13		2615	4796		299615

Notes: The # marks denote data that have been withheld by DEFRA due to the information in one or more of the regions.

The red figures are the calculated mean head number and farmed area (the red numbers in the 'number of holdings' column and 'TOTAL' row are the estimated numbers since DEFRA withheld these).

Table A1.13 a, b and c Cattle herd size by region (DEFRA, 2013a)

West Midlands

	18%			23%			26%			13%			11%			9%			Percentage of regional population		
	1 to 99 cattle			100 to 199 cattle			200 to 349 cattle			350 to 499 cattle			500 to 699 cattle			700 cattle and over			Total		
	Holdings with cattle	Number of cattle	Farmed area (ha)	Holdings with cattle	Number of cattle	Farmed area (ha)	Holdings with cattle	Number of cattle	Farmed area (ha)	Holdings with cattle	Number of cattle	Farmed area (ha)	Holdings with cattle	Number of cattle	Farmed area (ha)	Holdings with cattle	Number of cattle	Farmed area (ha)	Holdings with cattle	Number of cattle	Farmed area (ha)
TOTAL	3 665	134 950	178 980	1 240	178 780	128 295	773	201 834	106 444	242	98 681	43 468	142	82 501	31 754	75	67 105	25 384	6 137	763 851	514 327
AVERAGE		40	48		145	103		265	138		410	180		585	224		895	338			
With Maize	182		2135	237		2959	297		4879	113		2719	82		2596	41		2130	952		17420
With Arable	1052		49308	697		36633	536		31888	180		13106	114		11164	62		9560	2641		151659
With permament Grass	3435		101075	1180		70478	729		51225	225		21898	138		13213	73		10203	5780		268092

East of England

	22%			22%			22%			11%			9%			15%			Percentage of regional population		
	1 to 99 cattle			100 to 199 cattle			200 to 349 cattle			350 to 499 cattle			500 to 699 cattle			700 cattle and over			Total		
	Holdings with cattle	Number of cattle	Farmed area (ha)	Holdings with cattle	Number of cattle	Farmed area (ha)	Holdings with cattle	Number of cattle	Farmed area (ha)	Holdings with cattle	Number of cattle	Farmed area (ha)	Holdings with cattle	Number of cattle	Farmed area (ha)	Holdings with cattle	Number of cattle	Farmed area (ha)	Holdings with cattle	Number of cattle	Farmed area (ha)
TOTAL	1 454	45 616	139 174	324	45 292	57 262	178	46 106	47 229	56	23 044	19 850	32	18 198	10 679	28	31 620	14 975	2 072	209 877	289 168
AVERAGE		35	95		140	177		260	265		415	354		570	334		1 130	535			
With Maize	57		545	67		1135	67		1793	25		792	4		#	8		#	242		5648
With Arable	731		84111	243		29944	141		26810	48		10596	26		5135	22		6948	1211		163545
With permament Grass	1300		31083	306		15812	168		13879	52		5814	28		4247	28		6552	1882		77388

South West

	15%			22%			26%			15%			10%			12%			Percentage of regional population		
	1 to 99 cattle			100 to 199 cattle			200 to 349 cattle			350 to 499 cattle			500 to 699 cattle			700 cattle and over			Total		
	Holdings with cattle	Number of cattle	Farmed area (ha)	Holdings with cattle	Number of cattle	Farmed area (ha)	Holdings with cattle	Number of cattle	Farmed area (ha)	Holdings with cattle	Number of cattle	Farmed area (ha)	Holdings with cattle	Number of cattle	Farmed area (ha)	Holdings with cattle	Number of cattle	Farmed area (ha)	Holdings with cattle	Number of cattle	Farmed area (ha)
TOTAL	7 009	265 313	351 456	2 679	386 884	266 635	1 809	475 254	273 865	666	275 751	130 949	312	180 267	81 437	217	213 549	92 318	12 692	1 797 018	1 196 659
AVERAGE		40	50		145	100		265	151		415	197		580	261		985	425			
With Maize	382		5252	509		6554	698		13732	369		9645	185		6457	129		7542	2272		49181
With Arable	1823		68631	1428		51941	1264		64971	524		32341	258		23718	166		25189	5463		266790
With permament Grass	6587		202933	2550		151142	1743		137424	628		60383	291		33955	202		30935	12001		616771

Notes: The # marks denote data that have been withheld by DEFRA due to the information in one or more of the regions.

The red figures are the calculated mean head number and farmed area (the red numbers in the 'number of holdings' column and 'TOTAL' row are the estimated numbers since DEFRA withheld these).

Table A1.14 a, b and c Pig herd size by region (DEFRA, 2013a)

West Midlands

		5%			3%			4%			5%			15%			69%		Percentage of regional population		
	1 to 74 pigs			75 to 149 pigs			150 to 299 pigs			300 to 499 pigs			500 to 999 pigs			1000 pigs and over			Total		
	Holdings with pigs	Number of pigs	Farmed area (ha)	Holdings with pigs	Number of pigs	Farmed area (ha)	Holdings with pigs	Number of pigs	Farmed area (ha)	Holdings with pigs	Number of pigs	Farmed area (ha)	Holdings with pigs	Number of pigs	Farmed area (ha)	Holdings with pigs	Number of pigs	Farmed area (ha)	Holdings with pigs	Number of pigs	Farmed area (ha)
TOTAL	**675**	**8873**	**35875**	**49**	**5020**	**2795**	**35**	**7636**	**1775**	**22**	**8708**	**4313**	**39**	**29027**	**2475**	**59**	**129576**	**6086**	**879**	**188840**	**53320**
AVERAGE		**14**	**53**		**103**	**57**		**218**	**51**		**400**	**196**		**745**	**63**		**2200**	**103**			
With Maize	48		673			#			#			#	2		#	3		#	66		1120
With Arable	208		8908	18		834	14		548	13		2467	22		1336	38		4213	313		18307
With permament Grass	622		20365	43		1550	30		844	20		1215	29		603	43		10440	787		25617

East of England

		1%			0%			1%			3%			8%			88%		Percentage of regional population		
	1 to 74 pigs			75 to 149 pigs			150 to 299 pigs			300 to 499 pigs			500 to 999 pigs			1000 pigs and over			Total		
	Holdings with pigs	Number of pigs	Farmed area (ha)	Holdings with pigs	Number of pigs	Farmed area (ha)	Holdings with pigs	Number of pigs	Farmed area (ha)	Holdings with pigs	Number of pigs	Farmed area (ha)	Holdings with pigs	Number of pigs	Farmed area (ha)	Holdings with pigs	Number of pigs	Farmed area (ha)	Holdings with pigs	Number of pigs	Farmed area (ha)
TOTAL	**387**	**5579**	**30288**	**33**	**3490**	**1293**	**53**	**11432**	**4443**	**66**	**26333**	**4769**	**105**	**79094**	**6794**	**345**	**906088**	**44957**	**989**	**1032016**	**92545**
AVERAGE		**14**	**78**		**106**	**39**		**216**	**84**		**400**	**72**		**753**	**65**		**2630**	**130**			
With Maize	19		325	#		#	0		0	0		0	#		#	10		255	37		610
With Arable	188		17036	15		555	35		2894	46		3950	72		5154	179		31403	535		60992
With permament Grass	338		9154	26		368	38		899	39		379	71		868	162		4428	674		16097

South West

		5%			3%			3%			4%			14%			71%		Percentage of regional population		
	1 to 74 pigs			75 to 149 pigs			150 to 299 pigs			300 to 499 pigs			500 to 999 pigs			1000 pigs and over			Total		
	Holdings with pigs	Number of pigs	Farmed area (ha)	Holdings with pigs	Number of pigs	Farmed area (ha)	Holdings with pigs	Number of pigs	Farmed area (ha)	Holdings with pigs	Number of pigs	Farmed area (ha)	Holdings with pigs	Number of pigs	Farmed area (ha)	Holdings with pigs	Number of pigs	Farmed area (ha)	Holdings with pigs	Number of pigs	Farmed area (ha)
TOTAL	**1642**	**19879**	**102688**	**103**	**10906**	**6167**	**52**	**10673**	**2867**	**42**	**16634**	**2498**	**72**	**52188**	**10086**	**108**	**276249**	**12474**	**2019**	**386529**	**136780**
AVERAGE		**12**	**63**		**106**	**60**		**206**	**55**		**400**	**59**		**725**	**140**		**2560**	**116**			
With Maize	152		2606	9		239	#		#	#		#	10		257	24		610	208		3901
With Arable	501		22412	37		1475	16		534	20		804	37		3320	62		6936	673		35480
With permament Grass	1567		60806	95		3821	45		1774	36		1080	59		5233	78		2613	1880		75325

Notes: The # marks denote data that have been withheld by DEFRA due to the information in one or more of the regions.

The red figures are the calculated mean head number and farmed area (the red numbers in the 'number of holdings' column and 'TOTAL' row are the estimated numbers since DEFRA withheld these).

Table A1.15 a, b and c Laying and breeding fowl flock size by region (DEFRA, 2013a)

West Midlands	25%			20%			12%			7%			36%			Percentage of regional population		
	1 to 24,999 laying and breeding fowl			25,000 to 49,999 laying and breeding fowl			50,000 to 99,999 laying and breeding fowl			100,000 to 149,999 laying and breeding fowl			150,000 laying and breeding fowl and over			Total		
	Holdings with laying and breeding fowl	Number of laying and breeding fowl	Farmed area (ha)	Holdings with laying and breeding fowl	Number of laying and breeding fowl	Farmed area (ha)	Holdings with laying and breeding fowl	Number of laying and breeding fowl	Farmed area (ha)	Holdings with laying and breeding fowl	Number of laying and breeding fowl	Farmed area (ha)	Holdings with laying and breeding fowl	Number of laying and breeding fowl	Farmed area (ha)	Holdings with laying and breeding fowl	Number of laying and breeding fowl	Farmed area (ha)
TOTAL	**2211**	**1264550**	**104558**	**29**	**1021019**	**1261**	**8**	**582773**	**526**	**3**	**375000**	**372**	**5**	**1817051**	**1799**	**2256**	**5060393**	**108516**
AVERAGE		**575**	**47**		**35000**	**43**		**75000**	**66**		**125000**	**124**		**365000**	**360**			
With Maize	#		#	0		0	1		#	0		0	#		#	115		1707
With Arable	568		27410	6		581	3		#	0		0	#		#	579		29939
With permanent Grass	2103		60616	13		475	4		#	4		#	5		106	2126		61327

East of England	40%			25%			11%			0%			24%			Percentage of regional population		
	1 to 24,999 laying and breeding fowl			25,000 to 49,999 laying and breeding fowl			50,000 to 99,999 laying and breeding fowl			100,000 to 149,999 laying and breeding fowl			150,000 laying and breeding fowl and over			Total		
	Holdings with laying and breeding fowl	Number of laying and breeding fowl	Farmed area (ha)	Holdings with laying and breeding fowl	Number of laying and breeding fowl	Farmed area (ha)	Holdings with laying and breeding fowl	Number of laying and breeding fowl	Farmed area (ha)	Holdings with laying and breeding fowl	Number of laying and breeding fowl	Farmed area (ha)	Holdings with laying and breeding fowl	Number of laying and breeding fowl	Farmed area (ha)	Holdings with laying and breeding fowl	Number of laying and breeding fowl	Farmed area (ha)
TOTAL	**1416**	**1658767**	**90325**	**30**	**1028554**	**2019**	**6**	**450000**	**1095**	**0**	**0**	**0**	**4**	**1006936**	**294**	**1 456**	**4144257**	**93733**
AVERAGE		**1200**	**64**		**35000**	**67**		**75000**	**183**					**255000**	**74**			
With Maize	44		#	0		0	5		#	0		0	0		0	49		833
With Arable	608		54996	5		#	3		#	0		0	0		0	616		56989
With permanent Grass	1206		22566	13		702	3		#	0		0	2		#	1224		23585

South West	28%			21%			6%			9%			36%			Percentage of regional population		
	1 to 24,999 laying and breeding fowl			25,000 to 49,999 laying and breeding fowl			50,000 to 99,999 laying and breeding fowl			100,000 to 149,999 laying and breeding fowl			150,000 laying and breeding fowl and over			Total		
	Holdings with laying and breeding fowl	Number of laying and breeding fowl	Farmed area (ha)	Holdings with laying and breeding fowl	Number of laying and breeding fowl	Farmed area (ha)	Holdings with laying and breeding fowl	Number of laying and breeding fowl	Farmed area (ha)	Holdings with laying and breeding fowl	Number of laying and breeding fowl	Farmed area (ha)	Holdings with laying and breeding fowl	Number of laying and breeding fowl	Farmed area (ha)	Holdings with laying and breeding fowl	Number of laying and breeding fowl	Farmed area (ha)
TOTAL	**4653**	**1953970**	**227824**	**42**	**1463967**	**3284**	**6**	**412288**	**84**	**5**	**592141**	**92**	**6**	**2514008**	**863**	**4712**	**6936374**	**232147**
AVERAGE		**420**	**49**		**35000**	**78**		**70000**	**14**		**120000**	**18**		**420000**	**144**			
With Maize	321		5598	5		#	0		0	0		0	2		#	328		5794
With Arable	1112		42690	11		#	0		0	0		0	2		#	1125		44357
With permanent Grass	4460		146100	26		1090	4		#	3		#	3		#	4496		147734

Notes: The # marks denote data that have been withheld by DEFRA due to the information in one or more of the regions.

The red figures are the calculated mean head number and farmed area (the red numbers in the 'number of holdings' column and 'TOTAL' row are the estimated numbers since DEFRA withheld these).

Table A1.16 a, b and c Broiler flock size by region (DEFRA, 2013)

West Midlands

	0.6%			4.5%			10.3%			21.1%			63.6%			Percentage of regional population		
	1 to 24,999 broilers			25,000 to 49,999 broilers			50,000 to 99,999 broilers			100,000 to 149,999 broilers			150,000 broilers and over			Total		
	Holdings with broilers	Number of broilers	Farmed area (ha)	Holdings with broilers	Number of broilers	Farmed area (ha)	Holdings with broilers	Number of broilers	Farmed area (ha)	Holdings with broilers	Number of broilers	Farmed area (ha)	Holdings with broilers	Number of broilers	Farmed area (ha)	Holdings with broilers	Number of broilers	Farmed area (ha)
TOTAL	**34**	**77187**	**3910**	**14**	**554142**	**854**	**17**	**1276043**	**1865**	**21**	**2621468**	**2412**	**32**	**7909327**	**5013**	**118**	**12438166**	**14054**
AVERAGE		**3000**	**115**		**40000**	**61**		**75000**	**110**		**125000**	**115**		**250000**	**157**			
With Maize	#		#	#		#	#		#	#		#	#		#	18		514
With Arable	14		1049	7		344	12		971	15		1501	24		3400	72		7266
With permanent Grass	31		1756	11		258	13		474	10		131	25		772	90		3390

East of England

	0.8%			2.6%			20.6%			17.4%			58.6%			Percentage of regional population		
	1 to 24,999 broilers			25,000 to 49,999 broilers			50,000 to 99,999 broilers			100,000 to 149,999 broilers			150,000 broilers and over			Total		
	Holdings with broilers	Number of broilers	Farmed area (ha)	Holdings with broilers	Number of broilers	Farmed area (ha)	Holdings with broilers	Number of broilers	Farmed area (ha)	Holdings with broilers	Number of broilers	Farmed area (ha)	Holdings with broilers	Number of broilers	Farmed area (ha)	Holdings with broilers	Number of broilers	Farmed area (ha)
TOTAL	**61**	**170928**	**2801**	**14**	**520757**	**435**	**55**	**4174880**	**1220**	**29**	**3535950**	**237**	**45**	**11892181**	**2826**	**204**	**20294696**	**7519**
AVERAGE		**2800**	**46**		**38000**	**31**		**76000**	**22**		**125000**	**8**		**265000**	**63**			
With Maize	#		#	0		0	#		#	0		0	0		0	#		#
With Arable	26		1558	#		#	#		#	#		#	12		2314	48		5276
With permanent Grass	47		705	#		#	18		154	#		#	8		159	81		1036

South West

	7.8%			9.6%			24.2%			18.8%			39.7%			Percentage of regional population		
	1 to 24,999 broilers			25,000 to 49,999 broilers			50,000 to 99,999 broilers			100,000 to 149,999 broilers			150,000 broilers and over			Total		
	Holdings with broilers	Number of broilers	Farmed area (ha)	Holdings with broilers	Number of broilers	Farmed area (ha)	Holdings with broilers	Number of broilers	Farmed area (ha)	Holdings with broilers	Number of broilers	Farmed area (ha)	Holdings with broilers	Number of broilers	Farmed area (ha)	Holdings with broilers	Number of broilers	Farmed area (ha)
TOTAL	**220**	**889076**	**12088**	**30**	**1099362**	**1815**	**37**	**2771073**	**1495**	**17**	**2156175**	**1353**	**18**	**4554316**	**1379**	**322**	**11470001**	**18130**
AVERAGE		**4100**	**55**		**37000**	**61**		**75000**	**40**		**127000**	**80**		**255000**	**77**			
With Maize	15		270	6		172	#		#	#		#	#		#	32		756
With Arable	69		2715	14		649	11		601	#		#	#		#	105		5845
With permanent Grass	207		6438	28		759	27		587	12		182	7		274	281		8240

Notes: The # marks denote data that have been withheld by DEFRA due to the information in one or more of the regions.

The red figures are the calculated mean head number and farmed area (the red numbers in the 'number of holdings' column and 'TOTAL' row are the estimated numbers since DEFRA withheld these).

APPENDIX 4: MODEL ABBREVIATIONS

EE East of England
WM West Midlands
SW South West of England
G Grass
M Maize
HH Household kitchen waste
C Cattle
D Dairy
P Pigs
PL Poultry – Layers
PB Poultry – Broilers
Mix A range of different quantities of ALL the other mobile feedstock types (bar poultry layers and broilers, which are interchangeable)

Additional abbreviations used for naming during sensitivity analysis
CrD Distance of crops travelled to treatment facility
DEx Distance of digestate export required
DR Discount rate
EEf Engine's electrical efficiency
FC Diesel fuel costs
FiT Feed-in Tariff rate
HG Hours of generation (only affects engine size unless more feedstock found)
HHD Municipal waste distance travelled
IntR Base interest rate
IR Inflation rate
NHDV No (financial) heat or digestate value
PD Percentage of debt (lower % debt reduces IRR)
PHE Percentage of heat exported (utilised in addition to the digester)
TR Tax rate
V Value

For example, a model run code such as C900PLM 1 would mean cattle, 900 head herd co-digested with poultry layers' manure and maize. The end number represents the model-run number with that configuration.

APPENDIX 5: OUTPUTS

Table A1.17 Model output page

SUMMARY

PROCESS REQUIREMENTS		
Total MuniCommInd Waste Inputs	1500.00	tonnes
Total Livestock waste Inputs	2200.00	tonnes
Total Crop Inputs	2000.00	tonnes
OFF-Farm land requirement	44.44	ha
ON-Farm land requirement	0.00	ha
Digester loading	15.62	$tFM/m^3/day$
Digester capacity requirement	1496.00	m^3
Retention time	65.00	days
Biogas produced	801835.59	m^3a^{-1}
Methane produced	444495.17	m^3a^{-1}
CHP electricity produced	6084.05	GJ
	1690016.35	kWh
Generator required	210.20	kW
CHP heat produced	6541.15	GJ
Methane Upgraded & Compressed	0.00	m^3
Energy Value of methane injected	0.00	GJ
	0.00	MWh equivalent
Method of compensation	FiTs	

ON-FARM ELECTRICITY USE (GJ)	GJ	Source
Dairy electricity	0.00	CHP
seperator electricity	0.00	CHP

DIGESTATE AND NUTRIENT VALUES	N - Nitrogen (kg)	P_2O_5 - Phosphate (kg)	K_2O - Potassium (kg)
Digestate			
On-Farm (Total)	7920.00	4200.00	4200.00
Imported (Total)	37120.00	17230.00	34690.00
Nutrient available percentage	0.40	0.60	0.90
(Mineral fertiliser saving) or TOTAL	**45040.00**	**21430.00**	**38890.00**
Nutrient availability per tonne FM	2.44	1.74	4.75
On-Farm requirement			
Quantity (t) of digestate produced	**7374.83**		**0.00 t of digestate used on site**
Digestate required for Crops	0.00	0.00	0.00
Used from Digestate	0.00	0.00	0.00
Quantity exported	18016.00	12858.00	35001.00
ON-Farm **Requirement** or **Surplus added**	0.00	0.00	0.00
Off-Farm requirement			
Crop requirement	7777.78	2222.22	6333.33
Used from Digestate	2689.27	1919.33	5224.65
OFF-Farm **Requirement** or **Surplus added**	5088.51	302.89	1108.69
Quanity of digestate exported (t)	**7374.83**	£	**5.78 Value per tonne**

Assumes unused ON-Farm digestate is used on suppliers OFF-Farm first

DIESEL USE	litres	GJ	Value (£)
C & D of MuniCommInd Waste to centre	58484.96	0.00	£81,878.95
OFF-Farm-waste and Crops to Centre	911.05	32.67	£646.85
OFF-Farm Crops production	8147.51	292.17	£5,784.73
ON-Farm Crop production	0.00	0.00	£0.00
ON-Farm digestate use	0.00	0.00	£0.00
Export of digestate (gate to gate)	1503.84	53.93	£1,067.73

ENERGY BALANCE per year	On-farm		Off-Farm	
Crop production fuel direct	0.00	GJ	292.17	GJ
Crop production fuel indirect	0.00	GJ	330.15	GJ
Transport fuel for waste - direct	0.00	GJ		
Transport fuel for waste - indirect	0.00	GJ		
Sprays manufacturer	0.00	GJ	8.37	GJ
Required fertiliser Manufacturer	221.69	GJ	409.79	GJ
Digestate transport and application - direct	0.00	GJ	53.93	GJ
Digestate transport and application - indirect	0.00	GJ	60.94	GJ
Digester required parasitic electricity	420.00	GJ		
Digester required parasitic heat	2016.67	GJ		
Required dairy electricity	0.00	GJ		
Required seperator electricity	0.00	GJ		
			Source	
Imported fuel for onsite heat requirement	0.00	GJ		
Imported electricity for plant from grid	0.00	GJ		
Buffer Tank	0.98	GJ/a		
Digestate Storage tank embodied energy	0.00	GJ/a		
Digester embodied	155.52	GJ/a		
Approx Engine embodied	19.50	GJ/a		
Pasteuriser heat requirement	1120.14	GJ		
Pasteuriser embodied	1.30	GJ/a		
Silage Clamps embodied	54.17	GJ/a		
Biogas use	**CHP**			
Energy in CH_4 produced	15824.03	GJ		
electricity generated	6084.05	GJ	1690.02	MWh
heat generated	6541.15	GJ		
exportable electricity	5662.80	GJ		
	1573.00	MWh		
exportable heat	654.11	GJ		
	181.70	MWh		
energy content in upgraded CH_4	0.00	GJ		
Energy IN	5165.30	GJ		
Energy OUT	15824.03	GJ		
Energy Balance	**10658.73**	**GJ**		

ASSUMPTIONS
Av. Distance to digestate recipient - 4 miles
Digestate taken in 10t loads
The price is obtained for digestate exported
?MWe is "sold" to the farm @10p kWh
?% of heat generated is "sold" to the ? @4.5p kWh

Electricity for separator	0.00	kWh_e

ANNUAL PROCESS EMISSIONS from fossil fuel sources		
Diesel used in ALL crop production & digestate removal	31282.90	kg CO_2e
Diesel fuel used in waste transport	189567.31	kg CO_2e
Herbicides, pesticides & other sprays manaufactured	1588.13	kg CO_2e
Emissions from OFF-Farm fertiliser production	67578.80	kg CO_2e
Imported electricity for AD		kg CO_2e
Imported electricity for Seperator		kg CO_2e
Imported electricity for Gas upgrade to grid		kg CO_2e
Emissions from ON-Farm fertiliser production (if shortfall)	36559.14	kg CO_2e
Imported heat for AD		kg CO_2e
Imported heat for Pasteuriser		kg CO_2e
Emissions from leakage and Flaring	68151.28	kg CO_2e
Annual allocation of emissions from the embodied structure	38009.00	kg CO_2e
Annual emissions from **uncovered** digestate storage tank	0.00	kg CO_2e
Total emissions	432736.56	kg CO_2e

OFFSET EMISSIONS		
Emissions if electricity had been generated from UK grid mix	1003328.11	kg CO_2e
Emissions saved from equiv grid electricity generated	570591.55	kg CO_2e
Emissions saved from utilising the heat generated	56024.76	kg CO_2e
Emissions saved from gas upgrade equivilent		kg CO_2e
Emissions saved from fertiliser production (digestate use)	207807.18	kg CO_2e
Emissions saved from slurry that remains untreated	32508.00	kg CO_2e
Emission saved from methane escape from landfill	207191.93	kg CO_2e
TOTAL EMISSIONS SAVED FROM ANAEROBIC DIGESTION	1074123.41	kg CO_2e
Emissions per MWe generated	-635.57	**kg CO_2e/Mwe**
Emissons per tonne of feedstock treated	-188.44	**kgCO_2e/t**
Emissions from production per MWh exported (CHP only)	0.28	kgCO_2eq/MWhe
NET emissions per MJ of CH_4 produced	-0.07	Kg CO_2eq/MJ
NET emissions/kWh of electricity exported (CHP and CHP+upgrade)	-0.68	Kg CO_2eq/kWhe
NET emissions per kWh of CH_4 upgraded		Kg CO_2eq/MJ

FINANCIALS			
Total Capital Expenditure	£	1,250,560.00	
Income from electricity	£	319,767.30	
Income from Heat	£	8,176.43	
Income from Gas grid injection	£	-	
Income from Digestate (value)	£	42,621.72	
Total Gate Fees	£	30,000.00	
Total Income	£	400,565.45	
Direct fuel Use			
Used in Farming activities	£	-	
Digestate disposal diesel	£	1,067.73	
Cost of ON-Farm Sprays	£	-	
Collection			
Other Costs	£	291,290.20	**Payback within**
Total Costs	£	292,357.93	**(yrs)**
Profit/Loss	£	108,207.52	5
Internal Rate of Return		16.10%	at 20 years
Net Present Value (12% discount rate)	£	3,091,068.14	at 20 years
Costs per GJ CH4 produced	£	18.48	
Profit/loss per tonne digested	£	18.98	£/t
Av. Return on Capital		28.42%	

Electricity for dairy	0.00	kW_e

Table A1.18 Modelled outputs from the 13 case studies and 7 reference studies used in the model validation

Case No.	Engine kW	Modelled engine size (kW)	Advised or estimated CAPEX (£)	Modelled CAPEX (£)	Biogas Produced (m^3)	Modelled Biogas Produced (m^3)	Methane Produced (m^3)	Modelled Methane Produced (m^3)	Retention Time (d)	Modelled Retention Time (d)	Digester Size (m3)	Modelled Digester Size (m3)
1	498 **L**	500 (507)	£3,955,000	£3,450,000	1662244	1701076	1218890	1084743	69	53	3000	2243
2	160	130	£877,660	£891,000	763982	574471		292619	50	53	800	781
3	1400	1273	£5,800,000	£2,905,750		4834141		2465707	27	68	6600	6447
4	160	158	£1,000,000	£976,000	804000	636254		336887	40	48	1800	884
5	360	337	£847,000	£1,342,000		1406886		739350	76?	54	3600	2234
6	498 **L**	472	£1,815,000 ?	£1,883,000		2059151		984049	60?	54	5500	3755
7	190	180	£2,200,000	£1,526,000		630781		384390	5+15	23	1000	2568
8	500 **L**	500 (553)	£1,700,000	£1,870,000		2256421		1182178	56	65	4300	2939
9	-	14	£65,000	x10		67993		30805	30?	39	225	183
10	160	143	£700,000	£868,500		612421		305053	38	47	1600	1455
11	50	48	£800,000	£771,500		222800		103439	28?	39	550	592
12	498 **L**	500	£3,700,000	£3,655,000		1985406		1184579	50?	46	3500	3270
13	600	525	£2,025,000	£2,336,000	1581142	1728308	1078338	1104187	50	48	2500	1992
14	400	354	£1,297,000	£1,120,500	?	1565794	?	757827	?	48	2700	2499
15	500	434	£1,970,000	£1,919,000	?	1969955	?	927150	?	66	5500	3219
16	80	81	£600,000	£734,500	?	340807	?	178947	?	54	?	747
17	160	165	£750,000	£862,500	?	668731	?	352040	?	54	?	1447
18	240	247	£950,000	£997,500	?	1001015	?	527126	?	54	?	2177
19	320	369	£1,200,000	£1,245,500	?	1490778	?	768823	?	53	?	3253
20	480	526	£1,750,000	£2,076,000	?	2102820	?	1096230	?	55	?	4511

L = Limited. This is a CHP engine that has the capacity to generate more energy per hour, but has an agreed restriction with OFGEM to qualify for the high FIT level.

Table A1.19 Comparison of model outputs from the Cornwall Agri–food Council report

Variable	CAC 1	ADEE 1	CAC 2	ADEE 2	CAC 3	ADEE 3	CAC 4	ADEE 4
Heifer & Steer Slurry / Dairy cattle slurry	Dairy cattle slurry	Dairy cattle slurry	Dairy cattle slurry	Dairy Cattle slurry	Dairy Cattle slurry	Dairy Cattle slurry	Dairy cattle slurry	Dairy cattle slurry
Number of Cows	200 (1100t)	70 (1218t)	1500t	120			600 (4960t)	300 On-Farm
No of Weeks Housed	33	33	off farm	24			24 + Off-Farm	rest Off-Farm
Crop Feedstock travel								
Quantity of Pig manure (t)					FYM 563	FYM 563		
Quantity of Layer manure (t)			1350	1350				
Value of Layer manure (£)			10	10				
Quantity of Broiler litter (t)			500	500				
Value of Broiler litter (£)			10	10				
Quantity of Grass Silage (t)	500	500	1955	1955	3600	3600	500	500
Grass silage value (£)	22	22	22	22	22	22	22	22
Quantity of Maize Silage (t)	650	650	4500	4500				
Maize silage value (£)	30	30	30	30				
Quantity of Municipal waste (t)								
Municipal waste distance	10	10	25	25			50	50
Municipal waste Value (£)	30	30	30	30			30	30
Straw (t)	100 (as FYM)	153 (modelled)			100	100	75	75
Potatoes (t)			500	500				
WC Wheat Silage (t)							500	500
Crop grain (t)							100	100
Export of Digestate	4	4	4	4	4	4	4	
Engine electrical efficiency	32.9%	35.0%	38.2%	39.0%	0.39	39.0%	38.1%	38.1%
Discount Rate	12%	12%	12%	12%	0.12	12%	12%	12%
Pasteuriser	NONE	NONE	NONE	NONE	NONE	NONE	NONE	NONE
Seperation Unit	Yes	Yes	Yes	Yes	Yes	Yes	Yes	yes
Hours of generation per annum	8040	8040	8040	8040	8040	8040	8040	8040
Cost of diesel fuel	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Reception Building	0	0	0	0	0	0	0	0
Grant Value	0	0	0	0	0	0	0	0
Tax rate	Contemporary	17%	Contemporary	17%	Contemporary	17%	Contemporary	17%
Inflation Rate	unknown	3%	unknown	3%	unknown	3%	unknown	3%
Interest over base (2.5%)	8% total	5.5%	8% total	5.5%	8% total	5.5%	8% total	5.5%

Percentage of Debt	unknown	80%	unknown	80%	unknown	80%	unknown	80%
Total Labour costs	varied	9500	varied	9500	varied	9500	varied	9500
% heat used beyond the digester/pasteuriser	varied	10%	varied	10%	varied	10%	varied	10%
FiT tarrif up to 250kWh	ROCs	15.16	ROCs	15.16	ROCs	15.16	ROCs	15.16
FiT tarrif 251kWH up to 500kWh	ROCs	14.02	ROCs	14.02	ROCs	14.02	ROCs	14.02
FiT tarrif over 500kWh	ROCs	9.24	ROCs	9.24	ROCs	9.24	ROCs	9.24
RHI Tarrif for sub-200kWh	ROCs	7.1	ROCs	7.1	ROCs	7.1	ROCs	7.1
Annual Outputs	CAC 1		CAC 2		CAC 3		CAC 4	
Engine Requirement (kW)	50	56	400	436	190	163	104	107
Biogas Produced (m^3)	249460.00	285810.00	1677686.00	1815942.55	628745	726747.00	382615.00	470381.00
Methane Produced (m^3)	132806.00	140460.00	918206.00	941403.25	340151	351090.00	210998.00	231548.60
Electricity produced (MW)	436.93	486.00	3507.00	3505.13	1298	1307.00	803.90	859.84
Heat produced (MW)	641.00	583.00	3994.00	3848.00	1502	1435.00	930.50	946.50
Income from electricity (£)	£57,020.00	£93,331.82	£461,295.00	£633,754.45	£169,043.00	£254,010.19	£104,093.00	£161,894.63
Income from heat (£)	£6,599.00	£7,869.00	£5,616.00	£17,317.00	£44,032.00	£45,207.84	£-	£2,129.65
Total Income (£)	£69,854.00	£107,534.56	£505,889.00	£717,544.13	£240,056.00	£328,256.90	£112,702.00	£180,602.00
Total Expenditure (before grants) (£)	£506,921.00	£727,500.00	£1,364,085.00	£1,809,000.00	£953,176.00	£883,500.00	£470,054.00	£816,500.00
Total OpEx (£)	£119,219.00	£174,357.00	£476,692.00	£608,499.49	£271,430.00	£261,106.00	£134,511.00	£205,844.00
Retention Time	80	56	75	64	123	68	69	48
Digester size	1186	450	3707	2545	1854	1167	1854	908
Payback (yrs)	-44		11	6	26	6	32	11
Profit/(Loss)	-£49,364.00	-£71,463.73	£29,198.00	£109,044.00		£67,150.00	-£21,809.00	-£25,242.00

Continuation: Comparison of model outputs from the Cornwall Agri-food Council report

Variable	CAC 5	ADEE 5	CAC 6	ADEE 6	CAC 7	ADEE 7	CAC 8	ADEE 8
Heifer & Steer Slurry / Dairy cow slurry	Dairy cow slurry	Dairy cow slurry	Dairy cow slurry	Dairy cow slurry	Slurry	Slurry	Dairy cow slurry	Dairy cow slurry
Number of Cows	1000 (16000t+1170FYM)	16239 + 2038	150 (1500t)	(150) 1573	4066	4066	2500 (31,200t)	2500 (31,200t)
No of Weeks Housed	26	44	24	24			24	24
Crop Feedstock travel							6	6
Quantity of Pig manure (t)			17500	17500				
Quantity of Layer manure (t)								
Value of Layer manure (£)								
Quantity of Broiler litter (t)								
Value of Broiler litter (£)							2080 (abattoir W)	2080
Quantity of Grass Silage (t)			1792	1792	300	300		
Grass silage value (£)			22	22	22	22		
Quantity of Maize Silage (t)					200	200	7300	7300
Maize silage value (£)					30	30	30	30
Quantity of Municipal waste (t)							1950	1950
Municipal waste distance	100	100	10	25			10	10
Municipal waste Value (£)	30	30	30	30			30	30
Straw (t)			200t(as FYM)	198 (modelled)	Horse man. 360	Horse man. 360		
Potatoes (t)	500	500			Hay 30	Hay 30		
WC Wheat Silage (t)					100	100		
Crop grain (t)								
Export of Digestate	4	4	4	4	4	4	4	4
Engine electrical efficiency	37.6%	38.0%	37.8%	39.0%	32.6%	32.6%	38.6%	38.6%
Discount Rate	12%	12%	12%	12%	12%	12%	12%	12%
Pasteuriser	NONE	NONE	NONE	NONE	NONE	NONE	NONE	NONE
Separation Unit	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Hours of generation per annum	8040	8040	8040	8040	8040	8040	8040	8040
Cost of diesel fuel	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Reception Building	0	0	0	0	0	0	0	0
Grant Value	0	0	0	0	0	0	0	0
Tax rate	Contemporary	17%	Contemporary	17%	Contemporary	17%	Contemporary	17%

Inflation Rate	unknown	3%	unknown	3%	unknown	3%	unknown	3%
Interest over base (2.5%)	8% total	5.5%	8% total	5.5%	8% total	5.5%	8% total	5.5%
Percentage of Debt	unknown	80%	unknown	80%	unknown	80%	unknown	80%
Total Labour costs	varied	9500	varied	9500	varied	9500	varied	9500
% heat used beyond the digester/pasteuriser	varied	10%	varied	10%	varied	10%	varied	10%
FIT tarrif up to 250kWh	ROCs	15.16	ROCs	15.16	ROCs	15.16	ROCs	15.16
FIT tarrif 251kWH up to 500kWh	ROCs	14.02	ROCs	14.02	ROCs	14.02	ROCs	14.02
FIT tarrif over 500kWh	ROCs	9.24	ROCs	9.24	ROCs	9.24	ROCs	9.24
RHI Tarrif for sub 200kWh	ROCs	7.1	ROCs	7.1	ROCs	7.1	ROCs	7.1
Annual Outputs	CAC 5		CAC 6		CAC 7		CAC 8	
Engine Requirement (kW)	167	187	185	198	47	69	861	965
Biogas Produced (m^3)	705025.00	851355.00	742908.00	769808.00	229613.00	336586.00	2632887.00	3777258.00
Methane Produced (m^3)	388739.00	395704.00	427925.00	419177.00	127435.22	161195.00	1474083.00	2062878.00
Electricity produced (MW)	1461.70	1504.00	1617.60	1594.00	416.00	613.00	5689.90	7762.00
Heat produced (MW)	1780.40	1618.00	1951.30	1743.60	619.00	600.00	6942.90	
Income from electricity (£)	£190,111.00	£268,660.00	£211,326.00	£284,673.46	£54,142.00	£113,430.00	£738,415.00	£1,029,553.00
Income from heat (£)	£6,739.00	£7,279.00	£28,717.00	£53,975.00	£234.00	£2,965.00	£128,292.00	£132,812.00
Total Income (£)	£204,791.00	£284,558.54	£258,272.00	£350,240.05	£59,129.00	£134,079.00	£1,009,906.00	£1,262,080.00
Total Expenditure (before grants) (£)	£822,122.00	£1,105,500.00	£876,590.00	£1,096,500.00	£464,489.00	£790,500.00	£3,157,036.00	£3,589,000.00
Total OpEx (£)	£164,064.00	£220,077.89	£208,678.00	£255,476.07	£106,331.00	£181,376.00	£934,214.00	£893,157.00
Retention Time	53	39	41	32	64	45	44 + 25	48
Digester size	2669	2127	2669	1846	1186	744	8098	5817
Payback (yrs)	8	6	8	5	-40	15	10	5
Profit/(Loss)	£40,727.00	£64,480.66	£49,594.00	£94,763.97	-£47,202.00	-£47,296.63	£75,692.00	£368,527.00

Table A1.20 Results for the East of England

East of England: Maximising the use of AD on farms

% Population included	No. of Herds	Mean herd size	Half No of Herds	Mix of feedstock type (t) at each AD facility: Layers	Broilers	Grass	Maize	HHC&I	Total Feedstock requirement (t) regionally: Layers	Broilers	Grass	Maize	HHC&I	OUTPUTS: GHG Saving kg.MWh^{-1} per site (10% heat)	MWh.a^{-1} generated per site	MWh.a^{-1} generated		GHG savings $kgCO_{2e}$		FIT Income from electrcitiy (£/MW)	Cost per tonne of CO2eq mitigated	Total annual payments from FITs
78%		Cattle																				
15%	28	1130	14	500		750	1000	2000	7000	0	10500	14000	28000	916	3160	44240				140.2	153.06	£6,202,448.00
					1000	1000	500	2000	0	14000	14000	7000	28000	944	3066	42924				140.2	148.52	£6,017,944.80
24%	32	570	16	500		750	750	2250	8000	0	12000	12000	36000	810	2426	38816				140.2	173.09	£5,442,003.20
					500	750	750	2250	0	8000	12000	12000	36000	825	2355	37680				140.2	169.94	£5,282,736.00
35%	56	415	28	500		750	750	2500	14000	0	21000	21000	70000	762	2328	65184				140.2	183.99	£9,138,796.80
					500	750	750	2500	0	14000	21000	21000	70000	776	2257	63196				140.2	180.67	£8,860,079.20
57%	178	260	89	250		1000	1000	2500	22250	0	89000	89000	222500	654	2096	186544				151.6	231.80	£28,280,070.40
					650	1000	750	2250	0	57850	89000	66750	200250	684	1947	173283				151.6	221.64	£26,269,702.80
		140	0	750		1000	1000	2000	0	0	0	0	0	0	0	0				151.6	#DIV/0!	£0.00
					500	750	1250	2000	0	0	0	0	0	0	1857	0	Av generation			151.6	#DIV/0!	£0.00
									51250	**93850**	**268500**	**242750**	**690750**	**6371**	**21492**	**651867**	**1895**					**£95,493,781.20**
74%		Dairy																482806708	kgCO2e saved			
7%	4	365	2	500		750	1000	2000	1000	0	1500	2000	4000	730	2122	4244				140.2	192.05	£595,008.80
					500	750	1000	2000	0	1000	1500	2000	4000	760	2010	4020				151.6	199.47	£609,432.00
19%	16	245	8	750		750	1150	2250	6000	0	6000	9200	18000	685	2252	18016				140.2	204.67	£2,525,843.20
					250	750	1000	2250	0	2000	6000	8000	18000	698	1952	15616				151.6	217.19	£2,367,385.60
48%	70	140	35	500		750	1500	2000	17500	0	26250	52500	70000	661	2007	70245				151.6	229.35	£10,649,142.00
					750	750	1000	2000	0	26250	26250	35000	70000	675	1854	64890	Av generation			151.6	224.59	£9,837,324.00
									24500	**29250**	**67500**	**108700**	**184000**	**4209**	**12197**	**177031**	**1967**					**£26,584,135.60**
96%		Pigs																119626943	kgCO2e saved			
88%	345	2630	173	500		1000	1750	1750	86500	0	173000	302750	302750	701	2314	400322				140.2	200.00	£56,125,144.40
					1000	1000	1750	1700	0	173000	173000	302750	294100	726	2349	406377				140.2	193.11	£56,974,055.40
	105	753	79	0		0	0	0	0	0	0	0	0			0		628	1852	151.6	#DIV/0!	£0.00
					2000	1000	1000	1750	0	158000	79000	79000	138250	706	2008	347384	Av generation			140.2	198.58	£48,703,236.80
									86500	**331000**	**425000**	**684500**	**735100**	**2133**	**6671**	**1154083**	**2900**	820908528	kgCO2e saved			**£161,802,436.60**
								TOTALS	162,250	454,100	761,000	1,035,950	1,609,850	12,713	40,360	1,982,981		MWh generated				
										No of Ha required	**16,911**	**23,021.11**		**1,423,342**	**$tCO_2e.a^{-1}$ saved**							**£283,880,353.40**
									Assumes Grass and Maize have a yield of 45t.ha^{-1}					0.71778	$kgCO_{2e}kWh_e$	**247**		**MW installed capacity**				
															average saving					average cost per tonne CO2eq saved		**£199.45**

Waste Only – based on 100/-t units costing about £12M each

603kgCO2e/MWh or 247kgCO2e/t feedstock

Theoretical Model

641-944-kgCO2e/MWh or 114-208kgCO2e/t feedstock

161.91 ha.MW^{-1} installed capacity land requirement

49.66 MW.ha^{-1}

EAST OF ENGLAND	Numbers	Total Excreta production	Slurry (92.5%)	Manure (7.5%)	Ratio
Dairy Cows	20,477	190,925	176,606	12,028	
Steers and Heifers	209,877	1,163,557	1,076,291	73,304	
Pigs	1,032,016	1,671,866	1,546,476	105,328	
Poultry - Layers	4,144,257	163,118	109,000		1.0
Poultry - Broilers	20,294,696	453,789	303,000		2.8
C&I +Muni-waste		1,610,512	1,074,000		9.9
	TOTAL	**5,253,768**			

Figures in red, above represent 66% collection of feedstock

SCENARIO IV.: MIX OF BIOWASTE AND CROPS TO MATCH ENERGY OUTPUT OF HUB AND POD OUTPUT

	GHG Saving kg.MWh^{-1}	MWh.a^{-1} generated per site	MWh.a^{-1} generated	Income from electricity (£/MW)	Cost per tonne of CO_{2eq} mitigated	Total annual payments from FiTs	No of units required
biowaste only	655	17647	705880	£92.40	£141.07	£65,223,312.00	40
Crop only	540	10753	1279607	£92.40	£171.11	£118,235,686.80	119
			1985487			£183,458,998.80	
			247	Installed capacity			
			462351.4				
			690987.78				
		TCO2eq saved	**1153339**			**159.07**	**Cost per tonne saved**

Table A1.21 Results for the South West of England

South West of England: Maximising the use of AD on farms

% Population included	No of Herds	Av. Herd size	Half No of Herds	Mix of feedstock type (t) at each AD facility: Layers	Broilers	Grass	Maize	HHC&I		Total Feedstock requirement (t) regionally: Layers	Broilers	Grass	Maize	HHC&I	OUTPUTS: GHG Saving $kg.MWh^{-1}$	$MWh.a^{-1}$ generated per site	$MWh.a^{-1}$ generated			FIT Income from electricity (£/MW)	Cost per tonne of CO2eq mitigated	Total annual payments from FITs
		Cattle																				
12%	217	985	109	750		750	1000	1800		81750	0	81750	109000	196200	892	2989	325801			140.2	£157.17	£45,677,300.20
					725	1000	500	1800		0	79025	109000	54500	196200	929	2734	298006			140.2	£150.91	£41,780,441.20
22%		580	0	750		750	750	1750		0	0	0	0	0	818	2355	0			151.6		£0.00
	312				500	750	750	1750		0	0	0	0	0	839	2185	0			151.6		£0.00
37%		415	0	750		750	750	1500		0	0	0	0	0	780	2010	0			151.6		£0.00
	666				1000	750	750	1500		0	0	0	0	0	809	1974	0			151.6		£0.00
		265	0	1000		1000	1000	1500		0	0	0	0	0	651	1955	0			151.6		£0.00
	1809				1250	1000	750	1500		0	0	0	0	0	697	1764	0			151.6		£0.00
		145	0	1250		1000	1000	1250		0	0	0	0	0	623	1867	0			151.6		£0.00
	2679				1250	750	1250	1250		0	0	0	0	0	662	1726	0	Av generation		151.6		£0.00
										81750	**79025**	**190750**	**163500**	**392400**	**7700**	**21559**	**623807**	**2875**				**£87,457,741.40**
54%		Dairy																	567,462,066 kgCO2e saved			
	14	870	7	500		750	720	2000		3500	0	5250	5040	14000	946	3155	22085			140.2	£148.20	£3,096,317.00
					1000	750	720	2000		0	7000	5250	5040	14000	959	3211	22477			140.2	£146.19	£3,151,275.40
	30	575	15	500		750	1000	2000		7500	0	11250	15000	30000	859	2745	41175			140.2	£163.21	£5,772,735.00
					1000	750	1000	1500		0	15000	11250	15000	22500	891	2596	38940			140.2	£157.35	£5,459,388.00
15%	80	412	40	550		1000	750	2000		22000	0	40000	30000	80000	803	2432	97280			140.2	£174.60	£13,638,656.00
					1000	1000	750	1750		0	40000	40000	30000	70000	831	2367	94680			140.2	£168.71	£13,274,136.00
~ 34%	360	255	180	650		750	1150	1750		117000	0	135000	207000	315000	677	1977	355860			151.6	£223.93	£53,948,376.00
38%	401				500	750	1000	1750		0	90000	135000	180000	315000	698	1780	320400			151.6	£217.19	£48,572,640.00
		140	0	500		750	1500	1500		0	0	0	0	0	627	1859	0			151.6		£0.00
	1254				1250	750	1000	1500		0	0	0	0	0	686	1752	0	Av generation		151.6		£0.00
										150000	**152000**	**383000**	**487080**	**860500**	**7977**	**23874**	**992897**	**2051**				**£146,913,523.40**
96%		Pigs																	733,864,058 kgCO2e saved			
71%	108	2560	54	725		1000	1000	1700		39150	0	54000	54000	91800	732	2010	108540			151.6	£207.10	£16,454,664.00
					475	1000	1000	1750		0	25650	54000	54000	94500	741	1888	101952			151.6	£204.59	£15,455,923.20
	0	725	0	1000		1000	1000	1500		0	0	0	0	0	628	1851	0			151.6	£241.40	£0.00
	72				1000	1000	1000	1500		0	0	0	0	0	654	1710	0	Av generation		151.6		£0.00
										39150	**25650**	**108000**	**108000**	**186300**	**2755**	**7459**	**210492**	**1493**				**£31,910,587.20**
									TOTALS	270,900	256,675	681,750	758,580	1,439,200	18,432	52,892	1,827,196		154,997,712 kgCO2e saved			
											No of Ha required	15,150	16,857		**1,456,323.84**	**$tCO_2e.a^{-1}$ saved**						**£266,281,852.00**
																	227		**MWh installed capacity**			

Assumes Grass and Maize have a yield of $45t.ha^{-1}$

0.7970 $kgCO_{2e}.kWh_e$ average saving

average cost per tonne CO2eq saved **£182.85**

L33 to P33 and s33 have been changed to take into account no available feedstock

South West of England

	Numbers	Total Excreta production	Slurry (92.5%)	Manure (7.5%)	
Dairy Cows	434,428	3,182,620	2,943,923	200,505	
Steers and Heifers	1,797,018	7,827,809	7,240,724	493,152	
Pigs	386,529	626,177	579,214	39,449	Ratio
Poultry - Layers	6,936,374	273,016	183,000		1.1
Poultry - Broilers	11,470,001	256,469	171,000		1.0
C&I +Muni-waste		1,439,064	960,000		5.6
	TOTAL	**13,605,155**			

Figures in red, above represent 66% collection of feedstock

SCENARIO IV.: MIX OF BIOWASTE AND CROPS TO MATCH ENERGY OUTPUT OF HUB AND POD OUTPUT

	GHG Saving $kg.MWh^{-1}$	$MWh.a^{-1}$ generated per site	$MWh.a^{-1}$ generated	Income from electricity (£/MW)	Cost per tonne of CO2eq mitigated	Total annual payments from FITs	No of units required
biowaste only	655	17647	635292	£92.40	£141.07	£58,700,980.80	36
Crop only	540	10753	1193583	£92.40	£171.11	£110,287,069.20	111
		TOTAL	**1828875**			£168,988,050.00	
			416116				
			644535				
		TCO2eq saved	**1060651**			**£159** Cost per tonne saved	

Table A1.22 Results for the West Midlands

West Midlands: Maximising the use of AD on farms

				Mix of feedstock type (t) at each AD facility						Total Feedstock requirement (t) regionally					OUTPUTS								
% Population included	No of Herds	Av. herd size	Half No of Herds	Layers	Broilers	Grass	Maize	HHC&I		Layers	Broilers	Grass	Maize	HHC&I	GHG Saving kg.MWh^{-1}	MWh.a^{-1} generated per site	MWh.a^{-1} generated				FIT Income from electricity (£/MW)	Cost per tonne of CO2eq mitigated	Total annual payments from FITs
82%		Cattle																					
9%	75	895	38	800		750	1000	2000		30400	0	28500	38000	76000	869	2975	113050				140.2	£161.33	£15,849,610.00
					1000	1000	500	2000		0	38000	38000	19000	76000	906	2763	104994				140.2	£154.75	£14,720,158.80
20%	142	585	71	500		750	750	2000		35500	0	53250	53250	142000	820	2343	166353				140.2	£170.98	£23,322,690.60
					650	750	750	2000		0	46150	53250	53250	142000	837	2310	164010				140.2	£167.50	£22,994,202.00
33%	242	410	121	300		750	750	2250		36300	0	90750	90750	272250	767	2140	258940				140.2	£182.79	£36,303,388.00
	242				650	750	750	2500		0	78650	90750	90750	302500	778	2289	276969				140.2	£180.21	£38,831,053.80
		265	0	1000		1000	1000	1650		0	0	0	0	0	650	2017	0				151.6	£233.23	£0.00
	773				1250	1000	750	1650		0	0	0	0	0	696	1826	0				151.6	£217.82	£0.00
		145	0	1250		1000	1000	1500		0	0	0	0	0	626	1969	0				151.6	£242.17	£0.00
	1240				1250	750	1250	1500		0	0	0	0	0	662	1829	0	Av generation			151.6	£229.00	£0.00
										102200	**162800**	**354500**	**345000**	**1010750**	**7611**	**22461**	**1084316**	**2362**					£152,021,103.20
																			881,139,706.00	kgCO2e saved			
75%		Dairy																					
2%	7	565	4	500		750	750	2000		2000	0	3000	3000	8000	870	2614	10456				140.2	£161.15	£1,465,931.20
					1000	750	750	2000		0	4000	3000	3000	8000	887	2670	10680				140.2	£158.06	£1,497,336.00
7%	20	460	10	500		750	750	2000		5000	0	7500	7500	20000	836	2423	24230				140.2	£167.70	£3,397,046.00
					1250	750	750	2000		0	12500	7500	7500	20000	857	2542	25420				140.2	£163.59	£3,563,884.00
34%	177	260	89	750		750	1150	2000		66750	0	66750	102350	178000	678	2124	189036				151.6	£223.60	£28,657,857.60
	177				750	750	1000	2000		0	66750	66750	89000	178000	706	1950	173550				151.6	£214.73	£26,310,180.00
		140	0	500		750	1500	1500		0	0	0	0	0	632	1859	0				151.6	£239.87	£0.00
	495				1250	750	1000	1500		0	0	0	0	0	658	1752	0	Av generation			151.6	£230.40	£0.00
										73750	**83250**	**154500**	**212350**	**412000**	**6124**	**17934**	**433372**	**2124**					£64,892,234.80
																			311,303,808.00	kgCO2e saved			
84%		Pigs																					
69%	59	2200	30	750		1000	1000	2000		22500	0	30000	30000	60000	704	2125	63750				151.6	£215.34	£9,664,500.00
					1000	1000	1000	2000		0	30000	30000	30000	60000	731	2082	62460				151.6	£207.39	£9,468,936.00
	0	745	0	400		1000	1000	3000		0	0	0	0	0	632	2232	0				151.6	£239.87	£0.00
	39				1000	1000	1000	2000		0	0	0	0	0	658	1917	0	Av generation			151.6	£230.40	£0.00
										22500	**30000**	**60000**	**60000**	**120000**	**2725**	**8356**	**126210**	**1275**	90,538,260.00	kgCO2e saved			£19,133,436.00
									TOTALS	**198,450**	**276,050**	**569,000**	**617,350**	**1,542,750**	**16,460**	**48,751**	**1,643,898**						**£ 236,046,774.00**
											No of Ha required	**12,644**	**13,719**		**1,192,444**	**$tCO_2e.a^{-1}$ saved**						average cost per tonne CO2eq saved	**£197.95**
												Assumes Grass and Maize have a yield of $40t.ha^{-1}$					**204**		**MW Installed capacity**				
															0.72538	$kgCO_{2e}kWh_e$ average saving							

West Midlands

	Numbers	Total Excreta production	Slurry (92.5%)	Manure (7.5%)	
Dairy Cows	169,071	1,351,218	1,249,877	85,127	
Steers and Heifers	763,851	3,629,822	3,357,585	228,679	
Pigs	188,840	305,921	282,977	19,273	Ratio
Poultry - Layers	5,060,393	199,177	133,000		1.00
Poultry - Broilers	12,438,166	278,117	186,000		1.40
C&I +Muni-waste		1,542,957	1,029,000		7.75
	TOTAL	**7,307,212**			

Figures in red, above represent 66% collection of feedstock

SCENARIO IV.: MIX OF BIOWASTE AND CROPS TO MATCH ENERGY OUTPUT OF HUB AND POD OUTPUT

	GHG Saving kg.MWh^{-1}	MWh.a^{-1} generated per site	MWh.a^{-1} generated	Income from electricity (£/MW)	Cost per tonne of CO2eq mitigated	Total annual payments from FiTs	No of units required
biowaste only	655	17647	688233	£92.40	£141.07	£63,592,729.20	39
Crop only	540	10753	957017	£92.40	£171.11	£88,428,370.80	89
			1645250			£152,021,100.00	
			450793				
			516789				
		TCO2eq saved	**967582**		**157.11**	**Cost per tonne saved**	

GLOSSARY

biogas	a gaseous mixture, primarily of methane, carbon dioxide and other trace elements; the product of AD
biomass	biological material living or recently living, often referring to plants or plant material
biowaste	biodegradable garden and park waste; food and kitchen waste from households, restaurants, caterers and retail premises; and comparable waste from food-processing plants (it does not include forestry or agricultural residues, manures, sewerage sludge, other biodegradable waste such as natural textiles, paper or processed wood, or those by-products of food production that never become waste)
carbon dioxide equivalent	the global warming potential that a given type and quantity of greenhouse gas may cause, using the functional equivalent amount (or concentration) of CO_2 as the reference
hurdle rate	the minimum percentage return required from an investment project, taking into account the inherent risks of proceeding with the project, measured against the opportunity cost of investing elsewhere
mono-nitrogen oxides	the product of the reaction between nitrogen(g) and oxygen(g) in the air during combustion, particularly at high temperatures
project term	the lifespan of the AD facility (for the purposes of this research, this has been set at the length of the funding period – 20 years)

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