Review of Bioenergy Potential: Technical Report

For Cadent Gas Ltd

June 2017

Strategic thinking in sustainable energy

Disclaimer

This report has been produced by Anthesis Consulting Group PLC and E4tech UK Ltd within the terms of the contract with the client and taking account of the resources devoted to it by agreement with the client. Anthesis and E4tech disclaim any responsibility to the client and others in respect of any matters outside the scope of the above. Anthesis and E4tech have taken due care in the preparation of this report to ensure that all facts and analysis presented are as accurate as possible, within the scope of the project. However, no guarantee is provided in respect of the information presented and Anthesis and E4tech are not responsible for decisions or actions taken on the basis of the content of this report.

Should any third party rely on the report, they do so at their own risk. We have not verified the completeness and/or accuracy of the information contained in third party reports cited in this document or information gathered during the course of telephone conversations and used in preparing this document other than as expressly set out in this document. We have used all information provided to us by the client in the knowledge that we were provided with the information for the purpose of the project.

The IP presented in this report remains the property of Anthesis and E4tech respectively.

Bioenergy Market Review

For Cadent

Prepared for:

Huw Sullivan
Innovation Delivery Manager
National Grid Gas Distribution
Brick Kiln St
Hinckley
LE10 0NA

Prepared by:

Anthesis UK Ltd.,
Unit 12.2.1, The Leathermarket,
11-13 Weston Street,
London, SE1 3ER

E-mail: mail@anthesisgroup.com
Website: www.anthesisgroup.com

Tel: 01865 250818
Fax: 01865 794586

Company Registration 08425819

Report written by:
Peter Scholes, Hannah Dick, Claudia Amos (Anthesis)
Geneviève Alberts, Ausilio Bauen,
Michael Kenefick, Richard Taylor (E4tech)

In partnership with:
E4tech UK Ltd.,
83 Victoria Street,
London, SW1H 0HW

E-mail: enquiries@anthesisgroup.com
Website: www.e4tech.com

Tel: 020 3008 6140

Company Registration 4142898

Analysts:
Hannah Dick, Michael Kirk-Smith

Quality Assurance
Analysis:
Peter Scholes, 05/05/17
Report:
Debbie Hitchen, 12/05/17
Claudia Amos, 12/05/17

Scope of work of Anthesis and E4tech: Anthesis was responsible for collating this report and carried out the analysis on municipal, commercial and industrial waste streams. E4tech carried out the analysis on agricultural and forestry residues and energy crops.

Anthesis Consulting Group

Anthesis is a global specialist consultancy which believes that commercial success and sustainability go hand in hand. We offer financially driven sustainability strategy, underpinned by technical experience and delivered by innovative collaborative teams across the world.

The company combines the reach of big consultancies with the deep expertise of the boutiques. We take our name from the Greek word “anthesis”, the stage of a plant’s lifecycle when it is most productive. Sustainability is now at that exciting stage of flourishing; it has grown up and grown into the mainstream.

Anthesis has clients across industry sectors, from corporate multinationals like Coca-Cola, Tesco, Arjowiggins and Reckitt Benckiser to world class events like London 2012, 34th America’s Cup and Sochi 2014.

The company brings together expertise from countries around the world and has offices in the US, Canada, the UK, Germany, Sweden, Finland, the Middle East, China and the Philippines. It has a track record of pioneering new approaches to sustainability and has won numerous awards.

E4tech

E4tech is an international strategic consultancy focused on sustainable energy. Since 1997 we have worked with companies, governments, and investors to help them understand the global opportunities and challenges of clean energy. We have built a strong track record of providing objective and strategic business and policy advice backed up by sound technical knowledge. Our clients call on us for support in looking into the future and taking decisions under uncertain conditions. We support them through strategy development and business planning, market and competitor analysis, due diligence support, and policy analysis and development. We underpin this with detailed modelling and assessment work: techno-economic analyses of energy systems, greenhouse gas and sustainability assessments, and supply chain and primary resource evaluation.

Table of contents

Abbreviations

Acronym	Definition
ABP	Animal By-Products
AD	Anaerobic Digestion
AHDB	Agriculture and Horticulture Development Board
BEIS	Department for Business, Energy & Industrial Strategy
BioSNG	Biomass fuel derived Substitute Natural Gas
BVCM	Bioenergy Value Chain Model
C&I	Commercial and Industrial (Waste)
CA	Civic Amenity site
CAGR	Compound annual growth rate
CCC	Committee on Climate Change
CCC (2011)	Committee on Climate Change “Bioenergy Review”, December 2011
CCS	Carbon Capture and Storage
CD&E	Construction, Demolition and Excavation Waste
CLU	Constrained land use
CV	Calorific Value
Defra	Department for Environment, Food and Rural Affairs
DUKES	Digest of United Kingdom Energy Statistics
EA	Environment Agency
EfW	Energy from Waste
ELU	Extended land use
EWC	European Waste Code
FAPRI	Farm and Agriculture Policy Research Institute
FLC	Further land conversion
GHG	Greenhouse gas
GJ	Gigajoule
HaFS	Hospitality and Food Service
HHV	Higher Heating Value
HMRC	HM Revenue & Customs
HWRC	Household Waste Recycling Centre
IVC	In-Vessel Composting
ktpa	Thousands of tonnes Per Annum
LACW	Local Authority Collected Waste
LFT	Landfill Tax
LHV	Lower Heating Value
MBT	Mechanical Biological Treatment
Mha	Million hectares
MHT	Mechanical Heat Treatment
MRF	Materials Recycling Facility
MSW	Municipal Solid Waste
Mt	Million Tonnes
NIEA	Northern Ireland Environment Agency
NRW	Natural Resources Wales

Acronym	Definition
Odt	Oven dried tonnes
OSR	Oilseed rape
OWC	Open Windrow Composting
PJ	Petajoule
SEPA	Scottish Environmental Protection Agency
SNG	Substitute natural gas (also synthetic natural gas)
SOC	Substance Oriented Classification
SRC	Short rotation coppice
tpa	Tonnes Per Annum
TWh	Terawatt Hour(s)
TWhpa	Terawatt Hour(s) per Annum
WEEE	Waste Electrical and Electronic Equipment
WRAP	Waste and Resources Action Programme

Glossary

Term	Definition
Anaerobic Digestion	A process where organic matter is broken down by bacteria in the absence of air, producing a biogas, which can be used to generate renewable energy, and a digestate, which can be spread to land to provide agricultural benefit.
Animal By-products Category 1	Animal By-Products - entire bodies or parts of dead animals and carcasses containing specified risk materials at the point of disposal (unless the specified risk material has been removed and disposed of separately).
Animal By-products Category 3	Animal By-Products - carcasses and parts of animals slaughtered or, in the case of game, bodies or parts of animals killed, and which are fit for human consumption in accordance with EU legislation.
Arisings	Total amount of a particular waste stream that is generated and requires management
Available Arisings	Amount of a specific waste material available for the generation of bioenergy, taking into account competing uses and market situation.
Bioenergy	Renewable energy made available from materials derived from biological sources.
Biogas	Gas composed mainly of methane and carbon dioxide, produced from the anaerobic digestion of biomass.
Biogenic Waste	An organic waste produced by life processes (animal or plant), such as food waste, or cellulose fibres including wood and paper
Biomass	Organic materials of either animal or plant origin (which might be used for energy generation)
Biomethane	'Upgraded' biogas, which is almost entirely methane and is suitable for injection into the natural gas network and/or as a replacement for compressed natural gas for transport.
BioSNG	A form of synthetic natural gas (SNG), which is produced via the gasification of biomass.
Biosolid	Organic matter recycled from sewage, especially for use in agriculture
Commercial Waste	Controlled waste arising from trade premises.
Construction, Demolition & Excavation Waste	Controlled waste arising from the construction, repair, maintenance and demolition of buildings and structures.
Dry Recycling	Dry recycling is comprised of 'dry' materials (i.e. not food/garden waste, organic waste) such as paper, cardboard, plastics, metals and glass.
Energy from Waste	The conversion of waste into a useable form of energy, often heat or electricity.
Hazardous Waste	Waste that poses substantial or potential threats to public health or the environment (when improperly treated, stored, transported or disposed). This can be due to the quantity, concentration, or characteristics of the waste.
Household Waste	Refuse from household collection rounds, waste from street sweepings, public litter bins, bulky items collected from households and wastes which

Term	Definition
	householders themselves take to household waste recycling centres and "bring" sites.
Incineration	The controlled burning of waste. Energy may also be recovered in the form of heat (see Energy from Waste).
Industrial Waste	Waste from a factory or industrial process.
Inert waste	Waste not undergoing significant physical, chemical or biological changes following disposal, as it does not adversely affect other matter with which it may come into contact, and does not endanger surface or groundwater.
In-Vessel Composting	A system that ensures composting takes place in an enclosed but aerobic (in the presence of oxygen) environment, with accurate temperature control and monitoring to produce a stabilised residue.
Landfill	The permanent disposal of waste into the ground, by the filling of man-made voids or similar features.
Landfill Directive	European Union requirements on landfill to ensure high standards for disposal and to stimulate waste recycling and minimisation.
Landfill Gas	Similar to biogas but produced via the degradation of biomass within a landfill.
Local Authority Collected Waste	Household waste and any other waste collected by a waste collection authority, including trade waste and municipal parks and gardens waste, beach cleansing waste and waste resulting from the clearance of fly-tipped materials.
Materials Recycling Facility	A facility for sorting and bulking recyclable waste.
Mechanical Biological Treatment	The treatment of residual waste using a combination of mechanical separation and biological treatment.
Non-Hazardous Landfill	A landfill that is licensed to accept non-inert (biodegradable) wastes e.g. municipal and commercial and industrial waste and other non-hazardous wastes (including inert) that meet the relevant waste acceptance criteria.
Open Windrow Composting	A managed biological process in which biodegradable waste (such as green waste and kitchen waste) is broken down in an open-air environment (aerobic conditions) by naturally occurring micro-organisms to produce a stabilised residue.
Organic Waste	Biodegradable waste from gardening and landscaping activities, as well as food preparation and catering activities. This can be composed of garden or park waste, such as grass or flower cuttings and hedge trimmings, as well as domestic and commercial food waste.
Recyclate	Raw material collected for recycling (i.e. plastics, metals, glass, paper/card).
Renewable Gas	Umbrella term which includes biogas, biomethane and bioSNG
Residual Waste	Waste remaining after materials for re-use, recycling and composting have been removed.
Unconstrained arisings	Total amount of a specific waste material arising, irrespective of competing uses or market situation.
Waste Hierarchy	A framework for securing a sustainable approach to waste management. Waste should be minimised wherever possible. If waste cannot be

Term	Definition
	avoided, then it should be re-used; after this it should be prepared for recycling, value recovered by recycling or composting or waste to energy; and finally disposal.

1. Introduction

1.1 Background

On behalf of Cadent Gas ('Cadent'), Anthesis, in partnership with E4tech, is pleased to present this review of the UK Bioenergy Market, critiquing and updating the estimates of the energy potential of renewable gas produced from waste and non-waste feedstocks, contained in the 2011 report "Bioenergy Review" by the Committee on Climate Change (CCC). This report provides further detail relating to the methodology, assumptions and results which underpin the key findings presented in the Summary Report (of the same name), also undertaken by Anthesis and E4tech on behalf of Cadent.

Data published by the Department for Business, Energy and Industrial Strategy (BEIS) demonstrate that nearly half of the UK's energy consumption is required to meet the UK's heat requirements. Natural gas provides 80% of heat at times of peak demand, and is supplied to 23 million customers[1] through an established reception, storage, and transmission infrastructure, providing around 292 TWh per annum[2] to domestic customers.

The Climate Change Act (2008) has set the UK ambitious decarbonisation targets, which aim to reduce greenhouse gas emissions by 57% (from 1990 levels) by 2030 and by at least 80% by 2050. Heat accounts for around a third of UK greenhouse gas (GHG) emissions[3]. The UK is making good progress towards decarbonising the power sector, but very limited progress in respect of heat and transport.[4] Renewable gas is increasingly seen as the lowest cost pathway option to meeting future carbon emissions targets. Delivering low carbon gas via the existing natural grid could provide low carbon heat to customers without requiring changes within homes[5].

The production of renewable gas has grown significantly over the last decade. Alongside existing landfill gas generation, there has been huge growth in the number of anaerobic digestion (AD) facilities in the UK, which produce both biogas for power and heat generation, and biomethane for gas grid injection or transport. However, AD capacity is currently constrained by the limited types of biomass feedstock that can be utilised and their availability as well as the finite market (or land available) for the digestate produced by the process. In contrast, gasification of biomass to produce bio-substitute natural gas (bioSNG), has the potential to unlock a wider range of biomass feedstocks, enabling production of a far greater quantity of renewable gas.

The last major review of the potential of bioenergy was the aforementioned study published by the CCC in 2011[6]. This concluded that it would be difficult to meet the above emissions reduction targets without some 10% of total UK primary energy being derived from bioenergy (and that this proportion would need to be

---

[1] National Grid (2016) *The future of gas – supply of renewable gas*, National Grid, February 2016. Available at: http://www2.nationalgrid.com/WorkArea/DownloadAsset.aspx?id=45609

[2] BEIS (2016), *Digest of United Kingdom Energy Statistics (DUKES)*, July 2016 (updated September 2016). Available at: https://www.gov.uk/government/statistics/digest-of-united-kingdom-energy-statistics-dukes-2016-main-chapters-and-annexes

[3] DECC (2012) *Emissions from Heat: Statistical Summary*, January 2012. Available at: https://www.gov.uk/government/statistics/uk-emissions-from-heat

[4] Committee on Climate Change (2016) *Meeting Carbon Budgets – 2016 Progress Report to Parliament*, June 2016. Available at: https://www.theccc.org.uk/publication/meeting-carbon-budgets-2016-progress-report-to-parliament/

[5] KPMG (2016) *2050 Energy Scenarios – The UK Gas Networks role in a 2050 whole energy system*, July 2016. Available at: http://www.energynetworks.org/gas/futures/the-uk-gas-networks-role-in-a-2050-whole-energy-system.html

higher if carbon capture and storage (CCS) was not delivered in the wider market by 2050)[6]. In 2010, however, bioenergy equated to just 2% (79 TWh) of demand across power generation, heat, and transport sectors.

The same CCC report highlighted that assumptions relating to lifecycle emissions and land use constraints are critical considerations in determining how much energy might be derived from biomass sourced from the UK. It also emphasised other sustainability factors, including tensions between food and bioenergy production alongside consideration of the availability of waste feedstocks. Under the CCC's central assumptions, this approach resulted in an estimated 125 TWh per annum (TWhpa) of UK domestic bioenergy resource in 2020, rising to 140 TWhpa in 2050.

The report also explored the appropriate use of biomass feedstocks and developed a hierarchy of options for 2050. The analysis concluded that biomass has an important role in heat generation. This is because of the greater efficiency of conversion – and therefore far greater overall reductions in carbon dioxide (CO_2) emissions - compared, for example, with power generation.

Initial work undertaken on behalf of Cadent, based on data published in the CCC report, suggested that there is the potential for 100 TWhpa of renewable gas production by 2050.[7] Understanding the role that renewable gas can contribute to meeting decarbonisation targets depends upon the further development of the evidence base relating to the availability of sustainable feedstock supplies.

1.2 Scope and Objectives

The core goals of this study are to:

- Critique the UK waste and non-waste biomass feedstock potentials within the CCC Bioenergy Review, and provide updated estimates based on improved data and sustainability assumptions; and
- Generate a set of three illustrative scenarios (Low, Central and High) to 2050, combining the different UK biomass feedstocks suitable for renewable gas production, to produce new values for the total sustainable primary biomass potential (and hence TWh/yr of renewable gas).

This report includes analysis and quantification of both waste and non-waste resources for the production of renewable gas, before developing a range of conclusions and recommendations pertinent to the development of this market.

The scope of waste feedstocks for the purposes of this study includes those sourced from:

- Local authority collected waste (LACW), or what was previously known as municipal solid waste (MSW), which includes wastes collected from households and from some businesses;
- Commercial & Industrial waste (C&I):
    - Commercial wastes similar in composition to LACW wastes, but which are collected from businesses and sit outside of the LACW stream; and
    - Industrial wastes collected from businesses, which also sit outside the LACW stream, but are not similar in composition.

[6] Committee on Climate Change (2011*), Bioenergy Review*, December 2011. Available at: www.theccc.org.uk/publication/bioenergy-review/

[7] Cadent (2016) *The Future of Gas: Supply of Renewable Gas*, Cadent Gas, February 2016. Available at: http://cadentgas.com/getattachment/About-us/The-future-role-of-gas/Doc-promo-Supply-of-renewable-gas/Cadent_Gas_-_Renewable_Gas.pdf

- Construction and demolition (C&D) wastes, which are predominantly inert, but also contain significant fractions of wood; and
- Sewage sludge from waste water treatment.

To reflect the analysis methodology and reporting structure used for the original CCC (2011) report, however, waste forecasts are reported by key renewable waste type derived from these sources i.e. residual waste (from LACW and C&I sources), wood waste (from LACW, C&I and C&D sources), food waste (from LACW and C&I sources) and Sewage sludge.

In addition to waste feedstocks, the non-waste biomass feedstocks suitable for bio-SNG production included within the scope of the study can be summarised as follows:

- Dedicated energy crops, including Miscanthus, Short Rotation Coppice willow & poplar, and other non-food perennial crops;
- Agricultural residues, including straw, cobs, husks, shells, slurry and manure;
- Forestry and forest residues, including Short Rotation Forestry and small Roundwood;
- Industrial residues, including sawdust, shaving cuttings, wine lees, grape marcs, crude glycerine, molasses, brown & black liquor, tall oil and tall oil pitch;
- Macro-algae; and
- Woody biomass that is currently imported to the UK.

For both waste and non-waste feedstocks, both respective chapters presented below are structured as follows:

1. A critical assessment of the 2011 CCC biomass potentials, to ascertain the data sources used for these and identify the key assumptions;
2. A revision of the waste arisings baseline, which considers what assumptions have changed since 2011 together with actual progress reported in more recent sources, and provides an updated 2015 baseline; and
3. Modelling of each feedstock in the three illustrative scenarios, which have been designed to reflect the uncertainty associated with producing estimates of the total sustainable bioenergy potential from UK-derived waste and non-waste feedstocks through to 2050.

2. Waste Feedstocks

2.1 Critical Appraisal of the CCC (2011) Report

The CCC report, and its supporting technical paper[8], presented a picture of UK bioenergy supply at that time, split into "tradable bioenergy feedstocks" (e.g. energy crops, forest biomass and agricultural residues, referred to as "non-waste feedstocks" in this report) and "non-tradable bioenergy feedstocks" (essentially wastes, referred to as "waste feedstocks" in this report).

The CCC bioenergy potentials were derived primarily from a 2011 report undertaken by AEA[9] (referred to as "AeA (2011)" in this report). For waste feedstocks, the CCC report draws on the scenarios and assumptions set out in the AEA (2011) report and its supporting annex[10], supplemented by analysis from Defra, for resource estimates to 2030[11]. Estimates for 2050 resource potential were guided by a report by E4Tech on behalf of the Department for Transport (DfT)[12]. It is also noted that the AeA (2011) forecasts have been updated in a recently published document "Biomass Feedstock Availability" by Ricardo (previously known as AEA) for BEIS[13] in 2017 and where appropriate the updated figures are referenced throughout the report.

The CCC report, and that of the source data from AeA (2011), breaks down "non-tradable" waste feedstocks into key biogenic waste types, i.e.

- Waste wood;
- Renewable fraction of solid waste;
- Landfill gas;
- Food waste;
- Sewage sludge;
- Used cooking oil (not included in this report as negligible amounts available and most sustainable route is for liquid biofuel production); and
- Wet agricultural residues (manures) – addressed in this report as part of non-waste feedstocks.

Modelling of arisings for each waste generated both "unconstrained" and "constrained" arisings totals, from which bioenergy potentials were estimated using assumed calorific values (in GJ/t). Forecasts to 2050 were

---

[8] Committee on Climate Change (2011*) Bioenergy Review, Technical paper 2 - Global and UK bioenergy supply scenarios*, December 2011, Section 3 pp.30–46. Available at: https://www.theccc.org.uk/publication/bioenergy-review/

[9] AEA, Oxford Economics, Biomass Energy Centre, and Forest Research (2011) *UK and Global Bioenergy Resource – Final report*, Department of Energy & Climate Change, March 2011. Available at: http://www.gov.uk/government/publications/aea-2010-uk-and-global-bioenergy-resource

[10] AEA, Oxford Economics, Biomass Energy Centre, and Forest Research (2011) *UK and Global Bioenergy resource – Annex 1 report: details of analysis*, Department of Energy & Climate Change, March 2011, Section 4 pp.85–138. Available at: http://www.gov.uk/government/publications/aea-2010-uk-and-global-bioenergy-resource

[11] Source not referenced in the CCC report

[12] E4tech (2011) *Modes Project 1: Development of illustrative scenarios describing the quantity of different types of bioenergy potentially available to the UK transport sector in 2020, 2030 and 2050*, Department for Transport, March 2011. Available at: https://www.gov.uk/government/publications/biofuel-research

[13] Ricardo Energy & Environment (2017) *Biomass Feedstock Availability*, Department for Business, Energy & Industrial Strategy, March 2017. Available at: https://www.gov.uk/government/publications/uk-and-global-bioenergy-resource-model

generated using a range of scenarios based upon target recycling rates and assumed economic or population growth, and bioenergy prices.

In summary, the bioenergy potential of the studied waste feedstocks was reported as per Table 1, identifying between 47 and 53 TWh/yr bioenergy potential by 2050 from waste feedstocks.

Table 1: CCC bioenergy forecasts from non-tradable feedstocks (TWh/yr)

Waste Type	2020	2030	2050	Data Source
Wood Waste to EfW	22	22	22	AeA (2011)
Renewable Fraction to EfW	7–9	8–10	9–11	AeA (2011)
Renewable Fraction to Landfill Gas	17–18	8–9	4	Defra (2011)
Food Waste to AD	4–9	6–9	6–9	Defra (2011)
Sewage Sludge to AD/EfW	2.5–3.5	2.9–3.6	3.5–4.0	AeA (2011)
UCO/Tallow to EfW	1.3–1.8	1.5–2.0	2.5–3.2	AeA (2011)
Total	53.8–63.3	48.4–55.6	47–53.2	

The following sections provide analysis of how these forecasts were generated.

2.1.1 Renewable Fraction of Residual Waste

The AeA (2011) study, and therefore the CCC report, quantified and reported the potential of residual solid waste for bioenergy production via two bioenergy routes, i.e. that available for energy recovery, and that landfilled, which produces landfill gas. These were linked to avoid double counting.

AeA (2011) defined residual waste as the LACW and C&I mixed waste streams i.e. the waste left after segregation of specific wastes for recycling (such as paper, card, plastics, glass, etc.). In addition, the potential wood and food waste streams were excluded as these are being analysed as separate waste streams in the study. Estimates of total waste and available waste for bioenergy production were based upon 2008 data for LACW and a range of C&I data sources (mostly regional) dating back to 2004/5.

In producing forecasts to 2030, annual growth in arisings was modelled. For LACW, a growth rate of 0.3%pa was used, related to forecast growth in population numbers[14]. For C&I waste, models were generated using a zero growth rate. The CCC report was written at a time when the trend in annual waste growth and LACW arisings in particular was in decline, likely as a result of the economic recession. Since 2012, LACW have

[14] Growth rate sourced from work for the South East Regional Partnership Board, ERM 2009 (no link)

increased year-on-year by on average 1.4%/annum[15] and other waste streams have also shown growth in line with the economic recovery in the UK.

National recycling rates were also modelled; for LACW increasing linearly to 60% by 2025 and for C&I increasing to 70% by 2025, which effectively removed these proportions of waste from going to energy from waste (EfW) or landfill. From this modelling, AeA (2011) concluded there was 5.1 Mt available for bioenergy production in 2010, reducing to 12.5Mt by 2030. In converting these tonnage arisings to bioenergy potential, energy production potentials were factored by 62.5% to reflect the assumed renewable fraction of the input waste (by energy content). There does not appear to be any basis for this assumption, albeit a figure of 63.5% has since been used by Ofgem in the guidance for EfW projects seeking support under the Contract for Difference (CfD) mechanism.[16]

The main challenge with the AeA (2011) estimates was the lack of robust data on contemporary C&I arisings to base these models on. Consequently, the CCC used updated estimates from Defra based upon the 2009 England C&I survey results instead, producing reduced estimates of 4.5–5.8 Mt in 2020, 5.1–6.4Mt in 2030, 5.8–7.1Mt in 2050, equivalent to 7–9 TWh in 2020, 8–10 TWh in 2030, and 9–11 TWh in 2050. The assumptions used in generating these results, such as recycling or growth rates, were not reported.

The Ricardo (2017) update used C&I estimates based on a Defra estimation of English baseline arisings (45Mt in 2015) provided "internally by Defra" and extrapolated this data to a UK baseline total by multiplying with a factor of 1.27 "recommended by Defra". The modelling also assumed that all waste that is not recycled is deemed residual and available for bioenergy generation, which is highly questionable due to the considerable amount of inert material included in the overall C&I totals. A similar approach is taken in the original AeA (2011) and therefore both the 2011 and 2017 figures are likely to be overestimates. The update concluded that 11.0Mt in 2015 and 13.6Mt in 2050 of residual waste would be available for bioenergy generation.

As described further in Section 2.2, for this study it is assumed that all non-inert residual waste (or "household like" residual waste) was available for bioenergy production, and therefore the segregation into material for energy recovery and for landfill was not made. Updated recycling targets were also modelled to reflect changes in policy made at the national level in the time since the AeA (2011) report, and growth in arisings was modelled to reflect the BEIS forecast growth in population and employment.

2.1.2 Landfill Gas Generation

The CCC and AeA (2011) reports considered the bioenergy potential of the gas generated by the landfilling of residual waste separately to the renewable fraction available for energy recovery.

Using the same recycling, landfill diversion, and growth rate assumptions as reported for the renewable fraction, AeA (2011) concluded that the amounts of residual waste available for bioenergy production via landfill gas were 39.3 Mt in 2010, declining to 12.5 Mt in 2030. However, the CCC used updated Defra estimates of 15.3–16.2 Mt in 2020, to 7.2–8.1 Mt in 2030, and 3.6 Mt in 2050, equivalent to bioenergy potentials of 17–18 TWh in 2020, 8–9 TWh in 2030, and 4 TWh in 2050. The assumptions used in generating these results, such as recycling or growth rates, were not reported.

---

[15] See Defra's WasteDataFlow at http://www.wastedataflow.org/

[16] Ofgem (2014) *Applicant Guidance Note: Fuel Measurement and Sampling Explained,* Ofgem, June 2014. Available at: https://www.ofgem.gov.uk/ofgem-publications/82931/applicantguidancenotefuelmeasurementandsamplingexplained.pdf

The Ricardo (2017) update reported the biogenic fraction sent to landfill as 15 Mt in 2015 and 9.4 Mt in 2050,[17] based upon Defra landfill forecasts. These figures assume a considerable volume of waste to landfill in 2050, which is highly questionable given the current trend for widespread closure of landfill capacity across Great Britain.

Therefore, neither forecasts take into account long-term availability of actual landfill capacity and availability of landfill void space in the UK. Data published by the Environment Agency for England show a steady reduction in landfill input and capacity over at least the last 15 years, and suggest that if available landfill volumes continue to reduce by the rate of input seen in 2015, the available landfill capacity would be exhausted in just under 10 years. This is discussed in more detail in Section 2.2.2.2.

2.1.3 Waste Wood

The CCC acknowledged that the lack of a routine survey of wood waste generation in the UK was the main challenge in generating robust estimates of wood waste arisings; however, this situation has not changed in recent years. AeA (2011) estimates were based upon a 2009 WRAP report[18] and a 2009 Defra report[19]. It is notable that the AeA (2011) estimates assumed that "most waste wood sourced from post-consumer or treated waste is dried in production and remains reasonably dry through the waste chain".

AeA (2011) forecasted unconstrained arisings of 5.0 Mtpa from 2010 to 2030, building in no growth or decline in arisings over that period. Competition from panel board manufacture, horticulture, agriculture and wood energy plants was highlighted, giving a constrained arisings forecast of 4.3 Mt (2010) to 4.1 Mt (2030) available for bioenergy generation. Using these forecasts, the CCC reported 22 TWh bioenergy potential from wood waste in 2030, unchanged to 2050.

The Ricardo[20] update (2017) used updated data sources, but again, no growth in arisings to 2050 was assumed. The update cited figures of 5.0 Mtpa (from 2015 to 2050) available for bioenergy.

Although there is little new primary data for wood waste arisings since the publication of the original AeA (2011) study, understanding of the market has improved in the intervening period. For the modelling in in this study as set out in Section 2.2, therefore, updated arisings figures were used from recent studies[21], and growth in arisings was included to reflect forecast population and economy growth to 2050.

2.1.4 Food Waste

For food waste, AeA (2011) modelled WRAP and NNFCC[22] data on food and green waste availability. The report identified food and green waste arisings as 18–20 Mt/y (WRAP data), a total which included 6.7 Mt/y food waste from households, and 8.7 Mt/y from commercial and industrial businesses (broken down into 1.6

---

[17] Assumea a calorific value of 4 GJ/Te as used in the AEA, Oxford Economics, Biomass Energy Centre, and Forest Research (2011) study

[18] WRAP (2009) *Wood waste market in the UK*, August 2009. Available at http://www.wrap.org.uk/content/report-wood-waste-market-uk

[19] Resource Futures (2009) *Project WR0119 - Municipal Waste Composition: A Review of Municipal Waste Component Analyses*, Department for Environment, Food, and Rural Affairs, March 2009. Available at: http://randd.defra.gov.uk/Default.aspx?Module=More&Location=None&ProjectID=15133

[20] Previously known as AeA

[21] Results from recent studies collated in Anthesis (2017) *The UK Wood Waste to Energy Market*, Anthesis Group, February 2017. Available at http://anthesisgroup.com/uk-wood-waste-energy-market/

[22] NNFCC (2009) *Evaluation of Opportunities for Converting Indigenous UK Wastes to Fuels and Energy,* July 2009

Mt/y from retailers, 4.1 Mt/y food manufacturers and 3 Mt/y from food service and restaurants, based on data from NNFCC). The total waste available for energy was cited as 15.8 Mt, and for 2030 estimates, no growth in these baseline arisings was assumed. The NNFCC data appears to overestimate hospitality and other wastes compared to more recent studies[23]. Competing uses such as animal feed were considered in evaluating available food waste quantities.

The CCC study used Defra revised estimates (of food waste only) which were closer to 10 Mt, giving bioenergy potential values of 4–9 TWh in 2020, and 6–9 TWh in the period between 2030 and 2050. However, the assumptions used in deriving these results were not provided in the report. The forecasts assumed that 50% of household food waste was collected separately and 90% of C&I food waste by 2030, which both appear rather optimistic, particularly the latter, compared to current UK performance.

As described in more detail in Section 2.3.3, for the forecasts modelled in this study, more recent primary data was available, and waste growth was assumed to mirror the forecast growths in population and the economy.

2.1.5 Sewage sludge

AeA (2011) used data from the aforementioned NNFCC report and from Defra's Waste Strategy 2007[24] to develop baseline tonnages for sewage sludge generation. It estimated the baseline volume available for bioenergy to be 32.5 Mt (wet), forecasting bioenergy equivalents of 2.5–3.5 TWh in 2020, 2.9–3.6 TWh in 2030, and 3.5–4.0 TWh in 2050.

As described in Section 2.3.4, for this study, updated data was available, along with updated population forecasts, and these were used for forecasting future bioenergy potential.

2.1.6 Summary Analysis

An outline of key review points and changes made to the methodology adopted by the CCC are given in Figure 1. In summary, new data is available in a number of key areas considered in the CCC report. In forecasting future arisings, increased recycling rates were not reflected by the CCC in increases in key segregated materials, and this too is addressed. Finally, waste growth was not included in a number of material forecasts. Again, this is addressed through the development of scenarios to test the sensitivity of results to this assumption, as explained in Section 2.2.

---

[23] WRAP (2017), *Household food waste in the UK, 2015*, January 2017. Available at: http://www.wrap.org.uk/content/household-food-waste-uk-2015-0; WRAP (2013) *Overview of waste in the UK Hospitality and Food Service Sector*, November 2013. Available at: http://www.wrap.org.uk/content/overview-waste-hospitality-and-food-service-sector; WRAP (2016) *Quantification of food surplus, waste and related materials in the grocery supply chain*, November 2016. Available at: http://www.wrap.org.uk/content/quantification-food-surplus-waste-and-related-materials-supply-chain

[24] Defra (2007) *Waste strategy for England* 2007, May 2007. Available at: https://www.gov.uk/government/publications/waste-strategy-for-england-2007

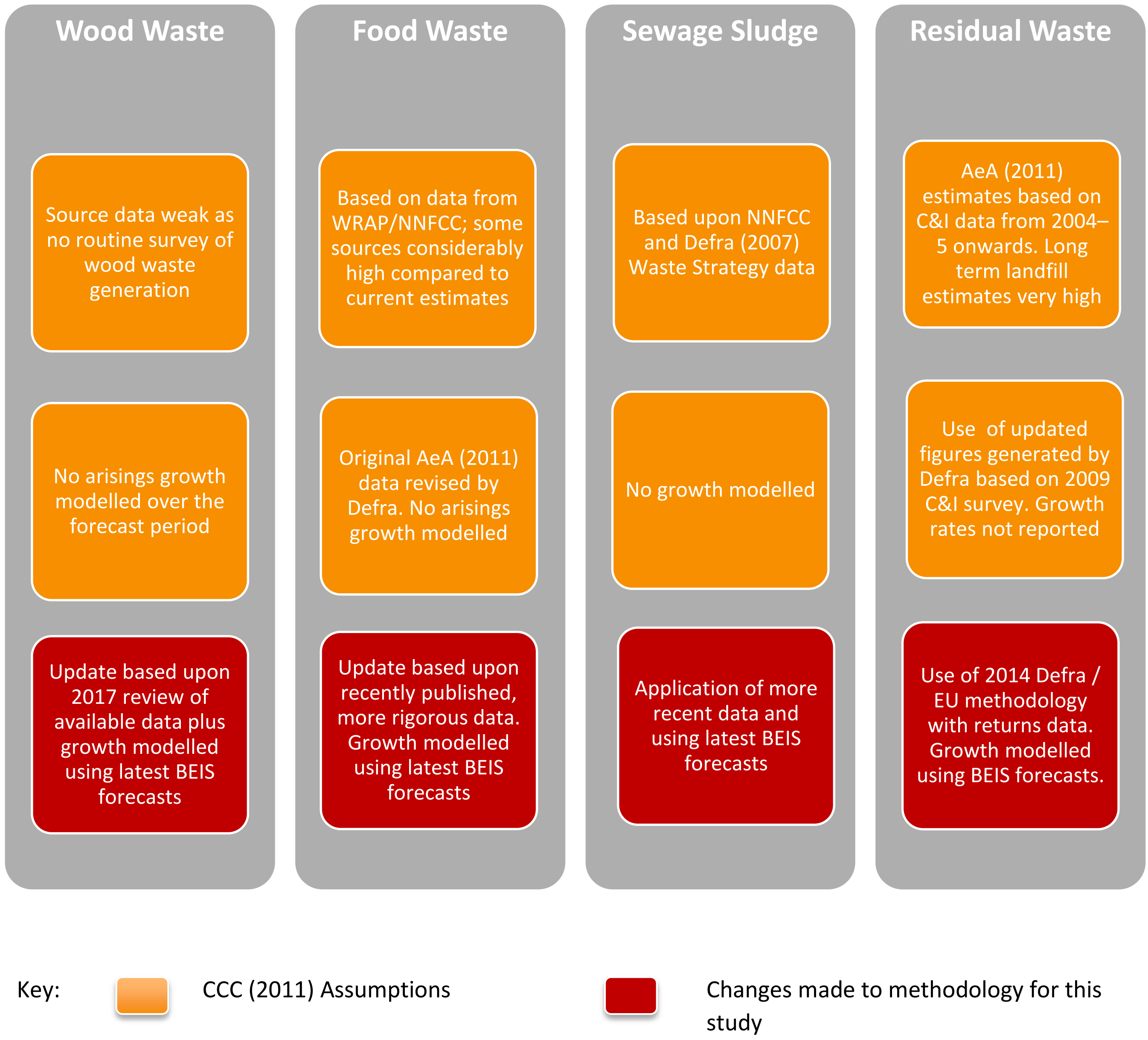


Figure 1 : CCC report - critical appraisal summary by waste type

2.2 Key Data Sources and Assumptions for this Study

Waste sources and the relevant bioenergy routes upon which this study is based, are summarised in the sections below. To ‘mirror’ the approach taken by the CCC, the potential for bioenergy production focusses on specific biogenic waste streams (food waste, wood waste, residual waste, sewage sludge) generated from LACW, C&I and C&D waste sources. Although many of these waste streams are already used to generate some form of energy — for instance, wood waste in biomass plants, and residual waste in EfW plants — for the purposes of this study, it is assumed that all waste which does not form part of meeting mandatory recycling targets (see Section 2.2.3.1) is available for renewable gas production.

Figure 2 summarises waste to renewable gas routes relevant to this study; it should be noted that other materials and forms of waste management are deliberately not included.

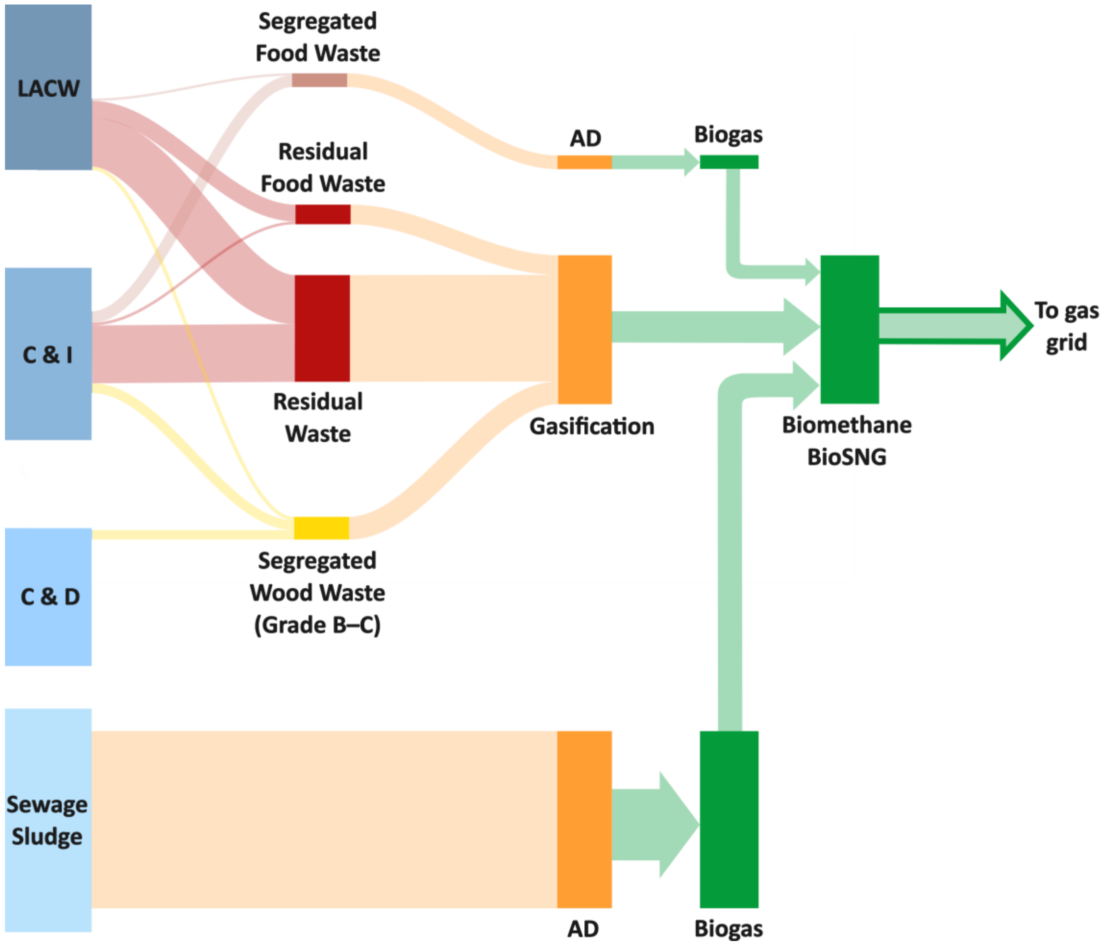


Figure 2: Waste feedstock sources and renewable gas routes relevant to this study

2.2.1 Baseline Waste Arisings

To generate updated baseline waste arisings estimates upon which forecasts could be based, extensive research was carried out to identify primary datasets and market reports generated since the original CCC report. In addition, regulatory authorities in each of the devolved nations were contacted to elicit up-to-date waste management facility returns data and other datasets to use as a foundation for these baselines. The baseline year for forecasting was either 2014 or 2015, depending upon the availability of data for each key waste type. Permit returns data, for instance, is not available for all UK nations beyond 2015, Scotland beyond 2014. For each feedstock, the specific approach is described in detail in Section 2.3.

Where possible, arisings data was checked and triangulated with a number of other datasets, and reports to test the generated arisings figures. In all cases, a top level “unconstrained” arisings estimate was produced for the baseline year, identifying the total amount of that particular waste stream generated in the UK. Competing uses of these wastes, i.e. different forms of recycling, were also considered, where these uses were of high economic value or higher up the waste hierarchy (as required by regulation) and likely constrain the use of the waste for bioenergy generation. These were subtracted from the unconstrained total to give an “available” quantity of waste for bioenergy production. This available quantity of waste was used as the baseline to generate forecasts to 2050.

The key challenge in any estimation of UK waste arisings is the availability and veracity of primary waste arisings or collection data. Whereas detailed records of municipal waste collections are submitted by local authorities to Defra's WasteDataFlow[25] system for all UK nations, the collection of primary data for C&I and C&D arisings is far less reliable. For instance, the last surveys for both waste types were delivered for Natural Resources Wales (NRW) in 2012[26]. In addition, there is no primary up to date survey data for key waste material types, such as food waste or wood waste. For this study, therefore, an analysis of all publicly available data sources and methodologies was undertaken, and a methodology was developed to address the uncertainties in publicly available data sets.

In the following sections all estimates and assumptions for each waste type have been referenced, including the data sources used and the relative data accuracy based on a qualitative assessment (as dataset error limits are rarely published). These are also summarised in Table 2.

Table 2: Available waste data sources and relative accuracy

Waste Type	Arisings Data Availability	Arisings Data Accuracy*
Residual Waste	Data collected quarterly via Defra's WasteDataFlow (WDF) for LACW, but no recent primary data collection (latest surveys 2009 England, 2012 Wales) for C&I wastes, albeit method based on site returns data and HMRC landfill tax receipts data	M-H
Food Waste	Data sources include WDF for household wastes, and additional primary data collection for manufacturers and retailers by WRAP	M
Wood Waste	Data collected quarterly via WDF for LACW, and estimates made from a range of data sources for C&I and C&D streams	L-M
Sewage Sludge	Various industry and bioenergy reports	M

Note: * H = high, M = medium and L = low relative accuracy

2.2.1.1 Residual Waste

As mentioned above, for LACW, there is a high level of confidence in the Defra WasteDataFlow (WDF) dataset. Summary data used provided by each UK nation from WDF raw input, for volumes recycled, landfilled, energy recovered.

For C&I wastes, there is a low level of confidence in the available data, particularly as the last C&I arisings survey in England was in 2009. A revised methodology from the "Reconcile Project" was introduced in 2014 alongside similar methodologies in other devolved nations.[27] However, results using this method tend to be vary significantly. Furthermore, the huge fall reported in C&I arisings for England in 2017[28] appears to be the result of significant changes in the data collation methodology by Defra and is not considered a true reflection

---

[25] See http://www.wastedataflow.org/

[26] Most recent surveys: "Commercial and Industrial Waste Survey 2009" Defra (for England), May 2011; "Survey of Industrial & Commercial Waste Generated in Wales 2012", Natural Resources Wales. No recent survey in Scotland or NI.

[27] Jacobs (2014) *New Methodology to Estimate Waste Generation by the Commercial and Industrial Sector in England*, Department for Environment, Food, and Rural Affairs, August 2014. Available at: http://randd.defra.gov.uk/Document.aspx?Document=12262_FinalProjectReport120814.pdf

[28] Defra (2017) *Digest of waste and resource statistics, 2017 edition*, March 2017. Available at: https://www.gov.uk/government/statistics/digest-of-waste-and-resource-statistics-2017-edition

of market changes over that same period. It is understood that industry is currently exploring this issue with Defra.

As a result of this lack of confidence in "top-down" C&I arisings data, the approach for this study is based on a "bottom up" method, which uses landfill, EfW, and other residual waste disposal data, assembled for each devolved nation, so yielding a UK total. This is broadly in line with the methodology used for the original Reconcile Project methodology. Related permit "returns" data for landfill and other residual waste treatment facilities but as this data does not identify the source of the waste input to an individual site, LACW data from WDF was subtracted to produce C&I residual waste estimates. Landfill returns were further refined using HMRC landfill tax receipts data[29].

In summary, the data sources used were:

- Environment Agency – Waste Data Interrogator (Waste Permit Returns Data 2014, 2015), RDF export data, "Waste Management for England" 2014, 2015;
- SEPA - Waste from all sources Discover Data tool and Scotland Business Waste Data (2014);
- NRW - Waste Permit Returns Data 2015;
- Northern Ireland - NILAS report and Waste Permit Returns Data 2015; and
- HMRC Landfill Tax Receipts (UK).

As presented in Table 3, the baseline estimate for total residual waste arisings is 19.3 Mt. In respect of this estimate, the following should be noted:

- 2015 as the baseline year with data extrapolated from the various sources listed above where required;
- Food waste and wood waste were removed from the available residual waste total to avoid double counting, as these are included in the estimates presented in 2.1.3 and 2.1.4;
- The estimates include rejects or "fines" from materials recycling facilities (MRFs); and
- The estimates exclude tonnages which are misreported as a result of waste crime, i.e. those from misclassification of fines, illegal burning and fly-tipping[30]; and
- This is an estimate for all constituents of the residual waste stream. As presented in Section 2.4, for the purposes of modelling the potential for renewable gas generation it is solely the biogenic fraction, which is of interest.

In terms of composition, residual commercial waste most reflects the range of materials seen in household residual waste and therefore reflects a similar opportunity for renewable gas production. Industrial residual waste is more likely to include "inerts" and a narrower range of waste materials. For this reason, the tonnages reported in Table 3 focus on current volumes to energy recovery and full rate tax landfill (to eliminate non-combustible inerts).

---

[29] "Landfill Tax (LFT) Bulletin", HMRC October 2016

[30] The economic analysis of waste crime undertaken by Eunomia on behalf of the Environmental Services Association (ESA) suggests that whilst these overall tonnages may be material, only a small fraction is likely to be suitable for bioenergy production. See Eunomia (2017) *Rethinking Waste Crime*, Environmental Services Association, May 2017. Available at: http://www.esauk.org/esa_reports/20170502_Rethinking_Waste_Crime.pdf

Table 3: Data sources and assumptions used in residual waste baseline and forecasts

Parameter	2015 Total (kT)	%
Landfill[31] (as inputs)	12,280	50%
Waste to Energy (as inputs)	8,821	36%
Co-incineration (i.e. Cement kilns, as inputs)	561	2%
RDF Export	3,024	12%
Total unconstrained arisings	**24,687**	
Removal to avoid double counting:		
Wood waste	-4,300	
Food waste	-1,037	
Total available arisings for energy generation	**19,350**	

The above baseline 'unconstrained' arising estimate of c.25 Mt is comparable with estimates published in a range of recent studies and reports, as summarised in Table 4. From more recent HMRC and EA data, which show further reductions in landfill volumes and increases in RDF exports, and the opening of new EfW capacity, it is clear that the move from landfill to energy recovery is increasing.

Table 4: Residual Waste Arising Estimates - alternate sources

Publication	Published by	UK Residual Waste Estimate (Mt)
The UK residual waste market (July 2014)	Green Investment Bank	27.7 (2012)
"Mind the Gap" UK residual waste infrastructure capacity requirements 2015-25	Suez	32.6 (2015)
"The Reality Gap" UK residual waste treatment capacity (Sept 2015)	Biffa	27.5 (2015)
Future UK Residual Waste Infrastructure Capacity and its Feedstock (April 2016)	CPI	23.1 (2021)
Infrastructure Review (Issue 11) December 2016	Eunomia	26.0 (2016)

2.2.1.2 Wood Waste

Wood waste that is potentially suitable for BioSNG generation comes from three key sectors:

- LACW via networks of Household Waste Recycling Centres (HWRC) and Civic Amenity (CA) sites;
- C&I sources; and
- Construction and demolition (C&D).

For LACW sources, data is again reported quarterly by local authorities via WasteDataFlow, which is, like that for residual waste and food waste, relatively up to date and accurate. However, there are few up-to-date estimates for C&I and C&D sources, largely due to a lack of reliable primary data and the changing nature of the waste flows. Therefore, waste wood baseline estimates for these sources have necessarily relied on

[31] Sum of household, industrial and commercial waste to Non-Hazardous landfill for UK was 22.53 Mt in 2014 and 20.55 Mt in 2015 (Source: EA, SEPA, NRW, NIEA). Reported figure is a sub-set of this, waste tonnage to landfill paying standard rate landfill tax (source: HMRC), the assumption being the reminder is lower rate therefore inert waste with little or no biogenic waste content.

historic data generated through surveys and meta-analysis, which were themselves carried out a number of years ago. This evaluation is explained in detail in a report published by Anthesis in February 2017[32], which was itself based on a range of other data sources.[33]

The following assumptions were made in generating the wood waste baseline arisings estimates presented in Table 5:

- 2014 as the baseline year with data extrapolated from the various sources listed above where required;
- All wood waste is available for renewable gas production, whether segregated or collected as part of a residual waste stream;
- Wood waste contained in the C&I residual stream is assumed to be available for renewable gas production as separated wood waste on the basis that growing market demand will encourage further segregation[34]. To avoid double-counting, however, this volume was removed from the residual waste baseline, as described in Section 2.2.1.1. It should be noted that this approach mirrors that undertaken by the CCC; and
- The tonnage of waste wood, which is currently sent for high-value competing uses, primarily manufacturing of panel board and animal bedding, is considered not to be available for bioenergy production.

As summarised in Table 5, the total unconstrained wood waste arisings in 2014 were 5.7 Mt. The C&D sector is the largest source, with 41% of the total. The C&I sector produces 44% of the wood waste generated; however, 40% of this is anticipated to be collected as part of the residual stream. Assuming that high-quality wood waste used for animal bedding (390kt) and panel board manufacture (1,110kt) is unlikely to be available for bioenergy production, this gives an available arisings figure of 4.2 Mt for 2014.

Table 5: Baseline Wood waste arisings by source (2014)

Parameter	2014 Total (kT)	%
Local authority – separated	864	15%
C&I – separated	1,448	25%
C&I – in residual	1,037	18%
C&D - separated	2,355	42%
Total unconstrained arisings	**5,704**	
To animal bedding[35]	-390	
To panel board manufacture	-1,110	
Total available arisings for renewable gas generation	**4,204**	

Sawmill residues are generally not classified as waste and not subject to waste regulatory controls, and therefore have been quantified in Section 3.3.2 for renewable gas potential as “non-waste” feedstock.

---

32 Anthesis (2017) *The UK wood waste to energy market*, February 2017. Available at: http://anthesisgroup.com/uk-wood-waste-energy-market/

33 WRAP (2009) *Wood Waste Market in the UK*, August 2009. Available at: http://www.wrap.org.uk/content/report-wood-waste-market-uk; Defra 2009 C&I Waste Arisings Survey for England, available at: https://data.gov.uk/dataset/survey_of_commercial_and_industrial_waste_arisings_in_england, and Defra’s WasteDataFlow

34 An estimated £6.3 billion has been invested over 2010–2013 in the overall biomass sector (including anaerobic digestion and waste biomass facilities), and further investments of £5–5.9 billion are expected by 2020. In the medium term, however, further demand will depend upon the number of such plants delivered within the final Renewable Obligation (RO) deadline of March 2018

35 Excludes non-waste feedstocks

However, there is likely to be a proportion of such material which has been injected with preservatives. Consequently, such material is better directed to the current fleet of waste wood combustion plants rather than domestic stoves and boilers used for heating.

2.2.1.3 Food Waste

Food waste is generated by households and by businesses of many types, i.e. those in the hospitality and food service sector (HaFS), food manufacturing, and food retail sectors. Food waste generated by industry is wide-ranging in type and quantity, and is managed in a variety of different ways, depending on the specific business and the foodstuffs involved, and on the adherence to the food waste hierarchy. WRAP has recently carried out a significant amount of work to support the commitments made by manufacturers and retailers under the voluntary Courtauld 2025 Commitment[36]. These datasets are the most recent and provide the most complete picture of food waste arisings for the UK, including a great deal of new primary data.

Food waste baseline arisings were collated using the following recent food sector studies:

- "Household food waste in the UK", WRAP, 2015;
- "Overview of waste in the UK Hospitality and Food Service Sector", WRAP, 2013; and
- "Quantification of food surplus, waste and related materials in the grocery supply chain", WRAP, 2016.

In developing the baseline estimates, the following assumptions were made:

- 2015 as the baseline year with data extrapolated from the various sources listed above where required;
- All wood waste is available for renewable gas production, whether segregated or collected as part of a residual waste stream;
- Food waste contained in the C&I residual stream is assumed to be available for renewable gas production as separated food waste on the basis that growing market demand will encourage further segregation. To avoid double-counting, however, this volume was removed from the residual waste baseline, as described in Section 2.2.1.1. It should be noted that this approach mirrors that undertaken by the CCC; and
- Food waste sent to competing uses which are higher up the waste hierarchy, or to established markets, or are that which is not accessible to waste collection (such as food redistribution, waste food for animal feed, and home composting) is excluded from the baseline.

Table 6 presents a summary the collated baseline data, broken down by source and collection route. This shows that total unconstrained food waste arisings are estimated to be 10.9 M tonnes, with 68% of this generated within the household. Of this 7.3 Mt of food waste generated by households and collected by local authorities, 0.6 Mt is separately collected and 4.3 MT is left in the residual waste stream. Just 8% of food waste is from the HaFS sector, with 22% from manufacturing. Once competing uses further up the waste hierarchy have been removed from the unconstrained potential, Table 6 shows that the available tonnage was 9,538 tonnes in 2015.

[36] http://www.wrap.org.uk/content/courtauld-commitment-2025

Table 6: Food waste arisings by source

Parameter	2015 Total (kT)	%
Household:		
Local authority – separately collected	600	
Local authority – in residual	4,300	
Home composted / fed to animals	800	
Household food waste disposed to sewer	1,600	
Total Household:	**7,300**	**68%**
HaFS		
Separately collected/managed	255	
Within residual	668	
Total HaFS	**923**	**8%**
Food manufacturing:		
Off-site disposal of sludge	130	
On-site treatment (e.g. DAF, AD)	760	
Off-site disposal of product (various forms)	745	
Other minor disposal routes	90	
Surplus - Redistribution	42	
Surplus - Animal feed	635	
Total manufacturing	**2,402**	**22%**
Retail		
Off-site disposal	210	
Surplus - Redistribution	5	
Surplus - Animal feed	27	
Total Retail	**242**	**2%**
Total unconstrained arisings	**10,867**	
Competing uses (animal feed, redistribution, home composting)	-1,509	
Total available for renewable gas generation	**9,358**	

2.2.1.4 Sewage Sludge

Recent data sources suggest that approximately 1.7 M tonnes of dry sewage sludge is generated every year[37]. To allow for comparison with the CCC study, this has been converted to be 4% dry solids (DS), resulting in a baseline figure of 42.5M tonnes of sewage sludge.

In generating these baseline figures, it has been assumed that:

- The baseline population of the UK is 65.1 million; and
- All sewage sludge is available for renewable gas generation.

[37] Mills (2016) *Unlocking the Full Energy Potential of Sewage Sludge*, University of Surrey & Thames Water, March 2016. Available at: http://epubs.surrey.ac.uk/809984/

A report from Defra provides detail as to how the sewage sludge is managed[38]. This data is presented in Table 7. It should be noted, however, that these data sets were from 2010, and so there may have been some changes in the intervening period, particularly as a result of requirements of the EU Urban Waste Water Treatment Directive (91/271/EEC). Notably, the report also notes that in 2010, 75-80% of sewage sludge generated is processed via AD (prior to application to land), as is presented in Table 7.

Table 7: Management of sewage sludge

Sewage sludge fate	2015 Total (Tonnes dry solids)
Soil & Agricultural	1,345,429
Other reuse	28,138
Landfill	10,573
Incineration	312,415
Other disposal	3,445
Total Unconstrained	**1,700,000**

2.2.2 Assumptions and Approaches to Feedstock Modelling and Forecasting

A number of influencing factors were identified which would have a direct impact upon the likely arisings of the key bioenergy producing waste materials, and which were used to build scenarios upon which forecasts up to 2050 were based. Three scenarios were developed: “High” and “Low”, based upon factors likely to maximise and minimise the quantity of available waste for bioenergy production, and a “Central” scenario presenting a realistic compromise between the two extremes.

2.2.2.1 Waste Growth

Although previous studies have suggested that waste arisings growth have been decoupled from economic growth[39], recent trends suggest that this link is not completely broken. In particular, the 1.4% average increase in LACW waste collected in England each year since 2012 seems to be in parallel with increases in population and growth in the economy. Consequently, for this study, growth rates for LACW were derived from annual population growth rates in a 2016 report by BEIS[40], whilst projected growth rates for C&I and C&D wastes were derived from economic growth figures from the same BEIS study, along with employment forecasts from a further BEIS report[41]. For each of the low, reference (central) and high scenarios, the waste growth rates used in this study are presented in Table 8.

[38] Defra (2012) *Waste water treatment in the United Kingdom*, August 2012. Available at: https://www.gov.uk/government/publications/waste-water-treatment-in-the-uk-2012

[39] WRAP (2012), *Decoupling of Waste and Economic Indicators*, October 2012. Available at: http://www.wrap.org.uk/content/decoupling-waste-and-economic-indicators-0

[40] BEIS (2017*) Updated Energy and Emissions Projections 2016* (including *Annex M Growth assumptions and prices*), March 2017. Available at https://www.gov.uk/government/publications/updated-energy-and-emissions-projections-2016

[41] BEIS (2016) *Employment projections from the Office for Budget Responsibility: Economic and fiscal outlook,* November 2016

Table 8: Assumed arisings growth rates

BEIS Scenario	Relevant Scenario for this study	Population Growth (applied LACW and Sewage Sludge)	Employment Growth (applied to C&I and C&D)
Low Growth Scenario	Low Scenario	0.6%pa 2015–2035 0.5%pa 2036–2050	0.19%pa 2015–2035 0.05%pa 2036–2050
Reference Scenario	Central Scenario	0.6%pa 2015–2035 0.5%pa 2036–2050	0.43%pa 2015–2035 0.30%pa 2036–2050
High Growth Scenario	High Scenario	0.6%pa 2015–2035 0.5%pa 2036–2050	0.66%pa 2015–2035 0.55%pa 2036–2050
Forecast Source		Office of National Statistics	Office for Budget Responsibility

The growth rates presented in Table 8 might be construed as conservative. However, both sets of assumptions may be somewhat higher than could be expected in reality due to the impact of “Brexit”, which is not yet known.

It should also be noted that, notwithstanding the possibility that the new national industrial strategy will drive greater industrial growth, the assumptions for C&I wastes may be overstated in respect of accurately reflecting growth in industrial wastes. However, the assumptions are probably conservative in respect of commercial wastes and so, in aggregate, they are suitably representative of the combined C&I stream.

2.2.2.2 Landfill Diversion Rates

The availability of landfill capacity is falling significantly, and is likely to continue to do so. Data published by the Environment Agency for England shows an average 4.7% reduction in landfill capacity (in cubic metres) annually from 2010, as presented in Figure 3. The capacity of non-hazardous and restricted landfill in England in 2015 was 338 Mm^3. If landfill volumes continue to reduce at the current rate, there will be no available landfill capacity by 2025.

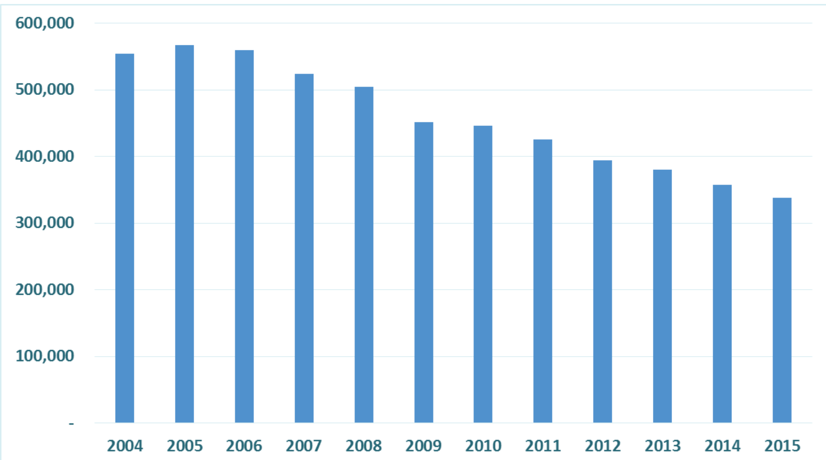


Figure 3: Non-Hazardous Landfill Capacity in England (in cubic metres x 1,000) 2014-2015

Landfill Tax is currently set at £86.10 per tonne, such that (when an additional gate fee is added) landfill is usually the most expensive residual waste disposal route by a significant margin (and likely to be considerably more expensive than any renewable gas production option). For this reason, operators are reluctant to invest in more void capacity and, due to the scale of environmental impacts and related local objections, planning authorities are similarly reluctant to give planning consent for new facilities, or for the extension of existing facilities. At the same time, landfill contracts tend to be short term (1–5 years), and therefore switching to alternative waste management routes can be straightforward if capacity is available.

These EU Circular Economy Package[42] contains a series of landfill diversion targets (expressed as maximum percentages of waste which can be landfilled), which depending upon Brexit, may be adopted by the UK. However, in the context of the approach adopted for this study, whereby all residual waste (including that sent for EfW or RDF export) is considered to be available for bioenergy generation, these targets are not relevant to the analysis.

2.2.3 Constraints to Feedstock Availability

There are a number of potential constraints to the availability of waste for this study, including:

- Increasing levels of recycling;
- Long-term residual waste treatment contracts;
- Ongoing export of residual wastes (as RDF) to continental Europe; and
- Regional variations in feedstock availability.

These are considered in the following sections, along with how they have been integrated into the modelling undertaken for this study.

2.2.3.1 Recycling Rates

As described above, all material that is assumed to be recycled is considered as unavailable for renewable gas (or wider bioenergy) production. Assumptions relating to the meeting of recycling rate targets are built into the forecasts presented in Section 2.3. The targets used are a combination of EU Waste Framework Directive targets, devolved national targets[43], and "stretch" targets (i.e. those which extend beyond what is considered to be mandatory). For the "High Recycling" scenario, the targets proposed in the EU Circular Economy Package have been used. The recycling targets built into the three scenarios are summarised in Table 9.

---

[42] http://ec.europa.eu/environment/waste/target_review.htm

[43] Assumed National Targets applied: England 50% recycling in 2020 (LACW); Scotland LACW 50% by 2020, 70% by 2025 (all waste); Wales 50% by 2020, 70% by 2025 (all waste); NI 50% by 2020 (LACW)

Table 9: Assumed recycling rates

Low Scenario	Central Scenario	High Scenario
▪ National targets until 2020 i.e. LACW all nations 50% by 2020 ▪ LACW England, Scotland and NI - 70% recycling of in 2030 (in line with proposed EU Circular Economy Package target) ▪ LACW Wales 80% by 2030[44]	National Targets i.e: ▪ LACW England 50% 2020 ▪ LACW Scotland 50% by 2020, 70% by 2025 (all waste) ▪ LACW Wales 50% by 2020, 70% by 2025 (all waste) ▪ LACW NI 50% by 2020 Stretch Targets: ▪ LACW England and NI 60% by 2025	▪ LACW Wales and Scotland; as per central scenario ▪ LACW England and NI; as per central scenario to 2020 then 55% by 2025
▪ C&I 55% to 65% 2020 (England, NI), 70% by 2030	▪ C&I 55% to 60% 2020 (England, NI), 65% by 2030	▪ C&I: 55% to 60% 2020 (England, NI), 65% by 2030
▪ Recycling rates flat from 2030 to 2050	▪ Recycling rates flat from 2025/30 to 2050	▪ Recycling rates flat from 2025/30 to 2050

As part of this modelling process, baseline recycling rates for LACW are based upon those reported in WDF for the baseline years, i.e. England 41%, Scotland 43%, Wales 56% and NI 41%. There is, however, no recent data from which to derive baseline recycling rates of C&I waste. The last time that these were measured by survey, the C&I recycling rate in England was reported as 52% (2009), and in Wales as 58% (2012). C&I waste recycling is driven by a number of factors, including the value of recycled commodities (which can fall as well as increase), and therefore year-to-year recycling rates may vary. For the purposes of this study, therefore, based on the two most recent data points available, the modelling is based on a baseline C&I recycling rate of 55%.

In relation to this study, increased recycling of biogenic material has the potential to increase the quantity of specific segregated materials for AD, whilst reducing the quantities of residual waste available for BioSNG. Increased recycling will also impact on the composition of the resultant residual waste, and therefore the biogenic content and bioenergy potential (measured as CV) of this waste stream over time. For instance, increased recycling of plastics and paper will reduce the CV per tonne of residual waste, whereas increased recycling of metals and glass will increase the CV per tonne of residual waste. As future waste composition will depend upon a range of factors (including consumer trends and global raw material prices), however, changes in CV over time have not been modelled for this study, which is in line with the approach in the CCC report.

Furthermore, as increased recycling of food waste effectively means that this will be directed to AD, we have not modelled any impact of this upon the tonnage available for renewable gas production. Similarly, we have modelled the impact of wood waste recycling via assumptions relating to the tonnage directed to competing markets (i.e. panelboard mills and animal bedding) discussed in Section 2.2.1.2. It is assumed that this alternative usage grows in line with the growth rates presented in Table 8 in respect of employment.

[44] http://ciwm-journal.co.uk/resource-conference-cymru-wales-considers-80-recycling-target/

The amount of waste recycled to meet Government Packaging Recycling targets (driven by the EU Packaging Directive) for key packaging materials such as plastics, glass, metals, wood equated to 7.3 Mt tonnes of material,[45] i.e. around 10% of total LACW and C&I waste arising in 2014. For the purposes of this study, it has been assumed that this packaging tonnage is subsumed within the national and EU recycling targets used for the scenario modelling.

2.2.3.2 Long-term contracts for residual waste treatment capacity

Operational EfW capacity in the UK has increased significantly in recent years, primarily due to the Private Finance Initiative (PFI) and Public Private Partnership (PPP) funding programmes which finance new facilities to deal with local authority-generated residual waste. EfW capacity in England grew from 5.3 Mt in 2010 to 7.6 Mt in 2014, and just under 9.9 Mt in 2015[46], with a further significant level of capacity currently under construction.

Most of these facilities have been financed based on 20–25 years contracts. This is such that the residual waste they process might considered to be unavailable for bioSNG production for the period of the contract concerned. However, for the purposes of the modelling undertaken for this study, it has been assumed that all residual waste tied up in such long-term contracts is available. This is because:

- Subject to long extensions, all of the contracts will have expired by 2040. This is shown in Figure 4, which plots the expiration dates for long-term contracts associated with PFI/PPP facilities (including pre-2000 facilities with extended contracts), and their associated capacity[47];
- Some contracts are likely to be re-let or at least renegotiated during the contracted period as local authority funding cuts force local government to re-evaluate expenditure for waste management. For example, Greater Manchester Waste Disposal Authority has recently terminated a contract with Viridor-Laing, which still had 17 more years to run, on the basis of lack of affordability;[48] and
- Any future Government support is likely to direct feedstock to higher generation efficiency technologies rather than to traditional incineration upon which the vast majority of contracts are based.

It should be noted that, whilst in reality, the availability of such contracted residual waste will change year on year, as presented in Figure 4, the model for this study assumes that all such tonnage is available for BioSNG in each year across the whole study period of 2015-2025.

[45] Defra (2017) *Digest of Waste and Resource Statistics*, March 2017. Available at: https://www.gov.uk/government/statistics/digest-of-waste-and-resource-statistics-2017-edition

[46] This includes 7 plants (capacity 2.3Mt) which started to accept waste in 2015 (EA (2016) *Waste Management Information 2015*)

[47] This analysis has been generated using individual contract end dates or, if not available, EfW facility start dates, assuming a 25 year contract life

[48] See http://www.letsrecycle.com/news/latest-news/viridor-laing-seeks-compensation-greater-manchester-ends-contract/

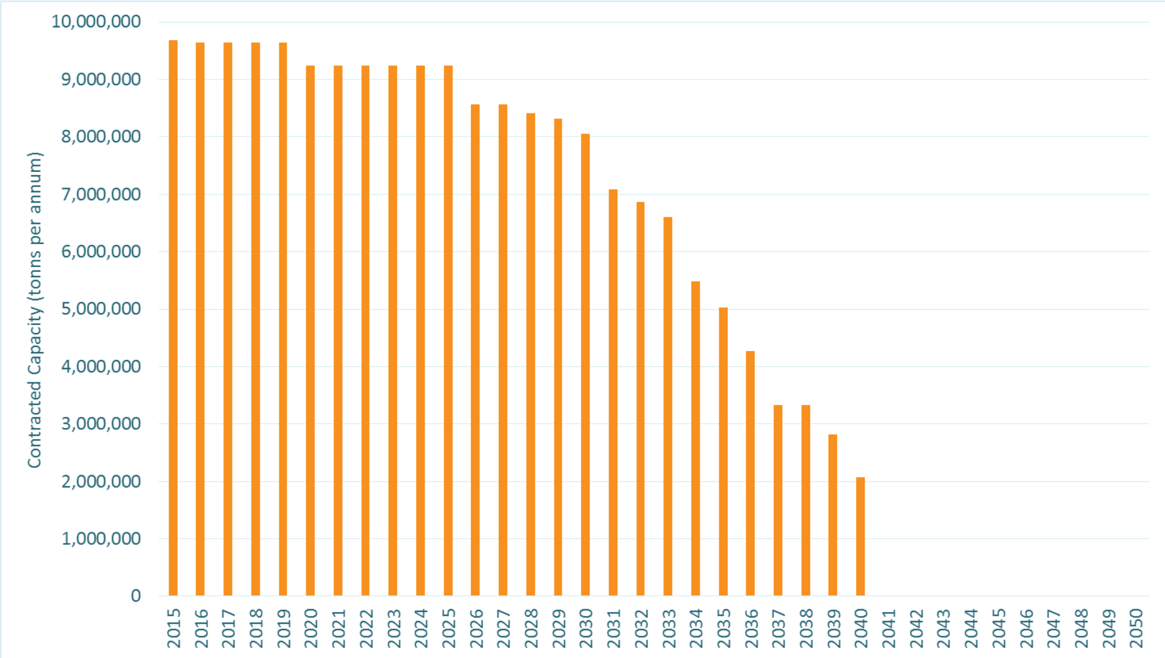


Figure 4: Contracted LACW EfW Capacity in England 2015-2050

2.2.3.3 RDF Export

Driven by the increasing price of landfill, the lack of sufficient energy recovery capacity in the UK, and available capacity on the European continent, the export of RDF from England increased to 2.8 Mt in 2015 and 3.2 Mt in 2016[49] — around 10% of the unconstrained residual waste available in the UK. Although this is an established market, exports have recently become more expensive due to reductions in spare capacity in mainland Europe, as well as significant changes in the pound (Stirling) exchange rate due to Brexit. This is such that RDF has become less attractive compared with EfW and landfill in the UK, albeit still cheaper in many cases.

Contracts for RDF export are typically short-term (albeit with limited exceptions). As a result, for the reasons set out above in respect of domestic contracts for residual waste treatment, it has been assumed for the purposes of this modelling in this study that all refuse-derived fuel (RDF) prepared for export is available for renewable gas production for each year of the forecast period to 2050.

2.2.3.4 Regional Variation

The availability of key wastes for renewable gas production in the short to medium-term will vary depending upon local market conditions. For instance:

- For residual waste, there are considerable regional differences in the market which have short to medium term impact on availability for renewable gas production. These include:
    - Delivery of new energy recovery capacity, either tied with local authority contracts or as merchant capacity, with concentration of capacity in particular parts of the UK. The M62 corridor in the north of England, for example, gives easy access to considerable merchant capacity with significant facilities in Cheshire, Lancashire and throughout Yorkshire;

[49] Environment Agency (2015) *International Waste Shipments Exported from England*, September 2015. Available at: https://data.gov.uk/dataset/international-waste-shipments-exported-from-england

  - Lack of energy recovery capacity in other parts of the UK, including Scotland and parts of Wales;
  - Early closure of landfill as some contractors attempt to pull out of the market before new replacement energy recovery capacity is built, for example, in London and the South East; and
  - Proximity to ports for export of RDF to mainland Europe, which is far greater in the North East, South East and East of England.
- For food waste, there are significant differences across England and the devolved administrations, including:
  - An obligation for food waste to collected as a segregated steam in Scotland and currently high gate fees there suggest demand is falling short of AD capacity, although this is likely to be addressed with new capacity coming on line;
  - In Wales local authority collected food waste is contracted to a number of PFI funded AD facilities, which have spare capacity for C&I food wastes;
  - In England, significant AD capacity has been built in response to the Feed-in Tariff (FiT) and Renewable Heat Incentive (RHI) but without a correspondingly high increase in food waste collection, as no similar supply side driver exists. As a result, gate fees are very low and there is likely to be some consolidation in the sector.
- For wood waste, regional differences in demand exist from competing markets:
  - Current demand for segregated material comes primarily from panel board manufacture (for instance Norbord, Devon; Kronospan, Wales), and energy recovery with main facilities in Scotland, North East England, Yorkshire, Cheshire, Essex and south Wales;
  - Supplying these demands involves a number of specialists with national logistics capabilities. It is thought that the delivery of further wood waste to energy capacity could produce a market with capacity exceeding demand[50].

2.3 Feedstock Availability to 2050

As highlighted above, based on the assumptions presented in Section 2.2, for each waste type (residual, wood, food and sewage sludge) three scenarios were developed (Low, Central and High) to reflect the uncertainty associated with modelling of this nature using waste management data.

2.3.1 Residual Waste

The assumptions relating to waste growth and recycling of residual wastes are described in detail in Sections 2.2.2.1 and 2.2.3.1 respectively. As presented in Table 10 and Figure 5, under each of the three scenarios, these assumptions result in an overall reduction in forecast residual waste arisings as recycling rates peak around 2030, followed by a subsequent growth in arisings due to the economic and population growth factors used.

From a baseline of 19.3 Mt in 2015, the modelling results in forecast residual waste arisings falling to 14.6 Mt by 2050 under the Central scenario, 16.3 Mt under the High scenario, and 10.4 Mt under the Low scenario.

---

[50] Anthesis (2011) The UK Wood Waste to Energy Market, February 2017. Available at: http://anthesisgroup.com/uk-wood-waste-energy-market/

These compare to a range of 9.4–10.7 Mt in 2050 reported by the CCC for 2050. As described in Section 2.1.1, this difference is the result of the lower growth rate for LACW and the zero growth rate for C&I wastes modelled by the CCC. The detailed waste flows which support these results are presented in A1.2.

In respect of these forecasts, the assumptions set out in Section 2.2.1.1 should be noted. In particular, that these are estimates for all constituents of the residual waste stream. As presented in Section 2.4, for the purposes of modelling the potential for renewable gas generation, it is solely the biogenic fraction, which is of interest.

Table 10: Available Residual Waste Arising Forecasts – High, Central and Low Scenarios, 2020 to 2050 ('000 tonnes)

	2020	2030	2040	2050
High Scenario	16,686	14,838	15,552	16,301
Central Scenario	16,741	13,511	14,061	14,635
Low Scenario	15,987	9,819	10,088	10,369
CCC (2011) [51]	19,800–22,000	12,300–14,500	-	9,400–10,700

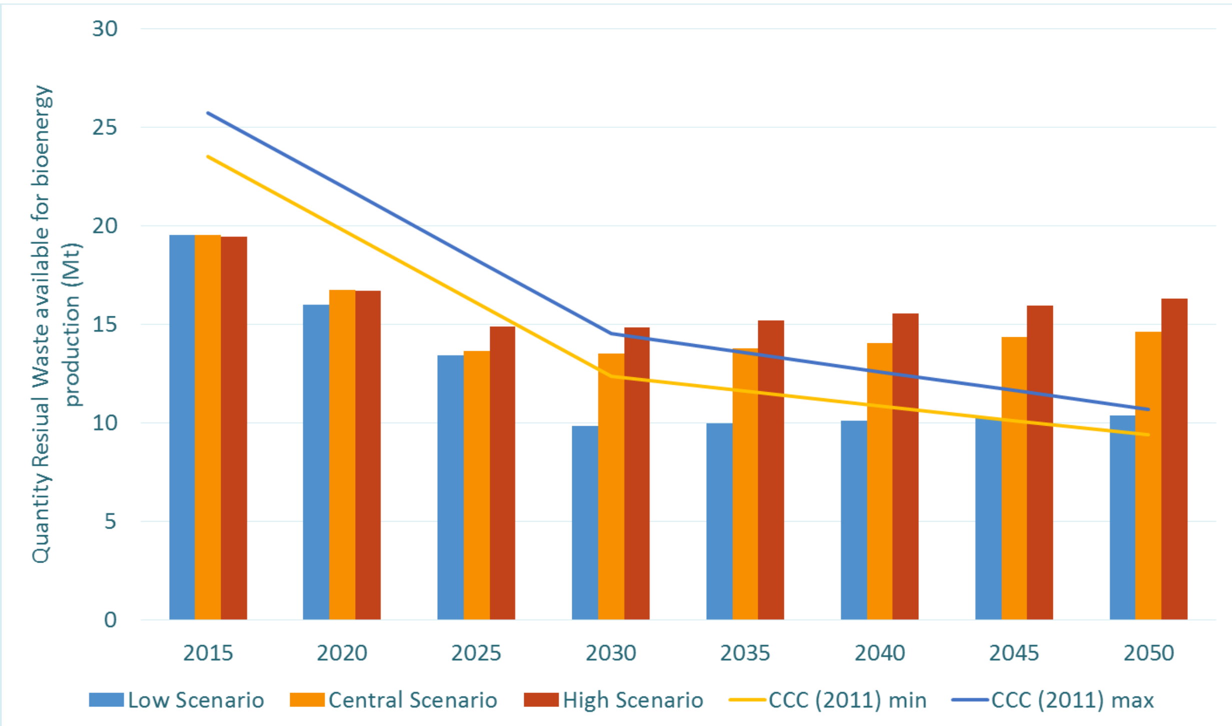


Figure 5: Available Residual waste forecasts 2015-2050, compared to forecasts in CCC (2011)

2.3.2 Wood Waste

The assumptions relating to growth and recycling (or separate collection) of wood wastes are described in detail in Sections 2.2.2.1 and 2.2.3.1 respectively. As presented in Table 11 and Figure 6, under each of the three scenarios, these assumptions result in growth of feedstock available for renewable gas generation from 4.2 Mt in 2015 to 5.3 Mt under the Central scenario for 2050. This increase is due to the impact of the

[51] Derived from reported TWh/yr bioenergy potential, from CCC (2011)

economic and population growth factors used to model waste growth[52]. Whilst the same factors are used to model increases in diversion of material to competing markets (panel board manufacturing and animal bedding), the net impact results in an overall increase in available feedstock. The detailed waste flows which support these results are presented in A1.3.

Figure 6 shows that whilst the baseline estimates are very similar to the CCC's estimates, the forecasts for the future years are somewhat higher. This is because the CCC study did not attempt to model either any growth forecasts or any changes in relation to increased segregation and recycling of wood waste and therefore the tonnages remained static.

Table 11: Available Wood Waste Arising Forecasts – High, Central and Low Scenarios, 2020 to 2050 ('000 tonnes)

	2020	2030	2040	2050
High Scenario	4,622	5,003	5,276	5,563
Central Scenario	4,579	4,962	5,138	5,321
Low Scenario	4,535	5,033	5,127	5,225
CCC (2011)[53]	4,200	4,200	-	4,200

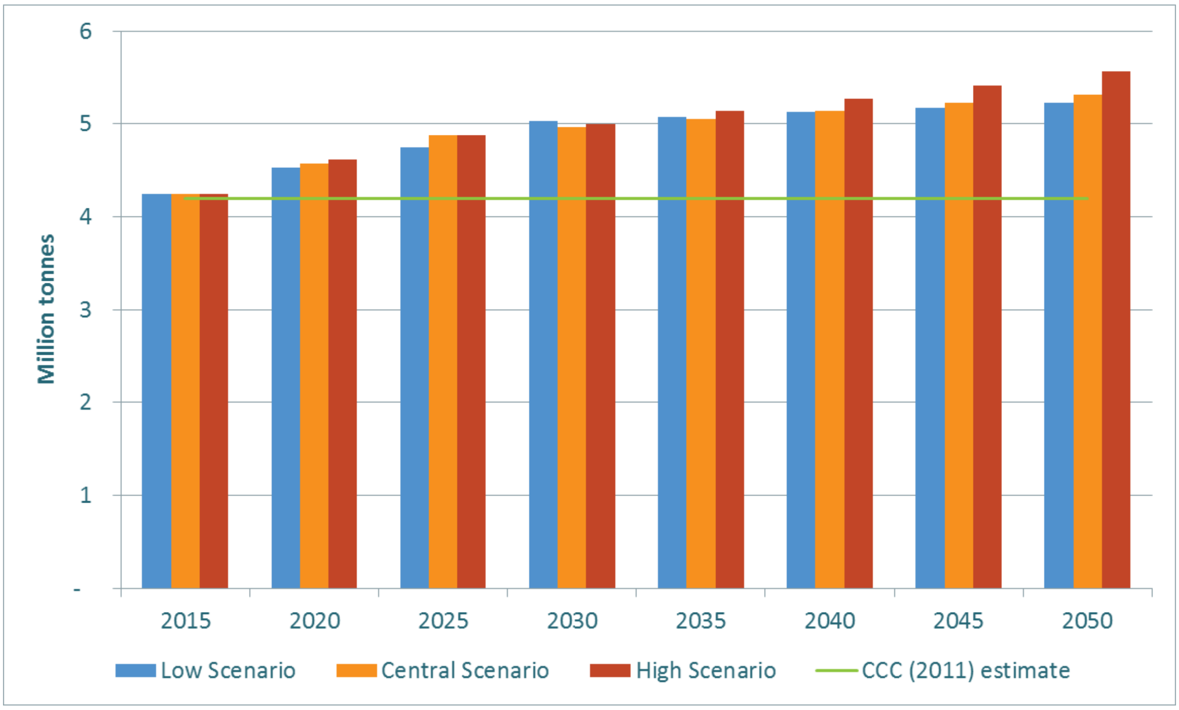


Figure 6: Available Wood waste forecasts 2015-2050, compared to forecasts in CCC (2011)

2.3.3 Food Waste

The assumptions relating to growth and recycling of food wastes are described in detail in Sections 2.2.2.1 and 2.2.3.1 respectively. As presented in Table 12 and Figure 7, under each of the three scenarios, these assumptions result in growth of feedstock available for renewable gas generation from 9.3 Mt in 2015 to 11 Mt under the Central scenario for 2050. Again, this increase is due to the impact of the economic and

[52] Although growth in wood waste arisings was not taken into account in the CCC (2011) reported forecasts, for this update it has been assumed that it is logical that an increased population and growing economy will increase demands in good manufactured from wood, and in wood based packaging and other related products, resulting in an increase in wood waste reaching the waste stream.

[53] Derived from reported TWh/yr bioenergy potential, from CCC (2011)

population growth factors used to model waste growth, combined with the fact that all food waste 'recycled' is assumed to be available for AD. The detailed waste flows which support these results are presented in Appendix 1.

The forecast tonnages under the Central scenario over 30% higher in 2050 than the maximum estimate in the CCC report. This is the result of the use of more up-to-date primary data relating to the baseline and the inclusion of the impact of population and economic growth, which is omitted in the CCC analysis.

Table 12: Food Waste Available Arising Forecasts – High, Central, and Low Scenarios, 2020 to 2050 ('000 tonnes)

	2020	2030	2040	2050
High Scenario	9,712	10,271	10,791	11,338
Central Scenario	9,675	10,156	10,591	11,045
Low Scenario	9,638	10,045	10,402	10,776
CCC (2011)[54]	3,600–8,200	5,500–8,200	-	5,500–8,200

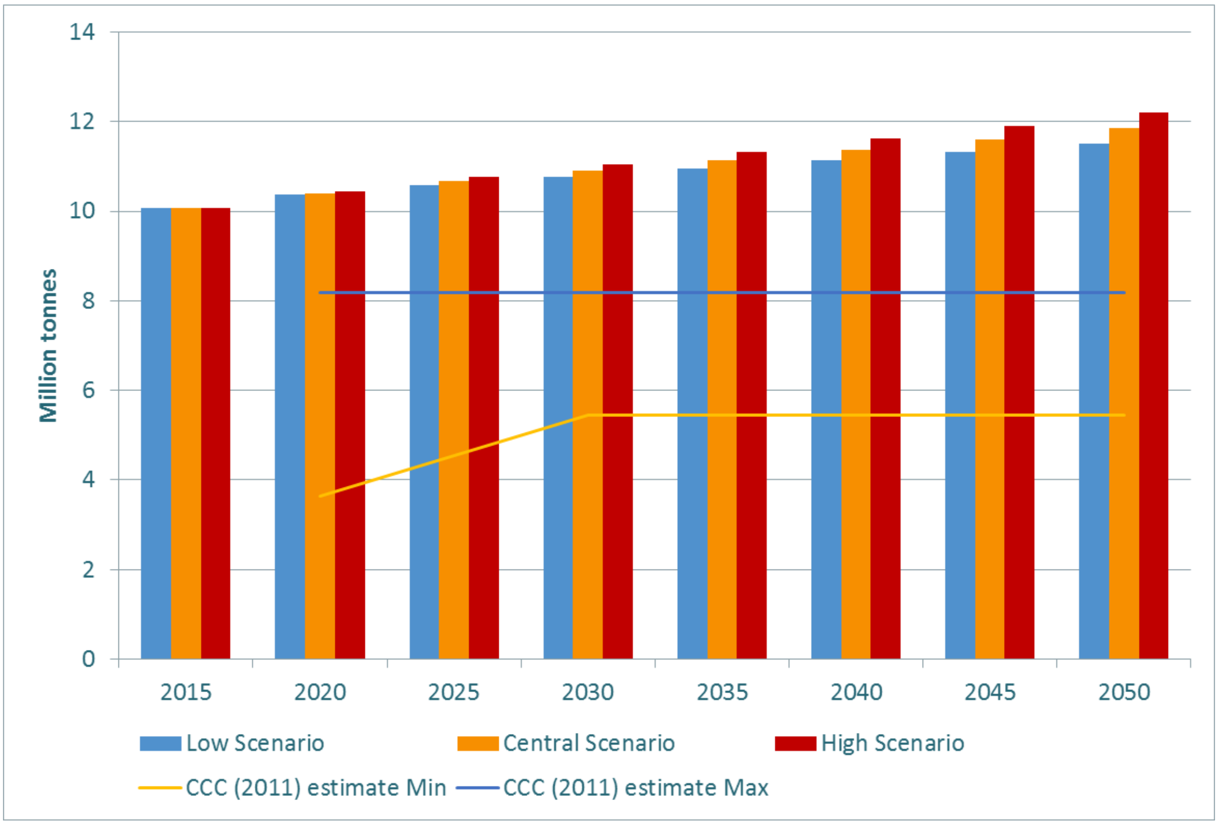


Figure 7: Food waste forecasts 2015 – 2050

2.3.4 Sewage Sludge

Table 13 and Figure 8 present the forecasts for sewage sludge. These suggest that by 2050 an estimated 51.3 M tonnes of sewage sludge (at 4% DS) will be generated. This uplift is the result of the assumed population growth, as described in Section 2.2.2.1. The detailed waste flows which support these results are presented in Appendix 1.

[54] Derived from reported TWh/yr bioenergy potential, from CCC (2011)

These estimates are higher than those modelled by the CCC as a result of new data having come available since 2011 in relation to the baseline, as highlighted in Section 2.1.5. However, it is notable that the growth in arisings follows a similar trajectory.

Table 13: Sewage Sludge Available Arising Forecasts – Central Scenario, 2020 to 2050 ('000 tonnes at 4% DS)

	2020	2030	2040	2050
Central Scenario	44,034	46,706	48,967	51,315
CCC (2011)[55]	22,500-31,500	26,100-32,400	-	31,500-36,000

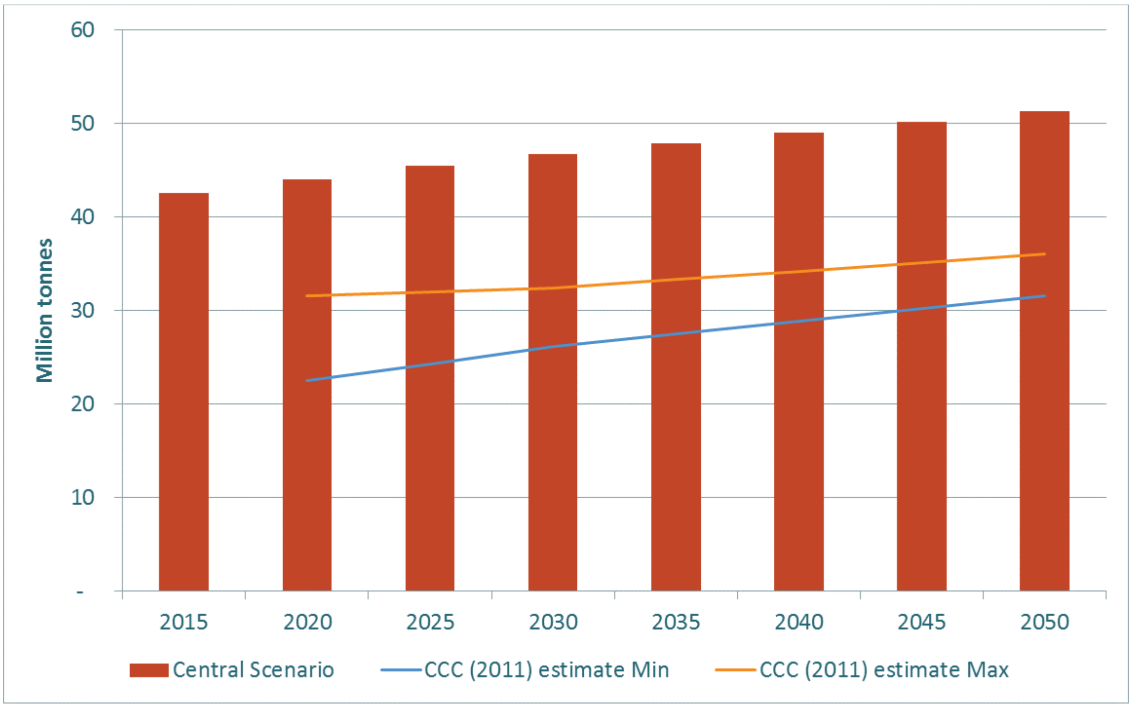


Figure 8: Sewage sludge forecasts (4% DS)

2.4 Total Bioenergy and Renewable Gas Forecasts

The amount of bioenergy that can be generated from each waste streams depends on:

- Residual waste composition, in terms of biogenic content, which for this study is assumed to be 62.5% in line with the assumption used in the CCC report;
- Assumptions relating to the CV of different waste types; for example, there are greater arisings of food waste than wood waste, but as the former has a lower CV/tonne, its total bioenergy potential is lower; and
- The energy generation technology used, i.e. AD, combustion, gasification and the conversion efficiency of that process. This is largely determined by what form of energy is produced, i.e. electricity or heat, and by what means, for example, syngas might be burned in an onsite steam turbine for electricity generation or upgraded to BioSNG for grid injection and subsequent combustion in a domestic gas boiler.

55 Derived from reported TWh/yr bioenergy potential, from CCC (2011)

Renewable gas potential is therefore a function of total bioenergy potential. The assumptions relating to CVs and conversion factors for different feedstocks to energy and ultimately, renewable gas, are presented in Appendix A1.1.

2.4.1 Bioenergy forecast to 2050

Based on the assumptions in Appendix A1.1 and those for feedstock arisings presented in Section 2.2.1, the modelling undertaken for this study results in a forecast total of just under 73 TWh of bioenergy potential under the Central scenario. As shown in Table 14 and Figure 9, residual and wood wastes are the largest contributors to total bioenergy potential. This varies between 64 TWh and 77 TWh, depending on the scenario. Total bioenergy potential falls to 2030, as the effect of recycling growth outweighs the impacts of waste growth. However, as recycling slows from 2030, the net effect of these two factors is an annual increase in bioenergy potential to 2050.

Table 14: Forecast Bioenergy Potential (in TWh) to 2050

Waste Type	2020			2030			2040			2050		
	Low	Central	High	Low	Central	High	Low	Central	High	Low	Central	High
Residual Waste[56]	27.5	28.8	28.7	16.9	23.3	25.6	17.4	24.2	26.8	17.9	25.2	28.1
Wood waste	23.9	24.2	24.4	26.6	26.2	26.4	27.1	27.1	27.8	27.6	28.1	29.4
Food Waste	10.6	10.6	10.7	11.0	11.2	11.3	11.7	11.7	11.9	11.9	12.1	12.5
Sewage Sludge	6.1	6.1	6.1	6.5	6.5	6.5	6.8	6.8	6.8	7.1	7.1	7.1
Total	68.2	69.8	69.9	61.0	67.1	69.7	69.8	69.8	73.3	64.4	72.6	77.0
CCC min		52.5			46.9			45.7			44.5	
CCC max		61.5			53.6			51.8			50.0	

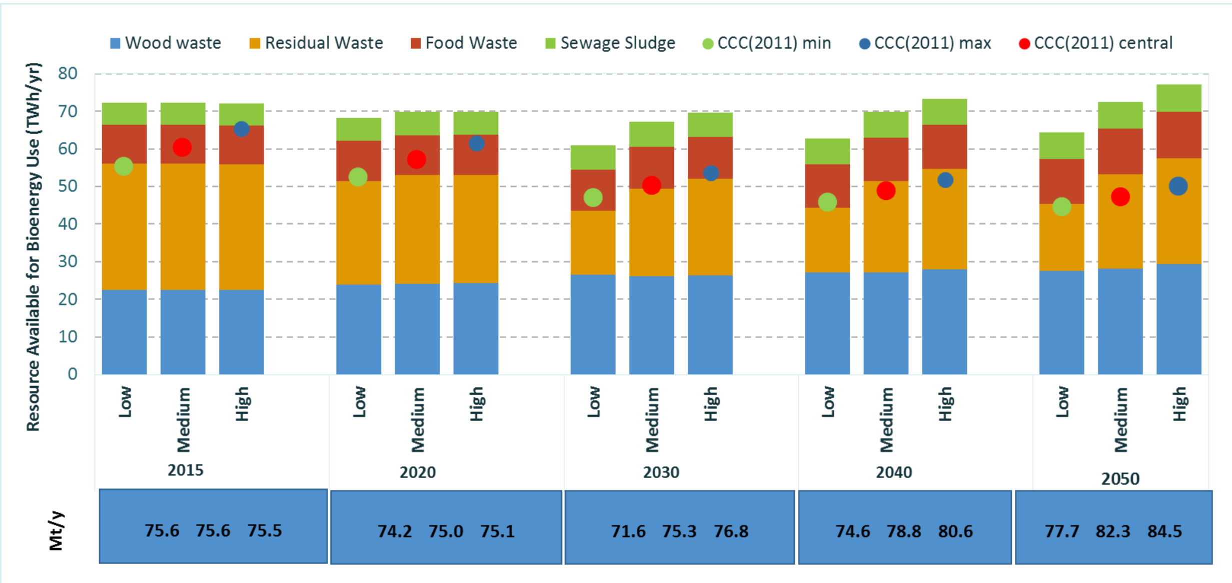


Figure 9: Bioenergy Forecast to 2050 (all scenarios in TWh)

As presented in Figure 9, the bioenergy potential forecasts in this study are higher than those in the CCC report, particularly for the period 2030–2050. This is largely the result of the use of more recent baseline

---

[56] Biogenic content only

datasets and the higher growth rate assumptions for all feedstocks compared with those used in the CCC study, which was undertaken at a time of recession and falling waste arisings.

It should also be noted, as discussed in Section 2.1.1 and 2.1.2, that the CCC splits residual waste into "renewable waste for energy recovery", and that directed to landfill for gas generation. In this study, we have assumed that all of the residual waste is available for bioenergy generation, as landfill contracts are very short and levels are likely to be negligible in 2050 (see Section 2.2.2.2). As a result, the total bioenergy forecast (under the Central scenario) in this study is 5.6 TWh higher than the level presented in the 2011 AEA report upon which the CCC estimates are based.

2.4.2 Renewable Gas forecast to 2050

The forecast bioenergy potential presented above has been converted to renewable gas output, using the arisings assumptions presented in Section 2.3 and the conversion factors for different feedstocks to renewable gas in Appendix 1. As presented in Table 15 and in Figure 10, this results in a total renewable gas potential of 47-56 TWh in 2050, with 83% of this coming from bioSNG and 17% from biomethane via AD. It should be noted that whilst the balance of the split between biomethane from AD and bioSNG may vary over time, this is unlikely to be sufficient to significantly change the total level of renewable gas generation.

Again, as for total bioenergy potential, total renewable gas potential falls to 2030, as the effect of recycling growth outweighs the impacts of waste growth. However, as recycling slows from 2030, the net effect of these two factors is an annual increase in bioenergy potential to 2050.

Whilst the total renewable gas potential presented in Table 15 and in Figure 10 should be regarded as significant, it should be acknowledged that whilst the fossil content of residual waste is rightly excluded from the estimates of bioenergy potential, in reality, if plastics are sent to landfill, significant volumes of biogenic waste (which is effectively wet and stuck to the plastics) is also sent to landfill. Consequently, use of this material to generate bioSNG would provide greater amounts of bioenergy (around 52 TWh/annum in 2050), whilst also diverting such material (which has significant biomethane potential) from landfill, thus resulting in GHG benefits and contributing to energy security.

Table 15: Forecast Renewable Gas Potential (in TWh) to 2050

	2020			2030			2040			2050		
	Low	Central	High	Low	Central	High	Low	Central	High	Low	Central	High
BioSNG potential	41.6	42.7	42.8	36.3	40.6	42.5	37.1	42.2	44.6	38.0	43.8	46.9
AD potential	7.8	7.8	7.8	8.0	8.0	8.1	8.3	8.4	8.5	8.7	8.8	8.9

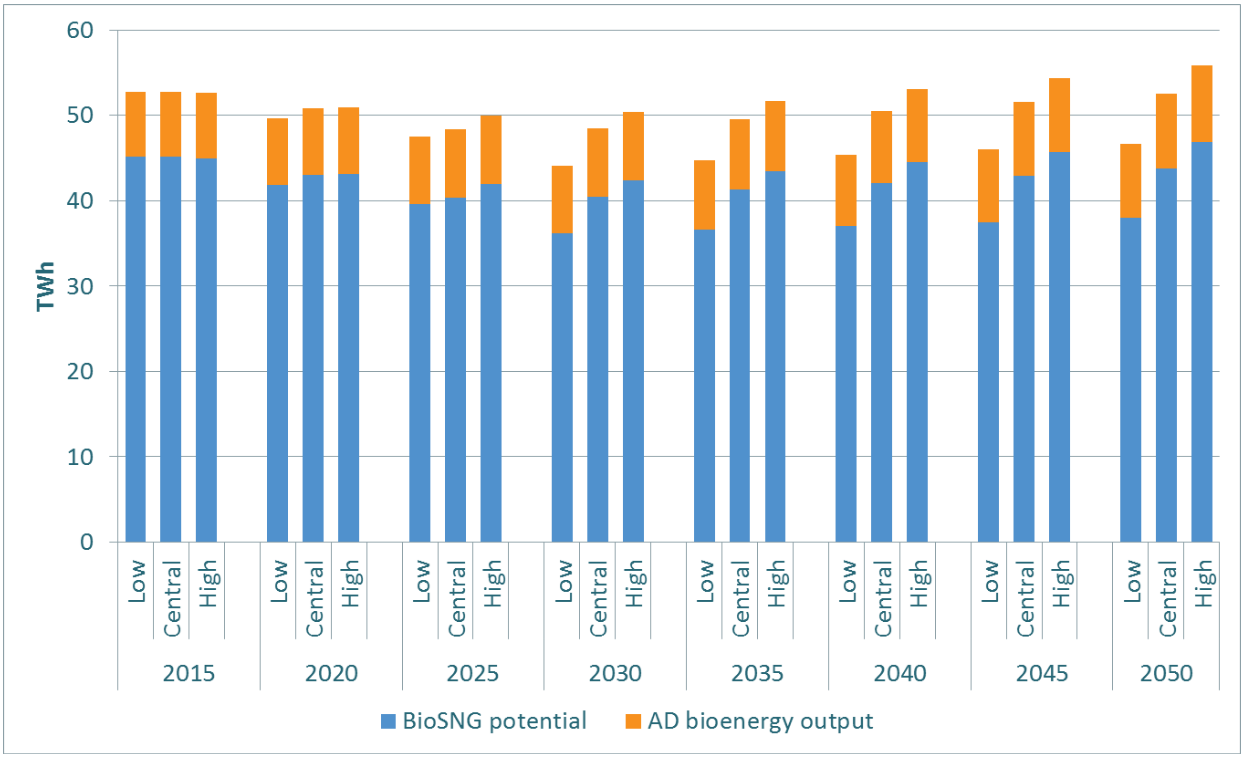


Figure 10 : Renewable Gas potential — forecasts to 2050

3. Non-Waste Feedstocks

3.1 Approach and methodology

Figure 11 presents the methodology followed in this study, which correlates with the sections that follow. The blue boxes in Figure 11 refer to the review of the CCC report, the dashed boxes reflect the tasks undertaken for each feedstock and the orange fill boxes represent the outputs from this study.

A key component of this study is a critical review of the CCC report, which aimed to understand where the data was derived from as well as the assumptions upon which the scenario modelling was built and the scenarios themselves. This is discussed in detail in Section 3.2. Using the latest available data, an unconstrained feedstock potential for 2015 was then established, which replaced the previous 2010 baseline (Section 3.3). This revised data, together with the critical review, is then used as the basis for building three updated scenarios for bioenergy potential across all the feedstocks (Section 3.6).

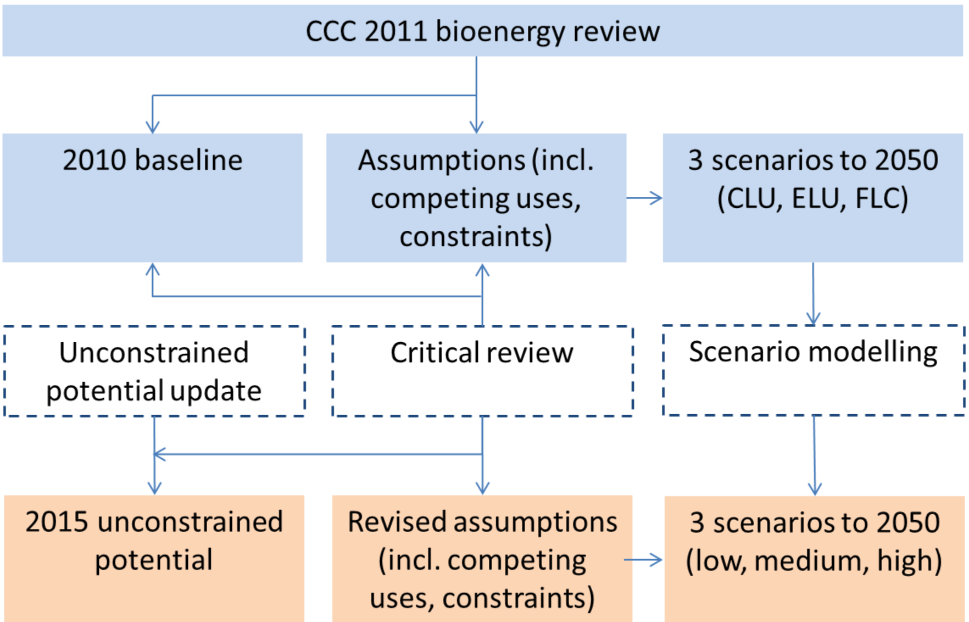


Figure 11: Study methodology

3.2 Critical appraisal of the CCC report

The CCC Bioenergy Review[6] modelled three scenarios: Constrained Land Use (CLU), Extended Land Use (ELU) and Further Land Conversion (FLC) which correspond to low, medium and high bioenergy potential scenarios. The CCC UK bioenergy potentials were derived primarily from the 2011 report "UK and Global Bioenergy Resource" by AEA[57] for the period 2010-2030, and for 2050 mainly using the 2011 report "Modes Project 1" by E4tech (which extended the AEA study to 2050)[58]. The general approach followed by the CCC when determining the UK potential of each feedstock, which is illustrated in the formula below, is to first estimate the total unconstrained feedstock potential in the UK - that is the total amount of feedstock before any competing uses or constraints are considered. The next step is then to subtract competing uses, and finally to apply potential reduction factors based on price and technical, market, policy and infrastructure constraints.

[57] AEA (2011), UK and Global Bioenergy Resource – Final report, DECC, June 2011. Available at www.gov.uk/government/publications/aea-2010-uk-and-global-bioenergy-resource

[58] E4tech (2011), *Modes Project 1: Development of illustrative scenarios describing the quantity of different types of bioenergy potentially available to the UK transport sector in 2020, 2030 and 2050*, Department for Transport, April 2011. Available at www.gov.uk/government/uploads/system/uploads/attachment_data/file/3238/modes-1.pdf

$$Bioenergy\ potential = (Unconstrained\ potential - Competing\ uses) \times (1 - Constraint\ factor)$$

Table 16 presents an overview of the bioenergy price 'type' (which is characteristic of the scenario environment and not a forecast) and barrier conditions chosen under each CCC scenario. These correspond to the constraint factors which are used to determine the bioenergy potential.

Table 16: Description of the characteristics of the CCC scenarios

CCC Scenario	Bioenergy price[59]	Barriers overcome
Constrained Land Use (CLU)	Low	None
Extended Land Use (ELU)	Medium	Easy only
Further Land Conversion (FLC)	High	Easy and medium only

Where CCC deviated from the AEA or E4tech analysis for the bioenergy potential estimates of a feedstock, detail was not always provided for the alternative assumptions. However, a review of the estimates reveals that CCC's most optimistic scenario – FLC – is more conservative in the deployment of bioenergy in 2020 than the most optimistic AEA estimates. As shown in Figure 12, the FLC data for 2020 are very similar to the ELU scenario for that year. This reflects the CCC's assumption that the near term ability to achieve those maximum AEA bioenergy potentials was anticipated to be challenging.

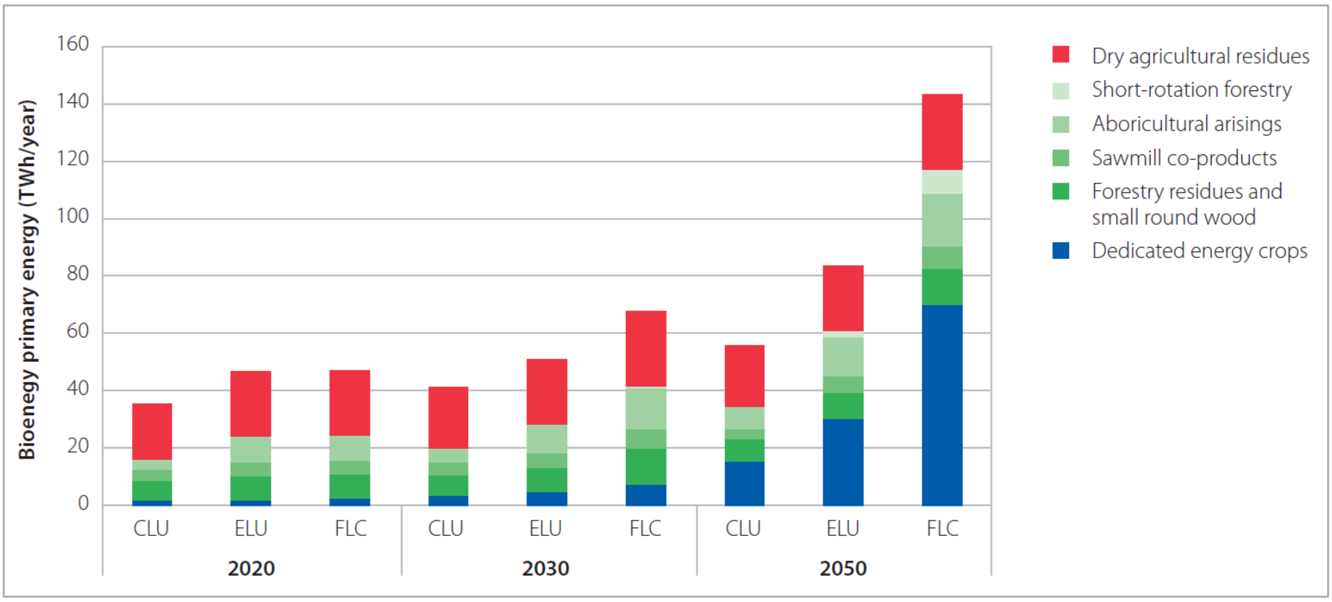


Figure 12: CCC estimates for the UK production of non-waste feedstocks in 2020, 2030 and 2050. Source: CCC (2011)

3.3 Dedicated energy crops

The CCC did not derive the energy crop potential from AEA or E4tech studies, and instead conducted its own analysis, applying its own assumptions to the most significant bioenergy feedstocks. Only Miscanthus and short rotation coppice (SRC) willow were considered for this estimate. As part of its review, the CCC considers environmental impacts such as land quality, biodiversity and soil carbon. As well as these environmental concerns, it refers to land competition and farmers' resistance to shift to energy crop cultivation as obstacles

[59] Low, medium and high bioenergy prices correlate with £4/GJ, £6/GJ and £10/GJ prices used in the AEA and CCC reports

to energy crops. On this basis, the CCC is cautious in its scenario estimates. This is primarily demonstrated by the available land areas the CCC selected for the three scenarios:

- For CLU, the available land in 2050 for energy crops is 0.3 Mha which is comprised of low-productivity and inaccessible arable land (higher risk land, steep banks, awkward corners), and/or a portion of land previously set-aside.
- For ELU, the available land area is 0.6 Mha which includes the CLU land area plus nearly all of the land previously set-aside.
- For FLC, 0.8 Mha is assumed to be available, comprising the ELU available land, plus some arable land and pasture land with arable potential which has been released due to improvements in agricultural productivity and/or intensification of livestock farming. The CCC analysis was conscious of the impact of land use change and allowed for little conversion of grass land, and no use of forestry land for biomass such as Short Rotation Forestry.

The 2010 yields for Miscanthus and SRC are higher in the FLC scenario than in the CLU and ELU scenarios, and the CCC did not assume any increase in yields over time. The CCC acknowledges that yield rates can be improved but states that this may lead to a greater input of resources and as a result an increase in emissions. However, our experience suggests that there may be options to improve yield rates without increasing emissions and it is reasonable to assume that yield rates can increase. The CCC assumed a fixed annual percentage rate increase in land cultivated with energy crops in order to achieve the land areas in 2050, although annual planting rates will likely be constrained by the availability of land, equipment and planting material in the UK.

In 2050, the CCC projected a bioenergy potential of 15, 30 and 70 TWh/yr of biomass for their CLU, ELU and FLC scenarios respectively. The CCC's conservative approach has been, to a certain extent, justified when slow progress to date in this sector is considered. However, its ramp-up assumptions have not been realised so far. Lack of industry progress is attributable to a number of reasons, including sporadic policy and market support, and the removal of planted areas at a number of farms. In the past, the UK has funded two rounds of Energy Crop Schemes (2000-2006; 2008-2013), which provided establishment grants for perennial energy crops and resulted in planting of ~11,300 ha[60]. However, the uptake of perennial energy crops has so far been limited due to lack of specialist planting and harvesting equipment, previously poor establishment and management practises, limited local supply infrastructure, high upfront establishment costs and low financial attractiveness for farmers[61].

3.3.1 Dry agricultural residues

The estimated unconstrained feedstock potential for dry agricultural residues in the base year included straw (8.8 Modt/yr), seed husks (1.2 Modt/yr) and poultry litter (1.1 Modt/yr). The base year feedstock potential was assumed to be constant from the base year until 2050, which is a reasonable assumption as recent projections by the Farm and Agriculture Policy Research Institute (FAPRI)[62] indicate that there is little projected variation in crop production. The straw estimate includes wheat, barley and oat straws. Oilseed rape (OSR) straw was not included due to harvesting difficulties, and has been excluded from other bioenergy estimates due to its difficult thermochemical processing characteristics (high ash and chlorine content leads to increased maintenance). However, the complete exclusion of OSR straw seems severe. Whilst a more difficult straw to

---

[60] NNFCC (2012) *Domestic Energy Crops; Potential and Constraints Review*, February 2012. Available at www.gov.uk/government/uploads/system/uploads/attachment_data/file/48342/5138-domestic-energy-crops-potential-and-constraints-r.PDF

[61] Defra (2016), *Area of crops grown for bioenergy in England and the UK: 2008-2015*, January 2016. Available at www.gov.uk/government/statistics/area-of-crops-grown-for-bioenergy-in-england-and-the-uk-2008-2015

[62] FAPRI (2015), *2015 Baseline Projections,* April 2015 Available at www.afbini.gov.uk/publications/fapri-uk-baseline-projections-2015

process than others, it is not impossible and its use can be included - though the increased processing costs should be accounted for.

The CCC considers several competing uses for the feedstock. The CCC's primary assumption is that half of straw is utilised for animal bedding and feed. However, a more recent estimate stated that 49% of straw production is utilised for animal bedding and composting, but not animal feed[63]. The CCC's assumptions have been succeeded by more recent studies and should be updated. The CCC assumes that barley straw and seed husks are not diverted to energy use as they have significant uses in animal feed and the removal of these feedstocks from the animal feed supply chain may result in higher animal feed prices. The straw would also need to be replaced by cultivated feed, which may induce indirect land use change and lead to greater GHG emissions. Barley and seed husks continue to be widely used for animal feed and it seems reasonable to assume this continued use for the foreseeable future.

The CCC did not comment about the levels of straw incorporation but the AEA (2011) estimates assume that approximately 30% of total straw production needs to be incorporated to aid soil structure (and applies this as an environmental constraint). The 30% assumption is higher than data from a 2008 report by the AHDB[63], which suggests that 25% of UK straw is incorporated back into the soil. A more recent report by the AHDB[64] explores this issue further and the results will be incorporated into our scenarios

In 2050, the CCC projected a bioenergy potential of 21, 23 and 26 TWh/yr of dry agricultural residues for its CLU, ELU and FLC scenarios respectively. As mentioned above, the CCC's scenarios were cautious in their estimates by excluding OSR straw; however, its other assumptions made for this analysis seem reasonable. New data have been published which provides revised estimates for many of the assumptions underpinning the CCC's estimates, and which will have a significant impact on the available potential (as discussed in Section 3.5.2).

3.3.2 Forestry and forest residues

For its reporting, the CCC combines forest residues, small round wood, arboricultural arisings, sawmill co-products and short rotation forestry. The CCC defines these feedstocks as follows:

- Forest residues: Brash, stemwood, stumps, branches bark and distorted wood;
- Small round wood: No definition provided;
- Arboricultural arisings: Biomass from tree surgeries in urban spaces and transport corridors;
- Sawmill co-products: Sawdust, shavings and other residues from the production of timber products; and
- Short rotation forestry: Fast-growing trees in 8 to 20 year rotations.

The estimates for these feedstocks were derived from AEA (2011). The unconstrained potential remains constant over time for many of the feedstocks, as more detailed projections were not available in 2011. The resource potential for these feedstocks is dependent on forestry activity, which according to the latest Forestry Commission projections[65] will increase until 2030 and then slowly decline until 2050. The primary assumptions for each feedstock potential are summarised in Table 17. The CCC applied constraint factors to these potentials to account for logistical difficulties in collecting such a dispersed feedstock. These constraint factors have been updated in the recent report by Ricardo[66].

---

[63] AHDB (2008), *Wheat straw for biofuel production*, April 2008. Available at https://cereals.ahdb.org.uk/media/737243/rd-2007-3690-final-project-report.pdf

[64] AHDB (2014), *Straw incorporation review*, May 2014. Available at https://cereals.ahdb.org.uk/media/470361/rr81-web.pdf

[65] Forestry Commission (2016), *Forestry Statistics 2016: Timber - Wood production*, June 2014. Available at www.forestry.gov.uk/forestry/infd-8w3lv3

[66] Ricardo Energy & Environment (2017), *UK and Global Bioenergy Resource Model*, January 2017 BEIS. Available at www.gov.uk/government/publications/uk-and-global-bioenergy-resource-model

Table 17: Commentary on primary CCC assumptions for forestry and forest residues bioenergy potential[67]

Feedstock	Unconstrained Potential (Modt/yr) 2020	2030	2050	Commentary on Competition	Commentary on Assumptions
Forest residues	1.0	1.0	1.0	No competition was assumed; however this feedstock is used for horticulture mulch	Residue retention within the forests was assumed as 50% - which is in line with the wider literature
Small round wood	3.3	3.3	3.3	Third of resource to panelboard manufacture, pulp mills and fencing	The availability of the feedstock is dependent on assumptions of carbon sequestration in forestry
Arboricultural arisings	2.4	2.7	3.5	CCC did not consider any competing uses but this feedstock is used for horticulture mulch	CCC do not discuss the logistical difficulties of gathering this feedstock, which will be highly dispersed
Sawmill co-products	1.6	1.6	1.6	CCC assumes half of resource goes to panelboard and pulp mills however AEA 2011, upon which the CCC report is based, does not apply this competing use	Resource potential was assumed to be constant over the model timeline. New data from Forestry Research indicates that resource availability will vary over time due to changing age class of the UK's forests
Short rotation forestry	0.0	0.0	7.5	The CCC did not provide details for competing uses, but as this feedstock is only grown for energy purposes, it may be assumed that no competing uses exist	Only included in the FLC scenario. The CCC was cautious in its SRF estimates due to concerns about land use change and the impact of foreign tree species on native trees and birdlife

In 2050, the CCC projected a bioenergy potential of 19, 28 and 47 TWh/yr of forest and forestry residue feedstocks for their CLU, ELU and FLC scenarios respectively. At the time of its publication, the CCC's estimates for the unconstrained potentials for forest residues, small round wood and sawmill co-products were reasonable but new data from Forestry Commission and Forest Research is available to revise these values. For arboricultural arisings, it is necessary to revise the unconstrained potential, in particular the 2050 assumption, which we believe to be an overestimate. The CCC was cautious in its estimates for short rotation forestry, but considering the slow progress in this sector since the CCC's review, this cautiousness seems justified. Overall it is plausible that for several feedstocks competing uses have been under-estimated, which has led to inflated available potential. It is therefore recommended that the figures for competing uses are revised.

3.3.3 Wet manure

The CCC estimates for wet manure bioenergy potential appear to be extracted from the AEA 2011 report. However, the details behind the baseline assumption of 66 Mt/yr of unconstrained bioenergy potential are provided by neither the CCC nor AEA. It is assumed that only cattle, pigs and laying chickens have been considered as sources of manure. The CCC assumed the same potential for wet manure for each of its three scenarios, with the exception of the FLC scenario in 2050 where the value corresponds with the high potential AEA scenario. No reason is provided for this assumption but it would suggest that the CCC does not expect

[67] ***Note*: Values were not extracted from the CCC reporting but from AEA (2011), upon which the CCC built its projections**

much variability in this sector. Only slurries were considered for the potential, whilst farmyard manures were excluded due to issues with digesting in AD plants. This is a reasonable assumption and is consistent with recent estimates. The CCC scenarios assumed that livestock numbers (which they derived from a 2004 source) would remain constant until 2050 – an assumption that correlates with recent FAPRI projections in which herd numbers vary only slightly out to 2024. However, the CCC projected estimates do not account for increasing herd numbers due to the intensification of livestock farming and the resulting increase in manure production, and it is thus recommended that some growth be considered.

With regard to competing uses, the CCC does not indicate the amount of feedstock utilised for non-energy purposes. The AEA (2011) data suggests that 10% of the resource is diverted to competing uses, due to spreading over land and the sale of poultry muck for its nitrogen value. However, more detail about the assumptions made by both the CCC and AEA with respect to manures and the constraints applied is required as we believe that this assumption for competing uses is low and it does not correlate with assumptions made by more recent estimates such as those by Ricardo (2017).

In 2050, the CCC projected a biogas (not biomass) potential of 4, 4 and 6 TWh/yr of manures for its CLU, ELU and FLC scenarios respectively. The CCC assumed a wet manure calorific content of 0.38 GJ/tonne (wet) and an AD conversion efficiency of 75%. These assumptions seem reasonable and similar values are used in our scenarios. Neither the CCC nor AEA provide clear justification for the unconstrained potential, which makes it difficult to examine the underlying assumptions and allows only a comparison of whether the value correlates with other estimates in the literature. Similarly, little detail is provided about their assumption of feedstock diverted to competing uses. Their assumption that only 10% of feedstock is used for land spreading is likely to be an underestimate as this is the current primary use of wet manures. The estimate for competing uses has been revised for the scenarios in Section 3.5.8.

3.3.4 Industrial residues

The CCC does not report on industrial residues such as wine lees, crude glycerine, molasses, lignin or tall oil. The current, small, amounts produced are briefly discussed in Section 3.4.9. These residues have also been excluded from the estimates for this current review.

3.3.5 Macro-algae

The DECC 2050 Pathways Analysis[68] estimated 0 - 13 TWh/yr of macro-algae (seaweed) energy potential in 2050. The CCC takes into account the key uncertainties and constraints e.g. technology, costs, interference with shipping routes and the existence of rough conditions at sea and apply appropriate constraint factors to derive 3.5 TWh of biogas potential in 2050 in the FLC scenario only (the CLU and ELU scenarios have zero potential). This approach seems fair, as significant support is required to encourage this technology - requiring more time for development and favourable policy and market conditions.

3.3.6 Summary of CCC resources

Based on the data presented in Figure 12, Table 18, Table 19 and Table 20 provide approximate estimates[69] of the available feedstock volumes for bioenergy in each scenario. These are presented in TWh/yr in keeping with the CCC's reporting, which allows an equal comparison between feedstocks (i.e. accounting for the differing calorific contents).

---

[68] HM Government (2010) *2050 Pathways Analysis*, February 2010. Available at www.gov.uk//government/uploads/system/uploads/attachment_data/file/42562/216-2050-pathways-analysis-report.pdf

[69] These values have been extracted using a plot digitiser, and thus may be subject to small errors

Table 18: Estimated available bioenergy potential of feedstocks in the CCC's Constrained Land Use scenario (TWh/yr)

Feedstock	2020	2030	2050
Dedicated energy crops	2.3	3.8	16.0
Dry agricultural residues	19.4	21.4	22.0
Forestry residues and small round wood	6.6	7.1	7.6
Sawmill co-products	3.8	4.5	3.5
Arboricultural arisings	3.8	5.0	7.6
Short rotation forestry	0.0	0.0	0.0
Wet manures (biogas)	3.3	3.1	4.2
Total	**39.1**	**44.9**	**60.8**

Table 19: Estimated available bioenergy potential of feedstocks in the CCC's Extended Land Use scenario (TWh/yr)

Feedstock	2020	2030	2050
Dedicated energy crops	1.6	4.3	30.1
Dry agricultural residues	22.9	22.9	22.9
Forestry residues and small round wood	8.8	8.5	9.2
Sawmill co-products	4.2	5.0	5.7
Arboricultural arisings	9.0	10.4	13.5
Short rotation forestry	0.0	0.0	0.0
Wet manures (biogas)	3.3	3.2	4.2
Total	**50.7**	**54.7**	**88.7**

Table 20: Estimated available bioenergy potential of feedstocks in the CCC's Further Land Conversion scenario (TWh/yr)

Feedstock	2020	2030	2050
Dedicated energy crops	3.0	7.5	70.2
Dry agricultural residues	22.7	26.6	26.6
Forestry residues and small round wood	8.5	13.0	13.0
Sawmill co-products	4.3	6.6	7.8
Arboricultural arisings	9.0	14.0	18.0
Short rotation forestry	0.0	0.7	8.3
Wet manures (biogas)	3.6	3.2	6.1
Total	**51.0**	**71.5**	**150.0**

3.4 Unconstrained 2015 baseline potential

This section provides an updated unconstrained potential for the non-waste feedstocks, updating the 2011 CCC baseline estimates to 2015. This update is derived from a number of publically available data sources, which have been published since the CCC review, and also considers changes to factors such as land availability, planting rates, sustainability considerations, and industry developments. The values in this section do not account for constraints such as competing uses, price dependencies or other constraint factors. These unconstrained potential baseline tonnages are used as the starting point for the scenario modelling in Section 3.5.

3.4.1 Dedicated energy crops

Dedicated perennial energy crops, primarily Miscanthus and short rotation coppice (e.g. willow and poplar), have been grown in the UK for the past 30 years, and have been successful in small areas in the UK. Though anticipated to be a significant future biomass resource in the UK, there is currently little contribution from dedicated energy crops. In 2015, 0.09 - 0.14 Modt/yr was estimated to have been harvested, with around 75-80% attributable to Miscanthus and 20-25% to short rotation coppice (SRC) respectively. This is derived from a total planted area of ~0.01 Mha (0.2% of England's total arable land), and yields of 6-15 odt/ha per annum[70,71]. This updated estimate for 2015 is around two thirds lower than was projected for 2015 in the CCC 2011 bioenergy review and background E4tech and AEA studies.

3.4.2 Dry agricultural residues

The unconstrained potential of dry agricultural residues is dependent mainly on the level of arable food crop production, which has been reasonably stable in recent years. Similarly to the CCC review, the unconstrained feedstock potential includes straw, seed husks, plus broiler chicken and turkey litter. Contrary to the CCC's

---

[70] NNFCC (2012), *Domestic Energy Crops; Potential and Constraints Review*, May 2012. Available at www.gov.uk/government/uploads/system/uploads/attachment_data/file/48342/5138-domestic-energy-crops-potential-and-constraints-r.PDF

[71] Defra (2016), *UK annual time series: 1984 to 2016, Structure of the agricultural industry*:, September 2016. Available at www.gov.uk/government/statistical-data-sets/structure-of-the-agricultural-industry-in-england-and-the-uk-at-june

review, we have included OSR straw as well as wheat, barley and oats straw. Although OSR straw is more difficult to process it is not impossible. The increased capital and operational costs for OSR straw have been taken into account.

The unconstrained potential estimates for straw production in this study are based on the most recent 2016 data released by Defra[72]. The production of poultry litter was estimated using Defra livestock numbers[73] and assumptions for the amount of excreta produced per head of poultry - 16.5 wet tonnes per 1,000 head per year[73] and 45 wet tonnes per 1,000 head for turkey litter[74], assuming that all litter is gathered during the housing period and has moisture content of 40%. These estimates are provided in Table 21. The baseline estimate for seed husks assumes the previous AEA (2011) value of 1.4 Mt/yr and a moisture content of 14.5%.

Table 21: Baseline straw and poultry litter production

Feedstock	Estimated current production (Modt/yr)
Wheat	5.5
Barley	2.6
Oats	0.4
Oilseed rape	0.9
Seed husks	1.2
Poultry litter	1.4

The resulting new baseline estimate for the unconstrained potential of dry agricultural residues is 12 Modt/yr, which is similar to the CCC reviews' 2011 estimate.

3.4.3 Forest residues

The CCC's baseline was derived from AEA (2011), which in turn used estimates from the Forestry Commission and the CARBINE model. The latest estimates from Ricardo (2017) used the newest data from the Forestry Research CARBINE and CSORT models (updated in January 2017), and are considered to be the most appropriate estimates available. The unconstrained potential for the 2015 baseline is 1.6 Modt/yr, which is higher than the CCC's 2011 estimate of 0.95 Modt/yr. However, the majority of this difference is the result of the methodologies used to calculate the two estimates. The CCC's estimate applies the residue removal rate prior to the unconstrained potential estimate whilst our estimate applies this afterwards. This updated approach was followed in order to explore the sensitivity around the industry assumed residue removal rate of 50% by applying a variable residue removal rate. The total unconstrained potential is also affected by updates to the forestry estimates.

---

[72] Defra (2016), *Area of crops grown for bioenergy in England and the UK: 2008-2015*. Available at www.gov.uk/government/statistics/area-of-crops-grown-for-bioenergy-in-england-and-the-uk-2008-2015

[73] Defra (2017) *Livestock numbers in the UK (data to December 2016).* Available at www.gov.uk/government/statistical-data-sets/structure-of-the-livestock-industry-in-england-at-december

[74] Defra (2013) *Guidance on complying with the rules for Nitrate Vulnerable Zones in England for 2013 to 2016*. Available at http://adlib.everysite.co.uk/resources/000/278/013/Defra_NVZ_guidance_Nov_2013.pdf

3.4.4 Small round wood

Small round wood is generated during first pass forestry operations and is defined as branches greater than 7cm and less than 18cm in diameter. As with the forestry residues, the CCC's estimate was derived from AEA[9], which calculated its estimates from the CARBINE model. Ricardo (2017) also uses the Forest Research models for its estimate of the small round wood potentials, which was updated in January 2017.

The latest estimate of 1.1 Modt/yr used for this study is based on the *LULUCF Stretch* scenario developed by BEIS, Defra and Forestry Commission. This scenario assumes an ambitious climate change mitigation programme exceeding current policy aspirations or funding and of the various scenarios used for the CARBINE model sees the greatest projection in carbon sinks through forestry management[75]. It was assumed that the *Stretch* scenario is the most conservative scenario for the unconstrained potential of small round wood and so is applied to our low scenario. 1.1 Modt/yr is a considerable reduction in comparison to the CCC's estimate of 3.3 Modt/year for the high scenario, with the medium scenario being an average of the low and high scenarios, at 2.2 Modt/year.

3.4.5 Arboricultural arisings

The CCC's 2015 unconstrained potential estimate of 2.3 Modt/yr is based on AEA (2011). This is derived from NNFCC (2008)[76], which is ambiguous in its definition of the resource type extracted (i.e. whether household garden wood is included). More recent estimates from Ricardo (2017) are derived from Mantau *et al*. (2010)[77]. This report estimates the UK availability of biomass trimmings from the management of non-forest woodlands, defined as landscape care wood, as 5.31 million m^3. Assuming a wood density of 0.5 odt per m^3, this equates to 2.7 Modt/yr of unconstrained feedstock potential. Although this is an increase on the CCC assumption, both reports state that data for these estimates is lacking and indicate that more research is required. More robust data was not identified.

3.4.6 Sawmill co-products

The unconstrained potential of sawmill co-products is dependent on sawmill activity. Neither CCC (2011) nor AEA (2011) provide background references for their estimates of sawmill co-product feedstock. Research of the literature indicates that Forest Research data from its CARBINE and CSORT models is the most suitable reference for an estimate of this feedstock. The CCC assumes a constant unconstrained feedstock potential of 1.6 Modt/yr, however the latest data revises this baseline potential to 1.4 Modt/yr to reflect the updated information for lower activity in the UK's sawmills.

3.4.7 Short rotation forestry

Similar to the CCC's estimate, the updated baseline unconstrained potential for short rotation forestry is **zero**. Although several years have elapsed since the CCC's estimate, there are still no plantations of short rotation forestry in the UK, and therefore no change in the baseline bioenergy estimate.

---

[75] CEH (2017) *Projections of emissions and removals from the LULUCF sector to 2050*. Available at https://uk-air.defra.gov.uk/assets/documents/reports/cat07/1703161052_LULUCF_Projections_to_2050_Published_2017_03_15.pdf

[76] NNFCC (2008), *National and regional supply/demand balance for agricultural straw in Great Britain*. Available at www.northwoods.org.uk/northwoods/files/2012/12/StrawAvailabilityinGreatBritain.pdf

[77] Mantau, U. *et al*. (2010) *Real potential for changes in growth and use of EU forests*. Available at www.egger.com/downloads/bildarchiv/187000/1_187099_DV_Real-potential-changes-growth_EN.pdf

3.4.8 Wet manure

Manures generated by cattle, pigs and laying chickens are included in this feedstock estimate. The CCC's total unconstrained feedstock of 66 Mt/yr was an estimate of total wet slurries, although the origin of this value was not sufficiently referenced.

The unconstrained potential for this study is estimated from the livestock numbers and the amount of volatile solids produced per head of livestock. Similarly to the CCC, the Ricardo[66] updated estimate only considers slurries as suitable for anaerobic digestion (AD) and excludes farm yard manures. The latest livestock data from Defra[78] was used for the baseline feedstock potential, and AHDB figures[79] are assumed for cattle and pig excreta production rates and assuming 40% are on a slurry system. These figures for 2015 are presented in Table 22. Laying chicken production assumption is based on Defra[80], which assumes litter is collected during the housing period and has a dry matter content of 30%.

Table 22: Wet manure assumptions for livestock

Feedstock	Livestock numbers ('000 head)	Excreta production (kg dm/head/day)
Cattle and calves	9,706	2.20
Pigs	4,491	0.32
Laying chickens	36,998	0.03

In contrast to the CCC's top-down approach using wet manures, our bottom-up estimate of manure levels indicate that **3**.8 Modt/yr of volatile solids are currently generated in the UK. Assuming that volatile solids account for 5% of manure's wet mass, the CCC's unconstrained potential estimate of 66 Mt/yr of wet manures equates to 3.3 Modt/yr of volatile solids. Our estimate for unconstrained potential is therefore an increase over the CCC's and is the result of updated herd numbers and a new methodology in which we have greater confidence.

3.4.9 Industrial residues

A very small volume of other industrial biogenic wastes and residues were produced in the UK in 2015 (Table 23). These industrial residues are not considered further in this study due to their size, and are not anticipated to provide significant resource into the future. These resources are also mostly already fully utilised in the UK, primarily for heat or power.

---

[78] Defra (2016), *UK annual time series: 1984 to 2016.*. Available at www.gov.uk/government/statistical-data-sets/structure-of-the-agricultural-industry-in-england-and-the-uk-at

[79] AHDB (2010) *Fertiliser Manual (RB209),* Defra. Available at www.ahdb.org.uk/documents/rb209-fertiliser-manual-110412.pdf

[80] Defra (2016), *Area of crops grown for bioenergy in England and the UK: 2008-2015*. Available at www.gov.uk/government/statistics/area-of-crops-grown-for-bioenergy-in-england-and-the-uk-2008-2015

Table 23: Current availability of UK industrial residues[81]

Feedstock	Estimated current production (Mt/yr, wet)
Black and brown liquor	0.28
Crude glycerine	0.03
Grape marcs	0.02
Wine lees	0.004
Tall oil pitch	0.001

3.4.10 Macro-algae

Macro-algae (seaweed) can be converted into biomethane through anaerobic digestion. However, there are currently no commercial scale macro-algae projects in operation in the UK or globally where the seaweed is being converted to energy (only some operations for much higher value food and pharmaceutical applications). Similar to the CCC's baseline, the assumption is that baseline 2015 unconstrained potential is zero.

3.4.11 Imported biomass

Although not a locally produced feedstock, imported biomass is considered in this Section to briefly examine its potential for use in the absence of sufficient or viable local feedstocks. The UK imported 6.5 Mtpa (as received) of wood pellets and 0.11 Mtpa of other wood including chips, sawdust and waste in 2015[82], predominantly from outside the EU (4.7 Mtpa). The vast majority of these imports, particularly the wood pellets, are for heat and/or power use.

Ricardo (2017) estimates the total surplus global supply of agricultural residues and woody biomass to 2050 (Figure 13), which grows as supply chains are established, and assumes that the UK is able to access a certain percentage of this global surplus - decreasing from 10% in 2015 to 2% in 2050 (due to increasing competing national energy supplies).

Although the UK does not currently import significant volumes of agricultural residues, the Ricardo (2017) analysis notes that this could also be a very significant source of feedstock for the UK - especially in the short to medium term. However, it is expected that some form of pelletisation or densification would probably have to occur prior to long-distance transportation to the UK, due to the low density of the feedstock. The economics and thermochemical characteristics of these resources could be poor and therefore why they are not currently imported to the UK. Significant doubts remain whether the global share of agricultural residues will be an available feedstock supply, given the lack of control the UK has over other country's agricultural systems, infrastructure and policy.

---

[81] E4tech (2014) *Advanced Biofuel Feedstocks – An Assessment of Sustainability*, Department for Transport, submitted by Arup URS Consortium. Available at www.gov.uk/government/uploads/system/uploads/attachment_data/file/277436/feedstock-sustainability.pdf

[82] DUKES (2016) *DUKES G.6 Imports and exports of wood pellets and other wood*. Available at www.gov.uk/government/statistics/dukes-foreign-trade-statistics

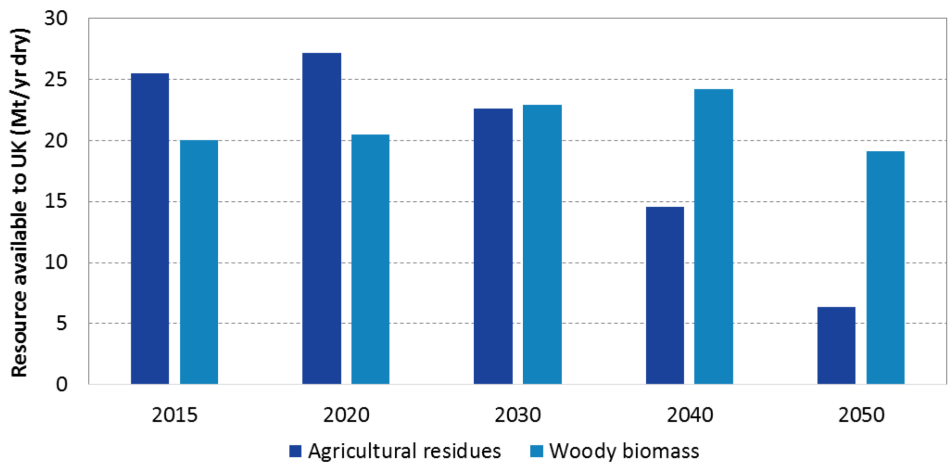


Figure 13: Woody biomass and agricultural residues potentially available for UK import, Source: Ricardo (2017)

However, for the woody biomass, the Ricardo (2017) data implies that the UK currently only imports ~30% of the global woody biomass that could be available to it. The amount of global woody biomass available to the UK is projected to remain broadly constant to 2030, suggesting that the UK could potentially import around three times more than it does currently. However, this availability decreases significantly to 2050, as surplus availability on global markets declines due to increasing demand. The DECC (2016)[83] survey of large power generators found that demand for imported biomass for heat and power use is expected to grow from around 5 Modt/yr in 2014/15 to around 9 Modt/yr in 2019/20 (Figure 14), with much less growth in heat and power in the 2020s. These findings, together with those of Ricardo, suggest that even with some additional demand from the power sector, the UK could potentially still import significantly more woody biomass feedstocks for bio-SNG production in the short to medium term.

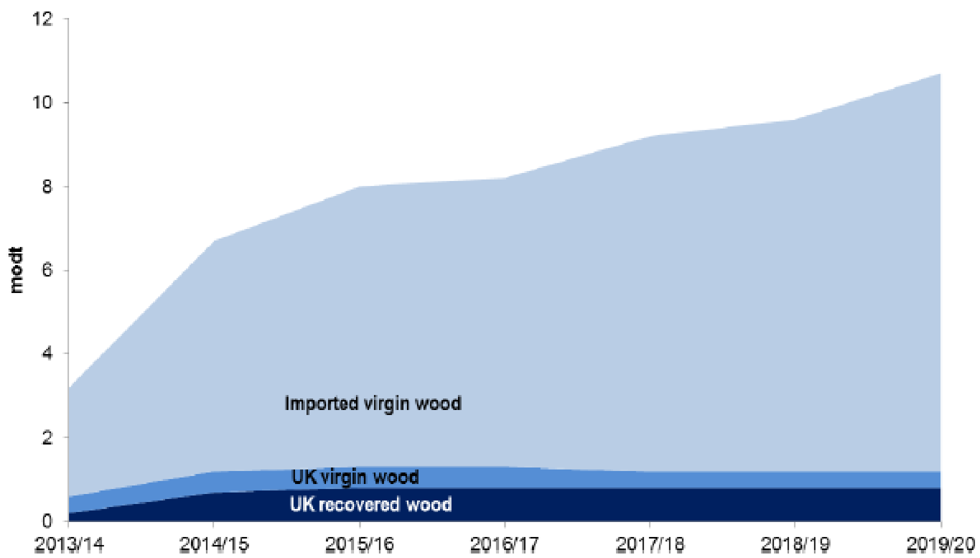


Figure 14: Expected increase in demand from UK power generators for imported wood[83]

Drax Power Station (North Yorkshire) imported 6.6 Modt/yr of certified sustainable wood pellets in 2016[84] for its 1.3 GW of dedicated biomass generation provides an example of the infrastructure adaption which could

[83] DECC (2016) *Woodfuel disclosure survey 2015*, Department for Energy and Climate Change. Available at www.gov.uk/government/publications/woodfuel-disclosure-survey

[84] Drax Group plc (2016) *Annual report and accounts*. Available at www.drax.com/wp-content/uploads/2017/03/Drax-Group-plc-annual-report-and-accounts-2016-Smart-Energy-Solutions.pdf

be reproduced for bio-SNG production. The 420 MW Lynemouth Power Station and 300 MW Tees Renewable Energy Plant, which is currently under construction, also indicate that sufficient biomass supply chains can be developed[85]. The ports of Port of Tyne (which now has handling capacity of 2 Mtpa of pellets), Immingham and Hull have been optimised for handling large quantities of biomass. Drax has also optimised its rail infrastructure to carry 50% more biomass from the ports to the power station compared to traditional freight trains[86]. Drax may have ceased operations by 2030, due to the plant age and expected finishing of subsidy support schemes in the late 2020s, hence there might be a possibility to repurpose some of the established import infrastructure for use in bio-SNG production. Although this post-2030 supply chain repurpose is heavily dependent on global availability of surplus woody biomass, based on the estimates projected in Figure 13, there is likely to remain scope for importing biomass to 2050.

3.4.12 Summary

A summary of the revised 2015 baseline of unconstrained potential, which is used as the basis for the scenario modelling in Section 3.5, is shown in Table 24 below, together with an indicator of how this estimate differs from the CCC estimates. It is important to note that competing uses and other constraints are not reflected in the potentials shown.

Table 24: Summary of revised 2015 unconstrained baseline potentials compared to CCC estimates

Feedstock	2015 unconstrained potential (Modt/yr)	Compared to CCC Bioenergy Review
Dedicated energy crops	0.1	↓↓
Dry agricultural residues	12.0	↔
Forest residues	1.6	↑
Small round wood	1.1	↓↓
Arboricultural arisings	2.7	↑
Sawmill co-products	1.4	↓
Short rotation forestry	0.0	↔
Wet manure	3.8	↑
Industrial residues	~0.3	-
Macro-algae	0.0	↔
Imported woody biomass	~20.0	↑
Key: Little change in availability ↔	Increased availability ↑	Decreased availability ↓

[85] BEIS (2017) *Renewable energy planning database monthly extract*, Available at https://www.gov.uk/government/publications/renewable-energy-planning-database-monthly-extract, Accessed 17/05/2017

[86] Drax (2013) *Biomass Sourcing*. Available at www.drax.com/wp-content/uploads/2016/09/2013-Capital-Markets-Day-2-Biomass-Sourcing-2013.pdf

3.5 Feedstock availability and bioenergy potentials to 2050

In order to derive theoretically available feedstock estimates, it is important to note that the feedstock potentials developed in this study consider only competing uses outside bioenergy (i.e. we do not consider competition from biomass heating, power plants or biofuels). The detailed data used in the modelling is included in Appendix 2. Further, the formula below is repeated as a reminder of how the bioenergy potential is determined.

$$Bioenergy\ potential = (Unconstrained\ potential - Competing\ uses) \times (1 - Constraint\ factor)$$

An example table, for the medium scenario in 2030, is included in Appendix 2 to further demonstrate the application of this approach.

3.5.1 Dedicated energy crops

The potential for dedicated energy crops is dependent on a number of factors, primarily planting rate, yield and land availability. These factors, which are derived from various literature sources, vary over time for the low, medium and high scenarios (as summarised in Table 25 below).

Table 25: Key assumptions for energy crops potential scenarios

Scenario	Maximum land availability in 2050 (Mha)	Yield 2015 → 2050 (odt/ha/yr)	Planting rate CAGR (%)
Low	0.30	Miscanthus: 10.0 SRC: 8.0	13.0
Medium	0.60	Miscanthus: 10.0 → 14.0 SRC: 8.0 → 11.0	16.0
High	1.15	Miscanthus: 10.0 → 18.0 SRC: 8.0 → 14.00	25.0

The maximum land availability for the low and medium scenarios is carried over from the previous CCC's CLU and ELU scenarios, while the high scenario is updated from the ETI's Bioenergy Value Chain Mode (BVCM)[87]. This reflects that both the ETI (with 1-1.8 Mha[88]) and the high estimate (of 1.85 Mha) in the Ricardo (2017) study assume that significantly more land might be available to energy crops in the UK than the 0.8 Mha in the CCC's FLC scenario. The ETI first excludes areas with high carbon stocks, high slope, special habitats etc. (i.e. the areas should be sustainable), and then assumes that 15% of remaining suitable arable land and 8% of grass land could be available to energy crops. However, the ETI does not explicitly consider any food competition or feasible rates of farming intensification. Implicit within these land availability estimates is therefore the assumption that these 2050 land areas could be surplus or less suited to food/feed crop production, but neither CCC nor ETI quantify the potential impacts on food production. This carries some risks, as currently only ~0.30 Mha of UK agricultural land is laying fallow[89]. The current total utilised agricultural area in the UK is 17.1 Mha, of which 5.9 Mha is arable. In 2015, provisional estimates indicate that 0.05 Mha of crop area, or 0.8% of total UK arable area, was used for biofuels supplied to the UK road transport market[89].

---

[87] Energy Technologies Institute (2015), *Bioenergy: Overview of the ETI's Bioenergy Value Chain Model (BVCM) capabilities*, Software Guide. Available at https://d2umxnkyjne36n.cloudfront.net/insightReports/BVCM-Guide-FINAL.pdf?mtime=20160909111422

[88] ETI (2015) *Bioenergy: Enabling UK biomass*. Available at https://d2umxnkyjne36n.cloudfront.net/insightReports/Biomass-Insights-%E2%80%93-Midres-AW.pdf?mtime=20160908155032

Both Miscanthus and SRC yields for the low scenario are assumed to remain constant from 2015 to 2020, in line with the CCC's original estimate. The medium and high scenarios see an increase in the yields over time. For Miscanthus, yields depend on factors such as planting method, species, site conditions and regional variation, and weather conditions. The scenarios' yields are in line with estimates found in literature which range from 10-15 odt/ha/yr today[89,90] and potentially up to 18 odt/ha/yr by 2050 as was estimated in Ricardo (2017). Once planted, Miscanthus takes 2-5 years to reach its full annual harvest potential, and plantations are typically expected to last for at least 20 years, although yields will likely decline over time[89]. SRC yields depend on similar factors to those mentioned above, and range from 8-14 odt/ha/yr, but the crop is only harvested every 2-4 years[89]. The ratio of Miscanthus to SRC planted areas is anticipated to remain broadly as it is today (~70/30), though there is a slight increase in Miscanthus in both the medium and high scenarios given the higher starting planting rate for Miscanthus[91].

We assume that under supportive farming policy, the energy crop industry would be able to recover to planting 1,000 ha/year in 2020, as the industry planted ~1,000 ha in 2012 at the end of the last support scheme[89] (and at its peak in 2005-2006 was planting ~3,000 ha/yr), plus equipment and rhizomes/cuttings suppliers are still available. Innovation to improve the feasibility of Miscanthus is underway in the UK, for example Terravesta is developing seed-based Miscanthus which would reduce the establishment costs of the crop[92]. The near-term planting rate also provides sufficient time to set up stable, long-term policy support for industry to be able to invest in the sector for the following 30 years, and education of growers to overcome non-financial barriers to uptake. We have not used the Ricardo (2017) study assumptions, as Ricardo assume a planting rate of 4,000 ha/yr in 2015, which starts the projections off from too high a baseline (actual planting in 2015 was likely only 100-200 ha).

From this common point of 1,000 ha/yr in 2020, then using a similar methodology to the CCC, we have determined the required planting growth rates so that energy crops are able to make use of all of the available land by 2050 in each scenario. However, the resulting growth rates of 13, 16, and 25% have then been sense-checked against previous industry projections, to test their robustness.

Due to the specialised planting stock[93] and the crop's physical growth limitations, planting/harvesting equipment required by farmers and their hesitance to planting energy crops (based on past experience, low profitability and long payback times), the planting rate is the primary near-term constraint to feedstock potential rather than land availability - which becomes the primary constraint in the long-term. The maximum planting rate, which is only reached in the high scenario, is assumed to be 110,000 ha/year - based on the maximum increase in Oil Seed Rape area when it was introduced into the UK[93]. The yield of perennial energy crops also varies by region; Miscanthus is prone to frost damage and therefore has higher yields in the east and southeast of Great Britain. SRC is water dependent and produces greater yields in north and northeast regions.

The resulting feedstock potential for dedicated energy crops, across the different scenarios, is shown in Figure 15. The potentials are similar until 2030, but diverge rapidly from 2035 onwards as the scenarios reflect the impact of the different planting rate, area and yield assumptions detailed above. No competing uses are

---

[89] Defra (2016) *Crops Grown For Bioenergy in England and the UK: 2015*. Available at www.gov.uk/government/uploads/system/uploads/attachment_data/file/578845/nonfood-statsnotice2015i-19dec16.pdf

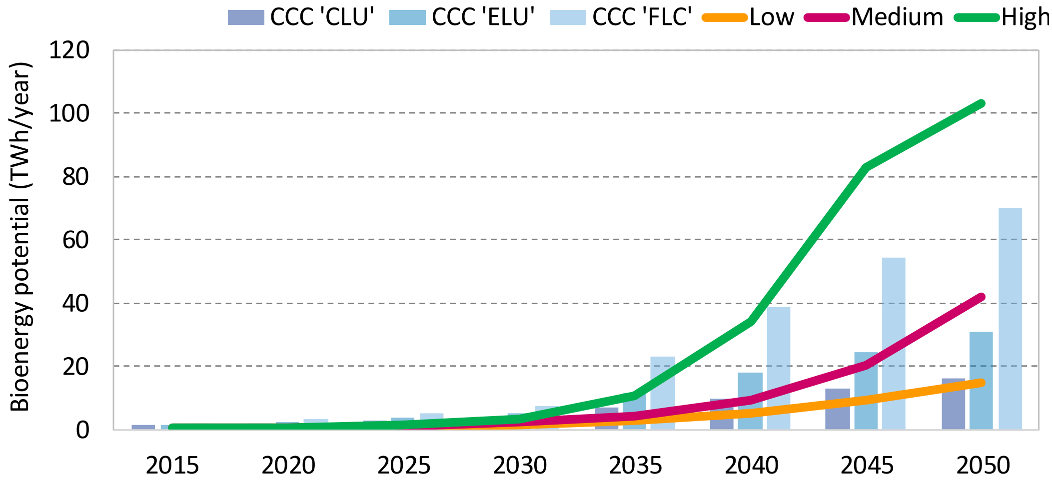
[90] NNFCC (2014) *Lignocellulosic feedstock in the UK*. Available at www.nnfcc.co.uk/files/mydocs/LBNet%20Lignocellulosic%20feedstockin%20the%20UK_Nov%202014.pdf

[91] Alexander *et al*. (2014), *Estimating UK perennial energy crop supply using farm scale models with spatially disaggregated data*, *GCB Bioenergy*, vol. 6, no. 2, pp. 142–155

[92] See www.terravesta.com

[93] ETI (2016) *Bioenergy: Delivering greenhouse gas emission savings through UK bioenergy value chains*. Available at https://s3-eu-west-1.amazonaws.com/assets.eti.co.uk/legacyUploads/2016/01/Delivering-greenhouse-gas-emission-savings-through-UK-bioenergy-value-chains.pdf?dl=1

assumed (as it is assumed that crops are grown specifically for bioenergy), and no further constraints are applied.



Modt/yr	0.1	0.1	0.2	0.3	0.5	1.0	1.8	2.8
	0.1	0.1	0.2	0.4	0.8	1.8	3.9	8.0
	0.1	0.1	0.3	0.7	2.0	6.5	15.8	19.8

Figure 15: Availability of dedicated energy crops to 2050 and comparison with CCC scenarios

In comparison to the CCC results, the new scenarios reflect a reduced potential in the short to medium term – especially in the low and medium scenarios. This is explained by the delayed rollout of dedicated energy crops since 2011, and thus planting rate acts as a key constraint until 2035-2040. However, all the scenarios show long-term growth in the bioenergy potential from dedicated energy crops which is equal to or higher than that projected by the CCC.

While energy crops show a high future potential, based on past experience, these figures are also highly uncertain. There is potentially some land already available for energy crops, and some future land with additional intensification, but scaling the industry is very challenging, and awareness about energy crops remains low. Farmers that do consider perennial energy crops require a compelling case for planting, with stable policy over 30 years and market support – these are preconditions for the scenarios above to be realised. Ramping up to a large scale industry will also take time, first to develop and acquire the skills, personnel, specialist machinery and propagation material, but also given the time lag between planting and full harvest yields. Based on the above, long-term policy support and financial incentives to address issues such as economic crop cultivation and creation of education initiatives should be considered vital to helping the industry to realise its potential.

3.5.2 Dry agricultural residues

The future estimates for unconstrained straw resource availability are based on crop area projections developed by the Farm and Agriculture Policy Research Institute (FAPRI)[94] and scaled to the 2015 baseline data. The FAPRI estimates project only as far as 2024. These projections do not vary greatly over that timeline (less than 4%), and it was assumed that resource levels then would remain constant from 2024 until 2050. For

[94] FAPRI (2015) *2015 Baseline Projections*. Available at www.afbini.gov.uk/publications/fapri-uk-baseline-projections-2015

comparison, the CCC assumed constant resource availability from the base year until 2050, presumably due to lack of other more sophisticated data at the time or only minimal changes over time.

Different methods are used to build the feedstock projections for the different resource types. For the straw potential, the crop area projections were combined with data from Defra[95] for yield rates for straw production: 3.5 tonnes (wet)/ha/year for wheat and oats, and 2.75 tonnes (wet)/ha/year for barley. The seed husks feedstock potential of 1.2 Modt was assumed to be constant over the model's timeline, as used for the CCC's estimates. The rate of broiler chicken litter production was assumed to be 16.5 wet tonnes per 1,000 head per year[96] and 45 wet tonnes per 1,000 head for turkey litter[97], assuming that all litter is gathered during the housing period.

These assumptions are used for the medium scenario, and held fixed over time. Variations for the low and high scenarios assume changes in the straw yields over time, but production of seed husks and litter are assumed to be constant across all scenarios. For the low scenario, it is assumed that straw yields might reduce by 20%, decreasing linearly from 2015 to 2050, due to a continued prioritisation of grain production over straw production (shorter, robust species). Conversely, the high scenario assumes a 20% increase in straw yields by 2050, increasing linearly from 2015, which would reflect greater emphasis on increased straw production for bioenergy purposes. This would be reversing the trend of the last 30 years in arable cropping, which has resulted in shorter crops which ~20% less straw per acre in order to increase grain yields[98]. This increase in straw production could be achieved through selective breeding of species with longer or thicker crop stems, and partly through lower straw cutting heights during harvesting. However, research has shown that taller crop heights do not proportionally correlate with equally increased straw yields[99].

There are several existing uses which are assumed to take precedence over bioenergy uses. For straw, this is the use for animal bedding and animal feed as well as a smaller portion which is used for over-wintering of carrots and compost for mushroom production. For the scenarios in this model, it is assumed that the baled rates when applied to the base year straw production equate to the existing use of the straw feedstock (although the 404,000 tonnes already baled and used for bioenergy is assumed to be available[100]). The competing use tonnages in the scenarios are derived from 2012 data which has 62% for wheat straw, 90% for barley straw and 80% for oats straw[101], and these absolute competing tonnages are subtracted from forecast tonnages. Seed husks are assumed to be entirely consumed as animal feed. No existing non-energy competing uses were assumed for the litter.

A report by AHDB[101] reviewed the subject of straw incorporation to promote soil organic matter and nutrients. The report highlights the advantages and disadvantages of straw incorporation, indicating that whilst incorporation can be an effective method of maintaining or building soil organic matter levels, it is usually more effective to use bulky organic materials such as manures, compost or biosolids for this purpose. It is also important to note the regional disparity and that in areas where these bulky materials are unavailable. For example, in eastern England - which has high arable production but few livestock, straw incorporation is likely

---

[95] Defra (2016) *Crops Grown For Bioenergy in England and the UK: 2015*. Available at www.gov.uk/government/uploads/system/uploads/attachment_data/file/578845/nonfood-statsnotice2015i-19dec16.pdf

[96] Defra (2017) *Livestock numbers in the UK (data to December 2016)*. Available at www.gov.uk/government/statistical-data-sets/structure-of-the-livestock-industry-in-england-at-december

[97] Defra (2013) *Guidance on complying with the rules for Nitrate Vulnerable Zones in England for 2013 to 2016*. Available at http://adlib.everysite.co.uk/resources/000/278/013/Defra_NVZ_guidance_Nov_2013.pdf

[98] Austin, Ford & Morgan (1989) *Genetic improvement in the yield of winter wheat: a further evaluation*, *The Journal of Agricultural Science*, vol. 112, no. 1, pp. 295-301

[99] AHDB (2008), *Wheat straw for biofuel production*. Available at https://cereals.ahdb.org.uk/media/737243/rd-2007-3690-final-project-report.pdf

[100] Defra (2016) *Crops Grown For Bioenergy in England and the UK: 2015*. Available at www.gov.uk/government/uploads/system/uploads/attachment_data/file/578845/nonfood-statsnotice2015i-19dec16.pdf

[101] AHDB (2014) *Straw incorporation review*. Available at https://cereals.ahdb.org.uk/media/470361/rr81-web.pdf

the most appropriate method to maintain soil organic matter levels. However, the AHDB report states that the soil changes are relatively modest, and that many farms could remove more straw with only limited long-term impacts on soil quality. The report indicates that 2 million fresh tonnes of straw not currently used in other markets, could potentially be available for other purposes rather than incorporation. In our model, a constraint factor of 24% was applied to limit the amount of straw available to match this 2 million fresh tonnes value in 2015 for the medium scenario. The AHDB report is the most reliable reference identified for the UK.

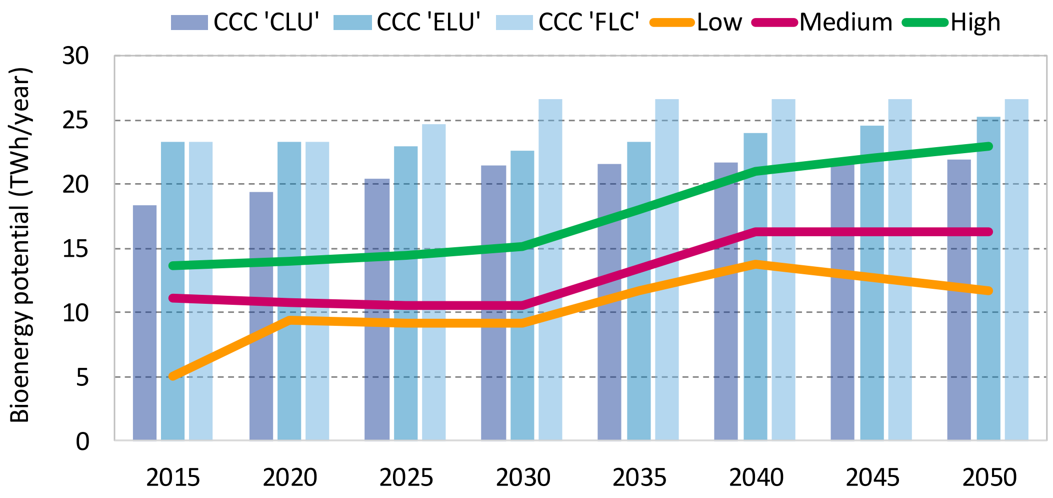
The use of straw is highly regionalised. Cereal and oilseed rape straw production is concentrated in the arable east of the UK, with 70% of wheat straw and 55% of barley straw generated in this area. As has been discussed, straw is often used as feed or bedding for livestock, however this is dependent on the proximity of the straw production to the livestock as due to the bulky nature of straw, it is not economical to transport the resource over long distances. Much of the livestock is concentrated in the western areas of Great Britain and a 2008 study by the NNFCC estimated the straw supply/demand imbalances in Great Britain with a straw surplus found in the eastern areas and a deficit in the western, primarily Wales[102].

Constraint factors are applied to the available feedstock potentials to account for the barriers to exploiting the total available bioenergy potential. These barriers account for regulatory constraints such as erratic policy, and infrastructure limitations of the collection and storage of the feedstocks and the subsequent difficulties of transporting a bulky feedstock like straw. For more details of the constraint factors applied, refer to Table 39 in the Appendix.

Several assumptions were applied to convert these mass potentials into energy potentials. It was assumed that all straws had moisture content of 14.5%[103] and poultry litter a moisture content of 40%. The energy content of the feedstocks was assumed to be 17.2 GJ/odt for straws[104] and 15.8 GJ/odt for poultry litter[105].

The results, shown in Figure 16 indicate a change in potential bioenergy of dry agricultural residues in comparison to the CCC's review is the result of a number of factors. The unconstrained potential has declined as a result of updated estimates for the baseline and projections. New data for competing uses are available which indicate higher competing uses and our scenarios apply a constraint factor for the required levels of straw incorporation. A combination of declining unconstrained resource potential and an assumption of constant values for competing uses led to a reduction in potential in the low scenario.

[102] NNFCC (2008) *National and regional supply/demand balance for agricultural straw in Great Britain*. Available at www.northwoods.org.uk/northwoods/files/2012/12/StrawAvailabilityinGreatBritain.pdf
[103] DEFRA (2016) *Farming Statistics: Final crop areas, yields, livestock populations and agricultural workforce*. Available at www.gov.uk/government/uploads/system/uploads/attachment_data/file/579402/structure-jun2016final-uk-20dec16.pdf
[104] Biograce v4d
[105] Phyllis database



Modt/yr	2015	2020	2025	2030	2035	2040	2045	2050
	1.1	2.0	2.0	2.0	2.5	3.0	2.8	2.5
	2.4	2.3	2.3	2.3	2.9	3.5	3.5	3.5
	2.9	3.0	3.1	3.2	3.8	4.5	4.7	4.9

Figure 16: Availability of dry agricultural residues to 2050 and comparison with CCC scenarios

The potential of dry agricultural residues is dependent on activity in the sector. The agricultural sector is mature in the UK, and there is little scope for significant growth in the unconstrained residues potential. Straw makes up the largest portion of UK dry agricultural residues and its availability for bioenergy is highly dependent on the competing uses for the straw (such as animal bedding and use as animal feed), and assumptions around sustainable removal levels instead of soil incorporation.

3.5.3 Forest residues

The most applicable estimates for the unconstrained potential of forest residues are derived from the Forest Research's CARBINE model. The CCC used an earlier version of this model for its estimates, and the latest published estimates from this model are found in Ricardo (2017). These latest estimates have been updated for the Forestry Commission's 50 year projection for forestry availability, an update on the 25 year projection previously used for CCC. The scenarios for this study have been built using the most recent results from the Ricardo report.

The main factors affecting the potential of forest residues are the standing volumes of woodland in the UK, reported by the Forestry Commission, and the removal rate of residues from forests. The CCC assumed a constant feedstock potential of 0.95 Modt/yr from 2010 until 2050. The latest projections by Forestry Commission indicate that standing volumes of UK forestry vary over time. This is reflected in the unconstrained potential for forest residues which can be found in Table 40 in the Appendix. This rise and gradual decline in the UK's forestry industry (a pattern seen in other countries in Europe) and the potential of the related feedstocks is a result of the underlying tree age class structure. High planting rates from the 1950's through to the 1980's were followed by decrease in the 1990's and correspond with a decline in wood availability from 2040[106]. The CARBINE results also indicate a dip in the available potential in 2020 which is because of the model's assumptions about planting rates, locations, yield classes and harvesting activity.

[106] Forestry Commission (2014) *50-year forecast of softwood timber availability.* Available at www.forestry.gov.uk/pdf/50_YEAR_FORECAST_OF_SOFTWOOD_AVAILABILITY.pdf/$FILE/50_YEAR_FORECAST_OF_SOFTWOOD_AVAILABILITY.pdf

The only competing use for forest residues is a requirement for residue retention or “brash mat”, to maintain the forest environment, to return nutrients to the soil and to maintain the soil stability and protect the ground from harvest operations. A removal rate of 50% is typically assumed for forest residues[107]. This removal assumption is decreased by 20% for the low scenario and increased by 20% in the high scenario to account for the sensitivity of this sustainability assumption.

The constraints factors applied to the available potentials mainly account for infrastructural and operational barriers. Table 26 provides an indication of the constraint factors applied to the potentials and the variability across the scenarios and over the model timeline. For more details on the constraint factors refer to Table 40 in the Appendix.

Table 26: Constraint factors applied to the forest residues potentials for 2015 and 2050

Scenario	2015	2050
Low	99%	87%
Medium	64%	58%
High	39%	38%

The constraint factors take into account that not all woodlands are properly managed or do not have the required equipment to harvest the residues, and that there is also a lack of facilities to dry and store these residues. The constraints factors also make allowance for the access and operation limitations caused by terrain features. Industry inertia and disinterest in residue harvesting due to poor economics, coupled with the lack of stable policy or subsidy support are also factored into the scenario constraints.

It was assumed that all wood feedstocks have a calorific value of 19 GJ/odt. This is the same assumption used by the CCC and other literature.

[107] NNFCC (2014) *Lignocellulosic feedstock in the UK*. Available at www.nnfcc.co.uk/files/mydocs/LBNet%20Lignocellulosic%20feedstockin%20the%20UK_Nov%202014.pdf

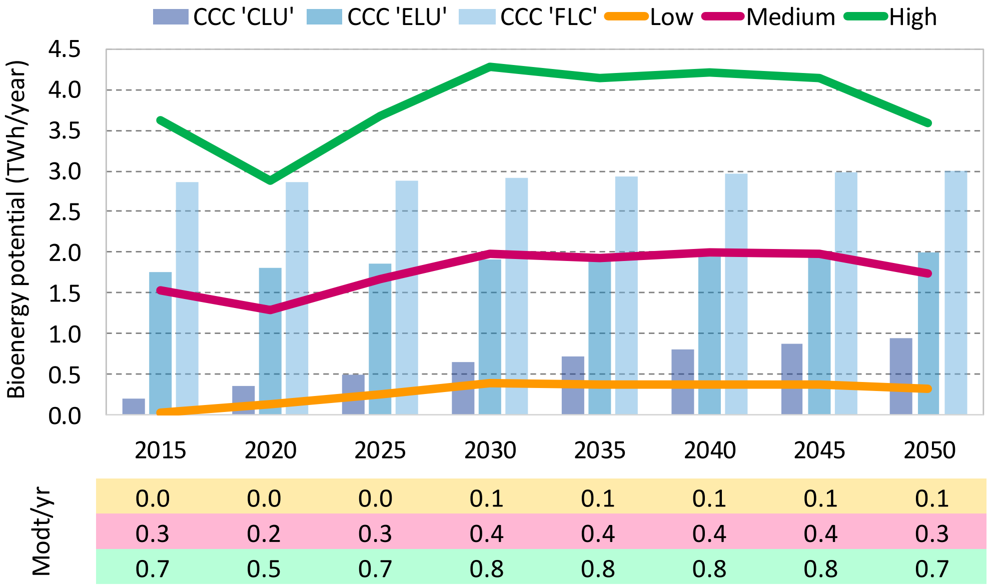


Figure 17: Availability of forest residues to 2050 and comparison with CCC scenarios

The volumes of forestry related feedstock is driven primarily by the standing volumes already present in the UK. The potentials shown in Figure 17 reflect the age class structure of the UK's forests which accounts for the declines and increases over time, a variation which was not accounted for by the CCC who assumed constant unconstrained feedstock potential. The medium scenario correlates closely to the CCC's ELU scenario, which is supported by assumed residue retention of 50% for both scenarios. A significant difference is noticeable between the high and the FLC scenarios, where the high scenario assumes residue removal of 70%. Residue retention is required to maintain the forest environment and varying this percentage was used to ascertain the sensitivity of this variable which when compared to the CCC's values, for example the FLC scenario, shows the significance of this assumption.

3.5.4 Small round wood

As discussed in Section 3.4.4, the unconstrained potential for forest residues and small round wood in 2015 is 1.1, 2.2 and 3.3 Modt/year for the low, central and high scenarios. The projections for these scenarios were scaled from the latest CARBINE model projection, which account for the Forestry Commissions latest projections. As with other forest related feedstocks, the 2020 low is a result of assumptions made by the Forest Research's models.

Many of the competing uses are cost dependent, such as the manufacture of panelboard, use in pulp mills, and fencing. At a low energy price for bioenergy, it is assumed that competing uses consume all the small round wood potential. For the medium and high scenarios, it is assumed that 0.5 Modt/yr and 0.2 Modt/yr respectively of the resource potential are used for competing uses, these were derived from Ricardo (2017). Another factor accounted for in the scenarios is the under-utilisation of the potential feedstock. Not all woodland would be harvested for small round wood. Small woodlands, particularly those that are privately owned, would not employ active management of their woodlands and would not harvest the small round wood. It is assumed that this resource of 0.3 Modt/yr will not become available in any scenario. It was assumed that all wood feedstocks have a calorific value of 19 GJ/odt. This is the same assumption used by the CCC and other literature.

As with forest residues, there are also constraints due to lack of infrastructure and operational equipment (or their capital cost) and facilities and the challenges due to terrain accessibility. For the values of these constraint factors, refer to Table 41 in the Appendix. Technical constraints include difficulties and costs in meeting sustainability standards and fuel quality standards.

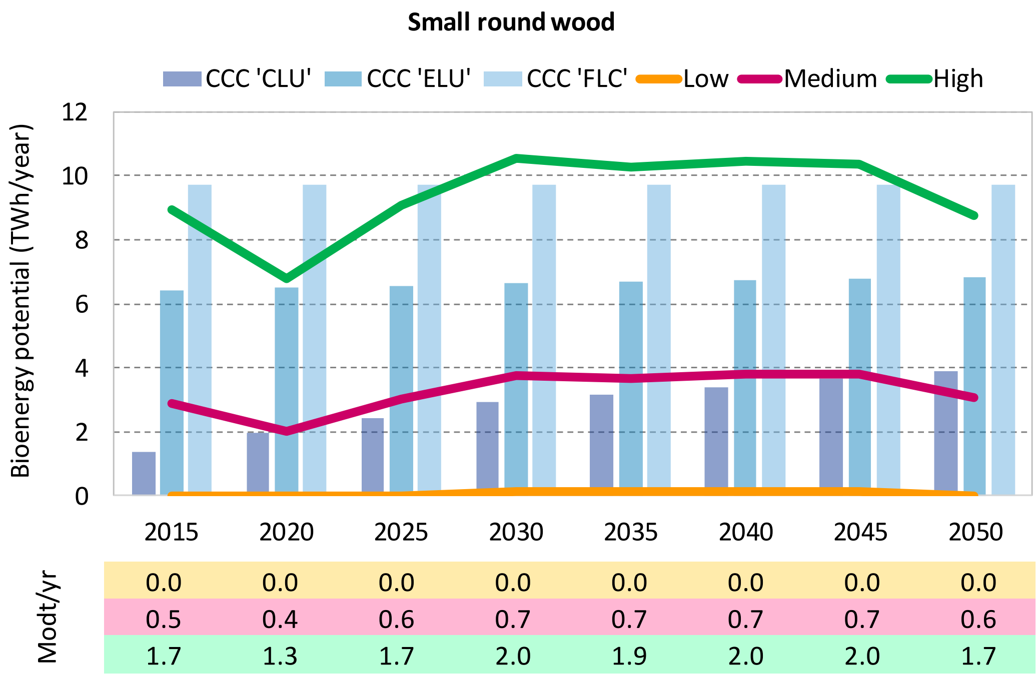


Figure 18: Availability of small round wood to 2050 and comparison with CCC scenarios

As seen in Figure 18, the high scenario correlates closely with the corresponding CCC FLC scenario as both are based on the same assumption for unconstrained potential. Significant differences can be seen in the other two scenarios where the unconstrained potential has been reduced to reflect changing assumptions which emphasis greater utilisation of forestry as a carbon sink as opposed to use for energy. As with other forestry feedstocks the trajectory of our scenarios is more variable to reflect the latest Forestry Commission's projections.

3.5.5 Arboricultural arisings

Data for the feedstock potential of arboricultural arisings is limited. The scenarios for this study assume a constant unconstrained feedstock potential of 2.7 Modt/yr from 2015 to 2050. There is no evidence to suggest this feedstock will vary in the future and other studies have also made this assumption. This constant feedstock potential differs from the original projections in AEA[9] which increased from 2.3 Modt/yr in 2010 to 3.5 Modt/yr in 2050 which we believe to be an over-estimate of potential resource.

Data on the use of arboriculture arisings is not available and any estimates on competing uses in the literature are based on expert opinion. The uses of arboriculture arisings are as fuelwood or mulch with the remainder of the resource simply not being collected and left in place. The literature provided varying estimates for these competing uses which are provided in Table 27. As stated in Section 3.4.5, AEA (2017) did not apply any competing uses for any of its scenarios which we do not believe is a reasonable assumption. Mantau *et al* [108] is a European-wide study and the competing use values are assumed uniformly across all countries, with no justification for these percentages provided. Similarly, no justification is provided for the Ricardo (2017) assumptions, which are assumed to be constant until 2050 for each scenario.

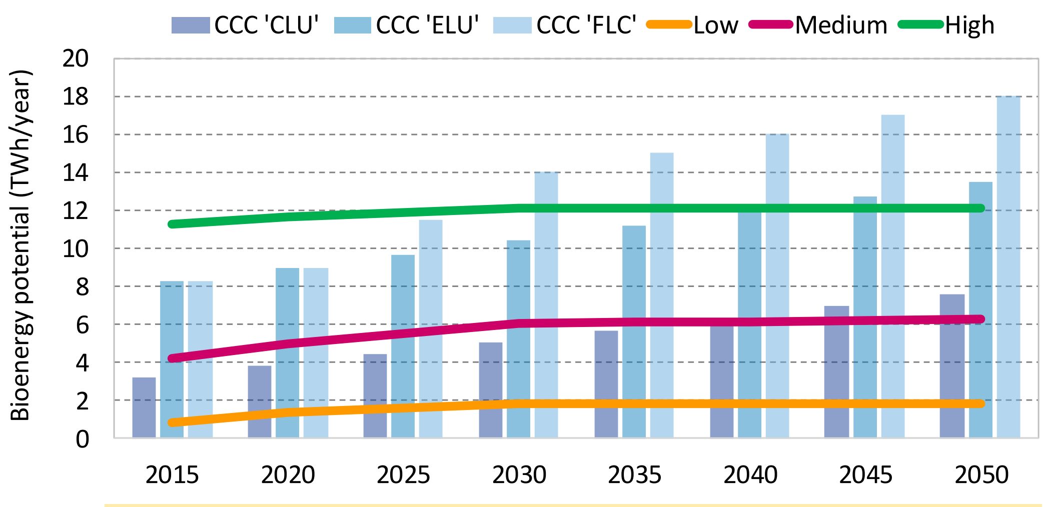
[108] Mantau, U. *et al.* (2010) *Real potential for changes in growth and use of EU forests*. Available at www.egger.com/downloads/bildarchiv/187000/1_187099_DV_Real-potential-changes-growth_EN.pdf

Table 27: Competing uses percentage for arboriculture arisings for the references identified in the baseline year and 2030 of the medium scenarios[109]

Source	Baseline	2030
AEA (2011)[9]	0%	0%
Mantau *et al*. (2010)[77]	55%	40%
Ricardo (2017)[66]	64%	64%

For our scenarios, we assumed the same competing use in our low scenario as the low scenario in Ricardo. Mantau *et al*. competing uses are used for our low and medium scenarios. The low scenario assumes that only feedstock diverted to composting is a competing use, while the medium scenario assumes that composting and non-use as a competing uses. Mantau *et al*. projected only as far as 2030 and so for our scenario we assumed the competing uses to be constant from 2030 to 2050. Due to the lack of more suitable data, we believe these competing use assumptions to be reasonable but would like to emphasise the uncertainty around the competing use estimates for this feedstock.

A major barrier to achieving the potential of this feedstock is the infrastructural and logistical challenges. This is a highly dispersed resource, given the arisings come from urban green spaces, suburban roadsides and the transport network across the UK. The challenges to establishing the required supply chain to collect, dry, store and transport this feedstock as well as achieving the necessary fuel and sustainability standards have been applied through constraint factors derived from Ricardo and can be found in Table 42 in the Appendix. It was assumed that all wood feedstocks have a calorific value of 19 GJ/odt. This is the same assumption used by the CCC and other literature.



Modt/yr	2015	2020	2025	2030	2035	2040	2045	2050
	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	0.8	0.9	1.0	1.2	1.2	1.2	1.2	1.2
	2.1	2.2	2.2	2.3	2.3	2.3	2.3	2.3

Figure 19: Availability of arboricultural arisings to 2050 and comparison with CCC scenarios

As shown in Figure 19, the underlying resource potential is unlikely to change significantly to 2050, given little change in the UK road network or parks, although UK population growth and the resulting slow spread of

[109] The competing uses are defined as mulch and non-use

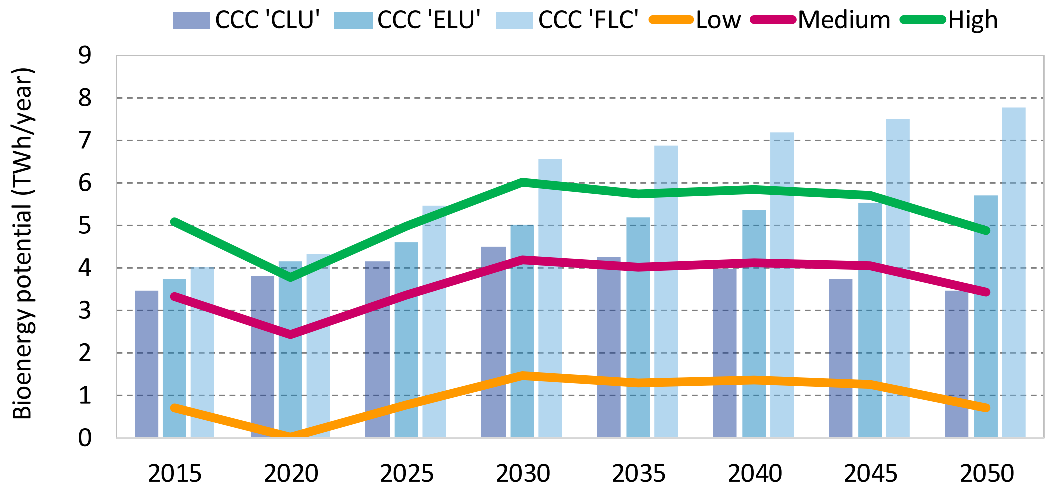
suburban areas might have some impact that is not modelled here. The CCC projected a significant increase in the unconstrained potential which accounts for a significant amount of the difference between our estimates and the CCC's. Another reason for the difference between the two studies is the application of competing uses in our scenarios. Arboricultural arisings remain a highly dispersed resource which poses problems for the collection and processing for bioenergy purposes, and hence a high price is required to justify the investment in the supply chain.

3.5.6 Sawmill co-products

The availability of this feedstock is determined by the throughput of sawlogs in UK sawmills, which is in turn determined by the demand for timber, the competition from overseas markets and the rate of lumber harvesting in the UK. The projections, shown in Figure 20, are based on Ricardo (2017) and its estimates from the CARBINE and CSORT models. The scenarios developed for this study's estimates vary slightly over the model timeline, however there is a dip in potential in 2020 because of Forest Research's model assumptions about planting rates, locations, yield classes and harvesting activity.

The model assumes there are no existing competing uses that are independent of price. The main price dependent competing uses for sawmill co-products are the manufacturing of panelboard, animal bedding and horticulture mulch, with 1.1 Modt/yr of competing demand assumed in the low scenario, 0.3 Modt/yr in the medium scenario and 0.2 Modt/yr in the high scenario. These competing assumptions are based on the Ricardo study, which relies on Forest Research expert opinion.

Constraint factors from the Ricardo estimates are applied to scenarios for this study. These can be found in Table 43 in the Appendix. The constraint factors account for the supply chain barriers - including collection of the resource from a dispersed network of sawmills, the cost of sustainability certification, and the risk of not achieving sufficient returns on investment.



Modt/yr	0.1	0.0	0.1	0.3	0.2	0.3	0.2	0.1
	0.6	0.5	0.6	0.8	0.8	0.8	0.8	0.7
	1.0	0.7	0.9	1.1	1.1	1.1	1.1	0.9

Figure 20: Availability of sawmill co-products to 2050 and comparison with CCC scenarios

The primary factors influencing the potential of sawmill co-products are the activity in the UK timber industry, the underlying forestry availability and the competing uses. The latest Forestry Commission projections indicate a decline in the UK forestry activity after 2030, which is reflected in Figure 20. This was not accounted for by the CCC and explains the growing divergence between the estimates after 2030. Another significant factor for the reduced potential in our scenarios is the inclusion of competing uses. The CCC did not apply any competing uses to its estimates but this is necessary to include and makes a noticeable impact, in particular to the low scenario. The feedstock is often used on-site at sawmills for heating/drying purposes, but its use in non-energy products varies by the prices offered for bioenergy as is seen in the scenarios developed for this current study.

3.5.7 Short rotation forestry

Short rotation forestry is woodland that grows at relatively short cycles of between 8 and 20 years. This study's scenarios assume a harvest cycle of 15 years. As seen in Figure 21, short rotation forestry is included in the medium and high scenarios, as opposed to being included only in the CCC's high scenario. It is excluded from the low scenario as the size of the potential feedstock was not at a large enough scale to suggest the industry would be feasible. The projections in this report are also slightly more optimistic than those in the CCC, with 1.9 Modt/yr in the high scenario by 2050 versus 1.6 Modt/yr in the CCC's FLC scenario.

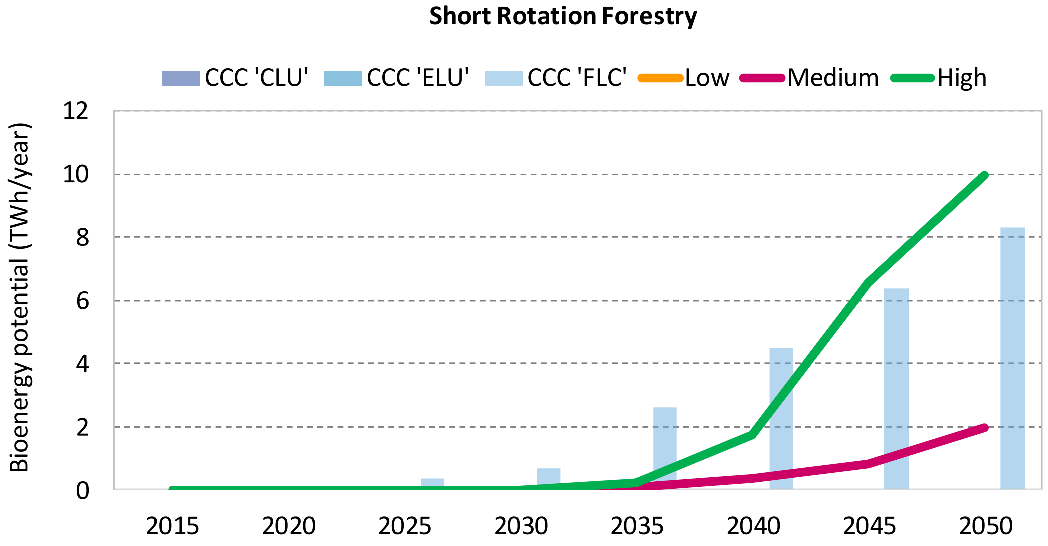
The scenarios vary by the growth in annual planting areas, the maximum planting area and the yields. Table 28 provides the details of each scenario. It is assumed that the industry would not start planting before 2020, due to the time required to establish supportive long-term policies, and obtain significant buy-in from the existing UK forestry industry. It is further assumed that harvested areas are replanted immediately.

Table 28: Summary of characteristics of the growth scenarios

Scenario	Planting rate in 2020 (ha/year)	Growth rate	Max planting area (ha)	Biomass yield (odt/ha/year)
Low	0	-	-	-
Medium	1,000	15%	10,000	5.3
High	1,000	30%	20,000	6.0

There are no competing uses for the feedstock, as short rotation forestry is grown specifically for bioenergy purposes. Due to land availability constraints, the cumulative planted area (which ranges from 0 to 0.43 Mha) for short rotation forestry is accounted for in combination with the land cultivated for dedicated energy crops.

The feedstock is further constrained by financial feasibility of short rotation forestry for bioenergy, regulatory and policy uncertainty and the suitability of species for grant programmes, and the challenges posed by the long-term nature of the investment. The Ricardo (2017) constraint factors have been applied to account for these barriers and can be found in Table 44 in the Appendix.



Modt/yr	2015	2020	2025	2030	2035	2040	2045	2050
Low	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Medium	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.4
High	0.0	0.0	0.0	0.0	0.0	0.3	1.2	1.9

Figure 21: Availability of short rotation forestry to 2050 and comparison with CCC scenarios

There has been minimal activity in short rotation forestry plantation in the past 6 years, and the CCC's cautious approach in its 2011 estimates seems justified. These scenarios are not quite as conservative as the CCC's, however. Were suitable policy, which recognises the long-term nature of the feedstock, to be put into place the potential for short rotation forestry is achievable given the land areas required are modest.

3.5.8 Wet manure

Projections of animal numbers are derived from FAPRI data and are scaled to the 2015 livestock herd numbers. The FAPRI[110] data only projects as far as 2024 after which the herd numbers are kept constant until 2030 and then assumed by Ricardo (20170 to grow by 1% per year until 2050, based on increasing intensification of livestock farming. To accommodate for these slightly increasing livestock numbers, it is assumed there is an increase in the portion of livestock housed during the year to allow for land and environmental constraints. The estimate is created from projected livestock numbers and assumptions for the volatile solids excreted by livestock. To calculate the biogas potential of the wet manures, a value of 7 GJ/tonne of volatile solids is assumed as the weighted average calorific content of cattle and pig slurries, 0.45 and 0.24 m^3 CH_4 per kg volatile solids respectively. This weighted value also accounts for this waste being converted to biogas through an AD plant with an efficiency of 75% which was used by both AEA (2011) and Ricardo (2017).

The scenarios assume that there are no cost-independent competing uses, however there is significant demand from cost-dependent competing uses. Slurries are widely used as a fertiliser via land spreading, and this is the greatest factor impacting the availability of the resource for bioenergy. Farmers often trade their slurries with neighbouring farms (and some take back farmyard manures after being used for animal bedding), however this is dependent on the region and the type of neighbouring farm. Transport costs can be considerable and they may include the transport costs of returning the digestate to the farmer for use as

---

[110] FAPRI (2015), 2015 *Baseline Projections*. Available at www.afbini.gov.uk/publications/fapri-uk-baseline-projections-2015

fertiliser. For this reason, it is assumed that 30% of all farms will always be too far from an AD plant for AD to be feasible.

The competing uses assumptions are provided in Table 29. The low scenario assumes the 2015 use of wet manures in AD which was derived from the 2014 volume of slurries going to AD[111] and scaling for the number of plants in 2015[112]. The 2020 value in the low scenario is derived from the known planned capacity of wet manure AD plants[111] and assumes no new plants onwards. In the medium scenario, 2015 was set to current values and 2030 was set to a Government policy aim for 20% of manures to be used in anaerobic digestion[113]. The values for the intervening years are interpolated which align with the CCC's assumption for manures going to AD in its third Budget[114]. It was assumed that manures going to AD were constant after 2030. The high scenario assumes the same competing uses as the Ricardo high scenario as this was deemed to be an optimistic and reasonable assumption.

Table 29: Scenarios for the competing uses for wet manure in the indicated years

Scenario	2015	2020	2025	2030	2050
Low	98%	93%	93%	93%	93%
Medium	98%	92%	84%	80%	80%
High	58%	44%	44%	44%	44%

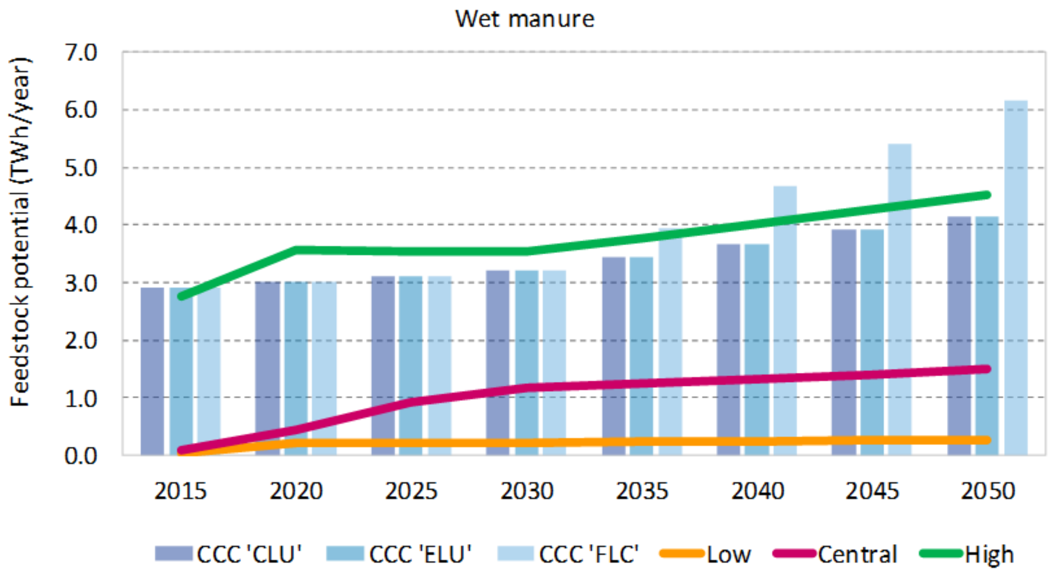
Due to transport costs, the distance of the farm to the anaerobic digestion plant, and the bioenergy price, will have an impact on the feasibility of using wet manures. These infrastructural constraints as well as policy, technical and market constraints were taken into account through the application of the constraint factors to each of the three scenarios, from Ricardo (2017). For more details of the constraint factors applied, refer to Table 45 in the Appendix.

111 Food & Farming Futures (2015), *Anaerobic digestion in the UK: agricultural wastes are relatively untapped*. Available at http://bit.ly/2qnTDfs

112 Farmers Weekly (2016), *Heating and transport offer big opportunities for biogas*. Available at www.fwi.co.uk/business/heating-transport-offer-big-opportunities-biogas.htm

113 Defra (2010) *Accelerating the Uptake of Anaerobic Digestion in England: an Implementation Plan.* Available at http://webarchive.nationalarchives.gov.uk/20130402151656/http://archive.defra.gov.uk/environment/waste/ad/documents/implementation-plan2010.pdf

114 CCC (2016) *Technical Annex 6: Agriculture and land use, land use change and forestry*, Available at www.theccc.org.uk/wp-content/uploads/2016/07/2016-PR-Agriculture-Tech-Annex.pdf



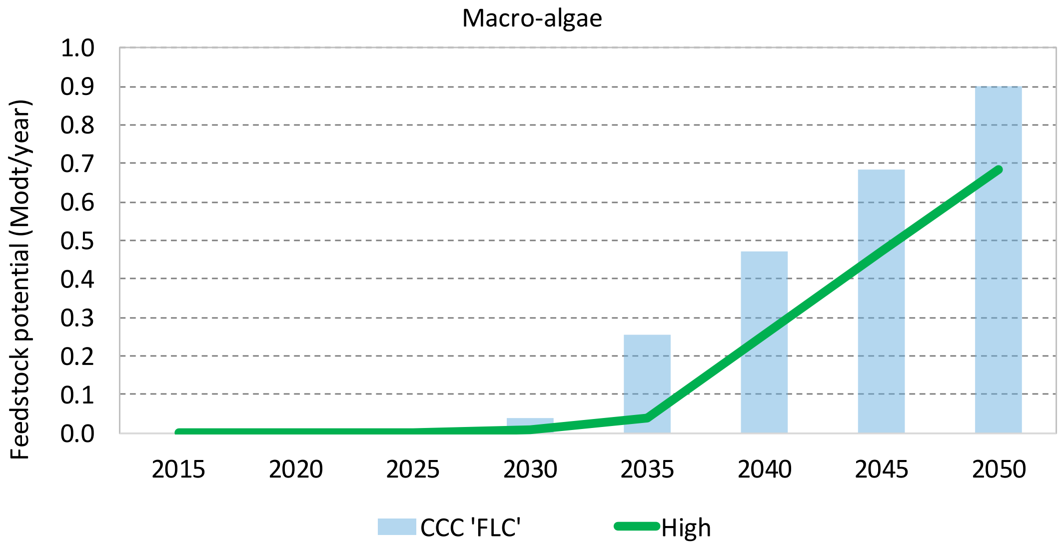
Modt(VS)/yr							
0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1
0.0	0.2	0.4	0.6	0.6	0.6	0.7	0.7
1.3	1.7	1.7	1.7	1.8	1.9	2.0	2.2

Figure 22: Availability of wet manure to 2050 and comparison with CCC scenarios

It is clear from Table 29 and Figure 22 that the potential of wet manure for bioenergy is highly dependent on the competing uses. The production of manure is highly regionalised, due to most cattle, pig and poultry farming occurring in the West of Great Britain - effectively the inverse to straw production. This geographic breakdown would indicate that some areas of the UK are more suitable to develop wet manure AD supply chains – particularly those where land spreading is limited due to nitrogen constraints. Effective supply chains are also necessary to collect the highly dispersed and very wet manures. We assumed a growth in livestock numbers due to industry intensification but this may be limited due to environmental concerns and the need to limit GHG emissions from the agricultural sector.

3.5.9 Macro-algae

Estimated potentials were first presented in the DECC 2050 Pathways analysis and since the CCC's estimate, there has been no new data on macro-algae potential. To account for the reported lack of progress in the development of macro-algae for bioenergy conversion, and the absence of revised potentials plus the uncertainty surrounding the CCC's estimates, the previous projection will be delayed by 5 years, and like the CCC will only be included in the high scenario as it shows in Figure 23. This delay of 5 years means that a maximum sea area of 0.03 Mha is occupied in 2050. It is assumed that dried seaweed has a calorific value of 14 GJ/tonne and an AD conversion efficiency of 75%. Any future potential is dependent on large cost improvements in cultivation and conversion technologies, and the ramp-up of a new industry in terms of infrastructure, investment and skills.



Modt/yr								
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	0.0	0.0	0.0	0.0	0.0	0.3	0.5	0.7

Figure 23: Availability of macro-algae to 2050 and comparison with CCC scenarios

3.5.10 Summary

A summary of the critical assumptions for each feedstock are summarised in Table 30. While the rationale for the assumptions is provided for each feedstock in the sections above, this summary offers the opportunity to evaluate which scenario seems most likely, based on both the current feedstock situation and the likelihood of the assumptions. It also considers what may increase the risk of a low scenario and what may provide a basis for to achieve the high scenario. The constraint factor assumptions are provided as of 2030 as an indicator (as this factor varies over time). The constraint factor refers to the reduction in the feedstock potential because of market, technical, regulatory and infrastructure limitations. This varies over time and the average is provided in Table 30.

Table 30: Critical assumptions for the feedstock potentials in each scenario.

Feedstock	Low scenario 2050	Medium scenario 2050	High scenario 2050
Dedicated energy crops	15 TWh/yr Land use 300,000Mha Yield 8 – 10 odt/yr CAGR planting rate 13% No competing uses	36 TWh/yr Land use600,000Mha Yield 11 – 14 odt/yr CAGR planting rate 16% No competing uses	103 TWh/yr Land use1,150,000Mha Yield 14 – 18 odt/yr CAGR planting rate 25% No competing uses
Dry agricultural residues	12 TWh/yr 20% reduction in straw yields 91% go to competing uses (constant absolute value for competing uses between scenarios) 46% constraint factor	16 TWh/yr Central straw yields assumption 78% go to competing uses (constant absolute value for competing uses between scenarios) 39% constraint factor	23 TWh/yr 20% increase in straw yields 65% go to competing uses (constant absolute value for competing uses between scenarios) 33% constraint factor
Forest residues	0.3 TWh/yr 30% residue removal rate No competing uses 90% constraint factor	2 TWh/yr 50% residue removal rate No competing uses 60% constraint factor	4 TWh/yr 70% residue removal rate No competing uses 38% constraint factor
Small round wood	0 TWh/yr High carbon sequestration 100% go to competing uses	3 TWh/yr Medium carbon sequestration 37% go to competing uses 59% constraint factor	9 TWh/yr Low carbon sequestration 15% go to competing uses 40% constraint factor 2030
Arboricultural arisings	2 TWh/yr 63% go to competing uses 70% constraint factor	6 TWh/yr 40% go to competing uses 29% constraint factor	12 TWh/yr 15% go to competing uses 0% constraint factor
Sawmill co-products	0.7 TWh/yr 81% go to competing uses 49% constraint factor	3 TWh/yr 22% go to competing uses 40% constraint factor	5 TWh/yr 15% go to competing uses 20% constraint factor
Short rotation forestry	None	2 TWh/yr 15% growth rate starting with 1,000 ha/year Max planting area: 10,000 ha/year Yield: 5 odt/ha/year 43% constraint factor	10 TWh/yr 30% growth rate starting with 1,000 ha/yearMax planting area: 20,000 ha/year Yield: 6 odt/ha/year 0% constraint factor
Wet manure	0.3 TWh/yr 93% go to competing uses 60% constraint factor	2 TWh/yr 80% go to competing uses 24% constraint factor	5 TWh/yr 44% go to competing uses 18% constraint factor
Macro-algae	None	None	3 TWh/yr 0.03 Mha of seaweed No competing uses

3.6 Bioenergy potential to 2050

The overall feedstock potential in 2050, which is the sum of all of the individual feedstocks discussed above, is estimated at 6.0, 15.4, and 34.3 Modt/yr for the low, medium, and high scenarios respectively. As shown in Figure 24, this equates to 2050 bioenergy potentials of 29.6, 76.3, and 170.4 TWh/yr for the low, medium, and high scenarios. These potentials are lower that the CCC's CLU and ELU scenarios but higher than the FLC scenario. The increase in 2050 potential is due to a significant increase in the potential for dedicated energy crops, although in the short to medium term the feedstock potentials are dominated by dry agricultural residues. However, it is important to note that prior to 2050, all new scenarios anticipate lower bioenergy potentials compared to the CCC. A full breakdown of the bioenergy potential in 2030 (under the medium scenario versus CCC 'ELU' scenario) is provided in Appendix 2.

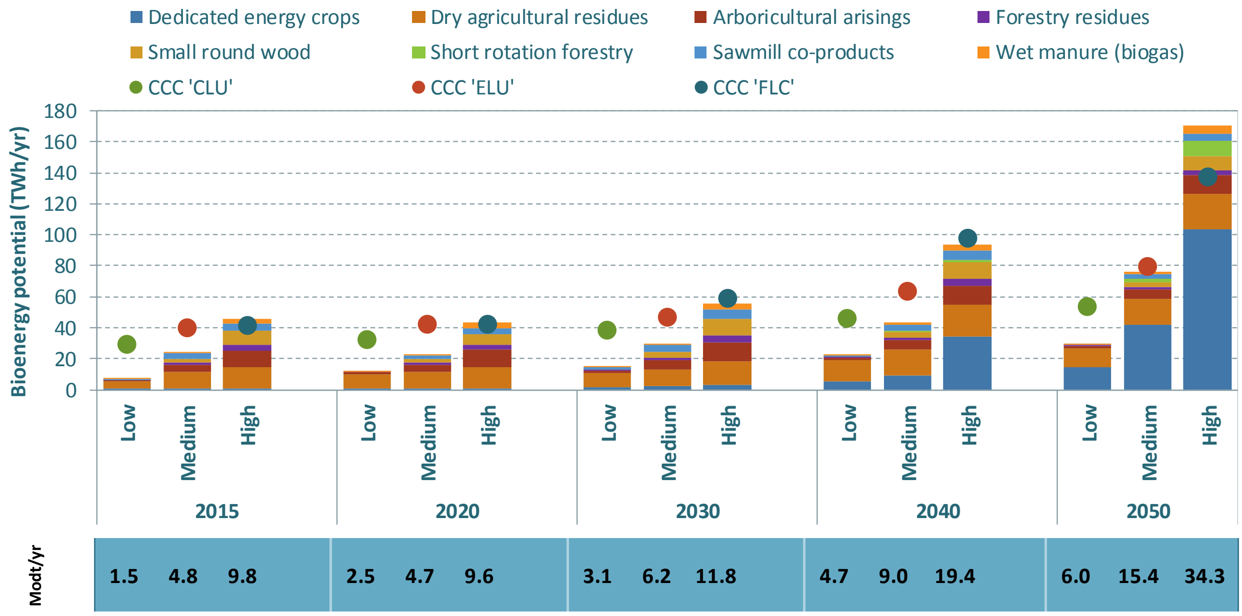


Figure 24: Bioenergy potential for each scenario, including CCC, to 2050

The above bioenergy potentials result in bioenergy and renewable gas potentials (bioSNG and bioemethane) which, over time, are lower than those originally anticipated by the CCC in 2011.

In respect of renewable gas specifically, total potential, calculated from the CCC data and our own estimate relating to bioenergy potential, is shown in Table 31. A conversion efficiency of 72% was assumed for the conversion of bioenergy potential to renewable SNG potential. Under our central assumptions, therefore, we estimate that renewable gas potential in 2050 will be of the order of 55 TWh/yr.

Table 31: Comparison of renewable gas potential for all scenarios in 2050 (TWh/yr)

Scenario	CCC review	This study (Cadent)	Comparison Cadent Vs CCC
Low *(vs. CCC CLU)*	38.3	21.0	↓
Medium *(vs. CCC ELU)*	57.3	55.4	↓
High *(vs. CCC FLC)*	98.7	124.1	↑*

** With the exception of 2050, all previous years(2020 – 2045) in this study show a lower potential than the CCC FLC*

3.7 Key considerations for the availability of non-waste feedstocks

The key considerations for each feedstock, drawn from the discussion in the previous sections, are summarised below.

While **energy crops** show a high future potential, based on past experience, these figures are also highly uncertain. There is potentially some land already available for energy crops, and some future land with additional intensification, as well as shifting production and consumption patterns. But, scaling the industry is very challenging, awareness about energy crops remains low, and there is controversy around their sustainability because of potential land use change impacts. Farmers that do consider perennial energy crops require a compelling case for planting, with long-term policy and market support – these are preconditions for the scenarios above to be realised. Ramping up to a large scale industry will take time because of the need to develop and acquire skills, specialist machinery and propagation material, but also given the time lag between planting and full harvest yields. Based on the above, long-term policy support and financial incentives to address issues such as economic crop cultivation and creation of education initiatives should be considered as vital to helping the industry to realise its potential.

The potential of **dry agricultural residues** is dependent on activity in the sector. The agricultural sector is mature in the UK, and there is little scope for significant growth in the unconstrained residues potential. Straw makes up the largest portion of UK dry agricultural residues and its availability for bioenergy is dependent on competing uses (such as animal bedding and use as animal feed), and assumptions around sustainable removal levels to maintain sufficient soil incorporation. Whilst straw incorporation has been accounted for, its use has not been varied between the scenarios. Further research into the use of straw for soil management would provide an indication to the levels required to maintain soil organic matter. Achieving the higher potential will require a shift in the trend from an emphasis on grain growth in cereal crops to an emphasis on straw yields.

The volumes of **forestry residues** are provided primarily by the standing volumes already present in the UK. The potentials shown in the scenarios reflect the age class structure of the UK's forests, which explains the near-term decline followed by an increase over time. Residue retention is required to maintain the forest environment, and the different scenarios reflect varying assumptions for residue removal along with different infrastructure and market barriers. Further research is required to provide guidance on the level of residue retention needed to maintain the forest environment as this has a major impact on the available resource potential. Barriers in infrastructure and processing the ability to access the resource in difficult terrain and then process this diverse feedstock into a uniform standard fuel, will need to be overcome if the higher potentials are to be achieved.

Similar to other forest related resources, the potential of **small round wood** is dependent on the standing volumes of the UK's forests which varies greatly out to 2050. The relative emphasis on carbon sinks will affect the resource available for bioenergy, and our scenarios reflect this with the low scenario having a third of the unconstrained potential of the high, with all of it going to competing uses (panelboard manufacture, pulp mills and fencing). The competing uses for this feedstock vary between the medium and high scenario based on the bioenergy demand.

The potential for **arboriculture arisings** is unlikely to change significantly to 2050, assuming little change in the UK road network or parks, although UK population growth and the resulting slow spread of suburban areas might have some impact that is not modelled here. Arboriculture arisings remain a highly dispersed resource which poses problems for collection and processing, which is reflected in the scenarios. An appropriate price signal could result in a reduction in the amount of resource going to mulch.

The primary factors influencing the potential of **sawmill co-products** are the activity in the UK timber industry, the underlying forestry availability (which is likely to decline after 2030 due to the age class structure of the UK's forests) and competing uses. The feedstock is often used on-site at sawmills for heating/drying purposes however this has not be accounted for as this study only considers non-energy competing uses. The use of this feedstock in non-energy products varies by the prices offered for bioenergy, the higher the bioenergy price, the less goes to competing uses such as panel board manufacture animal bedding. The reduction of existing non-energy competing uses between our scenarios is the primary factor affecting the potential of this feedstock.

There has been minimal activity in **short rotation forestry** plantation in the past 6 years. Our scenarios are not as conservative as the CCC's, however, to achieve its potential suitable policy is required that recognises the long-term nature of the feedstock. We believe the potential for short rotation forestry in our scenarios is achievable given the land areas assumed are modest. However, increased concerns over land use may limit the growth of short rotation forestry and maximum land available for the feedstock.

The potential of **wet manure** for bioenergy is highly dependent on the competing uses. A portion of manure is currently used in AD and, whilst there is further potential, land spreading could grow. The production of manure is highly regionalised, due to most cattle, pig and poultry farming occurring in the West of Great Britain - effectively the inverse to straw production. This geographic break down would indicate that there are some areas of the UK which are more suitable to develop wet manure AD supply chains – particularly those where land spreading is limited due to nitrogen constraints. Effective supply chains are also necessary to collect the highly dispersed and very wet manures.

While the biomass potential estimates are generally similar to the CCC estimates, the analysis indicates that the potential from agricultural and forestry / wood residues could be somewhat lower than those estimated by the CCC because of greater constraints resulting from competing uses, sustainability, access to the resource, and in some cases a lower unconstrained potential. In the medium and high scenarios this could be compensated by a limited additional amount of energy crops and short rotation forestry. In a low scenario, the gap with the CCC estimates is greatest mainly as a result of a reduction in the unconstrained potential of agricultural residues (lower straw yield) and competing uses for arboriculture arisings.

Achieving the higher scenarios for energy crops and short rotation forestry would require increasing land areas, but there is controversy around the sustainability of this option because of potential land use change impacts. The land area assumptions for the low and medium scenarios in this review are derived from the CCC's conservative estimates and only draw on low-productivity and set-aside land. The high scenario is less conservative than the CCC's but is less ambitious than the max scenario for energy crops in Ricardo-EE (2017). The potential of energy crops and short rotation forestry will depend on their recognition as a sustainable source of feedstock and support for their establishment.

For the residue feedstocks, the higher potential scenarios often mean the some diversion of the resource from competing uses. This study does not investigate these diversions in detail but further research is required to understand the indirect environmental impacts of diverting feedstocks from competing non-energy uses. For example, understanding what material will replace the use of sawmill residues in panel board manufacture or estimating the increase in artificial fertiliser use if wet manures are used for anaerobic digestion as opposed to the common practice of land spreading. In the high scenario around 12% of the biomass potential, or about a third of the residue potential, depends on diverting resources from competing uses.

4. Total Waste and Non-Waste Bioenergy and Renewable Gas Potential

4.1 Bioenergy Potential

Based on the revised assumptions for feedstock arisings, the modelling undertaken for this study results in a total forecasted bioenergy potential ranging from 94 – 250 TWh by 2050 as shown in Figure 25.

Under the medium/central assumptions (ELU for the CCC), the total bioenergy potential estimates are lower than those in the CCC report for the period 2020-2040. This is largely the result of lower estimates for non-waste feedstocks (for the reasons explained above) offsetting the slightly higher estimates (than those of the CCC) for waste feedstocks. In 2050, however, the estimate of total bioenergy potential is very similar to that of the CCC. As explained above, this is as a consequence of a potential significant uplift in energy crops, albeit this depends upon long-term policy initiatives and investment support.

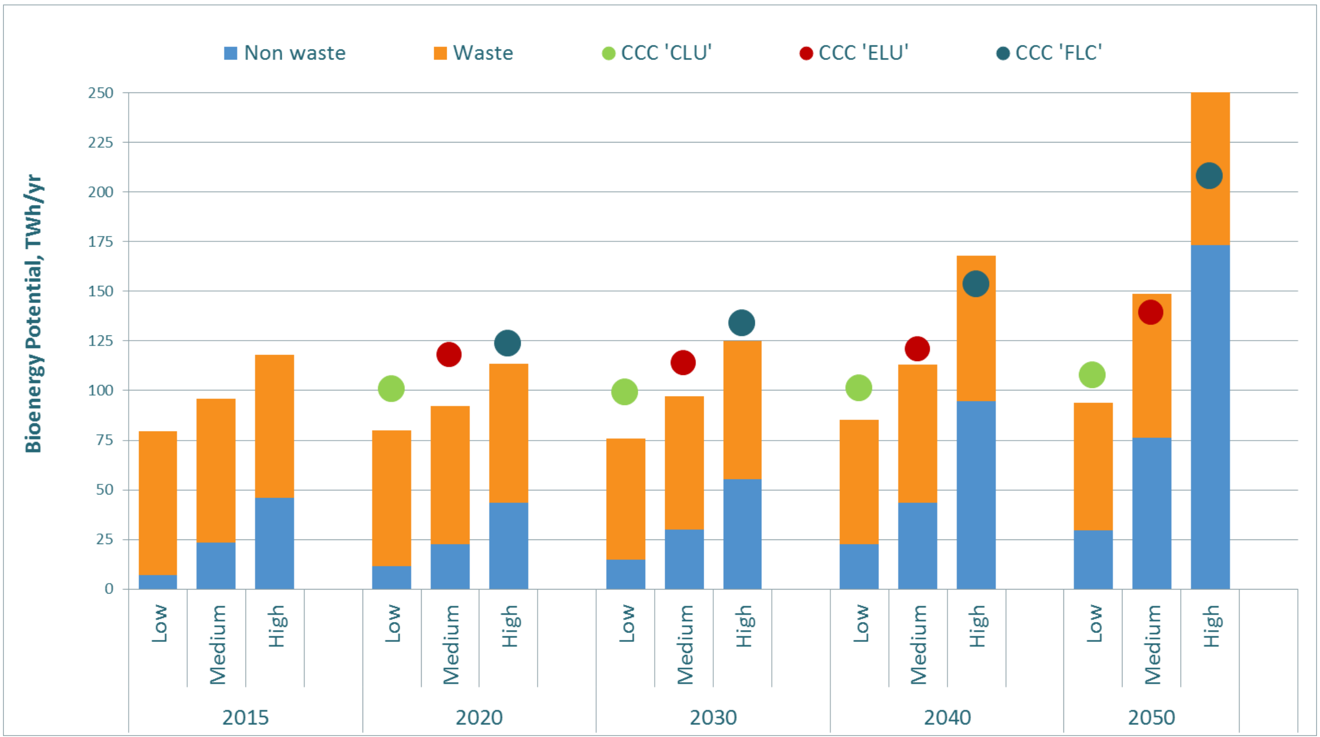


Figure 25: Bioenergy potential for each scenario, including CCC to 2050

4.2 Renewable Gas Potential

The forecast total bioenergy potential presented above has been converted into renewable gas potential, which results in a total renewable gas potential of around 108 TWh/annum in 2050 under the central scenario, as shown in Figure 26. Modelling of low and high scenarios results in a range of uncertainty of 68–183 TWh in 2050.

- 47-56 TWh from **waste feedstocks**, with 83% of this coming from bioSNG and 17% from biomethane via AD. It should be noted that whilst the balance of the split between biomethane from AD and bioSNG may vary over time, this change is unlikely to be sufficient to significantly change the total level of renewable gas generation; and
- 21-127 TWh from **non-waste feedstock,** with 97% of this coming energy crops, short rotation forestry and wood/forestry residues converted to bioSNG and the remaining 3% from biomethane via anaerobic digestion of wet manures and macro-algae.

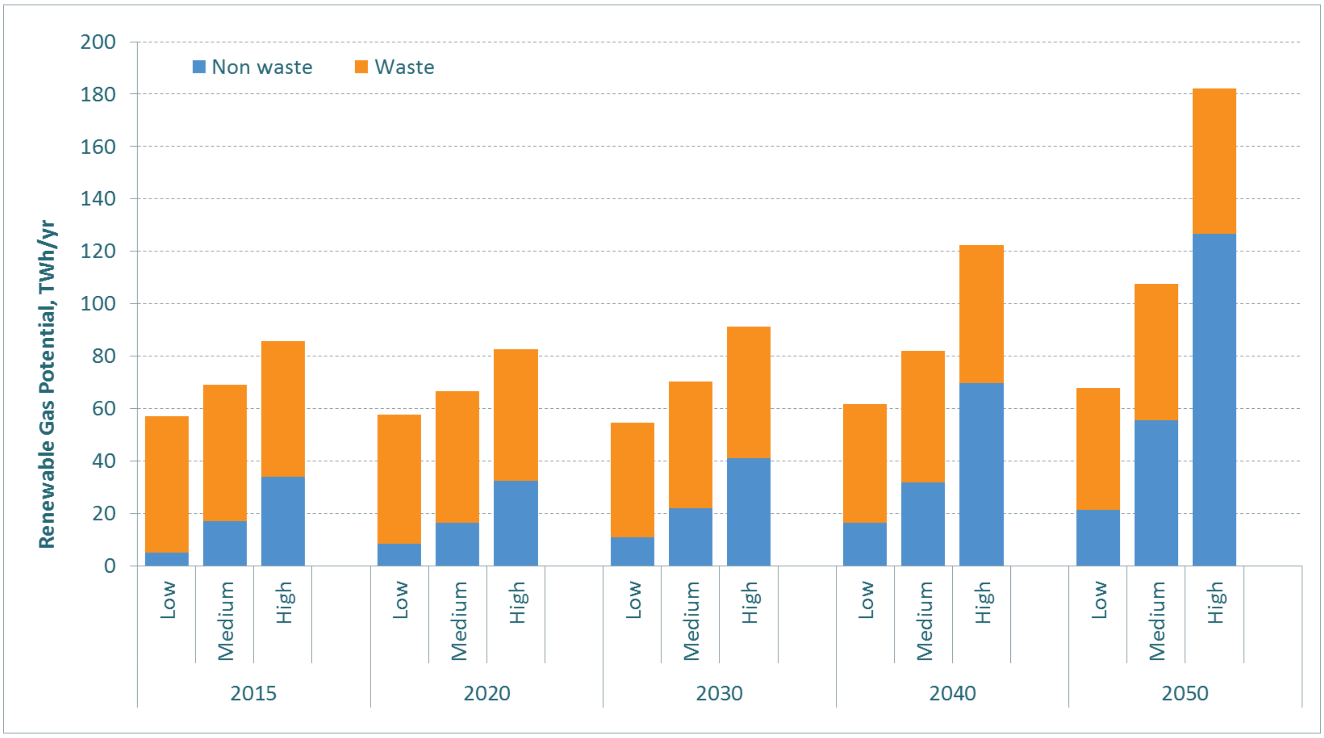


Figure 26: Renewable gas potential 2015 to 2050

5. Summary of Key Messages

The key messages which can be drawn from this study can be summarised as follows:

- A range of more up-to-date data and related new assumptions have been employed for this study, but the results for total bioenergy potential in 2050 are broadly similar to those modelled by the CCC in 2011:
  - In the early years, the lower estimates of bioenergy potential in this study are primarily the result of a lack of progress in respect of planting of energy crops since 2011.
- This work suggests that biomethane will continue to make an important contribution to renewable gas generation, but suggests that BioSNG has far greater potential through its greater versatility in respect of the range of feedstocks which might be processed (once the technology has been demonstrated at commercial scale);
- Bioenergy, and in particular renewable gas, can make a significant contribution to meeting 2050 climate change targets, in particular when supporting decarbonisation of the heat and transport sectors, which are currently lagging behind the electricity sector;
- To further enhance the evidence base for policy-making in this area, Government should:
  - Support the collection and assimilation of improved data for many feedstocks, in particular for C&I wastes and C&D wastes, to enable more detailed analysis of the local and regional potential for the production of renewable gas and the efficient use of these feedstocks; and
  - Continue to support development of best practices and improved sustainability frameworks, which will improve the understanding of potentials from agricultural and forestry residues, energy crops and short rotation forestry, and will provide assurance around their sustainable use.

Appendices

Appendix 1 Modelling for Waste Feedstock Scenarios

A1.1 Summary of Factors

The CVs energy content of each feedstock is presented in Table 32. These values are broadly in line with those within the CCC study.

In respect of BioSNG production, it is assumed that 0.72 MWh of BioSNG (on a HHV basis, as is usual in the gas industry) can be produced from 1.0 MWh of biomass (on a LHV basis as is usual in the biomass industry).

Table 32: Assumed Gross Calorific Value Fossil and Biogenic wastes

Waste Type	Gross CV - Fossil and biogenic content (GJ/t) - LHV	Gross CV Biogenic content (GJ/t) - LHV	Biogas yield (m^3/tonne)
Residual Waste	9.6[115]	6.0[116]	
Wood Waste	-	19[117]	
Food Waste (to AD)	-		110[117]
Sewage Sludge (to AD)	-		47[118]
Biogas (from AD)		22 GJ/Cubic Metre[119]	

---

[115] BEIS (2016), *Digest of United Kingdom Energy Statistics (DUKES)*, July 2016 (updated September 2016). Available at: https://www.gov.uk/government/statistics/digest-of-united-kingdom-energy-statistics-dukes-2016-main-chapters-and-annexes

[116] Gross CV x 62.5% biogenic energy content

[117] Carbon Trust (2009) *Biomass heating: A practical guide for potential users*, January 2009. Available at: https://www.forestry.gov.uk/pdf/eng-yh-carbontrust-biomass-09.pdf/$FILE/eng-yh-carbontrust-biomass-09.pdf

[118] SEAI (2012), *Gas Yields Table.* Available at www.seai.ie/Renewables/Bioenergy/Bioenergy/Gas_Yields_Table.pdf

[119] University of Southampton (2011) *Anaerobic digestion and energy.* Available at www.valorgas.soton.ac.uk

A1.2 Residual Waste Forecast Data

Table 33: Summary of modelling inputs and outputs for residual waste

Residual waste source	Scenario	2020	2030	2040	2050
Local authority (t)	Low	14,563,063	9,354,738	9,803,441	10,273,668
	Central	14,563,063	12,260,553	12,848,634	13,464,925
	High	14,563,063	13,626,201	14,279,786	14,964,723
C&I (t)	Low	7,490,650	6,492,538	6,527,204	6,562,055
	Central	8,266,019	7,488,324	7,718,544	7,955,841
	High	8,233,742	7,586,321	7,969,060	8,372,047
Total unconstrained arisings (t)	Low	22,053,713	15,847,276	16,330,645	16,835,722
	Central	22,829,082	19,748,877	20,567,178	21,420,766
	High	22,796,806	21,212,522	22,248,847	23,336,770
Food in residual waste stream (t)	Low	4,993,544	4,952,684	5,161,140	5,379,439
	Central	5,002,066	5,121,456	5,354,903	5,599,172
	High	5,010,673	5,215,487	5,472,094	5,741,375
Wood in residual streams (t)	Low	1,072,831	1,075,626	1,081,370	1,087,143
	Central	1,086,258	1,116,616	1,150,945	1,186,330
	High	1,099,819	1,159,060	1,224,807	1,294,284
Total Available Residual Waste (t)	Low	15,987,338	9,818,965	10,088,136	10,369,140
	Central	16,740,758	13,510,805	14,061,330	14,635,264
	High	16,686,314	14,837,974	15,551,945	16,301,111
Total available arisings as energy potential (TWh) - fossil and biogenic wastes	Low	42.6	26.2	26.9	27.7
	Central	44.6	36.0	37.5	39.0
	High	44.5	39.6	41.5	43.5
Total available arisings as bioenergy potential (TWh) - biogenic wastes	Low	27.5	16.9	17.4	17.9
	Central	28.8	23.3	24.2	25.2
	High	28.7	25.6	26.8	28.1

A1.3 Wood Waste Forecast Data

Table 34: Summary of modelling inputs and outputs for Wood Waste

Wood waste source	Scenario	2020	2030	2040	2050
Local authority – separately collected (t)	Low	1,079,871	1,568,987	1,644,244	1,723,111
	Central	1,079,871	1,365,538	1,431,036	1,499,676
	High	1,079,871	1,269,922	1,330,835	1,394,669
C&I – separated wood (t)	Low	1,498,033	1,501,935	1,509,955	1,518,017
	Central	1,516,781	1,495,899	1,467,693	1,440,473
	High	1,535,716	1,492,658	1,439,755	1,385,247
C&I – mixed stream (t)	Low	1,072,831	1,075,626	1,081,370	1,087,143
	Central	1,086,258	1,116,616	1,150,945	1,186,330
	High	1,099,819	1,159,060	1,224,807	1,294,284
C&D (t)	Low	2,436,372	2,442,720	2,455,762	2,468,874
	Central	2,466,864	2,535,806	2,613,767	2,694,124
	High	2,497,659	2,632,196	2,781,506	2,939,285
Total unconstrained arisings (t)	Low	6,087,108	6,589,268	6,691,330	6,797,145
	Central	6,149,773	6,513,859	6,663,441	6,820,602
	High	6,213,065	6,553,836	6,776,903	7,013,485
Used in animal bedding / panel board manufacture (t)	Low	1,551,829	1,555,872	1,564,180	1,572,531
	Central	1,571,251	1,615,163	1,664,819	1,716,002
	High	1,590,866	1,676,558	1,771,660	1,872,156
Total available arisings for renewable gas generation (t)	Low	4,535,278	5,033,396	5,127,150	5,224,614
	Central	4,578,523	4,898,696	4,998,621	5,104,600
	High	4,622,199	4,877,278	5,005,243	5,141,329
Total available arisings as bioenergy potential (TWh)	Low	23.9	26.6	27.1	27.6
	Central	24.2	26.2	27.1	28.1
	High	24.4	26.4	27.8	29.4

A1.4 Food Waste Forecast Data

Table 35: Summary of modelling inputs and outputs for food waste

Food waste source	Scenario	2020	2030	2040	2050
Local authority – separately collected (t)	Low	757,716	1,100,915	1,153,721	1,209,059
	Central	757,716	958,160	1,004,119	1,052,282
	High	757,716	891,070	933,810	978,601
Local authority - residual (t)	Low	4,312,591	4,269,957	4,474,767	4,689,401
	Central	4,312,591	4,412,712	4,624,369	4,846,179
	High	4,312,591	4,479,802	4,694,677	4,919,860
Home composting / fed to animals (t)	Low	827,805	876,877	918,937	963,014
	Central	827,805	876,877	918,937	963,014
	High	827,805	876,877	918,937	963,014
Household disposed of via sewer (t)	Low	1,655,610	1,753,754	1,837,874	1,926,028
	Central	1,655,610	1,753,754	1,837,874	1,926,028
	High	1,655,610	1,753,754	1,837,874	1,926,028
C&I – separated food (t)	Low	2,954,154	2,961,850	2,977,665	2,993,564
	Central	2,991,126	3,074,720	3,169,249	3,266,683
	High	3,028,466	3,191,594	3,372,636	3,563,947
C&I – in residual waste (t)	Low	680,953	682,727	686,373	690,037
	Central	689,476	708,745	730,534	752,994
	High	698,083	735,685	777,416	821,515
Total unconstrained arisings (t)	Low	11,188,830	11,646,081	12,049,335	12,471,103
	Central	11,234,323	11,784,968	12,285,081	12,807,179
	High	11,280,271	11,928,782	12,535,350	13,172,965
Food waste competing uses (t)	Low	1,550,391	1,601,346	1,647,274	1,695,240
	Central	1,559,434	1,628,954	1,694,135	1,762,045
	High	1,568,568	1,657,541	1,743,884	1,834,755
Total available arisings for renewable gas generation (tonnes)	Low	9,638,438	10,044,735	10,402,062	10,775,864
	Central	9,674,889	10,156,014	10,590,946	11,045,135
	High	9,711,703	10,271,241	10,791,467	11,338,209
Total available arisings as bioenergy potential (TWh)	Low	10.6	11.0	11.4	11.9
	Central	10.6	11.2	11.7	12.1
	High	10.7	11.3	11.9	12.5

A1.5 Sewage Sludge Forecast Data

Table 36: Summary of modelling inputs and outputs for sewage sludge

Waste type	Scenario	2020	2030	2040	2050
Sewage Sludge	Low	44,033,638	46,705,600	48,966,697	51,315,406
	Central	44,033,638	46,705,600	48,966,697	51,315,406
	High	46,705,600	46,705,600	48,966,697	51,315,406
Total available arisings as bioenergy potential (TWh)	Low	6.1	6.5	6.8	7.1
	Central	6.1	6.5	6.8	7.1
	High	6.1	6.5	6.8	7.1

Appendix 2 Modelling for Non-Waste Feedstock Scenarios

A2.1 Summary of factors

Table 37: Summary of factors common to all scenarios

Factor	Unit	Feedstock	Value
Calorific value (LHV)	GJ/tonne	Miscanthus	18.0
		SRC	19.0
		Straw, seed husks	17.2
		Chicken litter	15.8
		Forest residues	19.0
Moisture content	%	Straw	14.5
Biogas potential (HHV)	GJ/tonne (volatile solids)	Cattle and pigs	7.0

A2.2 Dedicated energy crops

Table 38: Summary of modelling inputs and outputs for dedicated energy crops

			2020	2030	2040	2050
Land suitable for energy crops	ha	Low	267,207	278,138	289,069	300,000
		Medium	268,991	379,328	489,664	600,000
		High	347,352	614,411	881,469	1,148,528
Miscanthus yield	odt/yr	Low	10.0	10.0	10.0	10.0
		Medium	10.6	11.7	12.9	14.0
		High	12.0	13.0	15.5	18.0
SRC yield	odt/yr	Low	8.0	8.0	8.0	8.0
		Medium	8.4	9.3	10.1	11.0
		High	8.9	10.6	12.3	14.0
Land split to Miscanthus	%	Low	71	72	72	73
		Medium	71	74	77	79
		High	71	77	80	80
CAGR planting rate	%	Low	13	-	-	-
		Medium	16	-	-	-
		High	25	-	-	-
Maximum planting rate	ha/yr		110,000	-	-	-
Cumulative planted area	Mha	Low	0.01	0.03	0.09	0.28
		Medium	0.01	0.04	0.13	0.51
		High	0.01	0.05	0.44	1.15
Total energy potential	MT/yr	Low	2.5	2.6	2.7	2.8
		Medium	2.7	4.2	6.0	8.0
		High	3.9	7.6	13.1	19.8
Planting rate constraint	MT/yr	Low	2.4	2.3	1.9	0.2
		Medium	2.6	3.8	4.4	1.2
		High	3.7	7.0	6.6	0.0
Available for bioenergy	TWh/yr	Low	0.6	1.5	4.5	13.9
		Medium	0.6	2.0	8.3	35.7
		High	0.7	3.4	34.1	103.3

A2.3 Dry agricultural residues

Table 39: Summary of modelling inputs and outputs for dry agricultural residues

			2020	2030	2040	2050
Unconstrained feedstock potential (straw)	Modt/yr	Low Medium High	8.76 8.32 8.55	8.13 8.20 8.90	7.61 8.19 9.36	7.10 8.19 9.83
Unconstrained feedstock potential (poultry litter)	Modt/yr		1.39	1.42	1.42	1.42
Unconstrained feedstock potential (seed husk)	Modt/yr		1.20	1.20	1.20	1.20
Competing uses that are independent of price:						
Straw			5.73	5.73	5.73	5.73
Chicken litter			0.00	0.00	0.00	0.00
Seed husks			1.20	1.20	1.20	1.20
Available for bioenergy						
Straw	Modt/yr	Low Medium High	3.03 2.59 2.83	2.40 2.47 3.17	1.88 2.46 3.63	1.37 2.46 4.10
Poultry litter	Modt/yr		2.59	2.47	2.46	2.46
Seed husks	Modt/yr		2.83	3.17	3.63	4.10
Available for bioenergy						
Low	Modt/yr		4.42	3.82	3.30	2.80
Medium	Modt/yr		3.98	3.89	3.89	3.89
High	Modt/yr		4.22	4.60	5.06	5.52
Reduction on resource due to constraint						
Low			61%	56%	24%	24%
Medium			51%	51%	24%	24%
High			40%	40%	24%	24%
Available resource after constraint reductions						
Low	Modt/yr		1.7	1.7	2.5	2.1
Medium	Modt/yr		2.0	1.9	3.0	3.0
High	Modt/yr		2.5	2.8	3.8	4.2
Available energy after constraint reductions						
Low	PJ/yr		28.9	28.1	41.7	35.0
Medium	PJ/yr		32.6	31.8	49.3	49.3
High	PJ/yr		42.4	46.2	64.6	70.7
Available energy after constraint reductions						
Low	TWh/yr		8.0	7.8	11.6	9.7
Medium	TWh/yr		9.1	8.8	13.7	13.7
High	TWh/yr		11.8	12.8	17.9	19.6

A2.4 Forest residues

Table 40: Summary of modelling inputs and outputs for forest residues

		2020	2030	2040	2050
Unconstrained feedstock potential	Modt/yr	1.3	1.9	1.8	1.6
Unconstrained feedstock potential	PJ/yr	24.32	35.53	34.96	29.83
Residue removal rate:					
Low removal		40%	40%	40%	40%
Medium removal		50%	50%	50%	50%
High removal		60%	60%	60%	60%
Competing feedstock uses which are dependent on price					
Demand for biomass from competing feedstocks uses at	Modt/yr	0.0	0.0	0.0	0.0
Available resource after competing uses					
Low removal	Modt/yr	0.51	0.75	0.74	0.63
Medium removal	Modt/yr	0.64	0.94	0.92	0.79
High removal	Modt/yr	0.77	1.12	1.10	0.94
Reduction on resource due to constraint					
Low		93%	87%	87%	87%
Medium		62%	60%	59%	58%
High		39%	38%	38%	38%
Available resource after constraint reductions					
Low	Modt/yr	0.0	0.1	0.1	0.1
Medium	Modt/yr	0.2	0.4	0.4	0.3
High	Modt/yr	0.5	0.7	0.7	0.6
Available energy after constraint reductions					
Low	PJ/yr	0.7	1.8	1.8	1.6
Medium	PJ/yr	4.6	7.1	7.2	6.3
High	PJ/yr	8.9	13.2	13.0	11.1
Available energy after constraint reductions					
Low	TWh/yr	0.2	0.5	0.5	0.4
Medium	TWh/yr	1.3	2.0	2.0	1.7
High	TWh/yr	2.5	3.7	3.6	3.1

A2.5 Small round wood

Table 41: Summary of modelling inputs and outputs for small round wood

		2020	2030	2040	2050
Unconstrained feedstock potential	Modt	0.84	1.22	1.21	1.04
Unconstrained feedstock potential	PJ	15.96	23.18	22.99	19.76
Competing use of which % that are independent of price:		36%	25%	25%	29%
Available for bioenergy use	Modt	0.54	0.92	0.91	0.74
Available for bioenergy use	PJ	10.26	17.48	17.29	14.06
Competing feedstock uses which are dependent on price					
Demand for biomass from competing feedstocks uses at low bioenergy prices (Mt):	Modt	0.5	0.8	0.8	0.7
Demand for biomass from competing feedstocks uses at medium bioenergy prices (Mt):	Modt	0.5	0.5	0.5	0.5
Demand for biomass from competing feedstocks uses at high bioenergy prices (Mt):	Modt	0.2	0.2	0.2	0.2
Available resource after competing uses					
Available for bioenergy uses at low bioenergy prices	Modt	0.00	0.12	0.11	0.00
Available for bioenergy uses at medium bioenergy prices	Modt	0.04	0.42	0.41	0.24
Available for bioenergy uses at high bioenergy prices	Modt	0.34	0.72	0.71	0.54
Reduction on resource due to constraint					
Low		88%	79%	75%	74%
Medium		60%	59%	58%	57%
High		40%	40%	40%	40%
Available resource after constraint reductions					
Low	Modt	0.0	0.0	0.0	0.0
Medium	Modt	0.0	0.2	0.2	0.1
High	Modt	0.2	0.4	0.4	0.3
Available energy after constraint reductions					
Low	PJ	0.0	0.5	0.5	0.0
Medium	PJ	0.3	3.3	3.3	2.0
High	PJ	3.9	8.2	8.1	6.2
Available energy after constraint reductions					
Low	TWh	0.0	0.1	0.1	0.0
Medium	TWh	0.1	0.9	0.9	0.5
High	TWh	1.1	2.3	2.2	1.7

A2.6 Arboricultural arisings

Table 42: Summary of modelling inputs and outputs for arboricultural arisings

Annual resource potentials		2020	2030	2040	2050
Unconstrained feedstock potential	Modt	2.7	2.7	2.7	2.7
Unconstrained feedstock potential	PJ	51.30	51.30	51.30	51.30
Competing use of which % that are independent of price:		0%	0%	0%	0%
Available for bioenergy use	Modt	2.70	2.70	2.70	2.70
Available for bioenergy use	PJ	51.30	51.30	51.30	51.30
Competing feedstock uses which are dependent on price					
Low	Modt	63%	63%	63%	63%
Medium	Modt	50%	40%	40%	40%
High	Modt	18%	15%	15%	15%
Available resource after competing uses					
Low	Modt	1.00	1.00	1.00	1.00
Medium	Modt	1.35	1.62	1.62	1.62
High	Modt	2.21	2.30	2.30	2.30
Reduction on resource due to constraint					
Low		74%	66%	66%	66%
Medium		30%	29%	28%	27%
High		0%	0%	0%	0%
Available resource after constraint reductions					
Low	Modt	0.3	0.3	0.3	0.3
Medium	Modt	0.9	1.2	1.2	1.2
High	Modt	2.2	2.3	2.3	2.3
Available energy after constraint reductions					
Low	PJ	4.9	6.5	6.5	6.5
Medium	PJ	18.0	21.9	22.2	22.5
High	PJ	41.9	43.6	43.6	43.6
Available energy after constraint reductions					
Low	TWh	1.4	1.8	1.8	1.8
Medium	TWh	5.0	6.1	6.2	6.2
High	TWh	11.6	12.1	12.1	12.1

A2.7 Sawmill co-products

Table 43: Summary of modelling inputs and outputs for sawmill co-products

		2020	2030	2040	2050
Unconstrained feedstock potential	Modt	1.1	1.6	1.6	1.4
Unconstrained feedstock potential	PJ	20.71	30.78	30.02	25.65
Competing use of which % that are independent of price:		0%	0%	0%	0%
Available for bioenergy use	Modt	1.09	1.62	1.58	1.35
Available for bioenergy use	PJ	20.71	30.78	30.02	25.65
Competing feedstock uses which are dependent on price					
Demand for biomass from competing feedstocks uses at low bioenergy prices (Mt):	Modt	1.1	1.1	1.1	1.1
Demand for biomass from competing feedstocks uses at medium bioenergy prices (Mt):	Modt	0.3	0.3	0.3	0.3
Demand for biomass from competing feedstocks uses at high bioenergy prices (Mt):	Modt	0.2	0.2	0.2	0.2
Available resource after competing uses					
Available for bioenergy uses at low bioenergy prices	Modt	0.00	0.52	0.48	0.25
Available for bioenergy uses at medium bioenergy prices	Modt	0.79	1.32	1.28	1.05
Available for bioenergy uses at high bioenergy prices	Modt	0.89	1.42	1.38	1.15
Reduction on resource due to constraint					
Low		52%	47%	47%	47%
Medium		42%	40%	39%	38%
High		20%	20%	20%	20%
Available resource after constraint reductions					
Low	Modt	0.0	0.3	0.3	0.1
Medium	Modt	0.5	0.8	0.8	0.7
High	Modt	0.7	1.1	1.1	0.9
Available energy after constraint reductions					
Low	PJ	0.0	5.2	4.8	2.5
Medium	PJ	8.7	15.0	14.8	12.4
High	PJ	13.5	21.6	21.0	17.5
Available energy after constraint reductions					
Low	TWh	0.0	1.5	1.3	0.7
Medium	TWh	2.4	4.2	4.1	3.4
High	TWh	3.8	6.0	5.8	4.9

A2.8 Short rotation forestry

Table 44: Summary of modelling inputs and outputs for short rotation forestry

		2020	2030	2040	2050
Unconstrained feedstock potential					
Low	Modt	0.0	0.0	0.1	0.1
Medium	Modt	0.0	0.0	0.1	0.6
High	Modt	0.0	0.0	0.3	1.9
Unconstrained feedstock potential					
Low	PJ	0.00	0.00	1.19	1.19
Medium	PJ	0.00	0.00	2.40	10.88
High	PJ	0.00	0.00	6.35	35.91
Competing use of which % that are independent of price:		0%	0%	0%	0%
Available for bioenergy use					
Low	Modt	0.0	0.0	0.1	0.1
Medium	Modt	0.0	0.0	0.1	0.6
High	Modt	0.0	0.0	0.3	1.9
Available for bioenergy use					
Low	PJ	0.0	0.0	1.2	1.2
Medium	PJ	0.0	0.0	2.4	10.9
High	PJ	0.0	0.0	6.3	35.9
Competing feedstock uses which are dependent on price					
Demand for biomass from competing feedstocks uses		0.0	0.0	0.0	0.0
Available resource after competing uses					
Low	Modt	0.00	0.00	0.06	0.06
Medium	Modt	0.00	0.00	0.13	0.57
High	Modt	0.00	0.00	0.33	1.89
Reduction on resource due to constraint					
Low		100%	100%	100%	100%
Medium		100%	100%	45%	35%
High		100%	100%	0%	0%
Available resource after constraint reductions					
Low	Modt	0.0	0.0	0.0	0.0
Medium	Modt	0.0	0.0	0.1	0.4
High	Modt	0.0	0.0	0.3	1.9
Available energy after constraint reductions					
Low	PJ	0.0	0.0	0.0	0.0
Medium	PJ	0.0	0.0	1.3	7.1
High	PJ	0.0	0.0	6.3	35.9
Available energy after constraint reductions					
Low	TWh	0.0	0.0	0.0	0.0
Medium	TWh	0.0	0.0	0.4	2.0
High	TWh	0.0	0.0	1.8	10.0

A2.9 Wet manure

Table 45: Summary of modelling inputs and outputs for wet manure

		2020	2030	2040	2050
Unconstrained feedstock potential					
Cattle & pigs	Modt	3.2	3.2	3.7	4.3
Laying chickens	Modt	0.5	0.5	0.5	0.5
Unconstrained feedstock potential	Modt	3.7	3.6	4.2	4.7
Cattle & pigs	PJ	22.38	22.16	25.91	29.98
Laying chickens	PJ	8.86	8.86	8.86	8.86
Unconstrained feedstock potential	PJ	31.23	31.01	34.77	38.84
Competing use of which % that are independent of price:					
Available for bioenergy use	Modt	3.19	3.16	3.70	4.28
Available for bioenergy use	PJ	31.23	31.01	34.77	38.84
Competing feedstock uses which are dependent on price					
Demand for biomass from competing feedstocks uses at low bioenergy prices (Mt):	Modt	3.1	3.1	3.6	4.2
Demand for biomass from competing feedstocks uses at medium bioenergy prices (Mt):	Modt	3.0	2.9	3.4	4.0
Demand for biomass from competing feedstocks uses at high bioenergy prices (Mt):	Modt	1.4	1.4	1.6	1.9
Available resource after competing uses					
Available for bioenergy uses at low bioenergy prices	Modt	0.51	0.51	0.52	0.53
Available for bioenergy uses at medium bioenergy prices	Modt	0.69	0.69	0.72	0.77
Available for bioenergy uses at high bioenergy prices	Modt	2.25	2.24	2.54	2.86
Reduction on resource due to constraint					
Low		60%	60%	60%	60%
Medium		30%	30%	30%	30%
High		25%	20%	30%	30%
Available resource after constraint reductions					
Low	Modt	0.2	0.2	0.2	0.2
Medium	Modt	0.5	0.5	0.5	0.5
High	Modt	1.7	1.8	1.8	2.0
Available energy after constraint reductions					
Low	PJ	1.7	1.7	1.8	1.8
Medium	PJ	4.1	4.1	4.3	4.5
High	PJ	14.4	15.2	15.1	17.0
Available energy after constraint reductions					
Low	TWh	0.5	0.5	0.5	0.5
Medium	TWh	1.1	1.1	1.2	1.3
High	TWh	4.0	4.2	4.2	4.7

A2.10 Macro-algae

Table 46: Summary of modelling inputs and outputs for macro-algae

Feedstock potential		2020	2030	2040	2050
Sea area	Mha	0.00	0.00	0.01	0.03
Mass of seaweed	Modt	0.00	0.01	0.25	0.68
Biogas potential	PJ	0.00	0.11	3.57	9.59
Biogas potential	TWh	0.00	0.03	0.99	2.66

A2.11 Comparison of Bioenergy Potential of Current Scenarios with CCC

Table 47: Detailed comparison of medium scenario versus CCC 'ELU' scenario in 2030

Feedstock	Unconstrained potential (TWh/yr)		Competing uses (TWh/yr)		Constraint factors (%)		Total (TWh/yr)	
	CCC	E4tech	CCC	E4tech	CCC	E4tech	CCC	E4tech
Energy crops	N/A	13.6	0.0	0.0	N/A	Planting	5.0	2.1
Dry agricultural residues	58.6	55.4	27.2	33.9	27%	51%	22.7	10.6
Small roundwood	17.6	6.4	1.4	9.1	67%	59%	6.6	3.7
Forest residues	5.0	9.9	0.0	4.9	70%	60%	1.9	2.0
Arboricultural arisings	13.9	14.3	0.0	9.0	29%	29%	10.4	3.7
Sawmill co-products	8.3	8.6	0.0	1.6	40%	40%	5.0	4.2
Short rotation forestry	0.0	0.0	0.0	0.0	100%	100%	0.0	0.0
Wet manure*	7.0	7.7	0.5	6.2	40%	30%	3.2	1.2
Macro algae*							0.0	0.0
						Total	**54.8**	**27.5**

** Biogas*