BIOENERGY HEAT PATHWAYS TO 2050
RAPID EVIDENCE ASSESSMENT
TECHNICAL ANNEX

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Acronyms

AD	Anaerobic digestion
B2C2	UK Solid and Gaseous Biomass Carbon Calculator
BAU	Business as Usual
BEIS	Department for Business, Energy and Industrial Strategy
BFB	Bubbling Fluidised Bed (gasifier type)
BioSNG	Bio-derived synthetic natural gas
$BioH_2$	Bio-derived hydrogen
BVCM	(ETI) Biomass Value Chain Model
CAPEX	Capital expenditure
CCC	Committee on Climate Change
CCS	Carbon Capture and Storage
CFB	Circulating Fluidised Bed (gasifier type)
DECC	Department for Energy and Climate Change
DFT	Department for Transport
EFB	(Palm) Empty fruit bunches
EPC	Engineering (design), Procurement and Construction
ESME	(ETI) Energy System Modelling Environment
ETI	Energy Technologies Institute
FFB	(Palm) Fresh fruit bunches
GHG	Greenhouse gas
GVA	Gross Value Add
HHV	Higher Heating Value
IRENA	International Renewable Energy Association
IRR	Internal Rate of Return
JRC	Joint Research Council (of the European Commission)
LHV	Lower Heating Value
LRF	Long rotation forestry

OPEX	Operating expenditure
RDF	Refuse Derived Fuel
REA	Rapid Evidence Assessment
RHI	Renewable Heat Incentive
RO	Renewables Obligation
RPI	Retail Price Index
RTFO	Renewable Transport Fuel Obligation
SRC	Short rotation coppice (willow or poplar)
SRF	Short rotation forestry
TEABPP	(ETI) Techno-Economic Assessment of Biomass Pre-processing
TESBIC	(ETI) Techno-Economic Study of Biomass to Power with CCS
TINA	(DECC) Technology Innovation Needs Assessment
TRL	Technology readiness level
UKAS	UK Accreditation Service

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1 Introduction

BEIS has commissioned a series of projects to better understand the contribution that bioenergy can make to decarbonising heat. This report, which is part of a larger project undertaken by Ecofys, E4tech and Economic & Human Value Engineering Ltd, forms the ‘Technical Annex’ for the Rapid Evidence Assessment (REA) and accompanies a ‘Summary Report’ that describes the key findings from the REA.

The evidence review considered the whole bioenergy value chain (from feedstock production to gas or heat production), focusing on those pathways that are most relevant to decarbonising the gas grid in Great Britain to 2050, and in particular, options using **biomethane, bio-synthetic natural gas (bioSNG), or biohydrogen (bioH_2)**. The focus was on evidence on the potential, cost and greenhouse gas (GHG) emissions of those routes to decarbonise the gas grid.

The review was primarily conducted between March and August 2017. The review was undertaken through literature research, supplemented by contacting key stakeholders in the industry.

This report presents the key evidence sources, categorised by feedstock, technology and GHG emissions. For each evidence source, we describe: how the work was undertaken, key assumptions taken and scenarios modelled, key report outcomes, dependencies on other evidence sources, and the quality and relevance of the source. An Evidence Log is provided alongside this report (in Excel), which gives summary information on a longer list of evidence reviewed and a rating of the quality and relevance of each piece of evidence. The outputs from this project will feed into the Government’s considerations as they take the next steps towards decarbonising the heating sector.

2 Feedstock evidence

This chapter includes information on the key evidence sources reviewed relating to feedstock deployment and cost. The scope of the review is the most suitable feedstocks to produce gas for use in the gas grid infrastructure, namely "wet" feedstocks and crops that can be used in anaerobic digestion (AD) and clean lignocellulosic (grassy), woody biomass and (dry) wastes that can be gasified to produce either bioSNG or bioH$_2$. The sections are structured according to the geographical origin of the feedstock, and within those sections in chronological order (most recent first).

2.1 Key evidence sources assessed

Table 2-1. Summary of feedstock evidence sources assessed

Title	Author	Date	Timescale	Feedstocks covered[1]	Geographical coverage
UK and Global Bioenergy Resource Model	Ricardo for BEIS	2017	2010-2050 (in 5 year snap-shots)	Agricultural residues, biodegradable "wet" waste, forestry residues, grassy energy crops, Industrial wood processing residues, Woody energy crops, Residual and post-consumer waste	UK, global
UK TIMES	BEIS	2017	2050	Agricultural residues, biodegradable "wet" waste, forestry residues, grassy energy crops, industrial wood processing residues, woody energy crops, residual and post-consumer waste	UK
Review of Bioenergy Potential (Review of UK feedstock availability for bioSNG)	E4tech & Anthesis for Progressive Energy/ Cadent	2017	To 2050	Wastes (food waste, residual waste, sewage sludge wood waste), Non-wastes (agricultural residues, arboricultural arisings, energy crops, forestry residues, sawmill co-products, small round wood, SRF, wet manure)	UK
Forestry Statistics 2017	Forestry Commission	2017	To 2016	Forestry residues, woody energy crops	UK

[1] Note in this column, we refer to the feedstock categories from **Error! Reference source not found.** of this report to keep the list of feedstocks shorter and more easily comparable. Within those categories, the evidence sources may cover multiple specific feedstocks

Title	Author	Date	Timescale	Feedstocks covered[1]	Geographical coverage
Characterisation of biomass feedstocks database	Forest Research/ Uniper	2017	2016	Woody and grassy energy crops	UK
Bioenergy supply chain in the UK	Ecofys for DECC	2016	2016, 2020, 2030	Grassy energy crops, woody energy crops, biodegradable "wet" waste, post-consumer waste	UK
Crops Grown for Bioenergy in England and the UK: 2015	Defra	2016	2015	Agricultural residues, grassy energy crops, woody energy crops	UK
Estimates of Food Surplus and Waste Arisings in the UK	WRAP	2016	2013 - 2016	Biodegradable "wet" waste	UK
Technology Innovation Needs Assessment: Bioenergy (refresh)	E4tech for DECC	2016 (not published)	To 2050	Macro-algae, woody energy crops, grassy energy crops	UK, Global
Technology Innovation Needs Assessment: Bioenergy	E4tech and Carbon Trust for DECC	2011	To 2050	Macro-algae, woody energy crops, grassy energy crops	UK, Global
Advanced Biofuel Feedstocks - An Assessment of Sustainability	E4tech for DECC	2014	2014-2020	Agricultural residues, woody energy crops, grassy energy crops	UK, EU-28, Global
The technical potential of Great Britain to produce lignocellulosic biomass for bioenergy in current and future climates	Hastings et al.	2013	2050	Energy crops	UK
Energy potential from UK arable agriculture: Straw – what is it good for?	Stoddart, and Watts	2011	2012	Agricultural residues	UK
The case for crop feedstocks in anaerobic digestion	ADBA, CLA, NFU and REA	2011	2011	Agricultural crops	UK
Maximising the yields of biomass from residues of agricultural crops and forestry biomass	Ecofys for European Commission (DG ENER)	2016	Potential availability provided for 2014 and annually thereafter	Agricultural residues, forestry residues	EU, Ukraine, Russia, Belarus
Wasted, Europe's untapped resource	ICCT	2014	2030	Agricultural and forestry residues, waste wood and post-consumer wastes	EU
Forest biomass for energy in the EU: current trends, carbon balance and sustainable potential	IINAS, European Forest Institute, Joanneum	2014	2020, 2030	Forestry residues, Woody energy crops	EU

Title	Author	Date	Timescale	Feedstocks covered[1]	Geographical coverage
	Research				
Low ILUC potential of wastes and residues for biofuels	Ecofys for FNR	2013	2013	Agricultural residues (straw and corn cobs), forestry residues and industrial wood processing residues and UCO	EU (12 Member States for agricultural residues, 27 for wood residues)
Global Bioenergy Supply and Demand Projections: A working paper for REmap 2030	IRENA	2014	2030	Agricultural residues, forestry residues	Global
Bioenergy potentials from forestry in 2050	Smeets & Faaij	2007	2050	Forestry residues, woody energy crops	Global
Brazil - Bio Trade2020plus	Intelligent Energy Europe	2016	2020, 2030	Agricultural residues, forestry residues, industrial wood processing residues	Brazil
Indonesia - Bio Trade2020plus	Intelligent Energy Europe	2016	2015, 2020, 2030	Agricultural residues	Indonesia
US - 2016 Billion-Ton Report	US Department of Energy	2016	2016-2040 (annual)	Agricultural residues, forestry residues, wastes	USA

The feedstock part of the REA considered whether the evidence includes information on feedstock potential, feedstock cost/price and the GHG emissions associated with cultivation of the feedstock. The following aspects are most relevant to understand estimates of feedstock potential:

- Current deployment or technical/sustainable potential
- How much feedstock is assumed to be available to the UK (for non-UK feedstocks)
- How much feedstock is assumed could be used for bioenergy / heat
- For crops: available land area, yield, sustainability criteria assumed, harvest cycle period/ plantation lifetime
- For residues: land area, yield, sustainable removal rate, existing uses
- For wastes: economic activity (i.e. availability of the main product), biogenic share of waste, collection potential

2.2 UK

2.2.1 UK and Global Bioenergy Resource Model (Ricardo Energy & Environment for BEIS, 2017)[2]

Plain English description of evidence: The UK and Global Bioenergy Resource Model allows users to estimate the potential sustainable bioenergy resource that may be available to the UK to 2050. The 2017 version is an update

[2] https://www.gov.uk/government/publications/uk-and-global-bioenergy-resource-model

to a model originally developed in 2011 (by AEA Technology, now part of Ricardo) in preparation for the 2012 Bioenergy Strategy. The original model covered the period 2010-2030. The update aims to improve and expand the model, increase transparency and make it suitable for use by the general public. The work was commissioned by BEIS (and formerly DECC). Key updates to the model, of relevance here, include:

- Extending the timeframe from 2030 to 2050 (in 5-year snap shots)
- Inclusion of sustainability constraints for solid and gaseous biomass
- Improvement of the input feedstock template for UK feedstocks to allow more information on price sensitivity to be included
- Complete separation of all input data and assumptions from calculations, and facility for user to edit input data and assumptions if required
- Inclusion of additional UK (biogas from crops) and international feedstocks (UCO and tallow)

The model covers supply of the following feedstocks (see section 2.4.1 for Global feedstocks):

- UK
    - Arboricultural arisings (residues produced from maintenance of domestic and municipal gardens, parks, and of road, rail, canal and other transport corridors)
    - Biomethane crops (new)
    - Dry agricultural residues (straw, poultry litter, seed husks and hulls)
    - Energy crops (Short Rotation Coppice (SRC) willow and Miscanthus)
    - Food waste for AD (household waste stream collected at kerbside, household waste recycling centres; waste stream from commercial and industrial sector from following sub-sectors: hospitality and food service, retail, wholesale, food manufacturing; food that is used for animal feed is not considered)
    - Forestry residues (brash, stumps and small round wood not suitable for other purposes)
    - Landfill gas
    - Renewable fraction of waste of MSW and commercial and industrial waste
    - Sawmill residues
    - Sewage sludge (watery residues and semi-solid materials that are produced as a result of sewage treatment of municipal wastewater)
    - Short rotation forestry (SRF, trees grown as conventional, single stems, harvested at approximately 8-20 years old for energy. 15-year rotation assumed)
    - Small round wood
    - Waste wood (produced by construction and demolition, commercial and industrial and from household waste)
    - Wet manure for AD (from cattle and pigs)
- Out of scope of this project but also covered:
    - UK Biodiesel & bioethanol crops, tallow, UCO

How the work was undertaken: The model provides default information on feedstock availability but many of the assumptions can be overwritten by the user, meaning it provides a tool to estimate bioenergy resource potential, rather than a most likely scenario. The approach, assumptions and sources of data are detailed in a clear and consistent way in the feedstock worksheets. Competing uses and constraints are listed transparently per feedstock in the individual feedstock worksheets.

Key assumptions taken and scenarios modelled: For each feedstock, the model estimates *unconstrained potential resource* available and the *accessible resource*, i.e. the resource available after price independent competing uses have been removed. In addition, price-dependent competing use estimates can be made at three price levels (£4, £6, £10/GJ), which represent typical prices paid for biomass in the market (although the authors acknowledge wastes and residues can be cheaper than this). The impact of other barriers on the availability of feedstock can be varied by the user according to whether 'no barriers' are overcome, 'easy barriers' are overcome or 'all barriers' are overcome.

For energy crops, users can select whether to prioritise annual crops, such as biomethane crops, or perennial crops, such as SRC and Miscanthus. The same underlying land availability assumption is used for both, so by prioritising one type of crop in the model, the potential of the other type decreases. The share of UK energy crop land used for Miscanthus versus SRC is set at 70:30, representing the current share of land use.

For the approach to Global feedstocks, see section 2.4.1.

For the approach to GHG emissions, see section 4.1.1.

Key report outcomes: Overall the 2017 version of the model aims to make relatively conservative assumptions about the feedstock resource. The estimated total underlying bioenergy feedstock resource in 2030 is 34% lower than in the 2011 version of the model, and the accessible resource (after price independent competing uses are removed) is reported to be about 28% lower. This varies per feedstock, but Ricardo report that the change in the overall total is largely driven by the fact that the SRF resource (estimated as 143 PJ in 2030 in the previous model) is now considered not available in 2030 (as significant planting of this resource has not occurred in the period 2010 to 2015). There are also significant reductions in the total waste and landfill gas resource. In terms of the accessible resource, the main reduction comes in the energy crops estimate, due to more conservative assumptions about what could be planted by 2030. The 2017 version of the model also includes sustainability constraints for solid and gaseous biomass.

Key output tables are:

- Table 3.1 Estimates of total and accessible UK bioenergy resource in 2030 (PJ/yr) (UK)
- Table 3.2 Accessible resource in 2030, if no barriers to supply are overcome (PJ/yr) (UK) – reproduced as an example below in Table 2-2
- Table 3.3 Accessible resource to 2030, if all barriers to supply are overcome (PJ/yr) (UK)

The total resource estimated (Tables 3.2 and 3.3) is between 22% and 31% less than that estimated previously (based on the estimates of the minimum amounts available from crop based feedstocks), depending on the price level.

Table 2-2. Accessible resource in 2030, if no barriers to supply are overcome. (Table 3.2 in the report.)

	Previous (2010) model			Current model			Change (%)			Change (PJ)		
	£4/GJ	£6/GJ	£10/GJ	£4/GJ	£6/GJ	£10/GJ	£4/GJ	£6/GJ	£10/GJ	£4/GJ	£6/GJ	£10/GJ
Dry agricultural residues	77	83	95	66	71	81	-14%	-14%	-14%	-11	-12	-14
Forestry residues	2	6	9	2	5	7	-29%	-25%	-24%	-1	-2	-2
Stemwood	11	22	31	0	3	7	-95%	-86%	-77%	-10	-19	-24
Short rotation forestry	0	1	2	0	0	0		-100%	-100%	0	-1	-2
Sawmill co-products	16	18	21	5	15	19	-68%	-18%	-11%	-11	-3	-2
Arboricultural arisings	17	21	30	6	8	13	-66%	-62%	-55%	-11	-13	-16
Waste wood	78	78	78	74	95	95	-6%	21%	21%	-4	17	17
Renewable fraction of wastes	35	39	42	30	35	35	-13%	-10%	-17%	-5	-4	-7
Food waste	33	39	46	17	19	21	-48%	-52%	-55%	-16	-21	-25
Landfill gas	38	40	42	35	35	35	-9%	-12%	-17%	-4	-5	-7
Sewage sludge	11	11	13	14	15	15	36%	29%	17%	4	3	2
Livestock manures	8	11	15	0	1	9	-99%	-91%	-40%	-8	-10	-6
Perennial energy crops (max)	65	150	231	27	39	62	-58%	-74%	-73%	-38	-111	-169
Perennial energy crops (min)	65	76	76	23	33	52	-64%	-57%	-31%	-42	-43	-23
Biogas from crops (max)	0	0	0	4	16	23				4	16	23
Biogas from crops (min)	0	0	0	4	7	7				4	7	7
Bioethanol from crops (max)	44	52	62	6	22	36	-87%	-57%	-42%	-38	-30	-26
Bioethanol from crops (min)	19	23	27	3	11	15	-83%	-52%	-45%	-16	-12	-12
Biodiesel from crops (max)	11	15	15	1	7	12	-87%	-50%	-23%	-10	-7	-3
Biodiesel from crops (min)	1	1	1	1	1	1	-30%	-45%	-47%	0	0	-1
UCO	5	7	7	7	7	7	21%	0%	-9%	1	0	-1
Tallow	5	9	10	4	4	4	-27%	-56%	-60%	-1	-5	-6
Total (based on maximums)	**457**	**600**	**749**	**298**	**395**	**482**	**-35%**	**-34%**	**-36%**	**-159**	**-206**	**-267**
Total (based on minimums)	**422**	**483**	**545**	**291**	**362**	**423**	**-31%**	**-25%**	**-22%**	**-131**	**-121**	**-122**

The bioenergy supply scenario included in UK TIMES (see section 2.2.3) is the "low low" scenario from the Ricardo 2017 model: "Amount available for bioenergy at £4/GJ if no constraints overcome and competing feedstock demands are also met."

Dependencies on other evidence sources: Data sources vary per feedstock. Key references listed in the updated model, in addition to the original AEA (2011) model, include DECC (2012) Bioenergy Strategy. The report draws on a variety of data and the key references per feedstock are summarised below:

- Arboricultural arisings
  - Maximum land potentially available for SRF planting: NNFCC 2008 Addressing the land use issues for non-food crops, in response to increasing fuel and energy generation opportunities
  - Starting point for the feedstock potential: Forestry Statistics 2014
  - Allocation of softwood and hardwood forest products into sawlogs, SRW, brash, etc.: Output from CSORT model 2011
  - Estimate of Landscape Care Wood or arboricultural arisings: Mantau, U. et al. 2010 EUwood - Real potential for changes in growth and use of EU forests.
- Biomethane crops (new in 2017 model)
  - Input to Land availability estimates, SRC yield estimates, economic constraints: FERA, Defra report NF0444, Assessment of the availability of marginal and idle land for bioenergy crop production in England and Wales
  - Input to estimate of new AD schemes in construction to 2020: Green Investment Bank, 2015, The UK anaerobic digestion market
  - Input to sustainability constraints: DECC, 2015, New biomass sustainability requirements for the RHI
  - One of the studies used in the land use estimates for the original study for DECC: Bauen 2010, Modelling supply and demand of bioenergy from SRC and Miscanthus in the UK

- Unconstrained potential for energy crop production in the UK: Lovett 2013, The availability of land for perennial energy crops in Great Britain
  - Used to sense check planting rate and energy crop area assumptions. Defra 2014, Area of crops grown for bioenergy in England and the UK: 2008-2013
  - Estimation of yields to 2050: Pollock 2011, Regional case study R1: The UK in the context of North-Western Europe. Options for sustainable increases in agricultural production
  - Used as input to land available for energy crops: Welfie 2014, Securing a bioenergy future without imports; Fischer 2010, Biofuel production potentials in Europe:sustainable use of cultivated land and pastures, part II: Land use scenarios
  - Arable crop yields in the UK: Defra 2014, Farming statistics: provisional crop areas, yields and livestock populations at June 2014- UK
  - Biogas yield: KWS 2015, Biogas in practice
  - Methane energy content: DUKES 2014, Digest of UK energy statistics
  - Energy content of biomass fuels: Biomass energy centre, n.d.
  - Price ranges for wheat and oil seed rape: Statistica 2015, Agricultural commodity prices in the UK 2002 to 2015
- Dry agricultural residues (straw, poultry litter, seed husks and hulls)
  - Crop areas for estimation of straw production: DARDNI, 2013, The Agricultural Census in Northern Ireland, Results for June 2013
  - Straw quantities: AHDB, HGCA Research Review No. 81: Straw Incorporation Review
  - Poultry litter quantity: Biomass Energy Centre website, n.d.
  - Seed husks and hulls: Howes et al., 2010. UK and Global Bioenergy resource – Annex 1 report: details of analysis. AEA, Harwell. UK and Global Bioenergy resource – Annex 1 report: details of analysis
- Energy crops (SRC willow and Miscanthus)
  - Starting point AEA 2010, UK and Global Bioenergy resources (i.e. AEA 2011 model)
  - Input to Land availability estimates, SRC yield estimates, economic constraints, FERA 2010, Defra report NF0444, Assessment of the availability of marginal and idle land for bioenergy crop production in England and Wales
  - One of the studies used in the land use estimates for the original study for DECC: Bioresource technology 101 (2010), Bauen 2010, Modelling supply and demand of bioenergy from SRC and Miscanthus in the UK
  - Input to Land availability estimates, SRC yield estimates, economic constraints, Aylott 2010, Estimating the supply of biomass from SRC in England, given social, economic and environmental constraints to land availability
  - Yield increases for SRC, Miscanthus, Hastings 2014, The technical potential of Great Britain to produce ligno-celloulosic biomass for bioenergy in current and future climates
  - Unconstrained potential for energy crop production in the UK: Global Change Bioenergy 2014, The availability of land for perennial energy crops in Great Britain
  - Used to sense check planting rate and energy crop area assumptions: Defra 2014, Area of crops grown for bioenergy in England and the UK: 2008-2013
  - Used as input to land available for energy crops: Energy policy 68 May 2014, Securing a bioenergy future without imports; Biomass and bioenergy 34 (2010), Biofuel production potentials in Europe: sustainable use of cultivated land and pastures, part II: Land use scenarios
  - Energy crop yields, farm gate prices: Global Change Bioenergy (2013), Estimating UK perennial energy crop supply using farm scale models with spatially disaggregated data

- Miscanthus yield. Production cost. Global change bioenergy 2012, Economic and GHG costs of Miscanthus supply chains in the UK
- Used to sense check land available for energy crops: Burgess 2009, Agricultural technology and land use futures; Hastings 2014, The technical potential of Great Britain to produce ligno-cellulosic biomass for bioenergy in current and future climates
- Use to assess constraints on uptake of perennial crops: Yemshanov 2015. A real options- NPV approach to assessing land use change: a case study of afforestation in Canada
- Arable crop yields in the UK: Defra 2014, Farming statistics: provisional crop areas, yields and livestock populations at June 2014- UK
- Yields, costs: NIX 2014 John NIX fam management handbook
- Energy content of biomass fuels: DUKES 2014, Digest of UK energy statistics; Biomass energy centre website (n.d.)

- Food waste for AD:
    - Background information: Digest of Waste and Resource Statistics – 2015 Edition
    - Data to estimate England Household Waste Arisings to 2020 are taken from: Defra Household Waste Arisings Forecasts for England 2013, first published October 2013
    - Recycling rates for England (2014): Statistics on waste managed by local authorities in England in 2013-2014, Defra Statistics Notice 2014
    - Baseline of waste arisings for England: Defra published Local Authority Collected Waste Management Statistics for England (n.d.)
    - Future recycling rates in Wales: Towards Zero Waste - the Overarching Waste Strategy Document for Wales (n.d.)
    - Household Waste Arisings and recycling rates in Wales: Stats Wales Local Authority Municipal Waste
    - Household Waste Arisings in Scotland: 2013 Household Waste Official Waste Statistics, Scotland waste statistics
    - Future recycling rates in Scotland: Scotland's Zero Waste Plan, Scottish Parliament (n.d.)
    - Household waste and treatment in Northern Ireland: Northern Ireland Local Authority Collected Municipal Waste Management Statistics Annual Report 2013-14
    - Quantity of C&I waste in England: DECC Solid Waste Data spreadsheet (n.d.)
    - Estimated total food waste available in English household waste stream: WRAP, 2013, Synthesis of Food Waste Compositional Data 2012
    - Percentage of food waste in household waste in Wales: WRAP 2010, The composition of municipal solid waste in Wales
    - Household organic waste composted/AD: Stats Wales 2013/14, Waste managed (tonnes) by management method and year
    - Percentage of food waste in MSW: DOE Environment and Heritage Service, 2008, Waste composition analysis of municipal solid waste in Northern Ireland
    - Separately collected organic household waste in Northern Ireland: NIEA (2014), Northern Ireland Local Authority Collected Municipal Waste Management Statistics Annual Report 2013/2014
    - Food Waste generated in C&I Sector, WRAP (2015), Estimates of Food and Packaging Waste in the UK Grocery Retail and Hospitality Supply Chains
- Forestry residues:
    - Starting point for the feedstock potential figures: Forestry Statistics 2014
    - To estimate proportions of SRW, forestry residues and Sawmill residues from raw figures: CSORT model 2011

  - To calculate timber availability forecast figures for consistency with sustainable management and LULUCF Stretch Scenario: CARBINE model 2016
- Landfill gas:
  - Landfill methane production data; waste receipts; waste composition: Ricardo-AEA for DECC (2014), MELMod landfill gas model, produced in support of the Greenhouse Gas inventory for 2013
  - Landfill methane production data, proportion of landfill methane collected and combusted in flares and engines 2014 to 2035: DECC (2015), forecasts of landfill methane production for 2014 to 2035, spreadsheet provided to Ricardo-AEA (updated 11/08/15)
  - Quantity of methane collected and combusted in engines: DECC (2014), Digest of UK Energy Statistics
  - Quantity of methane collected and combusted in flares: Environment Agency (2010 - 2014), Operator data on landfill methane flaring
- Renewable fraction of waste of MSW and commercial and industrial waste:
  - Figures to estimate England Household Waste Arisings to 2020 (Central Scenario): Defra Household Waste Arisings Forecasts for England 2013, first published October 2013
  - Recycling rates for England (2014): Defra Statistics Notice 2014
  - Baseline of waste arisings for England: Defra published Local Authority Collected Waste Management Statistics for England
  - Future recycling rates in Wales: Towards Zero Waste - Wales Waste Strategy
  - Household Waste Arisings and recycling rates in Wales: Local Authority municipal waste reuse/recycling/compositing rates by local authority (Wales)
  - Household Waste Arisings in Scotland: 2013 Household Waste Official Waste Statistics
  - Future recycling rates in Scotland: Scotland's Zero Waste Plan, n.d.
  - Future recycling rates in Northern Ireland: n.d.
  - Household waste and treatment in Northern Ireland: Northern Ireland Local Authority Collected Municipal Waste Management Statistics Annual Report 2013-14
  - Quantity of C&I waste in England: DECC Solid Waste Data spreadsheet. DECC 2015.
  - Quantities of RDF export: Environment Agency 2014. Records of International Shipments of Refuse Derived Fuel (RDF)
  - Percentage of biodegradability of waste to landfill: Defra 2014. Analysis of biodegradability of residual waste based on subtraction of diverted materials
- Sawmill residues:
  - Timber availability forecast figures: CARBINE 2016 model, CSORT 2011 used to allocate harvest to different fractions.
  - Proportions of SRW, forestry residues and Sawmill residues from raw data from CARBINE or FAOSTAT, CSORT 2011
  - Forestry Statistics 2014 use for feedstock potential figures
- Sewage sludge (watery residues and semi-solid materials that are produced as a result of sewage treatment of municipal wastewater):
  - Baseline arisings of sewage sludge (2014). Advanced Biofuel Feedstocks – An Assessment of Sustainability, 2014
  - Indication that AD of sewage sludge will increase: Water and Sewerage Journal, Trends in Sewage Sludge Treatment and Disposal, Rod Palfrey, n.d.
- Short rotation forestry:

    - Maximum land potentially available for SRF planting from NNFCC (2008) Addressing the land use issues for non-food crops, in response to increasing fuel and energy generation opportunities
- Small roundwood:
    - Carbine model from Forest Research, Carbine 2016
    - Estimate proportions of SRW, forestry residues and sawmill residues from raw figures from CARBINE or FAOSTAT: CSORT model from Forest Research, CSORT 2011
    - Usage of SRW for applications such as by panelboard and paper and pulp industries:
    - Forestry Statistics 2014
- Waste wood:
    - Baseline of waste wood markets: Wood Recyclers' Association market report for 2013
    - Quantity of waste wood to landfill: DECC Solid Waste Data spreadsheet
    - Data on quantity of waste wood used for panelboard manufacturing: WRA Magazine Spring/Summer 2015, Wood Recycling - The Magazine for wood recycling and biomass professionals
    - Waste wood arisings: AEA report for Defra on Environmental Impact of Management Options for Waste Wood, Defra 2010
    - Waste wood arisings and markets: Defra 2012, Wood waste: A short review of recent research
- Wet manure for AD (from cattle and pigs):
    - Percentage of outdoor herd of pigs, proportion on of pigs on straw base systems: CIWF (2013), Compassion in world farming, Statistics: Pigs
    - Livestock numbers UK: Food and Agriculture Policy Research Institute (FAPRI)- UKProject - DO108, n.d.
    - Unconstrained feedstock: Defra (Dec 2005). Assessment of Methane Management and recovery options for livestock manures and slurries
    - Data on the value and nutrient content of excreta from different livestock sectors, Defra (2010), Fertiliser Manual (RB209) 8th Edition
    - Exclusion of FYM as a feedstock: WRAP, 2013. The Methanogen Drygestore. WRAP Project Code: OIN001-010

Quality rating analysis: Overall the approach is systematic and transparent and takes a consistent approach to estimating potential and the impact of constraints for each feedstock. The model update is recent but some underlying data is slightly old, depending on the feedstock. The main feedstock that this could be expected to impact is energy crops (Miscanthus, SRC and SRF). Although the energy crop deployment has been delayed since the 2011 model, the planting rate still seems unrealistic in the near term given the lack of any planting today, so we expect that the potential for energy crops to 2050 is overestimated. The quality rating is summarised for each feedstock below:

- Arboricultural arisings: The approach is transparent but the data sources are relatively outdated (published between 2008 and 2014).
- Biomethane crops: The approach is transparent and most of the data is relatively recent.
- Energy crops (SRC willow and Miscanthus): The key sources are based on current data. Sources date back to the period between 2010 and 2015, thus some data is relatively outdated (i.e. older than five years). Future planting rates are ambitious and highly uncertain. They do not reflect what has been seen in recent years and so may overestimate the near-term potential for energy crops.

- Dry agricultural residues: Cereal straw data is from an AHDB report of 2013 but poultry litter from the biomass energy centre website is relatively outdated and seed husks and hulls data is based on previous report for this model in 2010 because of a lack of more recent data, as reported by Ricardo.
- Food waste for AD: Food waste data for the UK are relatively recent with most of the data sources dating back between 2013 and 2015. However, some data sources are outdated (e.g. percentage of food waste in MSW: DOE Environment and Heritage Service, 2008, Waste composition analysis of municipal solid waste in Northern Ireland). This is a key data point to determine the renewable share of waste and can be expected to have changed since 2008 as waste separation initiatives have increased, although this particular source only covers the share of waste from Northern Ireland.
- Forestry residues: The data are largely recent, apart from one data set which is used to estimate proportions of small roundwood, forestry residues and sawmill residues which is based on CSORT 2011.
- Landfill gas: The underlying data is recent, but note that landfill has today is largely used for electricity generation rather than for biomethane.
- Renewable fraction of waste of MSW and commercial and industrial waste: The underlying data is to a large extent recent, including the key data from Defra.
- Sawmill residues: The underlying data is recent except for output from CSORT model 2011.
- Sewage sludge (watery residues and semi-solid materials that are produced as a result of sewage treatment of municipal wastewater): Data is recent.
- Short rotation forestry: The underlying data is outdated (from 2008). Planting of SRF in the model has been delayed to reflect the current situation, but this still seems ambitious compared to very low planting rates today and may need delaying further.
- Small roundwood: The underlying data is recent except for output from the CSORT model 2011.
- Waste wood (produced by construction and demolition, commercial and industrial and from household waste): Some of the underlying data is outdated, e.g. Waste wood arisings: AEA report for Defra on Environmental Impact of Management Options for Waste Wood, Defra 2010; Waste wood arisings and markets: Defra 2012, Wood waste: A short review of recent research.
- Wet manure for AD (from cattle and pigs): Mixture of relatively recent and more outdated sources.

Relevance rating analysis: Highly relevant source, covering availability of crops from the UK and globally suitable for biomass-derived gas production in the UK from now until 2050 in a consistent and transparent manner. Model covers feedstock deployment and GHG, but no detailed cost data.

2.2.2 Bioenergy supply chain in the UK - High level review UK Bioenergy Feedstock Demand Analysis (Ecofys for BEIS, 2016, Not published)

Plain English description of evidence: The objective of the project was to study the current and future sectoral usage of bioenergy feedstock in the UK, identifying tensions and potential challenges. To do so, the report focuses on two topics:

- **Biomass Supply/Demand**: Investigation into the competing demands and end uses for current and future biomass resources, bringing out the tensions within and between sectors for particular bioenergy feedstocks
- **Policy**: Examining the key policies and regulations on bioenergy feedstock availability to assess cross sectoral tensions for bioenergy supply

How the work was undertaken: To carry out the demand analysis for bioenergy feedstock in the UK, it was necessary to first identify and quantify the key biomass and waste feedstocks that are currently used for bioenergy purposes and also likely to be used in the future. The work was carried out by desktop quick-scan of reports, publications, studies, news articles, factsheets and web pages.

Key assumptions taken and scenarios modelled. Most of the references found date back to before 2010 and make assumptions on the at-the-time projections towards 2015. Very little information was provided on potential future evolutions towards 2030 or 2050.

Key report outcomes: Section 3 of the report tabulates the findings of the supply/demand and policy analysis for a range of biogenic feedstocks, including wastes. It is divided, per category of feedstock, into:

- Current situation
- Future prospects
- End uses
- Sector interests
- Comments including any policy influences

Output graphs showing current and future availabilities of the feedstocks covered are shown below:

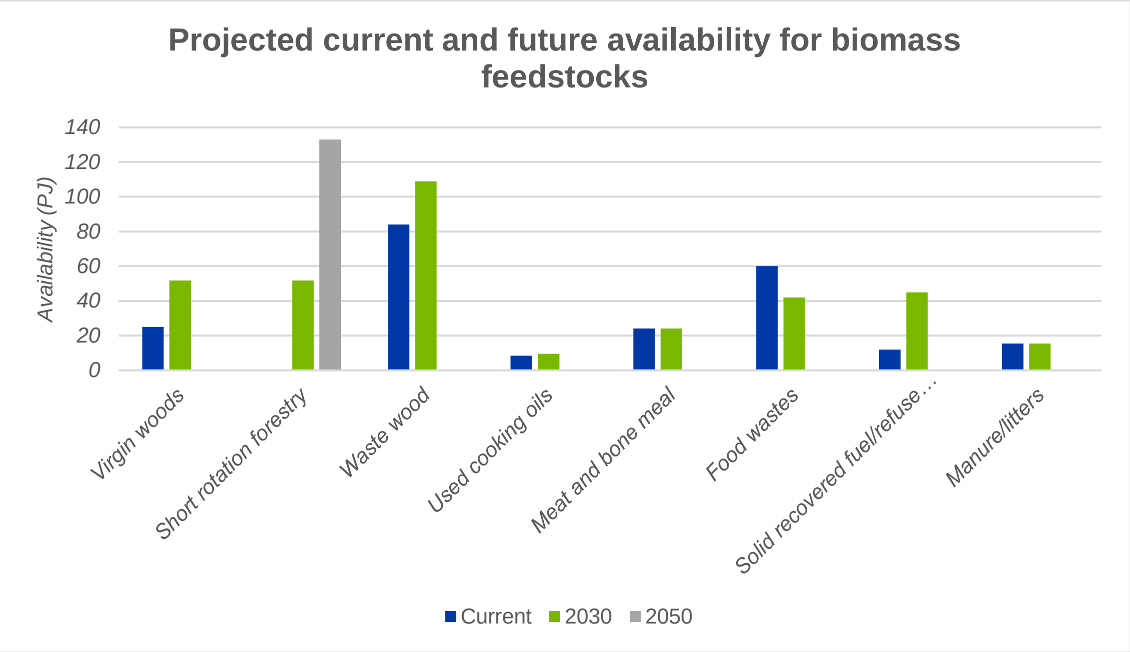

Figure 2-1. Current and future demand for virgin biomass and biogenic and biogenic fraction wastes and residues feedstocks.

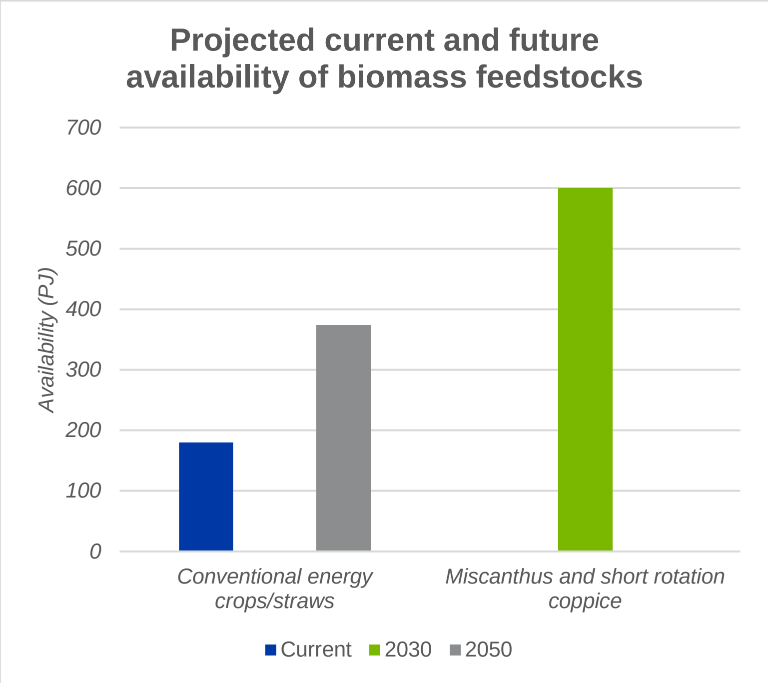

Figure 2-2. Current and future availability for virgin biomass feedstocks.

Dependencies on other evidence sources: The report cites many government statistical reports and government commissioned studies. Key sources of evidence are from the following ETI reports:

- ETI, 2015a, *Bioenergy: Enabling UK biomass* http://www.eti.co.uk/wp-content/uploads/2015/09/3504-Biomass-Insights-Lores-AW.pdf
- ETI, 2015b, *Bioenergy Insights into the future UK Bioenergy Sector, gained using the ETI's Bioenergy Value Chain Model (BVCM)*

Quality rating analysis: The report covers a wide range of biogenic feedstocks and gathers supply/demand information from a wide range of government statistical reports, industrial sector reports and reports commissioned by non-partisan bodies such as ETI and CCC. The report aims to provide forecast feedstock availability to 2050 where reliably sourced.

Relevance rating analysis: The report provides a meta-study of current and future energy crop and waste feedstock availabilities together with demand side information as forecast by a variety of sources.

2.2.3 UK TIMES (BEIS, 2017)[3]

Plain English description of evidence: The UK TIMES (The Integrated MARKAL-EFOM System) energy systems model (UKTM) is a partial equilibrium, bottom-up, dynamic, linear programming optimisation model. UKTM generates scenarios for the evolution of the UK energy system based on different assumptions around the evolution of demand and future technology costs, measuring energy system costs and GHG associated with the scenario.

[3] https://www.gov.uk/guidance/2050-pathways-analysis#the-analysis

UKTM was developed by UCL Energy Institute's whole SEM team, and was one of the principal tools used by DECC's Central Modelling Team in setting the UK's 5th carbon budget.[4]

How the work was undertaken: The underlying basis for UKTM is UK MARKAL[5], a technology-focused energy systems dynamic cost optimisation model. A revised bioenergy sector was developed by the TSEC-BIOSYS programme as a research version (BIOSYS-MARKAL) of the UK production version of UK MARKAL. According to UK TIMES (2017), the original source of the bioenergy costs and assumptions are taken from Table A1 in Jablonski et al. (2010)[6] and Jablonski et al. (2009[7]). The definitions of processes and commodities is given in Jablonski et al. (2008)[8]. Some parameter values have since been updated, but those updates have not been published in detail.

Key assumptions taken and scenarios modelled: The model version assessed was "uktm_model_v1.2.3_d0.6.1_DNP" as published on 9 May 2017. The "Resources" and "Process" data worksheets were assessed in this review.

UKTM is calibrated in 2010 (base year), and therefore represents the existing technologies and production routes at that time, along with their corresponding costs. The model can be run for the desired time horizon (up to 2050) and the internal time periods are treated in a flexible manner via different interpolation and extrapolation options.

Resources: The biomass resource estimates to 2050 are taken from the UK and Global Bioenergy Review and are based on the "low low" £4/GJ scenario "Amount available for bioenergy at £/GJ if no constraints overcome and competing feedstock demands are also met".

Biomass resource costs are provided in £/MWh are based on a variety of evidence sources. Wastes (including sawmill co-products) are all assigned zero cost (i.e. with no gate fee assumed) based on "discussion with the Committee on Climate Change". Costs are converted from £/MWh to £m/PJ. Costs are fixed over the period 2010 to 2050.

Bioenergy resources, commodities and processes, both imported and domestically produced are assumed to have zero GHG emissions in the present model version.

Key report outcomes: The feedstocks and processes which are reportedly most significant in terms of impact are the following, the last three of which are highly relevant to this study:

- imported biodiesel and bioethanol for road transport fuels
- imported biokerosene for air transport fuel
- imported wood pellets for boilers (heat) and for electricity generation
- biomethane (grid injection) from wastes and from UK-grown energy crops

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[4] http://www.wholesem.ac.uk/documents/uktm-documentation

[5] UK MARKAL was originally developed to provide insights for the UK Energy White Paper 2003.

[6] Jablonski et al. (2010), The role of bioenergy in the UK's energy future formulation and modelling of long-term UK bioenergy scenarios, Energy Policy, 8 (2010) 5799–5816.

[7] Jablonski et al. (2009), Proposed dataset for improved UK-MARKAL bioenergy structure - MARKAL Working Paper 2bis, Imperial College London.

[8] Jablonski et al. (2008), A systematic assessment of bioenergy representation in the UK MARKAL: Insights on the formulation of bioenergy scenarios, TSU Working Paper No. 1040.

- and potentially: SNG and hydrogen from imported wood chip or wood pellets

Dependencies on other evidence sources: The UK and Global Bioenergy Resource Model is a key dependence for the model. Biomass costs are based on a variety of reference sources, including E4tech (2010) "Biomass prices in the heat and power sectors in the UK", E4tech (2011) TINA bioenergy analysis for Carbon Trust, Nix (2011) Farm Management Pocketbook, E4tech (2009) "Biomass supply curves", NNFCC (2010) “Evaluation of bioliquid feedstocks and heat, electricity and CHP technologies” and the Committee on Climate Change. UK MARKAL is also a key dependency.

Quality rating analysis: UKTM is a comprehensive cost optimisation model of the UK energy sector. Included in the model are bioenergy pathways covering heat, power and transport. The set-up of the worksheets could be improved to aid transparency and facilitate review. Specific points include a general lack of referencing or in some cases the use of incomplete referencing (e.g. “Mott McDonald 2010”) and the use of hard-coded numbers without references. In addition, different formulae are applied in data series within tables, making it difficult to follow the calculations. Finally, data could be better labelled to aid transparency and facilitate review.

The biomass resource costs for primary products and agricultural residues are several years old (2009 or 2011). A simplifying assumption is made for waste feedstocks which are all assumed to be zero cost (i.e. with no gate fee), which is not reflective of current market conditions. For example, in the market today food waste, wood waste and refuse derived fuel (RDF) all currently command a gate fee, while sawmill co-products and used cooking oil both command a price.

Relevance rating analysis: UKTM is not considered to be a directly relevant source for obtaining detailed feedstock resources or feedstock costs estimates. The feedstock resource estimates are based on one scenario of the UK and Global Bioenergy Resource Model, which should be referred to. The feedstock cost estimates are several years old, or otherwise based on simplifying assumptions which are not fully representative of the current market.

2.2.4 Review of Bioenergy Potential (Review of UK feedstock availability for bioSNG) (E4tech & Anthesis for Progressive Energy / Cadent, June 2017)[9, 10]

Plain English description of evidence: Progressive Energy commissioned a study (financed by Cadent Gas Ltd) to review how much renewable gas (in TWh per year) could be supplied from sustainably sourced UK waste and non-waste biomass up to 2050. The study included biomethane based on biogas from AD as well as synthetic (substitute) natural gas and hydrogen from advanced thermal conversion. The study is a critique of the Climate Change Committee (CCC) UK biomass feedstock estimates in their 2011 Bioenergy Review. The study is published in two report formats: a “Summary” version and a detailed “Technical” report.

How the work was undertaken: The study was a desk-based review. The biomass feedstock part was undertaken by E4tech and the waste feedstock part undertaken by Anthesis.

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[9] https://cadentgas.com/getattachment/About-us/The-future-role-of-gas/Renewable-gas-potential/Promo-Downloads/Cadent-Bioenergy-Market-Review-SUMMARY-Report-FINAL.pdf

[10] https://cadentgas.com/getattachment/About-us/The-future-role-of-gas/Renewable-gas-potential/Promo-Downloads/Cadent-Bioenergy-Market-Review-TECHNICAL-Report-FINAL.pdf

Key assumptions taken and scenarios modelled: The approach applied to estimate the potential estimates is summarised in Figure 2-3.

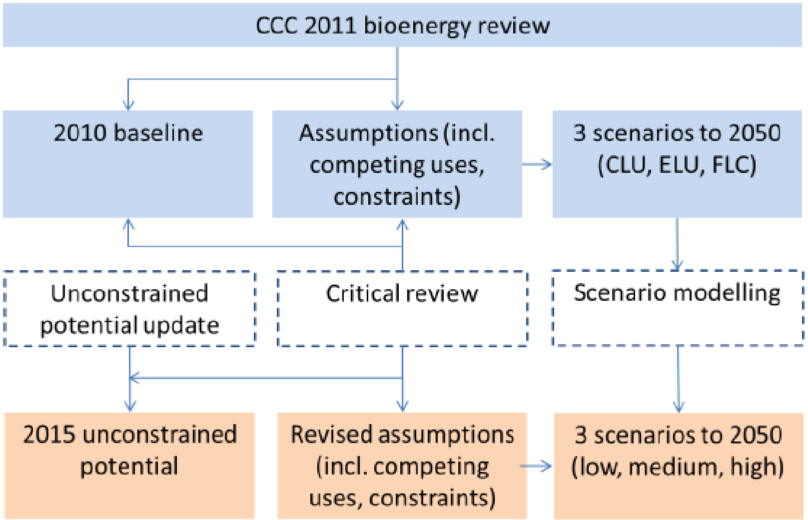


Figure 2-3. Methodology. (Figure 1 in the Summary report.)

The potential estimate was based on the following feedstocks.

- **Wastes:** Local authority collected waste (LACW), Commercial & Industrial (C&I) waste Construction and demolition (C&D) wastes, sewage sludge. (Tallow and UCO were excluded.)
- **Non-wastes:** Dedicated energy crops, residues (agricultural, arboricultural arisings, forestry, SRF, small round wood, sawmill co-products, wet animal manures, macro algae.

The report applied the following key assumptions for waste feedstocks:

- **Waste arising growth:** Derived from UK Government population and economic growth estimates.
- **Recycling rates:** Based on the achievement of EU and UK national targets, with additional 'stretch' targets modelled for particular scenarios.
- **Long-term contracting for residual waste treatment:** Not assumed to constrain material from being available for renewable gas production, as all such contracts will expire within the forecast period to 2050.
- **Refuse Derived Fuel (RDF):** Current export is available for future renewable gas production to 2050.

The non-waste feedstock potential was estimated as follows:

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

The *unconstrained potential* is the total feedstock resource that is available in the UK before any competing uses or constraints are applied. *Competing uses* refer to non-energy uses of the feedstock (*price independent* - constant throughout each of the scenarios and *price dependent* - vary per scenario). The *constraint factor* accounts for technical, market, regulatory and infrastructure factors which can limit the potential of the feedstock.

Table 2-3 presents the barrier conditions chosen under each CCC scenario. These correspond to the constraint factors which are used to determine the bioenergy potential.

Table 2-3. Description of the characteristics of the CCC scenarios. (Table 16 of the Technical report.)

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

Note: Low, medium and high bioenergy prices correlate with £4/GJ, £6/GJ and £10/GJ prices used in the AEA and CCC reports.

For dedicated crops, it is assumed that 600,000 ha are used in the UK in the Medium scenario to 2050 (with a range of 300,000 to 1,150,000 ha in the low and high scenarios). The Medium scenario also assumes a yield range of 11-14 odt/ha/yr. Assumptions for other feedstocks, including on competing uses, are summarised in Table 30 of the Technical report.

A conversion efficiency of 72% was assumed for the conversion of bioenergy potential to renewable SNG potential.

Key report outcomes: The report estimates a potential of **73 TWh** for waste feedstocks in 2050 in the medium scenario with a relatively narrow range of uncertainty from **64 to 77 TWh** for the low and high scenarios. Residual and wood wastes are the largest contributors. (See Figure 2-4.)

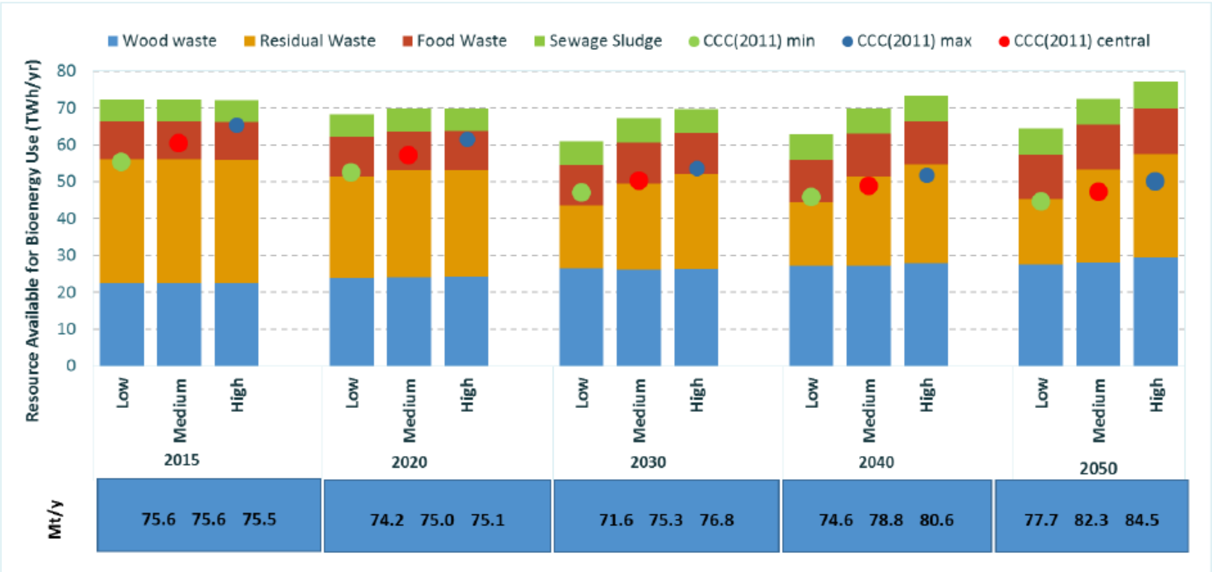


Figure 2-4. Waste resources available for bioenergy use, including CCC, to 2050. (Figure 3 in the summary report.)

The report estimates a similar potential for non-waste feedstocks of **76 TWh** of bioenergy potential in 2050 in the medium scenario. However, in contrast with waste feedstocks there is a larger degree of uncertainty in the low and high scenario estimates (of **30 to 173 TWh**). Energy crops are the largest contributor in terms of potential as well as uncertainty. The report indicates that scaling the energy crops industry is challenging and expensive, awareness amongst farmers and land owners remains low, and dedicated policy support would be critical for the industry to realise its potential (see Figure 2-5.)

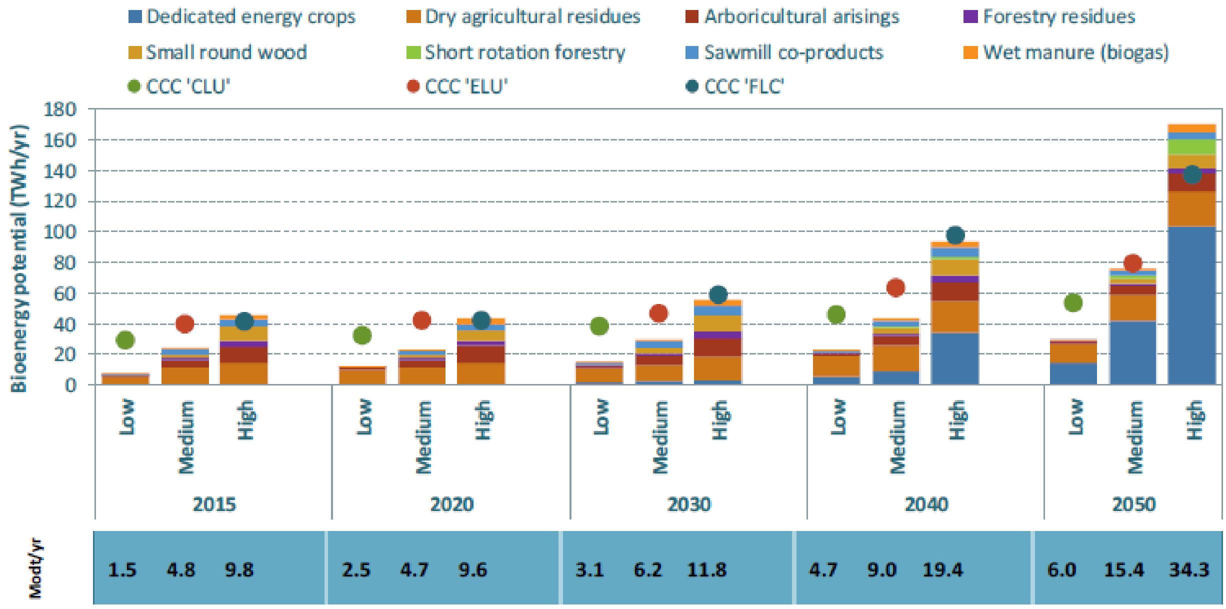


Figure 2-5. Non waste bioenergy potential for each scenario, including CCC, to 2050. (Figure 4 in the summary report.)

Based on the revised assumptions for feedstock arisings, the modelling undertaken for this study results in a total estimated bioenergy potential of **149 TWh** in 2050 for the medium scenario, ranging from **94 to 250 TWh** under the low and high scenarios. (See Figure 2-6.) Under the medium 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.

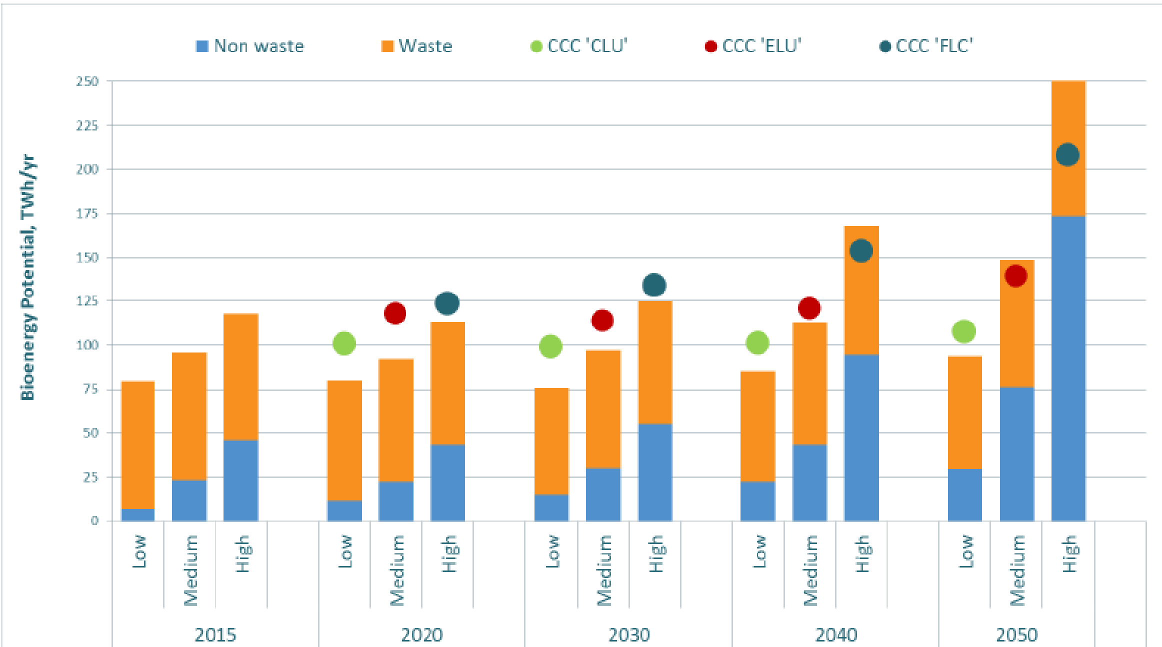


Figure 2-6. Bioenergy potential for each scenario, including CCC, to 2050. (Figure 5 in the Summary report.)

The bioenergy potential in Figure 2-6 was converted into renewable gas potential of around **108 TWh** in 2050 under the central scenario, with a range of **77 to 174 TWh** in the low and high scenarios (see Figure 2-7)

- 47 to 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 to 127 TWh from non-waste feedstock, with 97% of this coming energy crops, SRF and wood/forestry residues converted to bioSNG and the remaining 3% from biomethane via AD of wet manures and macro-algae.

Figure 2-7. Renewable gas potential 2015 to 2050. (Figure 6 in the Summary report.)

Dependencies on other evidence sources: Key data sources include the CCC's Bioenergy Review (2011) and Ricardo (2017) (see section 2.2.1), along with a number of additional sources published by: Defra, Forestry Commission, Food and Agricultural Policy Research Institute (FAPRI), National Non-food Crops Centre (NNFCC) and BEIS. The data sources used are fully described in chapters 2 and 3 of the Technical report.

Quality rating analysis: Very recent study. The approach applied is robust and very transparent (e.g. underlying assumptions and data applied).

Relevance rating analysis: Highly relevant source, covering both domestic waste and non-waste feedstock potential for renewable gas production in the UK from 2015 to 2050. The potentials are presented in a disaggregated format.

2.2.5 Forestry Statistics 2017 and Forestry Facts and Figures 2017 (Forestry Commission 2017)[11]

Plain English description of evidence: The UK Wood Production and Trade Statistics on UK wood production and trade are released twice yearly by the UK Forestry Commission. Detailed statistics are published in the web publication Forestry Statistics 2017, with an extract in Forestry Facts & Figures 2017 (and available in Excel format). They include UK statistics on woodland area, planting, timber, trade, climate change, environment, recreation, employment and finance and prices as well as some statistics on international forestry.

How the work was undertaken: The latest National Statistics on forestry produced by the Forestry Commission were released on 28 September 2017. Woodland area is based on National Forest Inventory (GB) and Forest Service estimates (NI). International data on forest area and carbon stocks are obtained from the Global Forest Resources Assessment (FRA) 2015[12], compiled by FAO.

Key assumptions taken and scenarios modelled: The report shows a stacked bar chart illustrating the area of woodland that is certified in the UK by its constituent countries, England, Wales, Scotland and Northern Ireland since December 2001. The area of certified woodland has increased over most of the period, from 1.1 million hectares in December 2001 to around 1.4 million hectares in the last few years. Figure 1.7 of the report is a stacked area chart illustrating the area of restocking in England, Wales, Scotland and Northern Ireland from 1976 to 2016. In the period 1976 to 1993, the area of restocking in the UK increased steadily from around 7,000 hectares to 17,000 hectares. The report also shows a line chart showing UK production, imports, exports, and apparent consumption since 1999. The chart shows that production and exports have remained very stable since 1999, while imports and apparent consumption dropped sharply in 2008 and again in 2009. Both apparent consumption and imports have recovered since then, although imports remain at a level lower than before 2008.

Key report outcomes: The key points from the latest releases are:

- The woodland area in the United Kingdom in 2017 is 3.17 million hectares. This represents 13% of the total land area in the UK[13], 10% in England, 15% in Wales, 18% in Scotland and 8% in Northern Ireland.
- Of this, 1.39 million hectares (44%) are independently certified as sustainably managed.
- 7,000 hectares of new woodland were created in the UK in 2016-17.
- 11 million green tonnes of UK roundwood (95% softwood and 5% hardwood) were delivered to primary wood processors and others in 2016, representing a 2% decrease on 2015. Around 2 million green tonnes were delivered to the woodfuel market.
- An estimated 661,000 green tonnes (mainly softwood) of woodfuel were supplied by sawmills in 2016 and a further 65,000 green tonnes were supplied by round fencing manufacturers. 88% of the total woodfuel supplied was sold to the bioenergy market (including pellet producers).
- Estimated 1.6 million tonnes of recycled wood were used for woodfuel (increase of 7% on 2015).
- Wood products imported into the UK in 2015 were valued at £7.5 billion and included 6.6 million cubic metres of sawnwood, 3.4 million cubic metres of wood-based panels, 6.8 million tonnes of wood pellets and 5.9 million tonnes of paper.

[11] https://www.forestry.gov.uk/forestry/infd-7aql5b

[12] http://www.fao.org/forest-resources-assessment/en/

[13] This is significantly lower than the EU-28 average of 38%.

Dependencies on other evidence sources: Primarily national statistics, so not applicable. Data on waste wood is provided by the Wood Recyclers' Association and out of scope of the national statistics. Data on volumes of woodfuel supplied by industry is based on the Sawmill Survey and Survey of Round Fencing Manufacturers. Data on wood pellet production is provided by the UK Pellet and Briquette Production.

Quality rating analysis: High quality - the United Kingdom Statistics Authority has designated these statistics as National Statistics, in accordance with the Statistics and Registration Service Act 2007 and signifying compliance with the Code of Practice for Official Statistics.

Relevance rating analysis: The data source provides a comprehensive overview of the UK forestry sector (both current and historical). It is considered highly relevant.

2.2.6 Characterisation of biomass feedstocks database (Forest Research/Uniper for ETI, 2017)[14]

Plain English description of evidence: The Excel Workbook presents the data arising from all experiments carried out under the Characterisation of Feedstocks Project, commissioned by the ETI. The data set is for UK grown energy crop biomass (Miscanthus, SRC poplar/willow, coniferous/ broadleaf (poplar) SRF) and their pelleted versions. The database includes: the sites sampled, the conditions at the time of sampling, provenance data, soil laboratory results and detailed biomass laboratory results.

The database includes a cost breakdown worksheet which details the various costs of production per grown hectare for each of the species sampled and crop costs ex-farm per oven dried tonne.

How the work was undertaken: In this project, over 520 samples were taken, covering several types of UK-grown biomass, produced under varying conditions. The biomass sampled included Miscanthus, SRF and SRC. The samples were tested to an agreed schedule in an accredited laboratory. The results were analysed against the planting, growing, harvesting and storage conditions (i.e. the provenance) to understand what impacts different production and storage methods have on the biomass properties.

Key assumptions taken and scenarios modelled: The samples were taken during a range of feedstock studies designed to look at the impacts and characteristics resulting from changes to growing, harvesting and production parameters to examine:

- the impact of climate zone, soil type, harvesting time, and storage on Miscanthus, SRC willow, SRC poplar, SRF poplar and conifer
- the variation between and within fields of Miscanthus and SRC willow
- the feedstock characteristics of SRC willow and SRF poplar leaves
- the feedstock characteristics of Miscanthus before and after pelletising
- the impact of harvest time on Miscanthus characteristics
- the impact of harvest time on SRC willow characteristics
- the impact of varieties on SRC willow characteristics
- the impact of storage time on Miscanthus characteristics

[14] http://www.eti.co.uk/programmes/bioenergy/characterisation-of-feedstocks

Samples represent commercial crops and samples of Sitka spruce harvested at approximately 15-years old from forests normally managed for longer rotation lengths. This is done to represent conifer short rotation forest crops as dedicated SRF is not practiced in the UK at this time.

Key report outcomes: As well as quantitative data on UK energy crop feedstock characteristics and costs, the study provides detailed qualitative information including: ultimate, trace element and ash composition analyses which can be manipulated to determine analyses for 'average' biomass, suitable to provide information to biomass gasification experts when assessing the suitability of the various technologies.

Another outcome is the feedstock at farm cost determinations with a breakdown of cost apportionment through the growth-harvest process (see Table 2-4).

Table 2-4. Summary of energy crop costs.

Biomass type	Ex Farm cost (£)	Delivered cost (£)
Miscanthus	74/odt	Not available
SRC willow	37/odt	Not available
SRC poplar	18/m^3	30-38/m^3
SRF poplar	75/odt	125-158/m^3

Dependencies on other evidence sources: The database is not dependent on any other evidence sources. All data has been derived from a fully provenanced sampling, supply chain and analysis methodology.

Quality rating analysis: The characteristics data provided is of high quality due to the quantity of biomass samples collected and analysed. It is also very recent. The sample provenance data has been collated to an agreed methodology and the samples analysed by a UKAS[15] accredited laboratory. The data can be manipulated by the user to extract key information for end treatment purposes. Although the report includes cost data for a range of UK energy crops, the underlying calculations are not provided and furthermore it is unclear what the sample basis for the data is. Costs data are also reported on both a m^3 and odt basis, making comparison between feedstocks more difficult.

Relevancy rating analysis: The data is UK specific, however it only covers crops grown for energy. Importantly, there is specific data covering SRF biomass which some projections forecast will be a key feedstock material from 2035 onwards.

2.2.7 Crops Grown for Bioenergy in England and the UK: 2015 (DEFRA, 2016)[16]

Plain English description of evidence: The report contains information on the areas of land in the UK devoted to the production of non-food energy crops. It also quantifies the amounts grown and provides high level information on the amounts grown in the major UK regions. The report focusses on the following crops:

[15] https://www.ukas.com/

[16] https://www.gov.uk/government/statistics/area-of-crops-grown-for-bioenergy-in-england-and-the-uk-2008-2015

- Areas and quantities of wheat, oil seed rape, sugar beet and maize for use in anaerobic digestion
- Areas and quantities of SRC willow and poplar, Miscanthus and straws grown specifically for energy production

The report is issued yearly and annual trend tables are shown going back to 2008 in many instances. An Excel dataset is published alongside the report.

The report also covers energy crops grown for biofuels and takes much of its data from the Renewable Transport Fuel Obligation (RTFO).

How the work was undertaken: The report is compiled from a variety of evidence sources. Statistics produced are a secondary analysis of those already published, mostly from UK National Statistics (see 'Dependencies on other evidence sources' below).

Key report outcomes: The report shows that 93,000 hectares of agricultural land were used to grow bioenergy crops in the UK in 2015, some 2% of all arable land available. The following table shows the crop usage for energy, other than transport fuel, during 2015.

Table 2-5. Summary of biomass costs, planted area and energy use in 2015.

Crop	Hectares	Total production (000's odt)	Energy use (000's odt)
Miscanthus	6,905	69 - 104	33
SRC willow	2,885	17 - 35	15
Straws	3,064	9,900	404
Maize for AD	52,280	300	300 (for AD use)

Note: Yields for Miscanthus and Willow are upper and lower yield estimates based on expert opinions.

Dependencies on other evidence sources: Sources of data include government commissioned surveys such as 'The June survey of Agriculture and Horticulture' in which farmers are asked about the area of crops grown as at 1 June; 'The Renewable Energy Statistics Questionnaire' RESTATS which gives an indication of the volume of UK grown crops which are processed into biofuels for use other than road transport and any that may be produced for export. Other sources of data are:

- Cereal and Oilseed Rape Production Survey
- Energy crops scheme
- Ofgem Renewable Obligation Annual Report - Biomass Sustainability Dataset
- WRAP Organics Recycling Survey 2012 and Survey of the UK anaerobic Digestion industry in 2013

Quality rating analysis: The data provided is based on UK National Statistics data and sector surveys. Much of the data has been collected annually since 2008 which enables trend analysis and as a result confidence in the data collected. Data is available in MS Excel format. Usage data is derived from Ofgem sustainability reports provided by generators.

Relevancy rating analysis: The study provides a detailed analysis of energy crops grown in the UK and their use for energy (provided in both pdf and Excel). It does not provide an analysis of woody biomass use for energy.

2.2.8 Estimates of Food Surplus and Waste Arisings in the UK (WRAP, 2016)[17]

Plain English description of evidence: This report compiles and presents a consistent picture of food waste arising, connecting various UK sources and statistics (Defra and other surveys from 2013 to 2016).

How the work was undertaken: This is a summary report based on various surveys undertaken on behalf of WRAP and Defra, between 2013 and 2016 (listed below).

Key assumptions taken and scenarios modelled: The overall food waste values from various surveys are ‘scaled’; to the total waste observed by DEFRA, as compiled in the Waste Data Flow database.

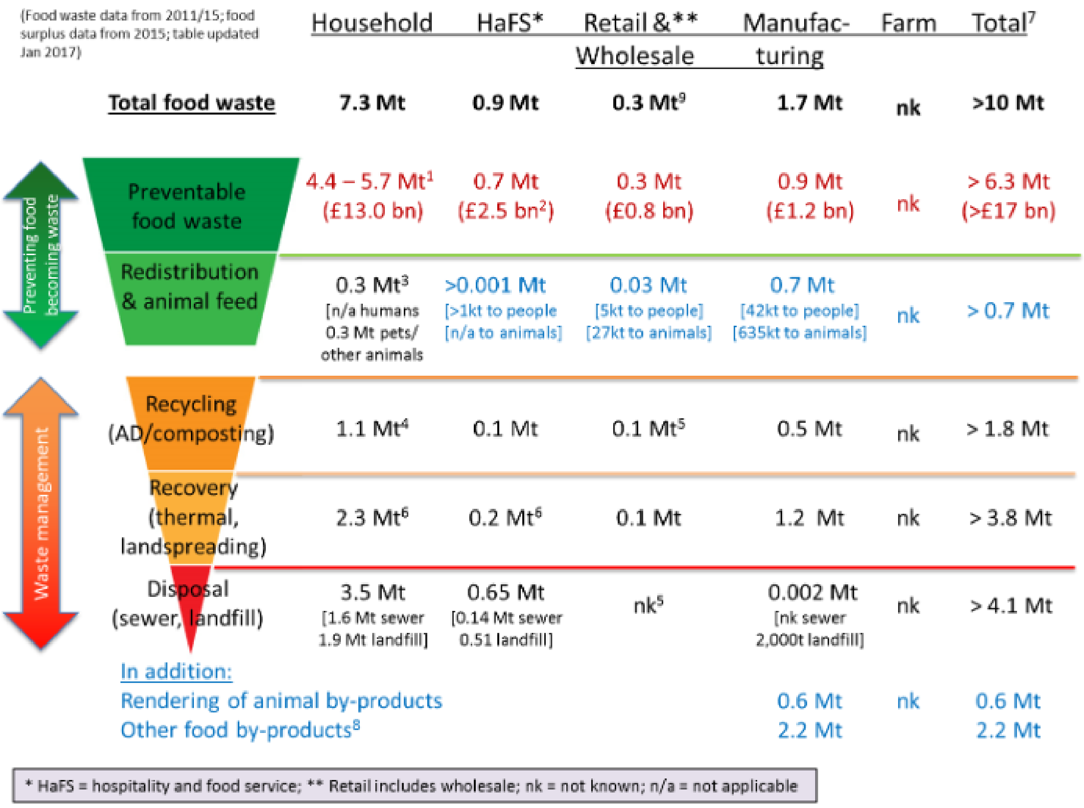
Key report outcomes: The report lists quantities of food waste arising. Total post-farm-gate food waste is estimated to be 10 Mt. Of this 70% is from households. It provides potential food cost saving and GHG emission savings.

Household food waste amounts to ~7.3 Mt/yr food & drink waste, the majority of which (4.4 Mt, having a carbon footprint of 19 MtCO_2e) is considered to be avoidable. The following breakdown is provided:

- 1.3 Mt/y is food that is avoided when eating (such as bread crusts, potato skins etc)
- 1.6 Mt/y is unavoidable (comprises egg shells, bones, fruit skins, tea bags etc)
- 2.0 Mt/y is avoidable (untouched or hold touched – apples, loaves, bacon etc)
- 1.3 Mt/y prepared/cooked excess to need
- 0.9 Mt/y accidents, personal hygiene related

Figure 2-8 (taken from the reference) shows the current management of food waste.

[17] http://www.wrap.org.uk/sites/files/wrap/Estimates_%20in_the_UK_Jan17.pdf



(Food waste data from 2011/15; food surplus data from 2015; table updated Jan 2017)	Household	HaFS*	Retail &** Wholesale	Manufac-turing	Farm	Total[7]
Total food waste	7.3 Mt	0.9 Mt	0.3 Mt[9]	1.7 Mt	nk	>10 Mt
Preventable food waste	4.4 – 5.7 Mt[1] (£13.0 bn)	0.7 Mt (£2.5 bn[2])	0.3 Mt (£0.8 bn)	0.9 Mt (£1.2 bn)	nk	> 6.3 Mt (>£17 bn)
Redistribution & animal feed	0.3 Mt[3] [n/a humans 0.3 Mt pets/ other animals	>0.001 Mt [>1kt to people [n/a to animals]	0.03 Mt [5kt to people] [27kt to animals]	0.7 Mt [42kt to people] [635kt to animals]	nk	> 0.7 Mt
Recycling (AD/composting)	1.1 Mt[4]	0.1 Mt	0.1 Mt[5]	0.5 Mt	nk	> 1.8 Mt
Recovery (thermal, landspreading)	2.3 Mt[6]	0.2 Mt[6]	0.1 Mt	1.2 Mt	nk	> 3.8 Mt
Disposal (sewer, landfill)	3.5 Mt [1.6 Mt sewer 1.9 Mt landfill]	0.65 Mt [0.14 Mt sewer 0.51 landfill]	nk[5]	0.002 Mt [nk sewer 2,000t landfill]	nk	> 4.1 Mt
In addition:						
Rendering of animal by-products				0.6 Mt	nk	0.6 Mt
Other food by-products[8]				2.2 Mt		2.2 Mt

* HaFS = hospitality and food service; ** Retail includes wholesale; nk = not known; n/a = not applicable

Figure 2-8. Summary of what is known about food waste and related material arisings in the UK, and the treatment and disposal routes of these. (Table 1 in study.)

Dependencies on other evidence sources: This reference links to Defra household waste statistics[18] and uses the following sources:

- **Households:** 'Household Food Waste in the UK, 2015'; WRAP (2016)[19];
- **Hospitality and Food Service:** 'Overview of Waste in the UK Hospitality and Food Service Sector'; WRAP (2013)[20] (data for 2011);
- **Wholesale:** 'Food surplus and waste in UK wholesale grocery, 2015'; WRAP (2016)[21];
- **Manufacturing:** 'Quantification of food surplus, waste and related materials in the grocery supply chain'; WRAP (2016); data on food waste for 2014, data for food surplus for 2015[22];
- **Retail:** Additional WRAP analysis of retail food waste based on 2015 BRC reported data; 'The Retail Industry's Contribution to Reducing Food Waste, Autumn 2016'[23] (data for 2015).

[18] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/481771/Stats_Notice_Nov_2015.pdf

[19] http://www.wrap.org.uk/content/household-food-waste-uk-2015-0

[20] www.wrap.org.uk/foodwastehafs

[21] http://www.wrap.org.uk/content/quantification-food-surplus-waste-and-related-materials-supply-chain

[22] http://www.wrap.org.uk/content/quantification-food-surplus-waste-and-related-materials-supply-chain

[23] http://brc.org.uk/making-a-difference/communities/tackling-food-waste

Quality rating analysis: This study is considered high quality. It presents a UK specific breakdown of food waste into constituent parts and is based on Defra and other survey data.

Relevancy rating analysis: Although this report covers current waste arisings (and not projections into the future) it points to possible areas where food waste arisings may change. For instance, future increases connected to population increase but also decreases (e.g. up to 50% of the food waste is considered avoidable) for use in sensitivity analyses.

2.2.9 Technology Innovation Needs Assessment: Bioenergy (E4tech & Carbon Trust for DECC, 2011)[24]

Plain English description of evidence: The report highlights the significant value of innovation opportunities in bioenergy that could reduce the costs of the UK meeting its decarbonisation targets; and the associated value add to the UK arising from international business development if UK organisations are successful in capturing market share based on their existing strengths. The report also discusses the main barriers and required innovation activities, highlighting the case for UK public sector intervention, before prioritising a set of recommendations.

The underlying workbooks contain deployment and cost data for a wide range of innovative biomass feedstocks and bioenergy conversion technologies, covering advanced biofuels, biomethane, biomass heating and unabated biomass power technologies, biochemicals, energy crops and algae.

How the work was undertaken: Mostly desk-based, with interviews to identify barriers, innovation priorities and potential impacts. Choices of scenarios, data sources and assumptions were regularly presented to a steering panel (which included DECC officials) throughout the project, and iterations made as required. Once agreed, deployment and cost data were used by E4tech to calculate the Value of Innovation and Gross Value Add (GVA) metrics to 2050 required under the TINA methodology, before the final models were handed to Carbon Trust for writing up.

Key assumptions taken and scenarios modelled: Low, Medium and High deployment scenarios are modelled for each feedstock (UK, imports and global), and for each conversion technology (UK and global). For energy crops, the unspecified UK consumption of domestic and imported biomass within the deployments was multiplied by an assumed percentage from energy crops. Macro-algae deployment was derived bottom-up from a maximum potential and UK scenarios for potential ramp-ups in sea areas. Cost data for energy crops and macro-algae were based on academic studies, with yield increases assumed over time. Cost data for biomass boilers, bioSNG and AD plants were taken from industry project data and policy impact assessment data (and the underlying consultancy studies).

Key report outcomes: The study estimated the Value of Innovation at £6-101 billion, with a GVA of £6-33 billion to the UK. Innovation priority areas were also highlighted where bioenergy offers the largest benefits to the UK:

- High efficiency biomass power technologies, robust to feedstock and CCS requirements
- Higher yielding energy crops grown on marginal land
- Lower cost advanced biofuels based on gasification, pyrolysis and ligno-cellulosic fermentation

Dependencies on other evidence sources: Global deployment numbers for energy crops were based on E4tech (2010) using Hoogwijk (2005) land areas, and macro-algae estimates were based on Ecofys (2008) data. UK

[24] http://www.lowcarboninnovation.co.uk/working_together/technology_focus_areas/bioenergy/

deployment of energy crops was based on old ETI ESME and CCC MARKAL scenario data to 2050, and assumptions regarding splits of deployments between energy crops and other biomass based on the DECC 2050 Calculator. UK macro-algae deployments are in line with the DECC 2050 Calculator.

The main pieces of evidence used for costs were NNFCC (2010) for bioSNG; Patterson (2011) and Mott MacDonald (2011) for AD plants. Biomass boiler costs were averaged from over 20 sources, including NERA (2009), Carbon Trust (2005), Poyry (2008, 2009), AEA (2006), Element Energy (2008, 2011), IEA (2008) and DTI (2007).

Quality rating analysis: The quality rating varies by feedstock or technology, but is generally Red (low) or Amber (medium). The data is now old, and required fairly significant transformations to fit into the required TINA format – with often the weakest step in the process being the assumptions around how to split unspecific scenario deployment data (from ESME, CCC, IEA) into the specific TINA sub-categories – or else how to extrapolate single or point year global data from IEA (given lack of background trajectory data). Model deployment scenarios do not necessarily start from current statistical data. The energy crop deployments have been superseded by the TINA refresh (section 2.2.10). The macro-algae UK deployments are still likely to be the most useful dataset available (although need delaying) and are similar to that used in the DfT Modes 1 project (although the TINA has a higher High scenario). The global macro-algae deployments in the TINA are effectively half of those in the DfT Modes 1 project. We note that the latest Ricardo model (section 2.2.1) does not include macro-algae.

The energy crop costs have been superseded by more recent, reliable industry data from ETI projects. Macro-algae costs are highly uncertain (and likely very high) given no commercial operations, and the underlying data sources are extremely old, but the TINA is one of the very few sources available. Biomass boiler and AD costs have been superseded by much more recent RHI scheme and industry data. The bioSNG plant data in the TINA is likely to still be useful for biomass feedstocks (same underlying source as used in the ETI BVCM database), although Progressive Energy are likely to have better waste to SNG industry data.

Relevance rating analysis: The quality rating varies by feedstock or technology. The energy crop and macro-algae deployment data is directly relevant, as are the cost datasets for energy crops, macro-algae, bioSNG, AD plants and biomass heating boilers.

2.2.10 Technology Innovation Needs Assessment: Bioenergy (refresh) (E4tech for DECC, 2015 – Not published)

Plain English description of evidence: The report highlights the significant value of innovation opportunities in bioenergy that could reduce the costs of the UK meeting its decarbonisation targets; and the associated value add to the UK arising from international business development if UK organisations are successful in capturing market share based on their existing strengths. The report also discusses the main barriers and required innovation activities for BECCS technologies, highlighting the case for UK public sector intervention, before prioritising a set of recommendations.

The underlying workbooks contain deployment and cost data for a selection of innovative biomass feedstocks and bioenergy conversion technologies, covering advanced biofuels, unabated biomass power and bioenergy with CCS (BECCS) technologies, perennial energy crops and new oil crops. This study is a partial refresh of the 2011 bioenergy TINA (see section 2.2.9).

How the work was undertaken: Starting from the basis of the 2011 bioenergy TINA, a brief scoping exercise was conducted to identify which feedstocks and conversion technologies had the largest future deployments, and which sectors had already departed significantly from their pathways projected in 2011 (typically due to lack of progress, i.e. deployments much lower than projected). These sectors were then prioritised for a refresh – this included woody and grassy energy crops, new oil crops, advanced biofuels, plus unabated combustion and gasification technologies.

The scoping also identified the need to add in biopower with CO_2 capture and biohydrogen with CO_2 capture, given their expected significant future deployment to meet UK climate targets. Deployments, costs, barriers and innovation needs were supplied for these BECCS technologies. Costs of unabated power conversion technologies were also updated to reflect new scale-up and commercialisation date assumptions.

Choices of scenarios, data sources and assumptions were regularly presented to a steering panel (which included DECC officials) throughout the project, and iterations made as required. Once agreed, deployment and cost data was supplied by E4tech to Carbon Trust, who then built the overall bioenergy TINA model to calculate the Value of Innovation and GVA metrics to 2050 required under the TINA methodology. Interviews were used to identify key barriers and market failures for BECCS, with findings and the draft report reviewed by the steering panel. At the end of the project, due to the unexpected cancellation of the UK CCS Competition, a 5-year delay in BECCS deployment was introduced.

Key assumptions taken and scenarios modelled: Low, Medium and High deployment scenarios are modelled for energy crop deployment (UK, imports and global). These use 2010-2015 actual data, and then use a ramp-up constraint until the scenario projections take over (as the model scenarios are often unrealistically high in the near-term). The global deployment of energy crops compared to primary biomass supply is applied as a % to the unspecified UK consumption of domestic and imported biomass, in order to derive UK deployment of energy crops.

The BECCS cost data was taken from a biomass IGCC power plant, but with the power generation unit (H_2 turbine) costs removed, to obtain bioH_2+CO_2 capture plant costs. “BAU”, “Expected” and “Stretch” cost reductions use projected savings by 2050 (based on component savings from the 2011 TINA), and intermediate years are back-cast using global deployment to derive learning curves.

Key report outcomes: The study estimated the Value of Innovation at £3-71 billion, with a GVA of £5-29 billion to the UK. Innovation priority areas were also highlighted where bioenergy offers the largest benefits to the UK:

- Demonstration of negative emission BECCS technologies at scale
- Proving the flexibility of gasification technologies to serve several different markets
- Higher yielding, cheaper to establish, sustainable energy crops
- Commercialisation of drop-in advanced biofuels

Dependencies on other evidence sources: The study relied on the previous 2011 bioenergy TINA analysis for those technologies or feedstocks where updating data was not in scope of this study. For the new analysis in this study, global deployment numbers were updated based on existing bottom-up estimates and databases of near-term planned plants, new IEA ETP scenario data and IPCC AR5 scenario data to 2050. UK deployment numbers were updated based on current UK statistics, new ETI ESME scenario data to 2050, and updated splits of global deployments. The main pieces of evidence used for BECCS costs were the ETI TESBIC and BVCM projects.

Quality rating analysis: The quality rating varies by feedstock or technology, but is generally Amber (medium). The data is recent, based on authoritative sources, but often required fairly significant transformations to fit into the required TINA format – with often the weakest step in the process being the assumptions around how to split unspecific scenario deployment data (from ESME, IEA, IPCC) into the specific TINA sub-categories. However, the deployment projections always start from current real-world known deployment statistics, and hence for UK energy crops, is more robust than for example the Ricardo model (which starts from 4,000 ha/yr planting in 2015).

BECCS deployments were the best available, but the impact of the cancellation of the UK CCS competition likely requires UK models to be re-run (ESME, TIMES etc) and the data to be updated again. A 5-year delay in the appearance of BECCS may not be enough, the whole deployment may need to move back 10 years. The cost data for BECCS is still likely to be the best available (given the lack of progress in the sector), although getting older, given the age of the ETI TESIBC project – very similar data is used in the BVCM model. Progressive Energy's bioH_2 with CO_2 capture study, published during the course of this evidence review, may well supersede this study.

Relevance rating analysis: The quality rating varies by feedstock or technology. The energy crop deployment data is directly relevant, as is the BECCS cost data.

2.2.11 Advanced Biofuel Feedstocks - An Assessment of Sustainability (E4tech for DfT, 2014)[25]

Plain English description of evidence: The study summarises the current and 2020 availability of biogenic residues and wastes within the UK, EU and the world. The study gathers detailed information on feedstock supply potentials, prices in £/t, biofuel production costs, technology pathway options and status, direct GHG emissions of different chains, competing uses and the indirect substitutions likely to occur (and their risks). The study also provides feedstock potentials and corresponding finished biofuel potentials, in PJ per year.

The study focuses on those feedstocks listed in the EU Renewable Energy Directive Annex IX: bio-fraction of MSW, bio-fraction of commercial and industrial (C&I) waste, straw, corn stover, animal manure, sewage sludge, palm oil mill effluent, empty palm fruit bunches, tall oil pitch, crude glycerine, bagasse, grape marcs and wine lees, nut shells, husks, cobs, bark, branches, leaves, saw dust and cutter shavings, black and brown liquor, UCO, animal fat categories I and II, Miscanthus, short rotation coppice, short rotation forestry & small round-wood, micro-algae, macro-algae, renewable electricity, and waste carbon gas.

How the study was undertaken: This desk-study is based solely on publicly available literature.

Key assumptions taken and scenarios modelled: The study provides a summary of feedstock prices (current price in £/t) and a summary of biofuel production costs (£/GJ biofuel). The main data sources used for the feedstock supply analysis are the best publicly available literature. In some cases, reliable data for current feedstock supply was not available and the study estimated potentials either by summing available data from key producing countries, scaling up (or down) data from global or EU estimates, or assuming split-outs where only combined data was available for several feedstocks. These more uncertain data points are flagged in Table 4 of the report (reproduced as Table 2-7 in this report) under the column title "Data quality" in terms of high, medium or low data quality.

[25] http://www.e4tech.com/reports/advanced-biofuel-feedstocks-an-assessment-of-sustainability/

Table 4 in the E4tech report also provides an indication of any likely expansion after 2020, i.e. whether each feedstock supply potential is expected to increase significantly to 2030, is close to a maximum/not expected to expand further, or is likely to decrease to 2030. Based on the technology efficiencies from the selected pathways the study also provides the feedstock potentials converted into finished biofuel, in PJ/yr. These biofuel production potentials do not consider the availability of novel conversion plant *capacity* to use the feedstocks.

Key report outcomes: The report results include the moisture content (percentage) per feedstock. The study then shows a summary of feedstock supplies (in wet "as received" tonne) and biofuel potentials (i.e. without conversion plant capacity constraints) without considering competing uses for feedstock in the UK, the EU and globally. Furthermore, the study shows a summary of feedstock prices (in "current price £/t" and in "current price £/GJ"), see Tables below.

Table 2-6. Summary of descriptive information. (Table 3 in the report.)

Feedstock	State	Moisture content %	LHV (GJ/t)	Density (g/cm^3)	Transport issues	Classification and land use	Key regions for production
Bio-fraction of MSW	Solid	general 60% food 70%	6.3	0.50	Toxicity	Waste	Population centres
Bio-fraction of C&I waste	Solid	food 60% paper, wood 10-20%	7.0	0.50	Toxicity	Waste	Population centres
Straw	Solid	15%	15.0	0.14	Low density	Agricultural residue	Arable cropping
Corn Stover	Solid	13%	14.0	0.20	Low density	Agricultural residue	Corn regions (US, China, Brazil)
Animal manure	Liquid	wet manure 90% poultry litter 35%	1.3*	0.99	Odour, high water, bio-toxicity	Agricultural residue	Intensive livestock farming (NW EU)
Sewage Sludge	Liquid	96%	0.5*	1.00	Odour, high water, bio-toxicity	Waste	Developed population centres
Palm oil mill effluent	Liquid	96%	0.8*	1.00	High acidity, water	Process residue	Malaysia, Indonesia
Empty palm fruit bunches	Solid	64%	4.5	0.18	Low density	Process residue	Malaysia, Indonesia
Tall oil pitch	Liquid	0%	38.0	0.95	Toxicity	Process residue	Pulp/paper mills (US, N EU, E Asia, Brazil)
Crude glycerine	Liquid	10%	14.2	1.20		Process residue	FAME biodiesel plants (EU, US)
Bagasse	Solid	48%	7.8	0.20	Low density	*Agricultural* residue	Sugarcane (Brazil, India)
Grape marcs & wine lees	Solid	65%	6.2	0.90	High water	Process residue	Wine regions (Med.)
Nut shells	Solid	10%	16.4	0.58		*Agricultural* residue	Nut regions (US, Med., SE Asia)
Husks	Solid	10%	13.0	0.035	Low density	Process residue	Rice regions (China, SE Asia)
Cobs	Solid	20%	12.4	0.27		Agricultural residue	Corn regions (US, China, Brazil)
Bark, branches, leaves	Solid	30% after natural drying	12.4	0.15	Low density	Forest residue	Existing forest (N EU, N America, Russia)
Saw dust & cutter shavings	Solid	20% after drying	15.2	0.35		Process residue	Forest industry (N EU, N America, Russia)
Black and brown liquor	Liquid	25%	12.0	1.40	Corrosion, toxic	Process residue	Pulp/paper mills (N EU, N Am, Brz, E Asia)
UCO	Liquid	0%	36.0	0.91		Process residue	Population centres
Animal fats Cat I & II	Solid	0.3%	32.7	0.83	Toxicity	Process residue	Livestock rendering plants
Miscanthus	Solid	16%	13.4	0.14	Low density	Product: land using	Agricultural land in temperate climates, avoiding frosts (US, Western EU)
Short rotation coppice	Solid	30% after natural drying	12.3	0.24		Product: land using	Agric land with high moisture availability
SRF/small round-wood	Solid	30% after natural drying	12.3	0.24		Product: land using	Existing forest (N EU, N Am, Brz, Russia)
Micro-algae	Liquid	oil 0%	36.0	0.92		Product: minimal area	Warm, sunny climates (MENA, US Gulf)
Macro-algae	Solid	seaweed 85%	2.0*	1.03	High water	Product: sea area using	Coastal waters (NW EU, E Asia, Chile)
Renewable electricity	Electricity	0%	NA	NA	Grid balancing	Product: minimal area	High renewable deployment (EU, US, China)
Waste carbon gases	Gas	0%	6.2	0.0014	Auto-combustion	Process residue	Steel mills (China, US, central EU)

Energy densities marked with * are theoretical biogas yields, not the Lower Heating Value of combustion (which would be negative, given the high moisture contents). We note that the EC classify bagasse and nut shells as agricultural residues, when in fact they are residues of a downstream processing step (sugarcane milling & juice extraction, or de-hulling).

Table 2-7. Summary of feedstock supplies (in wet “as received” tonnes) and biofuel production potentials (i.e. without conversion plant capacity constraints) – both before any competing uses for the feedstock are considered. (Table 4 in the report.)

Feedstock	Current feedstock supply (wet Mt/yr)			2020 feedstock supply (wet Mt/yr)			Expansion post 2020?			Data quality	Current biofuel production potential (PJ/yr)			2020 biofuel production potential (PJ/yr)		
	UK	EU	Global	UK	EU	Global	UK	EU	Global		UK	EU	Global	UK	EU	Global
Bio-fraction of MSW	22	189	861	22	147	1,039	↓	↓	↑↑	Medium	68	591	2,694	68	460	3,253
Bio-fraction of C&I waste	25	133	560	25	104	690	↔	↔	↑↑	Medium	85	460	1,941	87	359	2,390
Straw	7.4 - 11	72	885	7.4 - 11	155	934	↔	↓	↑↑	High	52	405	4,963	52	870	5,240
Animal manure	68	1,521	16,202	68	1,340	18,866	↔	↑	↑↑	Medium	43	969	10,320	43	853	12,016
Sewage sludge	35	632	1,069	37	648	1,183	↑↑	↑	↑↑↑	High	9	161	272	9.5	165	301
Palm oil mill effluent	0	0	159	0	0	338	-	-	↑↑↑	High	0	0	60	0	0	127
Empty palm fruit bunches	0	0	51	0	0	109	-	-	↑↑↑	High	0	0	81	0	0	172
Tall oil pitch	0.001	0.16	0.4	0.001	0.19	0.5	-	↑↑	↑↑	High	0.02	5.3	14	0.02	6.6	17
Crude glycerine	0.03	1.0	2.9	0.04	1.4	4.9	↔	↔	↑↑	High	0.25	8.3	25	0.36	12	42
Bagasse	0	0	413	0	0	599	-	-	↑↑↑	High	0	0	1,205	0	0	1,748
Grape marcs	0.02	4.1	7.7	0.02	4.1	8.5	↔	↔	↑	High	0.05	9.5	18	0.05	9.5	20
Wine lees	0.004	0.8	1.5	0.004	0.8	1.6	↔	↔	↑	High	0.01	2.6	4.9	0.01	2.6	5.4
Nut shells	0	0.8	10	0	0.8	11	-	↔	↑↑	Medium	0	4.5	55	0	4.5	61
Husks	0	0.5	120	0	0.5	133	-	↔	↑↑	Medium	0	2.3	583	0	2.3	645
Cobs	0.01	3.6	36	0.01	3.6	40	↔	↔	↑↑	High	0.04	17	167	0.04	17	185
Bark, branches, leaves	3.4	127	317	3.4	122	316	↔	↔	↑	Medium	15	554	1,377	15	532	1,376
Saw dust & cutter shavings	1.6	37	104	1.6	42	115	↔	↑↑	↑↑	High	8.5	199	552	8.5	221	614
Black and brown liquor	0.28	66	200	0.28	72	246	-	↑	↑	High	1.9	459	1,392	1.9	498	1,714
UCO	0.13	1.1	2.8	0.19	3.0	7.8	↔	↔	↑↑	High	4.3	37	94	6.6	102	266
Animal fats Cat I & II	0.12	1.2	3.5	0.12	1.3	3.8	↔	↔	↑↑	High	3.7	38	107	3.7	39	119
Miscanthus	0.12	0.9	1.2	0.36	4.1	4.7	↑↑↑	↑↑↑	↑↑↑	Medium	0.6	4.6	6.2	1.8	21	24
Short rotation coppice	0.04	0.3	9	0.11	1.3	11	↑↑↑	↑↑↑	↑↑↑	Medium	0.15	1.2	39	0.46	5.6	47
Short rotation forestry	0	0	0	0	0	0	↑↑↑	↑↑↑	↑↑↑	High	0	0	0	0	0	0
Small round-wood	3.3	333	829	3.3	310	772	↔	↑	↑	High	14	1,417	3,523	14	1,320	3,282
Micro-algae	0	0	0	0	0.0001	0.015	-	↑↑	↑↑↑	High	0	0	0	0	0.002	0.51
Macro-algae	0	0	0.01	0.01	0.24	2.2	↑↑↑	↑↑↑	↑↑↑	High	0	0	0	0.01	0.24	2.2
Renewable electricity *(Mtoe)*	2.2	51	403	7.8	82	575	↑↑↑	↑↑↑	↑↑↑	High	67	1,536	12,142	235	2,455	17,316
Waste carbon gases	0.9	10	101	0.9	10	138	↔	↔	↑↑	Medium	3.3	36	375	3.3	37	511

Dependencies on other evidence sources:

Main data sources for the feedstock supply analysis (as stated in the report): 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”, NNFCC (2011) “Advanced Biofuels: the potential for a UK industry”, Biomass Futures (2012) “Atlas of EU biomass potentials: Deliverable 3.3: Spatially detailed and quantified overview of EU biomass potential taking into account the main criteria determining biomass availability from different sources”, Ecofys (2013) “Low ILUC potential of wastes and residues for biofuels: Straw, forestry residues, UCO, corn cobs”, Ecofys (2013) “Assessing the EC ILUC proposal: Dutch National Impact Assessment”, plus data from IIASA (2012) “Chapter 7: Energy Resources and Potentials”, and a variety of other public sources for individual feedstocks which are not further defined in the study.

Main data sources for feedstock prices analysis (as stated in the report): WRAP (2013) Gate Fees Report, Farming Online (2013), Purdue University (2011), Biomass Futures (2012) Atlas of EU biomass potentials, Ofwat (2010), Wrap (2013), IFC (2009), Eco-ideal consulting Malaysia (2013) pers. comm., Industry confidential (2013) pers. comm., Oleline (2013) Glycerine Market Report, Industry confidential (2013) pers. comm., Pecege (2011), MixBioPells.eu (2012), de Pinares (2013), European Pellet Council (2012), Based on energy value, Biomass Futures (2012), Platts (2013), Ecofys (2012), Terravesta (2013), E4tech and NNFCC (2013), Tubby (2012), WRI (2011) North American Wood Fiber Review, E4tech (2011) As used in CT TINA analysis, DECC (2013) Onshore wind strike price, Holmgren (2013).

Quality rating analysis: The data are collected from publicly available literature. The underlying data for the cost estimates are presented largely in a transparent way. However, although the general source for the summary of feedstock supplies and biofuel production are provided, the specific data source for each feedstock is not always indicated for every feedstock. The report was published in 2014 and some of the key data sources used in the analysis are now older than five years.

Relevance rating analysis: The data is UK, EU and global specific. In addition, the study is feedstock specific.

2.2.12 The technical potential of Great Britain to produce lignocellulosic biomass for bioenergy in current and future climates (Hastings et al., 2013)[26]

Plain English description of evidence: This academic report used a model to estimate the potential yield of Miscanthus, SRC poplar and willow and SRF for the future (2050) UK climate.

How the work was undertaken: The study used different process and empirical models to estimate yields of the different feedstocks. These include: ForestGrowth-SRC, MiscanFor and ESC-CARBINE (see the reports “Material and methods” section).

Key assumptions taken and scenarios modelled: Feedstock yield calculated per 1 km^2 grid within the UK. Plant responses to irrigation, mineral fertilisation, pests and disease and genetic and/or agronomic improvements were not considered in this study. Constraint maps from Sunnenberg et al. (2013) were used to define which grid blocks could be used for feedstock production and the best feedstock for each grid block determined so that the energy yield could be determined under current and future conditions.

Key report outcomes: The study reports the following data:

- Table 1: Total yield of each feedstock type per NUTS-1 region
- Table 3: The land availability in the UK for different feedstock types and timeframe
- Table 4: The mean yield of each feedstock type per timeframe

In current climates, modelled yields for all feedstock crops varied between 8.1 and 10.6 Mg dry weight (DW)/ha with SRC willow and SRF poplar producing the lowest and highest yields respectively. For the medium emissions scenario (UKCP09) in 2050, mean yield for all feedstock crops varied between 7.6 and 12.7 Mg DW/ha with SRC willow and SRF poplar once again the lowest and the highest recorded yields.

Dependencies on other evidence sources: ForestGrowth-SRC, MiscanFor and ESC-CARBINE models. The study also refers to multiple other literature sources.

Quality rating analysis: The study uses a robust methodology and modelling approach to estimate energy crop yields to 2050.

Relevance rating analysis: The study provides UK specific data on energy crop yields projected to 2050. The data can be readily used without the need for further transformation.

[26] http://onlinelibrary.wiley.com/doi/10.1111/gcbb.12103/full

2.2.13 Energy potential from UK arable agriculture: Straw – what is it good for? (Stoddart & Watts, 2012)[27]

Plain English description of evidence: A short paper that shows how the straw production and its availability for energy/heat could be calculated, using the “Harvest Index” (defined as is the ratio between the grain yield on a dry basis and the total crop dry weight at harvest). This approach can be adopted to estimate future straw potential using data on grain production projections, which is important for modelling future scenarios.

How the work was undertaken: This was a desk study based on analysing the mass balances of different crops to straw production.

Key assumptions taken and scenarios modelled: The authors have linked the Harvest Index to observed yields of grain, straw and chaff materials for wheat, barley, oats and oil seed rape – assumptions of which are included in Table I of the paper (replicated in Figure 2-9 below).

For Wheat [2] and Barley [3]	For Oats [4]	For Oilseed rape [5]

100% dry weight crop at harvest, *of which:*
• Grain = 51%
• Stem and leaf material = 43%
  • of which 60% straw material able to be collected and baled [6]
• Chaff = 6%
	100% dry weight crop at harvest, *of which:*
	• Grain = 47%
	• Stem and leaf material = 47%
	  • of which 60% straw material able to be collected and baled [6]
	• Chaff = 6%
		100% dry weight crop at harvest, *of which:*
		• Seed = 35%
		• Stem and leaf material = 35%
		  • of which 50% straw material able to be collected and baled [6]
		• pod wall = 30%

Figure 2-9. Assumptions for Harvest Index of different crops.

Key report outcomes: The report shows how the quantity of straw can be estimated, as illustrated in Table II of the paper (replicated in Figure 2-10 below).

2011	Grain/seed Production [1]	Harvest Index for grain/seed (%)	Proportion of total biomass as straw (%)	Straw available for collection & baling (%)	Available Straw (thousand tonnes)
Wheat	15,257	51	43	60	7,718
Barley (winter)	2,200	51	43	60	1,113
Barley (spring)	3,294	51	43	60	1,666
Oats	613	47	47	60	368
Oilseed rape	2,758	35	35	50	1,379
Total					12,244

Figure 2-10. Estimated straw availability in the UK using the crop Harvest Index.

Of the estimated 12.2 Mt of straw in the UK in 2011, more than half is from wheat. Using the best estimates, the authors assume about 30% of wheat straw is used for animal bedding on farm, 30% is sold off farm (mostly for bedding), and about 40% is chopped up and returned to the soil (as summarised in Figure 2-11).

[27] http://www.etaflorence.it/proceedings/index.asp?detail=8129

2011 Straw production (thousand tonnes)	12,244
Animal bedding [6]	5,800
Carrots (over wintering) [7]	250
Bioenergy (electricity) [8,9]	300
Mushroom compost [7]	40
Export [1]	80
Total	6,470
Remainder (incorporated)	5,730

Figure 2-11. Estimated uses of straw in 2011.

Dependencies on other evidence sources: The analyses are based on Defra statistics[28] on cereals and oilseed rape production in the UK 2011. The animal bedding estimate was based on J. Kilpatrick - ADAS (2008), Addressing the land use issues for non-food crops, in response to increasing fuel and energy generation opportunities, NNFCC project 08-004.

Quality rating analysis: A good analytical approach with which to estimate straw availability. Data is UK specific, although several years old (but is not expected to be widely different to current estimates).

Relevancy rating analysis: The proposed methodology allows calculation of the quantities of straw using (current or future estimated) grain and oil seed production. The report also provides a summary of straw uses in the UK.

2.2.14 The case for crop feedstocks in anaerobic digestion (ADBA, CLA, NFU and REA, 2011)

Plain English description of evidence: This report was prepared by the AD/farming industry[29] in response to concerns expressed by Defra policy makers over the "The German model" of AD plants, where digesters are fed on crop feedstocks (e.g. maize), which could impact on the country's ability to supply of food for human consumption.

How the work was undertaken: The authors based their analysis on UK case studies.

Key assumptions taken and scenarios modelled: The study highlights key differences between the UK and Germany and presents five UK based case studies, only one of which provides specific technical and energy output data.

Key report outcomes: It concluded that crop feedstocks for AD can form a sustainable system and that there are good safeguards to protect farming and the environment through Standards of Good Agricultural and Environmental Condition (GAEC), Good Agricultural Practice for Nutrients, Fertilisers and Farm Assurance Schemes, and the Assured Combinable Crops Scheme.

Dependencies on other evidence sources: Not applicable.

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[28] http://www.defra.gov.uk/statistics/foodfarm/food/cereals/cerealsoilseed/

[29] Anaerobic Digestion & Biogas Association (ADBA), Country Land & Business Association (CLA), National Farmers Union (NFU) and Renewable Energy Association (REA).

Quality rating analysis: The report is largely based on the expert judgement of industry and is now more than 5 years old.

Relevancy rating analysis: The report is relevant as it is UK specific, but should be used with caution given that it relies upon expert judgement provided by the AD/farming industry.

2.2.15 The UK wood waste to energy market (Anthesis, 2017)[30]

Plain English description of evidence: The report includes a detailed literature review on the wood waste market in the UK. The report includes literature published between 2005 and 2011. The study shows estimates based on best available public data of the wood waste market for 2014/2015 for England, Wales, Scotland and Northern Ireland.

How the work was undertaken: The study consists of a literature review and provides estimates of the baseline wood waste market for 2014 and 2015.

Key assumptions taken and scenarios modelled: The report focuses on wood waste. The study models four different scenarios for the projected wood waste arisings: scenario one takes into account population growth, scenario two takes into account economic growth, scenario three takes into account high waste growth and the last scenario includes low waste growth estimates.

Key report outcomes: Using the latest recorded information from 2015, Anthesis estimates total wood waste arisings of approximately 5.7 Mtpa in 2015, with the breakdown as illustrated below. This estimate is based on the recorded actual wood waste streams, as well as estimates of wood waste content in the different mixed waste streams (from LA, C&I and C&D sources).

Table 2-8. Anthesis estimates of baseline wood waste market (2014/15; all figures in t/yr).

Region	LA wood waste	Separate C&I wood waste	Wood in C&I mixed waste	C&D wood waste	Total wood waste
England	668,000	1,217,000	860,000	2,022,000	4,767,000
Wales	67,000	90,000	76,000	81,000	314,000
Scotland	74,000	99,000	71,000	198,000	442,000
Northern Ireland	55,000	42,000	30,000	54,000	181,000
Grand total	**864,000**	**1,448,000**	**1,037,000**	**2,355,000**	**5,704,000**

[30] http://anthesisgroup.com/uk-wood-waste-energy-market/

Table 2-9. Projected wood waste arisings estimates across different scenarios (Mt/yr).

Scenario	2015	2020	2025	2030
Population Growth (ONS, 2012)	5.74	5.93	6.12	6.28
Economic Growth (avg. 0.71%)	5.74	5.95	6.16	6.39
High Waste Growth (avg. +1.35% p.a.)	5.78	6.18	6.61	7.07
Low Waste Growth (avg. -0.65% p.a.)	5.66	5.48	5.31	5.14

Dependencies on other evidence sources: The key literature includes Defra 2005, ERM 2007, WRAP 2009 and 2011, Tolvik 2011, Defra 2012.

Quality rating analysis: The report is based on current publicly available data.

Relevancy rating: The report is highly relevant. The Ricardo 2017 model (section 2.2.1) estimates 5 Mt/yr of unconstrained wood waste potential in the UK, constant from 2015 to 2050. The Anthesis report identifies a slightly higher baseline wood market for 2014/2015 of 5.7 Mt/yr. For 2030, the Anthesis report estimates range from 7 Mt/yr in a high waste growth scenario to 5.1 Mt/yr in a low waste growth scenario.

2.3 EU

2.3.1 Maximising the yields of biomass from residues of agricultural crops and forestry biomass (Ecofys for EC - DG ENER, 2016)[31]

Plain English description of evidence: The report estimates the potential for *yield increase* of agricultural crop residues and forestry residues in the EU, Ukraine, Russia and Belarus. The report provides estimates for the *theoretical potential*, the *technical-sustainable potential*, and *the realistic potential* of agricultural and forestry residues in 2013. The study takes into account the sustainable removal rate for residues and excludes unsustainable cultivation.

How the work was undertaken: This desk-study bases its quantification on national statistics, FAOSTAT (2013) and Eurostat statistics and literature based data.

Key assumptions taken and scenarios modelled: The report provides estimates of the *theoretical potential* based on crop- and forest-type specific best practices for yield increase (with data mainly based on Eurostat data for cultivated area for 2013), and the *technical-sustainable potential*.

The *theoretical potential* describes the physical upper limit of the yield increase of residues for a specific crop- or forest-type in an ideal scenario due to defined best practices.

[31] https://ec.europa.eu/energy/sites/ener/files/documents/Ecofys%20-%20Final_%20report_%20EC_max%20yield%20biomass%20residues%2020151214.pdf

The *technical-sustainable potential* is derived from the *theoretical potential* and takes into account limitations for yield increase of residues due to technical constraints (based on literature resources specified on the report). Sustainability constraints are also considered which reduce the use and effect of best practice strategies for yield increase.

Based on literature, a sustainable removal rate has been calculated thereby also taking into account soil organic carbon content in the specific regions and the provision of alternative sources of organic matter, with the aim to increase the removal rate without negative impacts. Due to environmental concerns, some measures have been excluded from the best practice strategy (e.g. irrigation). Technical constraints are assumed to mainly result from general cost limitation (i.e. investment in residue-specific machinery).

The concept of sustainable forest management (SFM), as agreed by the Ministerial Conference on the Protection of Forests in Europe (MCPFE), was always taken into consideration as a guiding principle while developing the yield measures and the realistic yield increase for forestry residues.

The *realistic potential* is derived from the *technical-sustainable potential*. Developed best practice strategies for residue yield increase were assessed with regard to their feasibility of application in the EU, Ukraine, Russia and Belarus. The *realistic potential* is further limited due to the barriers identified which prevent or reduce the impact of best practice strategies of residue yield increase. A barrier is only caused by regional aspects, e.g. policies, social acceptance, regional economic resources.

The time period with which the best practise strategies can be fully deployed are characterised as 0-5 years (Short term) to 10-20 (Long term) for agricultural residues and 1-5 years (Short term) to >20 years (long term) for biomass from forestry.

Key report outcomes: The key outcomes of this report show that within the EU, there is a *realistic potential* for agricultural crop residue yield of 74.89 Mt/yr and biomass from forestry of 43.5 Mt/yr. For the Ukraine, the report shows a potential for agricultural crop residues of 17.67 Mt/yr and 43.5 Mt/yr for biomass from forestry. For Belarus, the report shows a potential for agricultural crop residues of 1.75 Mt/yr and 43.5 Mt/yr for biomass from forestry. For Russia, the report shows a potential for agricultural residues of 27 Mt/yr and a potential for forestry residues of 2.57 Mt/yr. The potential for agricultural residues can be realised within 0-20 years depending on the best practise strategy deployed, whereas the potential for biomass from forestry will take at least 30 years to be realised.

Table 2-10. Realistic potential from agriculture crop residues and biomass from forestry. (Table 1 of the report.)

Region	Agricultural crop residues (excluding grass) – Realistic potential (Mt/yr)	Biomass from forestry – Realistic potential (Mt/yr)
EU	74.89	43.5
Ukraine	17.67	
Belarus	1.75	
Russia	27.00	2.57
Total	**121.30**	**46.07**

Dependencies on other evidence sources: The study draws on data retrieved mainly from Eurostat and from FAOSTAT. In addition, the report relies on a significant number of journal articles and other evidence sources, which are fully referenced in the report.

Quality rating analysis: The underlying data used to derive the *realistic potential* for agricultural and forestry residues is mainly based on Eurostat data for cultivated area for 2013. The estimates are presented in a transparent way.

Relevancy rating: The study provides estimates for the theoretical potential but also technical and sustainable potential as well as a realistic potential for agricultural residues and forestry residues for the EU as a whole, Russia, Ukraine and Belarus. The data is relevant and could be used to benchmark the final dataset selected against it. The report largely depends on current data.

2.3.2 Wasted, Europe's untapped resource (ICCT, 2014)[32]

Plain English description of evidence: The study aims to quantify the sustainable potential of cellulosic wastes and residues (agricultural and forestry) available in the EU in 2030 that can be used for biofuel production. GHG emission performance and cost estimates are also covered in this study.[33]

How the work was undertaken: The study bases its quantification on statistics and available literature.

Key assumptions taken and scenarios modelled: For agricultural residues, the study assessed the availability of the EU's 12 most produced crops using data from the Food and Agriculture Organization of the United Nations Statistical Division (FAOSTAT) (2002-2011). The study assumes that 33% of total residues should be left in the field (based on "best practice" guidance published by the EU Joint Research Centre), and furthermore assumes that 33% of available residues have existing uses (it is indicated that this is likely to represent a "conservative" estimate). Future availability to 2020 and 2030 is estimated using extrapolation, based on 2012 projections of increased agricultural production to 2022.

For forestry residues, the study applied EU roundwood production (2011) FAOSTAT data. This data is reported as "underbark" (i.e. with the bark removed) on a m^3 basis. The "overbark" volume was estimated based on the assumption that bark represents 15% of the total roundwood volume (IPCC assumption); furthermore a density of 0.5 t/m^3 was assumed to convert this into tonnes. The total residue availability was estimated by assuming that 24% of the above-ground biomass is available as residues (Mantau et al., 2010). The study assumed that it is sustainable to harvest 50% of the available residues if combined with good land management practices.

For wastes, the category "all potentially available waste" includes all waste that is not recycled for material use—this includes waste that is disposed of, incinerated (for energy or disposal), and "other recovery", but not recycled or composted waste. "Sustainably available waste" includes only waste that is disposed of with no other use.

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[32] https://europeanclimate.org/wp-content/uploads/2014/02/WASTED-final.pdf

[33] Separate reports were published for each of these aspects which fed into the main report, details of which are included in each of the separate chapters of the main report.

Table 2-11. Summary of potential estimates for agricultural residues, forestry residues and wastes. ('Total availability' refers to the maximum potential feedstock available, while the 'Sustainable potential' takes into account existing industrial uses and sustainability restrictions.)

Country / Region	Feedstock	Total availability - 2011 (Mt/yr)	Sustainable potential - 2011 (Mt/yr)	Total availability - 2030 (Mt/yr)	Sustainable potential - 2030 (Mt/yr)
EU	Agricultural residues[1]	366	139	417	139
EU	Forestry residues[2]	81	40	81	40
EU	Paper and cardboard[3]	23.2	16.3	17.6	12.3
EU	Wood[3]	62.2	43.5	8.0	5.6
EU	Food and garden waste[3]	74.6	52.2	37.6	26.3
Total		**607**	**291**	**561**	**223**

Note 1: Agricultural residues include wheat, barley, maize, rapeseed, sugar beet, triticale, rye, oats, sunflower, rice, soybeans, olives (ordered in terms of volume).

Note 2: Forestry residues include stumps, leaves, small branches, and small stem wood.

Note 3: Data is for 2010 (not 2011) and 2030.

Dependencies on other evidence sources: Mantau et al. (2010) was used as the basis for estimating shares of woody biomass.

Quality rating analysis: The underlying data used to derive the estimates is based on data reported by Member States to FAOSTAT/Eurostat, although it covers the period 2002-2011. The technical and sustainable potential estimates were calculated following approaches outlined in the literature (including studies for the European Commission and peer-reviewed academic journals). The estimates are presented in a transparent way enabling a check of the data to be performed, although the background Excel datasets are not available. A number of environmental NGOs, energy analysts and industry provided input to the study. In addition, the report was peer-reviewed by the consultancy IEEP. The data has not been reviewed in the last 3 years.

Relevance rating analysis: The study provides an analysis of the EU feedstock potentials for a selection of materials. The study, however, does not provide any UK-specific estimates.

2.3.3 Forest biomass for energy in the EU: current trends, carbon balance and sustainable potential (IINAS, European Forest Institute, Joanneum Research, 2014)

Plain English description of evidence: The study estimates the amount of forest-derived and woody biomass that could be sustainably supplied in the EU by 2020 and 2030 for energy uses, without compromising material uses of wood. The role of sustainable woody bioenergy in the future EU energy system was also analysed for electricity, heat and transport fuels, taking into account the potentials for energy efficiency, and non-bioenergy renewables. The study was commissioned by the NGOs Birdlife Europe, European Environment Bureau and Transport & Environment.

How the work was undertaken: The study was primarily undertaken using the European Forest Information SCENario model (EFISCEN)[34].

Key assumptions taken and scenarios modelled: The maximum theoretical availability of forest biomass in Europe in 2020 and 2030 was estimated using EFISCEN. The projections were based on National Forest Inventory (NFI) data on species and forest structure, and categorised by tree species type (broadleaved and coniferous) and biomass type: stemwood; logging residues (stem tops, branches and needles); stumps and pre-commercial thinnings. The realisable potential was then estimated taking into consideration economic, environmental and technical constraints. The constraints considered in the study included site productivity, slope, soil surface texture, depth, compaction risk, bearing capacity, retained trees and protected forest. These were assessed using the ArcMap GIS program[35], with a resolution of 1 km.

Some key differences between the reference and low mobilisations include:

- Soil productivity was not considered a constraining factor for crown biomass removal after early thinning / residue removal after final felling bin the reference mobilisation as it was assumed that fertiliser could be applied to replace lost nutrients.
- A maximum of 67% residue removal from thinning was allowed on poor soils for the reference mobilisation but residue extraction was not allowed for the low mobilisation scenarios.
- 67% of stumps after final felling were extracted on poor soils for reference mobilisation, 0% for low (i.e. stump extraction did not occur in the low mobilisation scenario).
- The study assumed that residues could only be harvested in protected areas that have a high or very high fire risk.

Two main scenarios were modelled to evaluate how sustainable woody bioenergy could be used by 2020 and 2030. A reference scenario which is based on the maximum realisable potential using the B2 socioeconomic scenario from the IPCC and a low mobilisation scenario which applies strict environmental criteria.

[34] http://www.efi.int/portal/virtual_library/databases/efiscen/

[35] http://desktop.arcgis.com/en/arcmap/

Key report outcomes: The key outputs are shown below.

Table 2-12. Forest biomass potentials for Reference mobilisation, Additional constraints, and Low mobilisation 2010-2030. (Table 4 in the report.) The data is also provided on a m^3 overbark basis. (Table 3 in the report.)

Energy (PJ)	PC Thin stemwood	PC Thin residues	Thin stemwood	Thin residues	Thin stumps	Harvest stemwood	Harvest residues	Harvest stumps	Total
REF 2010	81.8	18.3	1947.1	143.6	0.0	3376.5	665.6	81.8	**6314**
REF 2020	95.7	40.9	1902.7	484.6	307.1	3503.5	730.8	557.7	**7623**
REF 2020 without dedicated constraints on stump and residue removal in protected areas	95.7	49.6	1902.7	571.6	361.1	3503.5	853.5	654.2	**7992**
REF 2020 + additional 5% strict forest protection	90.5	39.2	1807.9	460.2	307.1	3328.6	694.3	529.8	**7258**
REF 2020 + add. 5% strict forest protection and 5% retention trees	86.1	36.5	1713.0	435.9	307.1	3152.9	657.7	502.0	**6891**
REF 2030	90.5	38.3	1945.3	503.7	315.8	3522.6	743.0	570.7	**7730**
REF 2030 without dedicated constraints on stump and residue removal in protected areas	90.5	46.1	1945.3	593.3	369.8	3522.6	865.7	668.2	**8101**
REF 2030 + additional 5% strict forest protection	86.1	35.7	1848.8	479.4	315.8	3346.0	706.4	542.9	**7361**
REF 2030 + add. 5% strict forest protection + 5% retention trees	81.8	33.9	1751.3	454.1	315.8	3170.3	669.0	514.2	**6990**
LOW 2020 + 5% retention trees	82	5	1612	0	0	2966	421	0	**5086**
LOW 2030 + 5% retention trees	77	4	1646	0	0	2981	425	0	**5134**

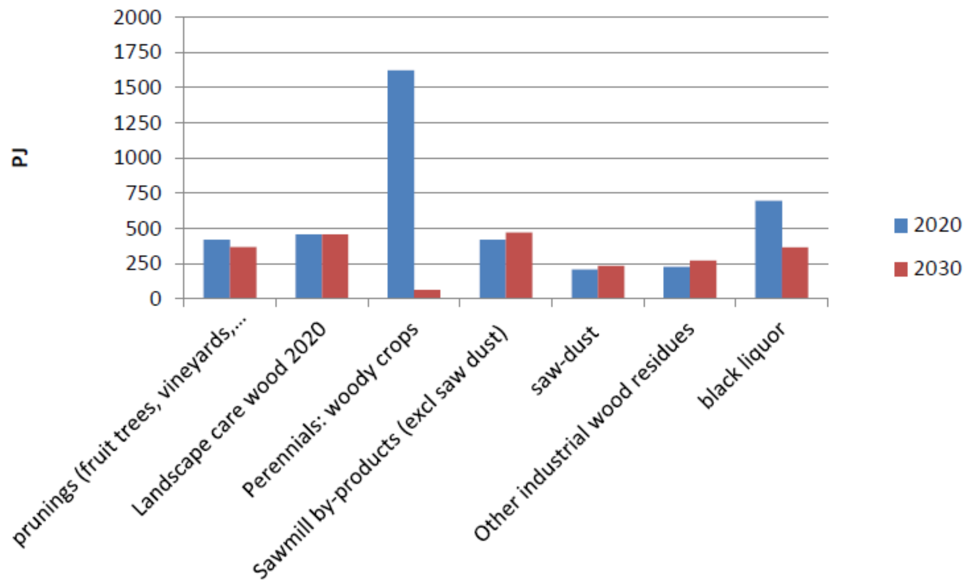

Figure 2-12. Non-forest woody bioenergy potentials in 2020 and 2030. (Figure 3 in the report.)

Dependencies on other evidence sources: The study is reliant on the EFISCEN model for the estimates of the maximum technical forest biomass availability. Environmental constraints are based on the EUWood study[36]. The

[36] Mantau U et al. 2010, EUwood - Real potential for changes in growth and use of EU forests. Final report. Hamburg.

estimates for non-forest woody biomass are taken directly from the Biomass Futures project (sustainability scenario)[37].

Quality rating analysis: A rigorous approach was applied to estimate the forest biomass potentials. The estimates were derived using the EFISCEN forest model and ArcMap GIS software. The estimates for non-forest biomass were based on a secondary source, rather than the author's own analysis.

Relevance rating analysis: The study outputs provide a useful overview of the forest biomass potential assuming specific sustainability constraints. Data is at an aggregated EU level and not available for individual Member States.

2.3.4 Advanced Biofuel Feedstocks - An Assessment of Sustainability (E4tech for DfT, 2014)[38]

See section 2.2.11 for a description, methodology and key results.

2.3.5 Low ILUC potential of wastes and residues for biofuels (Ecofys for FNR, 2013)[39]

Plain English description of evidence: This study assesses the potential of cereal straw, woody residues (bark, branches, leaves, sawdust and cutter shavings), corn cobs (quick scan only) and used cooking oil with a low Indirect Land Use Change (ILUC) risk that can be used for biofuel production. The potentials were assessed at an EU and Member State level, except for UCO which was assessed at a global level. The report was undertaken on behalf of the German, Dutch and Danish governments.

How the work was undertaken: The study bases its quantification on statistics, available literature and interviews with a large number of selected experts.

Key assumptions taken and scenarios modelled: A step-wise approach was taken. First, the *theoretical potential* of each of the materials was estimated (the quantity of the material which is available and could in theory be harvested or collected). From this, the *sustainable potential* was estimated (the quantity which can be harvested or collected in a sustainable way). Finally, the *low ILUC potential* was estimated. This potential takes into account the current non-bioenergy uses of the material, which are then deducted from the sustainable potential.

The following methodology was used to estimate the sustainable straw potential and existing uses. It largely follows the approach taken in Scarlat et al.[40]:

1. Crop production data per Member State based on Eurostat (2002-2011).
2. Theoretical straw potential calculated using straw to crop production ratios per crop and based on correlations proposed by Scarlat et al. (2010).

[37] Imperial College London et al. 2012, Biomass Futures – Analysing Europe's Future Bioenergy Needs; collaborative EEU-IEE project carried out by Alterra, CRES, ECN, IC, ICCS, IEEP, IIASA, and Oeko-Institut. London.

[38] http://www.e4tech.com/reports/advanced-biofuel-feedstocks-an-assessment-of-sustainability/

[39] http://www.ecofys.com/files/files/ecofys-2013-low-iluc-potential-of-wastes-and-residues.pdf

[40] Scarlat et al. (2010), Assessment of the availability of agricultural crop residues in the European Union: Potential and limitations for bioenergy use, Waste Management, Number 30, pages 1889-1897

3. Sustainable straw potential calculated assuming a default sustainable removal rate (SMR) of 40% as proposed by Scarlat et al. (2010). SMRs for Hungary, Germany and France were amended to 33%, 34% and 50% based on literature/validation with experts.
4. Straw uses estimated using the approach described in Scarlat et al. (2010), complemented with estimates from literature and validation with experts.

The above methodology was also used to estimate corn cob potential. An estimate of corn cob use was not considered due to limited quantitative data availability.

The following methodology was used to estimate the sustainable woody biomass potential and existing uses. It largely follows the approach taken in Mantau et al. (2010).

1. Area of managed forest available for wood supply, annual roundwood removal and sawnwood and panel production by Member State, based on Eurostat (2010). Eurostat data also used for woody farm residues.
2. Theoretical potentials calculated: Biomass Expansion Factors (BEF) used to estimate the volume of 'branches & tops' as set out in Antilla et al (2009)[41]. For bark, 6% losses along the supply chain assumed.
3. Sustainable straw potential calculated: For 'branches & tops' a default sustainable removal rate (SMR) of 20% was assumed. For 'Woody farm residues' 75% of the annual increment is assumed to be harvested each year (Mantau et al., 2010). For 'sawmill residues' the sustainable potential was assumed to be the same as the theoretical potential.
4. Woody biomass uses estimated using literature and validation with experts.

Key report outcomes: The study outcomes for cereal straw and woody biomass are presented in Table 2-13 and Table 2-14 below. In addition, the total sustainable corn cob removal in the EU was estimated at around 3.6 Mt/yr.

Table 2-13. Cereal straw potential estimates (sustainable and low ILUC) and existing uses in the UK and EU-12.

Country / Region	Feedstock	Sustainable potential (Mt/yr)	Existing uses (excluding energy generation, incorporation and burning) (Mt/yr)	Low ILUC potential (Mt/yr)
UK	Cereal straw (wheat, barley, oat, rye, triticale)	7.4	6.3	1.1
EU-12	Cereal straw (wheat, barley, oat, rye, triticale)	72.2	50.7	21.4

Note: EU-12 covers Denmark, France, Germany, Hungary, Italy, Poland, Romania, Spain, the Netherlands and the UK.

[41] Antilla, Perttu, Timo Karjalainen and Antti Asikainen (2009), Global Potential of Modern Fuelwood, METLA

Table 2-14. Woody biomass potential estimates (sustainable and low ILUC) and existing used in the EU-27 (excluding Croatia).

Country / Region	Feedstock	Sustainable potential (1,000 m^3/yr)	Existing uses (excluding energy generation, incorporation and burning) (1,000 m^3/yr)	Low ILUC potential (1,000 m^3/yr)
EU-27	Bark	62,005	(62,005)	(0)
EU-27	Branches and tops from managed forests	28,699	0	28,699
EU-27	Woody farm residues	15,982	0	15,982
EU-27	Sawdust (from sawmills)	27,461	27,461	0
EU-27	Cutter shavings (from sawmills)	20,219	(20,219)	(20,219)
EU-27	**Total**	**154,366**	**27,461**	**44,681**

Dependencies on other evidence sources: Scarlat et al. (2010) was used as the main data source for estimating the cereal straw potential. Mantau et al. (2010) was used as the main data source for estimating the woody biomass potential.

Quality rating analysis: Production data for straw and woody residues is not officially recorded by EU Member States, or reported by Eurostat. Similarly, data on the uses of these feedstocks is not widely recorded. In the absence of available data, it is therefore only feasible to derive potential estimates.

The underlying data used to derive the estimates is based on data reported by Member States to Eurostat, although it covers the periods 2002-2011 and 2010 for agricultural residues and forestry residues respectively, so is a little old. The technical and sustainable potential estimates were calculated following approaches outlined in the literature (including studies for the European Commission and peer-reviewed academic journals). The estimates are presented in a transparent way enabling a check of the data to be performed, although the background Excel datasets are not published. Expert stakeholder contact was applied to verify the estimates, where possible. The data has not been updated in the last 3 years.

Relevance rating analysis: The study provides a detailed analysis of the straw potential and existing uses in the UK. 11 other EU Member States are also covered (in varying detail), including key straw producing countries. The study does not provide an analysis of the woody biomass potential and existing uses in the UK, only at an aggregated EU-27 level.

2.4 Global

2.4.1 UK and Global Bioenergy Resource Model (Ricardo for BEIS, 2017)[42]

Plain English description of evidence: The UK and Global Bioenergy Resource Model allows users to estimate the potential sustainable bioenergy resource that may be available to the UK to 2050. The 2017 version is an update to a model originally developed in 2011. The original model covered the period 2010-2030. The update aims to improve and expand the model, including expanding the timeframe to 2050, to increase transparency and to make

[42] https://www.gov.uk/government/publications/uk-and-global-bioenergy-resource-model

the model suitable for use by the general public. The work is commissioned by BEIS (formerly DECC). See section 2.2.1 for further detail and section 4.1.1 for information on the GHG approach.

The model covers supply of the following global feedstocks (see section 2.2.1 for UK feedstocks):

- Global
  - Agricultural residues (bagasse, olive resides, palm oil residues, nut shells (from shea nuts, groundnuts and walnuts), husks (cocoa, oats and soya), corn cobs and sunflower pellets)
  - Forestry products (small roundwood, forestry residues, sawmill coproduct)
  - Perennial energy crops (A different perennial energy crop is assumed per (17) world region, according to the most appropriate crop in that region. The background worksheet does not list the actual feedstocks assumed.)
- Out of scope of this project but also covered:
  - Global UCO and tallow (new)
  - Global Annual energy crops (most common bioethanol and biodiesel crops per region)

Key assumptions taken and scenarios modelled: For each feedstock, the model estimates *unconstrained potential resource* available and the *accessible resource*, i.e. the resource available after price independent competing uses have been removed. In addition, price-dependent competing use potentials can be estimated at three price levels (£4, £6, £10/GJ) which represent typical prices paid for biomass in the market (although the authors acknowledge wastes and residues can be cheaper). The impact of other barriers on the availability of feedstock is modelled in the same way as in the 2011 report.

For all global feedstocks, the **share in global trade that the UK can access** can be defined by the user. As a default it is set to 10% in 2015 and 2020, declining to 2% in 2050 in line with the medium supply scenario in the UK Bioenergy Strategy (DECC, 2012). Estimates for the proportion of regional bioenergy potentials that might be available to the UK stem from Matzenberger (2015)[43]. In the previous version, this a constant 10% out to 2050.

The study shows availability of **global agricultural residues** (in PJ per year for 2015 to 2050) for the following supply regions as defined by Ricardo: US, Canada, Mexico, Brazil, Argentina, other South and Central America, Middle East, Northern Africa, Sub-Saharan Africa, EU, Other Europe and Eurasia, Russia, India, China, Indonesia and Malaysia, Other Asia, Japan, Australia and New Zealand. The data presented for each supply region is largely based on FAOSTAT (2015). For each agricultural residue feedstock, Ricardo identified the top ten countries of origin for the feedstock, based on the FAOSTAT data. These top ten countries of origin per feedstock were categorised according to the regional categorisation used in the Ricardo model (described above). The current feedstock potential in the top ten countries (as included in the Ricardo model) covers between 75% to 97% of the total global feedstock potential, depending on the feedstock.

For **global forestry residue** availability (in PJ per year for 2015 to 2050), the report uses the Forestry Commission's Carbine (2015) model which includes data on the level of wood and timber production, development of forest age class structure over time. Specifically, the Ricardo model uses data from Carbine (2015) to estimate total sustainable wood production resources from the US, Canada, EU and Russia. For countries and regions for which

[43] Matzenberger (2015), Future perspectives of international bioenergy trade

Carbine data was not available, data from FAOSTAT 2015 for industrial round wood conifers and non-conifers was used.

For **global perennial crops** the Ricardo study uses the original AEA 2011 model developed for DECC as a starting point and where no updated data was available, the model uses the parameters from this study.

Estimates of biofuel and **global perennial energy crop** production are based on assumptions about the amount of spare agricultural land available, which includes “abandoned agricultural land” and “abandoned pasture (rest) land”. Note this implies that the estimates for biofuel crops and perennial energy crops are based on the same underlying estimate of abandoned agricultural land or pasture land and so there is a trade off in the model between the availability of the two types of crops for energy. As the estimate is based on abandoned agricultural land, agricultural land area is first prioritised for food and feed production.

As with the 2011 version of the Ricardo model, the IMAGE ecological-environmental model from Utrecht University (Netherlands) is used as the basis for estimates of global abandoned land area available for bioenergy, but the scenarios are updated for the 2017 version. The 2011 version of the Ricardo model used Hoogwijk (2005)[44], as the basis for the underlying data on energy crop land availability. Hoogwijk produced estimates of land availability based on two of the scenarios (A1 and A2) contained in the IPCC Special Report on Emissions Scenarios (2000). The 2017 Ricardo model uses updated land scenarios, but also based on the same IMAGE model from Utrecht University that was used by Hoogwijk. The new estimates of land availability are based on three shared socioeconomic pathways (SSPs) which represent alternative futures of societal development. The Ricardo BAU/continuing trends scenario is based on SSP2, the high investment/globalisation scenario is based on SSP1 and the low investment/regionalisation is based on SSP3. All Ricardo values for abandoned pasture land use SSP1, which is the highest of the three scenarios. The scenarios are set to the highest biodiversity standards, and all assume compliance with the Aichi biodiversity targets.

As with the 2011 version of the model, the land availability is constrained in line with Van Vuuren et al (2009)[45], which estimates areas which are unavailable for crop growing e.g. because they are too severely degraded or because of water scarcity.

Overall, the land availability estimates used in the 2017 version of the Ricardo model are significantly lower than in the 2011 version (see Table 2-15), to the extent that land availability now constrains the availability of global perennial energy crops in the model in later years, whereas in the 2011 model planting rates were more often the constraint to increasing energy crop production.

[44] Hoogwijk 2005, On the global and regional potential of renewable energy sources, Utrecht University

[45] Van Vuuren et al (2009), Future bioenergy potential under various natural constraints

Table 2-15. Comparison of estimates of abandoned land available to grow biofuels and energy crops in 2030 in previous (2011) version of the Ricardo morel and current (2017) version of the Ricardo model (Table 2.2. in the Ricardo report).

	Agricultural land (Mha)	'Rest' land (Mha)	Total (Mha)
Previous version of model			
BAU scenario	650	339	989
High investment scenario	650	339	989
Low development scenario	320	400	720
Current model			
BAU scenario	123	466	668
High investment scenario	435	466	900
Low development scenario	141	466	607
Reduction from previous version			
BAU scenario	-91%	-57%	-79%
High investment scenario	-80%	-57%	-72%
Low development scenario	-86%	-64%	-74%

For each of the 17 world regions, an appropriate perennial crop is chosen according to the climatic conditions, and allocated an appropriate yield figure (GJ/ha). Annual yield increase is modelled as low, BAU or high, the same for all world regions. It is not fully transparent what the different crops are in the 17 world regions and therefore whether the crops relate to woody or grassy energy crops (the technical report indicates both, but the worksheet suggests woody only). Underlying information on current yields of energy crops and yield increases to 2050 are derived from Hoogwijk 2005. This study is old, but very detailed and is used as the basis for many studies on global land availability and yield evolution. There is a reduction in yield applied also to take into account that a certain proportion of land may be degraded and so not able to achieve high yields (based on Hoogwijk and Van Vuuren).

The other key assumptions for global perennial energy crop availability are initial planted area and planting rates. The initial planted area is 0.27% of the assumed land available for all global regions, based on the area currently planted in the UK (4/1500kha). This is an oversimplification, but is considered to be a reasonable estimate as current planted area for energy crops is very low globally. The planting rates can be adjusted by the user of the Ricardo model. As a default, the planting rates are the same as in the 2011 version of the model and are detailed in Table 2-16 below (included in Ricardo worksheet "Global perennial energy crops"). These planting rates were sense checked in the preparation of the 2017 Ricardo model against a study by Kroeger (2012)[46] on plantation expansion rates for the pulp industry. This shows that the high assumed planting rates are feasible for developed countries, but remain optimistic for developing countries.

Table 2-16. Annual expansion of planting rate assumptions (Ricardo worksheet "Global perennial energy crops", tab "Planting rate assumptions").

Expansion of planting rates, % pa	BAU/ continuing trends	High investment/ globalisation	Low investment/ regionalisation
Developed economies	20%	20%	20%
Transition economies	10%	20%	8%

[46] Kroegar (2012), Global tree plantation expansion: a review

Emerging economies	5%	20%	2%

Overall, the estimates of global land area assumed for perennial energy crops are considered to be conservative. They only include abandoned land and are based on high sustainability constraints. On the other hand, if population increases are higher than assumed in the underlying scenarios, the availability of abandoned land could be lower still. The planting rates assumed have been shown to be possible in some areas of the world for plantation forestry for the pulp industry. However, the key uncertainty, as with UK energy crops, is achieving the high estimates of planting rates in practice.

Key report outcomes: Key output tables are detailed in a summary report, which includes a table with estimates of globally traded solid biomass available to the UK in 2030 (Table 2-17). Note that this includes an assumption about the percentage of global biomass surplus that could be traded to the UK (which varies from 10% in 2015 to 2% in 2050).

Table 2-17. Estimates of solid biomass available to the UK in 2030 (Table 3.4 in the Ricardo report).

Land use	Biomass Demand	Supply scenario	Previous (2010) model PJ	Current model with 2010 import assumptions PJ	Change %	Current model with new import assumptions PJ	Change %
Maximise annual 1G biofuel crops	BAU	Low	1,115	869	-22%	609	-45%
		BAU	3,509	970	-72%	679	-81%
		High	4,562	1300	-72%	910	-80%
	High	Low	102	650	539%	455	347%
		BAU	1,633	717	-56%	502	-69%
		High	2,686	879	-67%	615	-77%
Maximise perennial energy crops	BAU	Low	2322	882	-62%	618	-73%
		BAU	5305	1014	-81%	710	-87%
		High	8873	1375	-85%	963	-89%
	High	Low	498	658	32%	460	-8%
		BAU	3429	743	-78%	520	-85%
		High	7005	956	-86%	669	-90%

Dependencies on other evidence sources: Data sources vary per feedstock. Key references listed in the updated model, in addition to the original AEA (2011) model, are:

- Hoogwijk (2005) and Van Vuuren et al. (2009) used to inform global estimates of abandoned agricultural land that could be available for bioenergy and yield development of global perennial energy crops by region
- IEA (2016) World Energy Outlook – used as the basis for the global energy demand scenarios used to calculate demand for woody biomass (and first generation biofuels), updated from WEO 2009 in the previous report

Quality rating analysis: The model update is recent, as is much of the underlying data. Overall the approach is systematic and transparent and takes a consistent approach to estimating the potential and the impact of constraints for each feedstock. However, the approach to estimating global feedstocks is less detailed than for UK feedstocks.

- The global data on agricultural residues is very transparent and uses recent data from FAO, which is an authorative source of information. The top 10 producing countries are identified per feedstock and in most cases this represents >80% of the world supply, so a large share of global agricultural residue potential is captured in the model.
- The global data on forestry residues is based on recent data, using the UK Forestry Commission's CARBINE model and FAOSTAT for countries that Carbine does not cover.
- The approach to global data on perennial energy crops is based on estimates of abandoned agricultural land and abandoned pasture land which are from a well respected source. The estimates have been updated since the previous model version and are now significantly lower. The yield estimates are from a source which is somewhat older, but there has been little development in the global energy crop market in recent years so these are still considered to be representative. Assumptions on the proportion of woody versus grassy energy crops are less clear. Planting rate assumptions have been sense checked against the pulp wood industry and seem achievable, but only with significant actions to promote crop planting.

Relevance rating analysis: Highly relevant, although it is questionable how much of the global agricultural residue market the UK could realistically access as agricultural residues tend to be less dense and therefore more expensive to transport than woody residues, unless pelletised.

2.4.2 Advanced Biofuel Feedstocks - An Assessment of Sustainability (E4tech for DfT, 2014)[47]

See section 2.2.11 for a description, methodology and key results.

2.4.3 Global Bioenergy Supply and Demand Projections: A working paper for REmap 2030 (IRENA, 2014)[48]

Plain English description of evidence: The report provides an estimate of the supply potential of bioenergy crops (cereals), agricultural residues (harvesting and processing residues), forest products, post-consumer waste and animal waste in 118 countries across 6 global regions: Africa, Asia, Europe (including Russia), North America, Latin America and the OECD Pacific. High-level information on feedstock costs are also provided.

How the work was undertaken: This study bases its quantification on statistics (including FAO) and available literature.

Key assumptions taken and scenarios modelled: The study provides low-high availability estimates.

The supply potential of agricultural residues was estimated by multiplying the residue coefficients (percentage of residue in total harvest) with the commodity production volumes (in tonnes per year) projected to 2030. Specific crop

[47] http://www.e4tech.com/reports/advanced-biofuel-feedstocks-an-assessment-of-sustainability/

[48] https://www.irena.org/remap/IRENA_REmap_2030_Biomass_paper_2014.pdf

residue coefficients were applied, based on Smeets et al. (2004)[49]. 25% of the potential was assumed to be recoverable (based on a 50% sustainable removal rate and the assumption that 50% of that can be collected economically). The estimated straw use for animal feed is then deducted from this estimate. For agricultural processing residues, a recovery rate of 25-90% was assumed.

The supply potential of forest products was based on the assessment made by Smeets and Faaij (2007)[50], see section 2.4.4 for further details of this study. This study classified availability according to four categories: “surplus forest growth” (surplus forest products after first meeting the demand of industrial roundwood and woodfuel), “logging residue”, “wood processing residue”, and “discarded wood-based products” (covered under post-consumer waste in IRENA’s study). Surplus forest growth is estimated by subtracting the demand for industrial roundwood and woodfuel from forest productivity growth. Furthermore, it was assumed that 25% of the total wood logging residue and 75% of the total wood processing residue and wood waste can be sustainably recovered. The low scenario is limited to the forest stock in disturbed areas (forests that are currently under commercial operation), while the high scenario is the potential that can be produced at economically profitable levels in the areas of available supply with protected areas excluded (assumed to be 10% of each country’s total forest area).

To estimate the supply potential of bioenergy from household food waste, region-specific data for per capita municipal solid waste (MSW) generation were used from the Intergovernmental Panel on Climate Change (IPCC) guidelines[51]. It was assumed that waste can be collected only from urban areas where the population density is high and waste collection and treatment systems are relatively well-organised. Wastes currently treated for “solid waste disposal systems” and “incinerated” are assumed to be the only collectable fraction. An LHV of 15 GJ/t (dry basis) was assumed for all waste types. For wood products, the estimate from Smeets and Faaij (2007) was used (this applies a residue generation factor and recovery rate to the volume of industrial roundwood consumption).

For animal waste, the assessment was based on the number of animals (FAO estimates to 2030) multiplied by an estimated manure production per animal type and region and recovery rate. The manure recovery rate was assumed to be 100% when the manure management system collects all animal manure in one place and no specific utilisation other than digestion is indicated. No distinction was made between a low-high supply.

The estimate of bioenergy crops is based on cereal crops only. The potential is estimated by multiplying the bioenergy crop yields by the available surplus land. The available surplus land is calculated by subtracting land demand for non-energy uses from potentially available land.

Actual market prices of primary biomass in 2010 were used as a proxy for the prices in 2030. For residues and wastes price estimates from the literature were used and global averages were assumed in regions for where there were no reliable statistics. Corn stalk (stover) price estimates in the US were used as a representative commodity for “harvesting residue” (USD 2.2-3.5 per GJ depending on the transport distance). For “processing residue”, “animal waste” and “household food waste”, only the transport cost was considered. For all the biomass supply costs, USD 2 per GJ of primary biomass delivered was added to the final consumer. Finally, for biomass which can exported, an international transportation cost was set for each region and added to the supply cost for each type of residue. In

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[49] Smeets, E Faaij, A, Lewandowski, I (2004), A quickscan of global bio-energy potentials to 2050 An analysis of the regional availability of biomass resources for export in relation to the underlying factors. Report NWS-E-2004-119, March 2004. Utrecht University, Utrecht.

[50] Smeets, EMW and APC Faaij (2007), Bioenergy potentials from forestry in 2050 Climatic Change 81, pp 353-390

[51] A reference source is not provided in the study.

USD 1 per GJ of primary biomass was added for international trade to represent transaction costs, such as tariffs or any kind of policy measures to promote domestic supply.

Key report outcomes: The study estimates that between 97-147 EJ of biomass is available in 2030, as indicated in Figure 2-13. This is broken down by global region in Figure 2-14.

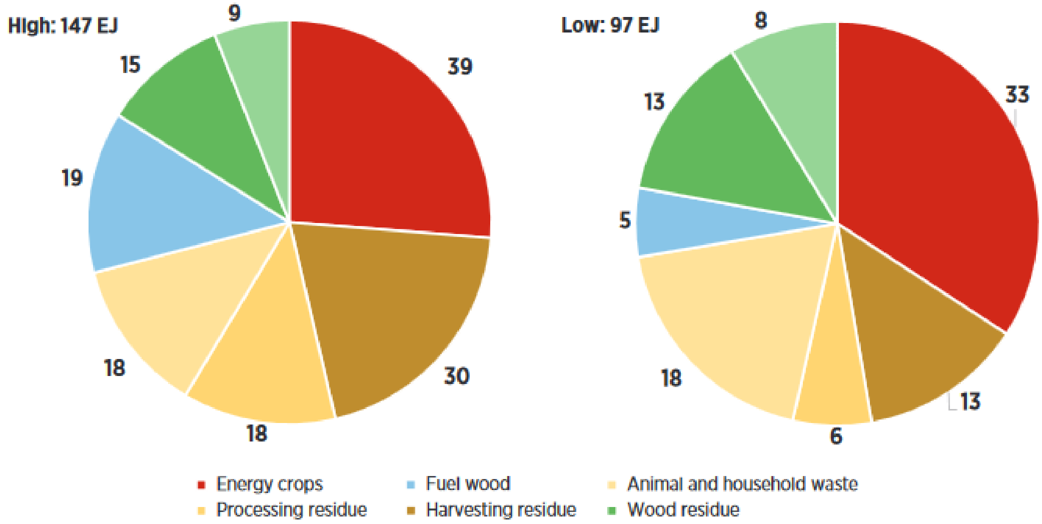

Figure 2-13. Breakdown of biomass supply potential estimates by type in 2030. (Figure 12 in the report.)

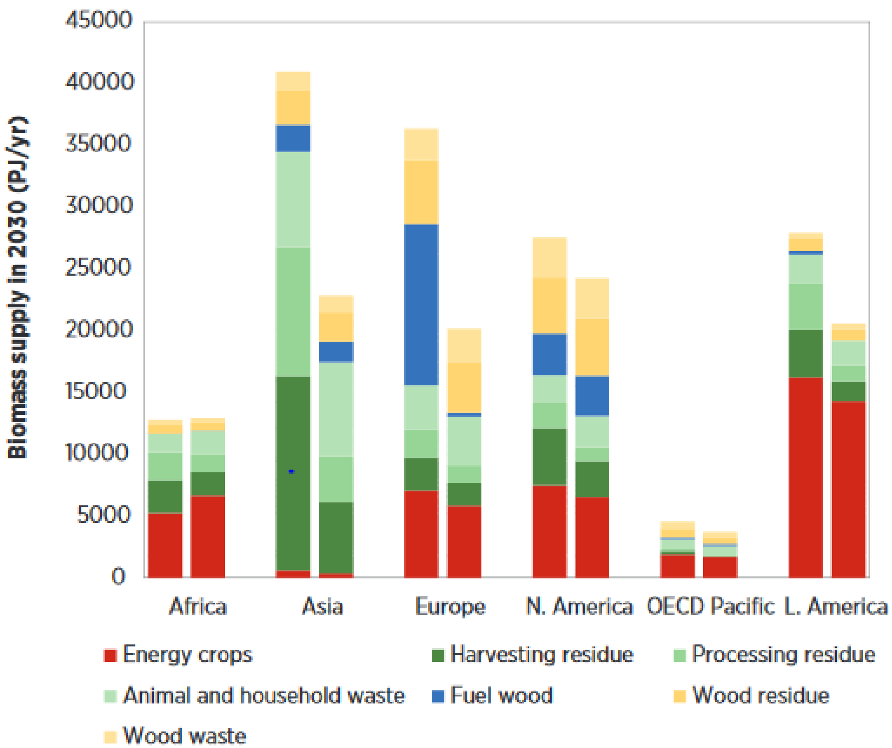

Figure 2-14. Breakdown of biomass supply by region in 2030. (Figure 16 in the report.)

Dependencies on other evidence sources: The following key evidence sources were used in this study.

- Agricultural residues: FAOSTAT statistics (2014) and FAO World Agriculture Towards 2030/2050 for current and future crop production. The crop residue coefficients were based on Smeets et al. (2004).
- Forest products: The estimates provided by Smeets and Faaij (2007) were used.

Quality rating analysis: For agricultural harvest residues, the underlying crop data are based on a robust source. Furthermore, the harvesting residue coefficients are crop specific, although they are based on a literature source from 2004. The estimate of the recoverable fraction of residues is based on the same assumption for all crops and all global regions which is an oversimplification. Finally, the estimate of alternative straw uses is restricted to animal feed.

The estimates for forest products are based on Smeets and Faaij (2007), rather than the author's own analysis. However, it is not sufficiently transparent how the data has been applied in this study.

The information on feedstock costs is at a high level and not readily applicable to the UK market.

Relevance rating analysis: Although the study has its limitations due to the simplified assumptions applied, the outputs nonetheless provide a useful high level overview of the likely range of biomass availability per feedstock type and global region. (Data for Russia is included in the Europe totals.) However, the estimates for bioenergy crops are based on cereals only, and so not directly relevant. The estimates for global bioenergy availability are considerably higher than in the 2017 Ricardo model (section 2.4.1), although it should be noted that the Ricardo results shown also include an assumption about the percentage of global biomass surplus that could be traded to the UK (which varies from 10% in 2015 to 2% in 2050).

2.4.4 Bioenergy potentials from forestry in 2050 (Smeets and Faaij, 2007)[52]

Plain English description of evidence: The purpose of this study was to evaluate the global energy production potential of woody biomass from forestry for 2050 using a bottom-up analysis of key factors. Woody biomass from forestry was defined as all the above-ground woody biomass of trees, including all products made from woody biomass. This includes the harvesting, processing and use of woody biomass.

How the work was undertaken: The projection was performed by comparing the future demand with the future supply of wood, based on existing databases, scenarios and outlook studies. Through this the most important factors that determine the bioenergy potential of woody biomass were identified. An Excel spreadsheet tool was then developed to identify and quantify the key factors that determine the energy potential of woody biomass and in which the various databases and scenarios derived from literature could be combined.

Key assumptions taken and scenarios modelled: Figure 2-15 provides an overview of the key parameters used in estimating the woody biomass supply and demand.

On the supply side three sources of woody biomass were included:

- **Forests:** Five types of potentials of wood supply from forests were included, namely theoretical, technical, economical, and/or ecological barriers.

[52] https://link.springer.com/article/10.1007/s10584-006-9163-x

- **Plantations:** Three scenarios were composed that represent the ranges found in the literature. They varied with respect to the rate of plantation establishment and yield level.
- **Trees outside forests:** The contribution of trees outside forests to the supply of wood was estimated using values found in the literature and our own assumptions.

On the demand side two categories were distinguished:

- **Industrial roundwood:** Three scenarios for the consumption of industrial roundwood in 2050 were composed based on the ranges found in the literature.
- **Woodfuel:** Three scenarios for the consumption of woodfuel in 2050 were used based on the ranges of woodfuel consumption projected by other researchers

The study outputs are presented for 11 global regions (as defined by the FAO in 2003), although the underlying data are available at the national level.

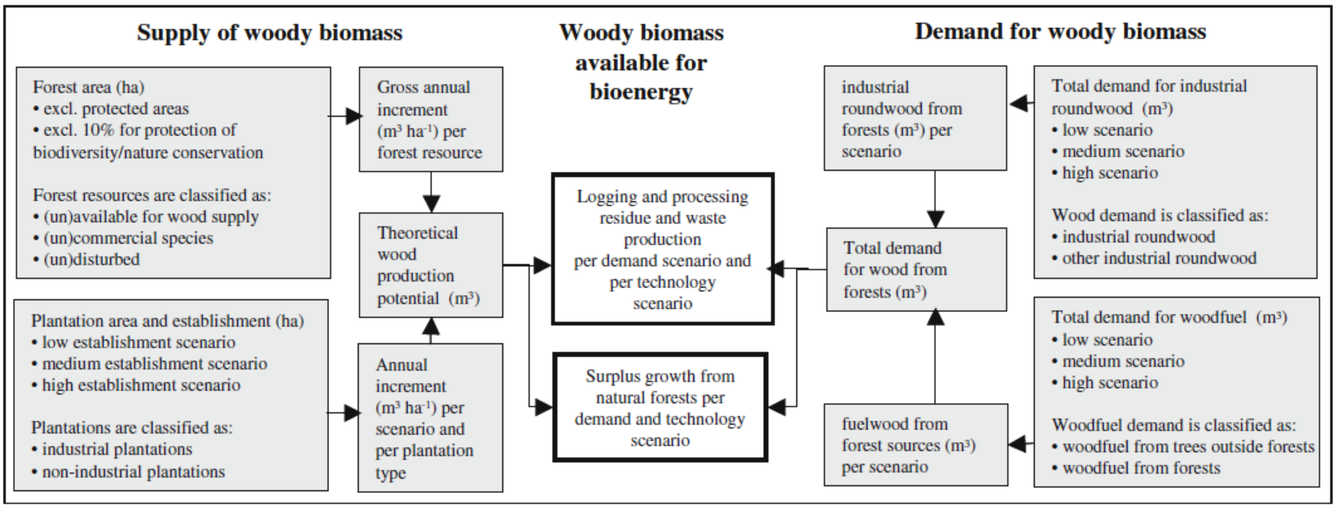

Figure 2-15. Overview of key parameters used in the study. (Figure 1 in the study.)

Key report outcomes: Based on a medium demand and medium plantation scenario, the global theoretical potential of the surplus wood supply (i.e. after the demand for woodfuel and industrial roundwood is met) in 2050 was calculated to be 6.1 Gm^3 (71 EJ) and the technical potential to be 5.5 Gm^3 (64 EJ). Economic considerations further reduced the surplus wood supply from forests to 1.3 Gm^3/yr (15 EJ/yr). When ecological criteria were also included, the demand for woodfuel and industrial roundwood exceeded the supply by 0.7 Gm^3/yr (8 EJ/yr). The bioenergy potential from logging and processing residues and waste was estimated to be equivalent to 2.4 Gm^3/yr (28 EJ/yr) wood, based on a medium demand scenario. These results indicate that forests can, in theory, become a major source of bioenergy, and that the use of this bioenergy can, in theory, be realised without endangering the supply of industrial roundwood and woodfuel and without further deforestation. Regional shortages in the supply of industrial roundwood and woodfuel, however, occur in some regions (e.g. South Asia and the Middle East and North Africa).

Supply and demand data is summarised in Figure 2-16 below.

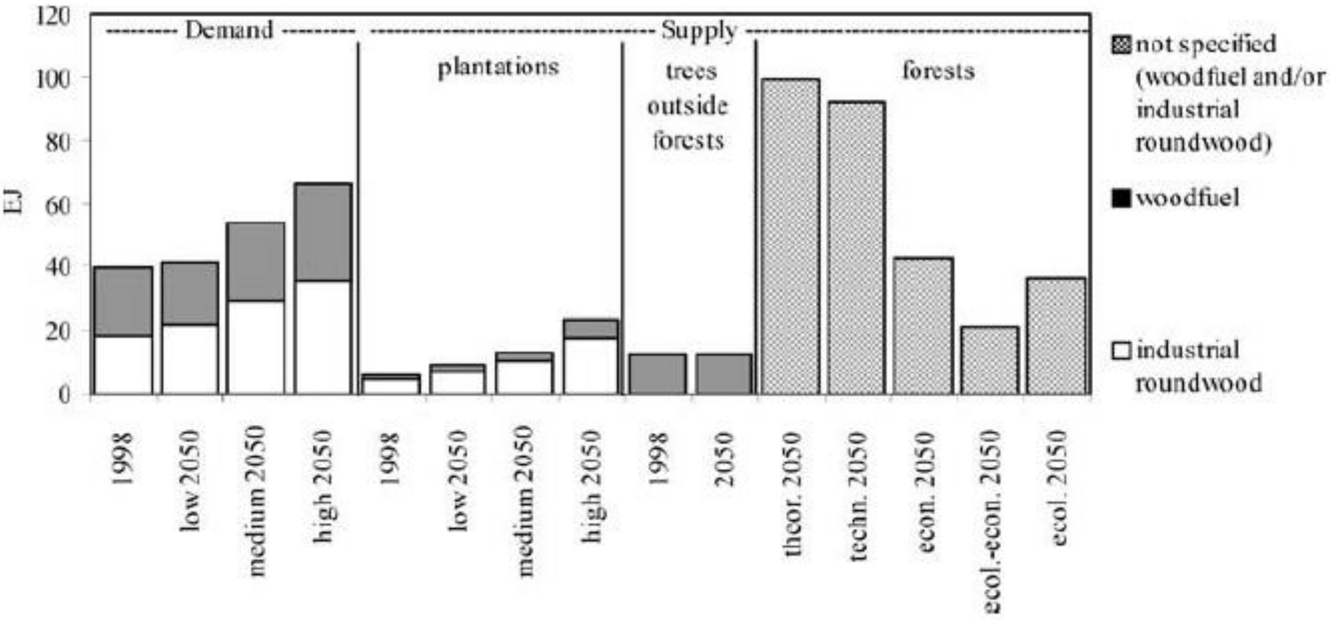

Figure 2-16. Demand for industrial roundwood and woodfuel in 1998 and 2050, the supply of wood from plantations and trees outside forests in 1998 and 2050, and the potential supply of wood from forests in 2050 based on the theoretical, technical, economical, economical–ecological, and ecological supply potentials of wood from forests (including deforestation). (Figure 4 in the study.)

Dependencies on other evidence sources: The study is based on an extensive list of literature, including multiple reports published by the FAO.

Quality rating analysis: The study outputs are intended to serve as “a rough estimate of the potential in 2050”. Study limitations are cited as the static approach taken to estimate the demand and supply of forest growth, forest areas and wood demand, as well as not estimating the technological change in the wood processing and plantation industries that may occur to 2050. The study furthermore acknowledges several key uncertainties, including the supply of wood from trees outside forests, woodfuel consumption, and the impact of various theoretical, technical, economical, or ecological limitations on forest productivity and, in particular, the impact of sustainable forestry management on these limitations. The study was published in 2007 and is primarily based on literature that was published prior to 2000 (and so is now quite dated). A key strength of the study is the comprehensive and transparent approach taken. Supply/demand data is presented in stacked bar charts alongside detailed disaggregated supply data per global region.

Relevance rating analysis: The study provides a useful reference for the woody biomass potential in 2050 (and underlying supply/demand relationships) per global region.

2.4.5 Forest Products Annual Market Review 2015-2016 (FAO, 2016)[53]

Plain English description of evidence: The 2016 edition of the UNECE/FAO report provides a review of market developments in the UNECE region (Europe, Commonwealth of Independent States, North America) in 2015.

How the work was undertaken: This study bases its quantification on UNECE/FAO Forestry and Timber Section Forestry statistics and from official country statistical correspondents and expert estimates.

Key assumptions taken and scenarios modelled: The review includes industrial roundwood, wood-based panels, paper and paperboard, sawn softwood and sawn hardwood.

Key report outcomes: Sectors included are pellets and wooden packaging, wood raw materials, sawn softwood and hardwood, wood-based panels, paper, paperboard and woodpulp. For each sector, production, consumption and trade are considered and relevant developments in the markets and policies are included. Results are presented such as in Table 2-18 below which shows the apparent consumption of different categories of woody material.

[53] https://www.unece.org/fileadmin/DAM/timber/publications/fpamr2016.pdf

Table 2-18. Apparent consumption of industrial roundwood, sawnwood, wood-based panels and paper and paperboard in UNECE region, 2011-2015. (Table 1.5.1 in the report.)

	Thousand	2011	2012	2013	2014	2015	Change (volume) 2014-2015	Change (%) 2014-2015	Change (%) 2011-2015
Europe									
Industrial roundwood	m³	385,483	375,656	381,804	393,757	401,642	7,885	2.0	4.2
Sawnwood	m³	103,354	96,971	96,832	100,787	101,127	340	0.3	-2.2
Wood-based panels	m³	66,901	64,645	71,393	67,942	68,392	450	0.7	2.2
Paper and paperboard	m.t.	92,477	90,690	92,948	89,443	87,998	-1,445	-1.6	-4.8
CIS									
Industrial roundwood	m³	166,846	173,690	175,075	181,566	185,259	3,692	2.0	11.0
Sawnwood	m³	19,024	19,717	19,936	19,014	18,125	-889	-4.7	-4.7
Wood-based panels	m³	16,045	17,701	17,839	17,581	16,770	-810	-4.6	4.5
Paper and paperboard	m.t.	9,537	9,366	9,387	9,311	8,975	-336	-3.6	-5.9
North America									
Industrial roundwood	m³	487,212	481,158	486,764	490,150	494,286	4,136	0.8	1.5
Sawnwood	m³	89,811	95,467	101,090	106,274	112,701	6,427	6.0	25.5
Wood-based panels	m³	42,011	46,391	47,968	49,889	51,979	2,090	4.2	23.7
Paper and paperboard	m.t.	79,721	81,144	75,345	76,053	75,923	-130	-0.2	-4.8
UNECE region									
Industrial roundwood	m³	1,039,540	1,030,503	1,043,642	1,065,474	1,081,186	15,713	1.5	4.0
Sawnwood	m³	212,189	212,155	217,859	226,075	231,953	5,878	2.6	9.3
Wood-based panels	m³	124,957	128,737	137,200	135,412	137,141	1,730	1.3	9.8
Paper and paperboard	m.t.	181,734	181,200	177,680	174,807	172,896	-1,911	-1.1	-4.9

Note: Sawnwood does not include sleepers.
Source: UNECE/FAO TIMBER database, 2016.

Dependencies on other evidence sources: The review presents and analyses annual statistics for 2015-2016 collected by the UNECE/FAO Forestry and Timber Section Forestry and from official country statistical correspondents and expert estimates.

Quality rating analysis: The report is based on latest data collected by FAO for 2015-2016.

Relevance rating analysis: The report is relevant, covering the Roundwood market in the EU, North America and the Commonwealth of Independent States. It covers the industrial Roundwood balance and price indexes feedstock deployment and GHG, but no detailed cost data.

2.5 Other country-specific studies

2.5.1 Brazil - Bio Trade2020plus – Supporting a Sustainable European Bioenergy Trade Strategy - Progress report on WP 3 case studies Brazil (Intelligent Energy Europe, 2016)[54]

Plain English description of evidence: The study considers primary agricultural residues, primary forestry residues and secondary forestry residues (arising from wood processing). The study estimates sustainable sourcing of biomass residue potential for imported biomass to the EU. Sustainability criteria considered are conservation areas and land with significant biodiversity values, life cycle GHG emissions including direct land use change, human and labour rights and occupational health and safety for workers. In addition, maintaining soil quality is considered to be important and a sustainable removal rate is taken into account. The aim of the study is to anticipate possible trends and changes to costs and quantities of biomass trade and to reflect market developments. Two scenarios are created, for 2020 and 2030.

How the work was undertaken: The study bases its quantification on statistics, available literature and interviews. Data on the production volumes of feedstocks was collected from FAOSTAT and IBGE[55].

Key assumptions taken and scenarios modelled: A selection of most promising agricultural and forestry feedstocks was made based on agricultural and forestry production statistics of Brazil. The feedstocks are chosen based on production volume, the Residue to Product Ratio (RPR), and the suitability of the residue product to be transformed into wood pellets (technology development). The report selected the most promising states in Brazil. The states or regions were identified where the majority of biomass is produced, the infrastructure (road/rail transportation, shipping routes) is easily accessible, and logistics are competitive. It was considered unfeasible to include the entire country, considering the size of Brazil and the fact that transporting biomass pellets over such a great distance is unrealistic. Furthermore, it was recognised that some states in Brazil should be excluded entirely because they are part of protected or high-biodiversity areas such as the Amazon. Furthermore, agricultural production is highly concentrated in Brazil, therefore some states have very little potential to offer.

The GHG emissions along the entire supply chain, including agricultural processes, pre-treatment and intra/inter-national transport are calculated for each region and feedstock in Brazil. By creating a GHG supply curve of the net export potential, the part of the potential that does not meet GHG reduction criteria set by the European Commission can easily be excluded.

The study takes the sustainable removal rate for the individual agricultural residues into account. The values were obtained from literature research and for sugarcane cross-checked with interviews with a farmer and a sugarcane mill employee. Similarly, for forestry residues it was assumed that 50-55% of the forestry residues from eucalyptus and pine trees generated on forest plantations can be sustainably removed. Wood processing residue like sawdust, chips, and shavings are secondary residues produced at production facilities, and therefore it is assumed that 100% of these could be sustainable utilised.

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[54] http://www.biotrade2020plus.eu/images/case_studies/D3.2._CS_Brazil_Final_01.06.2016.pdf

[55] Instituto Brasileiro de Geografia e Estatística. For more information, see: https://ww2.ibge.gov.br/english/

The business as usual scenario for agricultural and forestry feedstock production is based FIESP / ICONE 2012 Outlook Brazil 2022: agribusiness projections.[56] It is assumed that the projections indicate that the agri-business will follow the observed historical growth rates. For the BAU scenario, the average annual growth rates for planted area and yields were calculated over the 1990-2012 period (the longest historical data set available on state level). Extrapolations from 2012 until 2030 were made with these growth rates. The agricultural yield is considered to be limited by the current yields in the US. Yields in the US are the highest in the world for many crops, and have been more or less stable for years. Data on state level was obtained from the 'Banco de Dados Agregados' (Database of Aggregated Data) of IBGE. Within states, the average annual growth rates were considered to be equal in all micro-regions. Multiplying the projected yields in 2020 and 2030 with the projected planted area gave the production volumes of agricultural feedstocks and round wood for paper and cellulose, and for other purposes. Planted area is also projected according to historical rates. However, the total agricultural area is considered to be limited by the maximum area that is technically available for agriculture, as calculated with the PLUC model according to Verstegen et al. (2015). This means that in some states, such as Paraná, the total agricultural area remains the same, since any increase would exceed the suitable land availability.

Considering that it is not feasible to export untreated ligno-cellulosic biomass to the EU, the available pellet producing capacity is considered a limitation for the net export potential. The current potential is calculated based on capacity in existing plants. Existing installed capacity is taken from the Bioenergy International Inventory. The capacity in the case study regions is currently 630 kton. A capacity factor of 80% was used to calculate the actual pellet producing capacity. This is considered optimistic since in reality pellet plants often run at lower capacity because of supply limitations (Wood Pellet Association of Canada, n.d.).

To estimate the cost of ligno-cellulosic pellet production, the following cost components are included:

$$C_D = C_P + C_{Pt} + C_{Tdf} + C_{Tdp} + C_{Ti} + C_H$$

Where:

C_D = Total production cost of biomass residues

C_P = Cost of production of feedstock

C_{Tdf} = Cost of domestic transport from field to pre-treatment facility

C_{Tdp} = Cost of domestic transport from pre-treatment facility to export location

C_{Ti} = Cost of international transport from facilities to the EU

C_{Pt} = Cost of pre-treatment

C_H = Cost of handling

The assumption is made that biomass is sourced within a 50 km radius; therefore the cost of transporting biomass to the pellet plant is taken as 50 km for all states. Cost of transport of biomass from the ports in Brazil to ports in the Netherlands is calculated through a web-based sea freight calculator.

Key report outcomes: The study shows the technical potential of agricultural residues of seven selected feedstocks. The study also shows the net export potential for forestry residues in 2020/2030 and BAU/optimistic scenario. The net export potential in all the scenarios is considerably lower than the sustainable surplus potential, as a result of the limited pellet plant capacity installed in Brazil.

[56] For more information, see: http://apps2.fiesp.com.br/outlookDeagro/en-US/Publicacao/Cafe/Brasil/2022-23

Table 2-19. Sustainable surplus and net export potential of agricultural and forestry residues for 2012/2020/2030 and the BAU and High Export scenarios. (Table 30 of the report).

	Potentials (PJ)	2012	2020 BAU	2020 OPT	2030 BAU	2030 OPT
Sustainable Surplus	Agricultural residues	627.0	597.0	828.7	459.4	935.1
	Forest residues	91.2	87.0	101.9	70.0	124.4
Net Export	Agricultural residues	0.0	0.0	0.0	15.5	286.6
	Forest residues	8.6	18.9	36.6	55.2	124.4
	Total net export	**8.6**	**18.9**	**36.6**	**70.7**	**411.0**

Chapter 7 in the report shows the cost-supply curves of the current situation. Delivery costs range from €14.2/GJ (232 €/t) to €15.3/GJ (251 €/t). It should be noted that forest residues are more expensive than agricultural residues. The fact that in this scenario only wood pellets are produced increases the cost. The study shows cost supply curves. The study also shows the GHG supply curve of pellets delivered from Brazil to Austria, Italy or the Netherlands. In the high export scenario, the costs range from €10.4/GJ (177 €/t) to €15.3/GJ (251 €/t). The lower prices can be explained by the availability of cheaper agricultural residues from 2030.

Dependencies on other evidence sources: Data on the production volumes of feedstocks were collected from FAOSTAT and the Brazilian Institute of Geography and Statistics (IBGE). Data on production volumes from forestry plantations were collected from FAOSTAT, IBGE, the Brazilian Tree Industry (IBÁ) and the Brazilian Biomass Industry and Renewable Energy Association (ABIB). When data were not available from these sources, external reports and interviews with local stakeholders were used.

Quality rating analysis: Data provided in the report on Brazilian feedstock volumes and costs are based on robust sources including the latest data from FAOSTAT and the IBGE.

Relevance rating analysis: The study is relevant as it determines a net sustainable export potential of biomass from Brazil and related cost and GHG supply curves are applied and tested.

2.5.2 Indonesia - Bio Trade2020plus – Supporting a Sustainable European Bioenergy Trade Strategy - Assessment of sustainable lignocellulosic biomass export potentials from Indonesia to the European Union (Intelligent Energy Europe, 2016)[57]

Plain English description of evidence: The study focuses on agricultural residues from the oil palm industry in Indonesia, which is the largest agricultural commodity in Indonesia. Currently, palm residues including fronds, trunks, empty fruit bunches (EFB), shells and fibre are used locally. Typically fronds, trunks and EFBs are mostly left in the field whilst shells and fibre are burnt for electricity generation at oil mills, but with low efficiency. This indicates a potential for export of residues to the EU.

How the work was undertaken: The study bases its quantification on statistics, available literature and interviews.

[57] http://www.biotrade2020plus.eu/images/case_studies/D3.1._CS_Indonesia_Final_01.06.2016.pdf

Key assumptions taken and scenarios modelled: The study focuses on the Kalimantan region of Indonesia only because Kalimantan has an expanding area of oil palm plantations, the logistics are favourable and government policies aim to increase the productivity of palm plantations.

At a national level, the Indonesian government target estimates that palm oil production by 2020 will be over three times the current production. Under this plan, about 1 million ha of forested land will be deforested. Rizaldi et al. (2012) recommends that Central Kalimantan could revise its current target of 3.5 million hectares oil palm to 2.9 million ha to avoid deforestation without a significant reduction of the production level. The report follows their recommendation regarding land expansion for 2020 and 2030. In order to avoid the deforestation of the 1 million ha of the "forested land", two principal mechanisms are important:

- undertaking a 'land swap' between 'forested' and 'non-forested' areas, coupled with a broader spatial planning exercise, and
- improvement of smallholder yields.

The study is centred on two key scenarios, business as usual (BAU) and High Export, giving results for 2020 and 2030.

Scenario BAU 2020: Under this scenario, land increase is assumed to follow government policy targets. Even from a BAU perspective, the study does not assume any deforestation or forest conversion for palm plantations. Palm yield is assumed to increase for all the palm growers. In the BAU case, the total land to be potentially exploited is 2,844,000 ha (in comparison to 3,500,000 ha planned to be used for oil palm plantations).

Scenario High Export 2020: Different to the BAU 2020 perspective, a survey of Rizaldi Boer et al. (2012) indicated that a land swap mechanism if implemented could provide an addition of 315,000 ha for oil palm plantation, increasing the total area which could be accessed in the future to 3,159,000 ha. Palm yields are assumed to further increase for independent small holders due to better management and more fertiliser use. There is no yield increase assumed for private estates because they are assumed to already implement good agricultural practices.

The following two Indonesian sustainability criteria for the oil palm industry are also taken into consideration in the High export scenario:

- (S1) There are certain amounts of residues that need to be left in the field to maintain soil quality and used as fertilisers for oil palm growth. These amounts might be reduced in the future depending on soil management and additional fertiliser being used.
- (S2) Land expansion does not result in deforestation.

Scenario BAU 2030: Under the BAU scenario to 2030, additional improvements in palm yield are assumed but land areas are kept the same as in the BAU 2020 scenario due to no further investment in appropriate land use changes. Palm yield is assumed to continue to increase for all the palm growers. Especially for private estates, yield is assumed to attain the maximum level of 29,050 kg/ha.

Scenario High Export 2030: Similar to the High Export 2020 scenario, an addition of 315,000 ha for oil palm plantations are assumed to be possible. Palm yields achieve their highest productivity due to maximum fertiliser use, but are still in line with good agricultural practices.

Key report outcomes: Table 2-20 to Table 2-23 show the potential estimates under the various scenarios.

Table 2-20. Estimated availability of EFBs under "BAU 2020" scenario.

Producer type	Planted area (ha)	Fresh Fruit Bunches yield (t/ha)	Empty Fruit Bunches produced (t)
Independent small holders	568,800	9.575	2,178,504
Plasma holders	682,560	14.958	4,083,756
Private estates (ordinary + RSPO)	1,592,640	23.375	14,891,184
Total	**2,844,000**	**-**	**21,153,444**

Note 1: Independent small-holder: Farmer who manages, finances, and operates his/her own farm by himself/herself

Note 2: Plasma famer: Farmer that is supervised and supported by a partner company in managing, financing, and operating his/her farm under a partnership scheme.

Note 3: Private company: Refers to an oil-palm estate company that is either a) practicing good agricultural principles, but is currently not certified under the RSPO (Roundtable Sustainable Palm Oil), or b) certified by third parties, having compliance with RSPO.

Table 2-21. Estimated availability of EFBs under "High Export 2020" scenario.

Producer type	Planted area (ha)	Fresh Fruit Bunches yield (t/ha)	Empty Fruit Bunches produced (t)
Independent small holders	631,800	11.973	2,723,983
Plasma holders	758,160	18,550	5,064,595
Private estates (ordinary + RSPO)	1,769,040	23,375	16,540,524
Total	**3,159,000**	**-**	**24,329,102**

Table 2-22. Estimated availability of EFBs under "BAU 2030" scenario: Palm yield is assumed to continue to increase for all palm holders.

Producer type	Planted area (ha)	Fresh Fruit Bunches yield (t/ha)	Empty Fruit Bunches produced (t)
Independent small holders	568,800	11.97	4,765,975
Plasma holders	682,560	18.59	8,882,153
Private estates (ordinary + RSPO)	1,592,640	29.05	32,386,334
Total	**2,844,000**	**-**	**46,034,462**

Table 2-23. Estimated availability of palm residues under "High Export 2030" scenario: Similar to the High Export 2020, an addition of 315,000 ha for palm oil plantation could potentially be attained.

Producer type	Planted area (ha)	Fresh Fruit Bunches yield (t/ha)	Empty Fruit Bunches produced (t)
Independent small holders	631,800	14.880	6,580,829
Plasma holders	758,160	23.040	12,227,604
Private estates (ordinary + RSPO)	1,769,040	29.050	35,973,428
Total	**3,159,000**	**-**	**54,781,861**

The costs of palm residue pellets supplied to the EU in the BAU and High Export scenarios in 2020 and 2030 are presented in Figure 2-17.

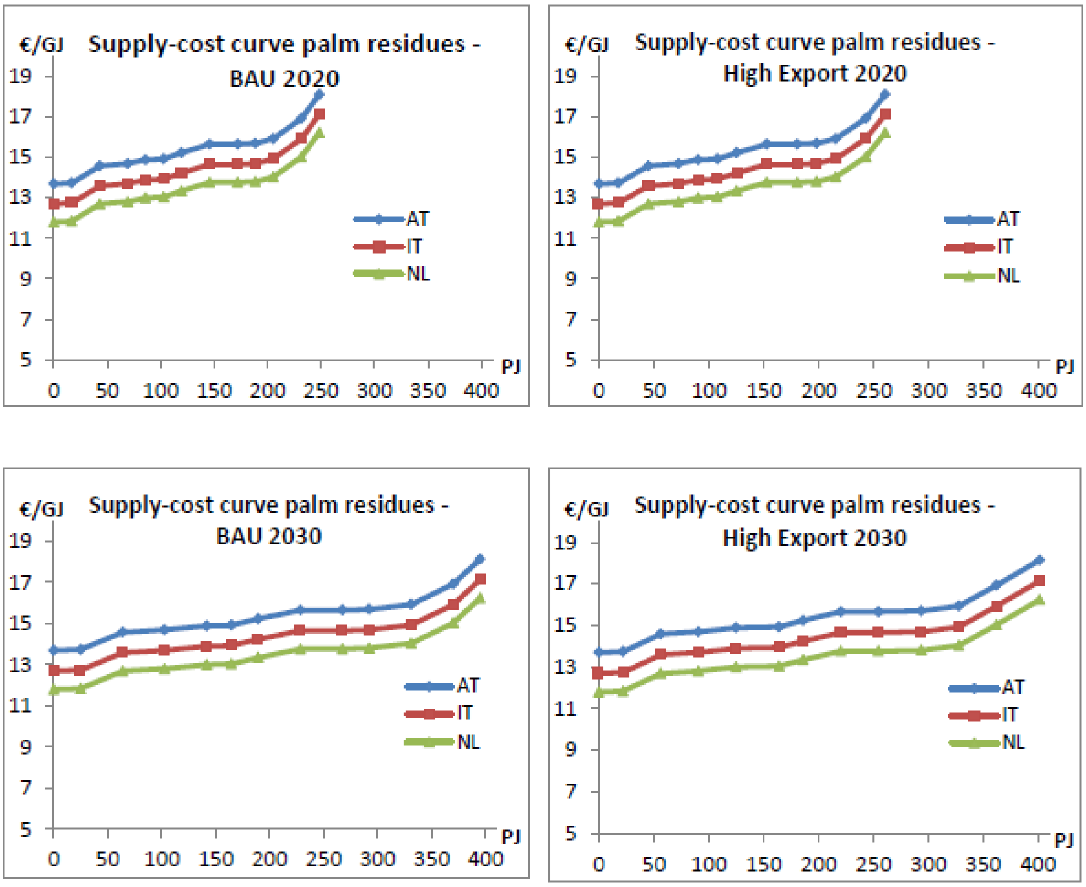

Figure 2-17. Summary of supply-cost curves of palm residues to the EU in 2020 and 2030.

Dependencies on other evidence sources: Rizaldi Boer et al., 2012. Reducing agricultural expansion into forests in Central Kalimantan – Analysis of implementation and financial gaps.

Quality rating analysis: The estimated feedstock potential for Indonesian EFBs is based on robust sources including the latest data from FAOSTAT.

Relevance rating analysis: The report is relevant as it provides data on the export potential of agricultural residues (specifically EFBs) from Indonesia to the EU. However, the scope of the study is restricted to the Kalimantan region of Indonesia.

2.5.3 US - 2016 Billion-Ton Report Advancing domestic resources for a thriving bioeconomy (US Department of Energy, 2016)[58]

Plain English description of evidence: This report was developed by the US Department of Energy (DOE) and provides the most recent estimates of biomass available for biorefining in the US. It focuses on biomass potentially available at specified prices and changes in environmental sustainability indicators associated with select production scenarios. This report is the third report sponsored by the DOE to evaluate the availability of biomass resources in the US and follows the 2005 Billion-Ton Study (BTS) and the 2011 US Billion-Ton Update (BT2). The report looks at the time horizon from 2016 to 2040 in annual time steps.

How the work was undertaken: This desk-study bases its quantification on statistics and available literature.

Key assumptions taken and scenarios modelled: The report shows the potential economic availability of biomass resources based on biomass available at $60 per dry ton. The report provides results for base case and high-yield scenarios. The high-yield scenario assumes a 3% annual increase in yield. The base-case scenarios follows the USDA baseline projections and demands, extrapolated to 2040, and assumes a 1% annual increase in yield.

Data on agricultural residues is based on the Policy Analysis System (POLYSYS).[59] POLYSYS is a multi-crop, multi-sector agricultural model developed and maintained by the University of Tennessee and used by the USDA-Economic Research Service. POLYSYS is based on the US Department of Agriculture (USDA) Baseline Projection from 2015 to 2025, extended linearly to 2040. An important component of POLYSYS is its ability to simulate how commodity markets balance supply and demand via price adjustments based on known economic relationships. The starting year of simulation in POLYSYS is crop year 2014 (most current complete year in the 2015 USDA Baseline). Excel data sets are available online.[60]

Near-term yield assumptions are mainly taken from the SunGrant Initiative Regional Feedstock Partnership Report (Owens, Karlen, and Lacey 2016).

The study uses the Forest Sustainable and Economic Analysis Model (ForSEAM). ForSEAM is a linear optimization model which can be used to assess the quantity of biomass that might be available as energy feedstocks with respect to certain cost. The data are scaled down to the regional level using the Forestry Inventory and Analysis (FIA) database, the US Forest Products Module / Global Forest Products Model (USFPM/GFPM) market model, and the inventory data model Subregional Timber Supply (SRTS).

Key report outcomes: Combined forestry resources, agricultural resources, wastes resources potentially in 2040 available at $60 or less are estimated as 1.2 billion tons under the base-case scenario and 1.5 billion under tons a high-yield scenario (Table 2-24).

[58] https://energy.gov/sites/prod/files/2016/12/f34/2016_billion_ton_report_12.2.16_0.pdf

[59] http://en.openei.org/wiki/Policy_Analysis_System_(Polysys)

[60] For more information, see https://bioenergykdf.net/billionton2016/overview

Table 2-24. Summary of potential forest, agricultural, and waste biomass available at $60/odt or less, under base-case and high-yield scenario assumptions.

Feedstock	2017	2022	2030	2040
Current feedstock use (Million dry tons)				
Forestry resources	154	154	154	154
Agricultural resources	144	144	144	144
Waste resources	68	68	68	68
Total currently used	**365**	**365**	**365**	**365**
Base case scenario potential (Million dry tons)				
Forestry resources (all timberland)	103	109	97	97
Forestry resources (no federal timberland)	84	88	77	80
Agricultural resources	104	123	149	176
Energy crops		78	239	411
Waste resources	137	139	140	142
Total base-case scenario potential (all timberland)	**343**	**449**	**625**	**826**
Total base-case scenario (currently used + potential)	**709**	**814**	**991**	**1,192**
High-yield scenario potential (Million dry tons)				
Forestry resources (all timberland)	95	99	87	76
Forestry resources (no federal timberland)	78	81	71	66
Agricultural resources	105	135	174	200
Energy crops		110	380	736
Waste resources	137	139	140	142
Total high-yield scenario potential (all timberland)	**337**	**483**	**782**	**1,154**
Total high-yield scenario (currently used + potential)	**702**	**848**	**1,147**	**1,520**

Dependencies on other evidence sources: The report relies on a significant number of journal articles and others. The research and references are detailed through the report.

Quality rating analysis: The study uses high quality data, recent data, and projections to 2040. In addition, the report refers to traceable references. A sensitivity analysis of key assumptions is provided in chapter 4.8 of the report.

Relevancy rating: The study provides a detailed analysis of the availability and costs of currently used and potential forest and agricultural residues and energy crops available in the US. There is no explicit assessment of export potential, but the analysis of current uses gives insights into this.

3 Technology evidence

This chapter includes information on the key evidence sources reviewed relating to conversion technology. The scope of the review is biomass conversion technologies that offer greatest overall potential for decarbonising the gas grid in Great Britain to 2050, namely, Anaerobic Digestion to produce biogas, which can also be upgraded to produce grid-quality biomethane (the process of upgrading to biomethane removes CO_2 from the biogas, which could be captured), thermal gasification to produce bioSNG and thermal gasification to produce bioH_2. The sections are structured according to the main technology covered, and within those sections in chronological order (most recent first).

3.1 Key evidence sources assessed

Table 3-1. Summary of technology evidence sources assessed.

Title	Author	Publication date	Timescale	Technology covered	Geographical coverage
Review of support for Anaerobic digestion and Micro Combined Heat and Power - Government response	BEIS	2017	Current	General	UK
Consultation Stage IA: The Renewable Heat Incentive: A reformed and refocused scheme	DECC	2016	Current	General	UK
Technology Innovation Needs Assessment: Bioenergy (refresh)	E4tech for DECC	Unpublished (2015)	2050	General	UK
Bioenergy Value Chain Model	E4tech for ETI	2011-2017	2050	General	UK
Small scale generation cost update	Parsons Brinckerhoff for DECC	2015	Current	General	UK
Best available technologies for the heat and cooling market in the European Union	JRC	2013	Current	General	EU
RHI Biomethane Injection to Grid Tariff Review	DECC	2014	Current	AD	UK
RHI Biomethane Injection to Grid Tariff Review – Government Response	DECC	2014	Current	AD	UK
DECC Industrial 2050 Roadmaps - The use of gasification for industrial decarbonisation	Ecofys for DECC	2016	Current	Gasification	UK
Biomass Gasification	NREL	2012		Gasification	US

Title	Author	Publication date	Timescale	Technology covered	Geographical coverage
Technology Assessment Consolidated Report					
The potential for bioSNG production in the UK, final report	E4tech/NNFCC for DECC	2010		Gasification	UK
Bio SNG Feasibility Study. Establishment of a Regional Project	Progressive Energy & CNG Services	2010	Not applicable	Gasification	UK
Review of technologies for the gasification of biomass and wastes	E4tech/NNFCC for DECC	2009	Pre 2009 and emerging technologies	Gasification	Global
Gasification of non-woody biomass, economic and technical perspectives of chlorine and sulphur removal from product gas	ECN	2006	Not applicable	Gasification	Netherlands
Biomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly Heated Gasifier	NREL	2005		Gasification	US
Techno-economic analysis of biomass liquefaction via fast pyrolysis	VTT and PNNL for NREL	2014		Pyrolysis	US
Techno economic analysis of biomass fast pyrolysis to transport fuel	NREL	2010		Pyrolysis	US
Techno-Economic Assessment of Biomass Pre-Processing	E4tech for ETI	2017	2017	Pre-processing technologies	UK

The evidence review, with respect to technologies, considered whether the evidence includes information on the following aspects:

- Cost/price – CAPEX, fixed and variable OPEX
- Feedstocks
- Technology scale
- Operating hrs
- Conversion efficiency (e.g. biomass to syngas)
- Technology lifetime
- Build time
- GHG emissions and Qualitatively other Sustainability risks (e.g. air quality)

3.2 General

3.2.1 UK TIMES (BEIS, 2017)[61]

Plain English description of evidence: See section 2.2.3.

How the work was undertaken: See section 2.2.3.

Key assumptions taken and scenarios modelled: The model version assessed was "uktm_model_v1.2.3_d0.6.1_DNP" as published on 9 May 2017. The "Resources" and "Process" data worksheets were assessed in this review.

UKTM is calibrated in 2010 (base year), and therefore represents the existing technologies and production routes at that time, along with their corresponding costs. The model can be run for the desired time horizon (up to 2050) and the internal time periods are treated in a flexible manner via different interpolation and extrapolation options.

Process: Conversion costs are included in the "prc_model_tables" worksheet (see "New Biofuel Processing" section, rows 457-503):

- Biomass gasification to produce biomethane
- Pre-treatment of bioresource (e.g. biowaste treatment, pyrolysis)
- Pelletization
- Biomass gasification to produce biomethane
- Anaerobic digestion of bio-feedstocks to produce biogas
- Biooil upgrade to LFO
- Pellet pyrolysis to produce bio-oil
- Upgrade of biogas to biomethane

Costs are expressed in both activity units (£m/PJ) and capacity units (£m/PJ/yr) in 2010, 2030 and 2050. It is our understanding that the underlying source of the costs is UK MARKAL (as described above). Technology lifetimes are assumed to range from 20 to 30 years. Plant utilisation factors are around 90% for the majority of technologies. Process efficiencies range from 100% for biomass pre-treatment (e.g. pelletisation), 87% for anaerobic digestion and 55% for biomass gasification to 54% for bio-SNG.

The "data" worksheet includes also cost data on biomass gasification for hydrogen production (see "Hydrogen production and delivery cost" section, rows 365-425). The CAPEX costs are summarised in **Error! Reference source not found.**. These show a CAPEX reduction of around 40-50% over the period 2010 to 2040. OPEX costs are assumed to be 7% of CAPEX for all technologies. A plant lifetime of 30 years is assumed. However, it is not certain whether this data is used at the present time in UK TIMES.

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[61] https://www.gov.uk/guidance/2050-pathways-analysis#the-analysis

Table 3-2. CAPEX costs assumed in UK TIMES. Units: £2010/kW. (Source: UK TIMES, data worksheet, Hydrogen production and delivery costs, rows 365 to 425.)

Technology	2010	2020	2030	2040
Biomass gasification	3,449	2,720	2,253	1,868
Biomass gasification with CCS	4,559	3,561	3,065	3,049
Biomass IGCC	4,010	3,281	2,814	2,429
Biomass IGCC with CCS	5,120	4,122	3,411	2,842
Waste gasification	6,898	3,626	3,004	2,491
Waste gasification with CCS	8,008	4,467	3,816	3,672

Key report outcomes: The feedstocks and processes which are reportedly most significant in terms of impact are the following, the last three of which are highly relevant to this study:

- imported biodiesel and bioethanol for road transport fuels
- imported biokerosene for air transport fuel
- imported wood pellets for boilers (heat) and for electricity generation
- biomethane (grid injection) from wastes and from UK-grown energy crops
- and potentially: SNG and hydrogen from imported wood chip or wood pellets

Dependencies on other evidence sources: The source of the gasification cost data included in Table 3-2 is cited as Mott McDonald (2010). The source of the technology cost data in the "prc_model_tables" worksheet is not explicitly indicated, although it is understood to be derived from UK MARKAL.

Quality rating analysis: UKTM is a comprehensive cost optimisation model of the UK energy sector. Included in the model are bioenergy pathways covering heat, power and transport. The set-up of the worksheets could be significantly improved to aid transparency and facilitate review. Specific points include a general lack of referencing or in some cases the use of incomplete referencing (e.g. "Mott McDonald (2010)") and the use of hard-coded numbers without references. In addition, different formulae are applied in data series within tables, making it difficult to follow the calculations. Finally, data could be better labelled to aid transparency and facilitate review.

Relevance rating analysis: UKTM provides costs data for a range of bioenergy technologies. The costs are specified in £m/PJ/yr and as such would need to be transformed into appropriate units to enable comparison with other evidence sources which are typically expressed on a £/kW basis, however the underlying data does not readily enable this transformation to be undertaken.

3.2.2 Review of support for Anaerobic digestion and Micro Combined Heat and Power Under the Feed-In Tariff Scheme - Government response (BEIS, 2017)[62]

Plain English description of evidence: This document provides the outcome of a government consultation focused on AD and micro-combined heat and power (mCHP), published on 26 May 2016. BEIS received many comments from the respondents and therefore the proposed assumptions were re-evaluated.

[62] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/590330/FITs_AD_mCHP_government_response.pdf

How the work was undertaken: Analyses based on consultant reports commissioned by DECC/BEIS and then consultation with stakeholders.

Key assumptions taken and scenarios modelled: Primary assumptions used in the analyses are provided in the accompanying Impact Assessment (IA)[63]. These are summarised in the tables below.

Table 3-3. Unchanged assumptions for anaerobic digestion. (Table 1 of the report.)

Assumption	Tariff band	Value
Capex	500-5,000 kW	£4,628/kW
Counterfactual heat fuel	all tariff bands	natural gas, gas oil, wood
Electricity uses	all tariff bands	on-site use, export, parasitic load
Export value	all tariff bands	current export tariff
Feedstock costs/revenues	0-250 kW and 250-500 kW	zero for manure/slurry and digestate
Heat-to-power ratio	all tariff bands	1.1:1
Target rate of return	all tariff bands	9.1%
Load factor	all tariff bands	91%
Reference size	0-250 kW	125 kW
	250-500 kW	375 kW
	500-5,000 kW	2,000 kW
Type of installation	0-250 kW	farm-based CHP
	250-500 kW	farm-based CHP
	500-5,000 kW	waste-fed CHP

Table 3-4. Updated CAPEX assumptions. (Table 2 of the report.)

Assumption	Tariff band	Consultation value	Government Response value
Capex (£/kW)	0-250 kW	£6,843	£6,055
	250-500 kW	£6,843	£5,340

Table 3-5. Updated OPEX assumptions. (Table 3 of the report.)

Assumption	Tariff band	Consultation value	Government Response value
Opex (£/kW)	0-250 kW	£820	£509
	250-500 kW	£644	£449
	500-5,000 kW	£447	£389

Respondents commented that the assumption of 100% food waste feedstock in the 500-5,000 kW tariff band was implausible, and that a composition of 80% food waste and 20% other wastes and residues (such as dairy or abattoir wastes) was more realistic. The gate fee assumption for food waste, which accounts for 80% of the total feedstock tonnage, has been reduced from £20 to £15 per tonne. For the remaining 20% of feedstock, which is made up by other wastes and residues, the gate fee assumption is £3 per tonne. The weighted average of these two figures gives the new gate fee assumption of £12.60 per tonne of feedstock.

[63] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/590331/FITs_AD_mCHP_impact_assessment.pdf

Table 3-6. Updated feedstock and gate fee assumptions. (Table 4 of the report.)

Assumption	Tariff band	Consultation value	Government Response value
Feedstock	500-5,000 kW	100% food waste	80% food waste; 20% other waste
Gate fee (£/tonne)	500-5,000 kW	£20	£12.60

The digestate disposal cost assumption has been revised downwards, as a result of an update of the evidence base, which led to a decrease in the assumed cost of disposal (from £10 to £5 per tonne). In the analysis, it was assumed that digestate tonnage is 81.4% of the feedstock input.

Table 3-7. Updated digestate disposal cost assumption. (Table 6 of the report.)

Assumption	Tariff band	Consultation value	Government Response value
Digestate disposal (£/kW)	500-5,000 kW	£289	£94

Key report outcomes: Based on the evidence provided, the Government decided to implement revised AD generation tariffs.

DECC also decided to introduce sustainability criteria and feedstock restrictions, to apply to all new AD installations from 1 May 2017, and will monitor the implementation of these criteria to ensure objectives are being met, as well as how best to support AD in a way which minimises any negative air quality impacts. Every feedstock consignment must meet the minimum GHG threshold, currently 66.7 gCO_2e/MJ of electricity generated, and the land criteria. Feedstock that is made up wholly of waste will not have to comply with the applicable GHG emissions limit. The land criteria are similar to the requirements currently in place on the RO and RHI and will allow the use of material from a protected area (including wetlands), where the production of the material does not interfere with the nature protection of the area. Payments will be limited to 50% of the total biogas yield, on an annual basis, in relation to electricity generated through the anaerobic digestion of feedstocks not derived from wastes and residues. Annual independent audits will be required for plants with a total installed capacity >1MWe.

Dependencies on other evidence sources: Review of support for Anaerobic Digestion and micro-Combined Heat and Power under the Feed-in Tariff scheme (26 May 2016)[64]. Earlier analysis undertaken by WSP Parsons Brinckerhoff on behalf of DECC and the 2014 Biomethane Review was used to supplement this report with data specific to combined heat and power (CHP) AD plants (see sections 3.3.1, 3.3.2 and 3.2.6). Additional evidence from Waste and Resources Action Programme (WRAP), and the National Non-Food Crops Centre (NNFCC), was also taken into account.

Quality rating analysis: This document represents a good set of UK specific information on biogas plants, which takes into account the consultation responses and the final government decision.

Relevancy rating analysis: This is a relevant source of evidence for UK biogas plants in the capacity ranges 0-250 kW_{el}, 250-500 kW_{el} and 500-5 MW_{el}.

[64] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/535842/FITs_ADmCHP_consultation_document_May_2016_1_-_14_July_deadline.pdf

3.2.3 Consultation Stage IA: The Renewable Heat Incentive: A reformed and refocused scheme[65] (DECC, 2016)

Plain English description of evidence: The Impact Assessment (IA)[66] accompanied the 2016 consultation on proposed changes to the Renewable Heat Incentive (RHI)[67], published on 3 March 2016. Included in the IA are cost and operational data for biomass combustion (domestic and non-domestic) and biomethane.

How the work was undertaken: The IA was a desk-study based on a variety of evidence sources, including previously commissioned UK Government studies, RHI scheme data and market intelligence.

Key assumptions taken and scenarios modelled: For biomass, CAPEX cost assumptions were based on previous DECC commissioned work and/or DECC judgement. OPEX cost assumptions were based on DECC judgement. Load factor assumptions used were inferred from scheme data. Fuel prices were based on market intelligence. For biomethane, all the assumptions were consistent with the 2014 Biomethane injection to grid tariff review[68], except for CAPEX data which was estimated at being 20% lower based on market intelligence.

Key report outcomes: The input assumptions are detailed per technology: Table A.1 for domestic biomass, Table A.2.11 for non-domestic biomass and Table A.21.7 for biomethane. Key data is summarised in Table 3-8.

Table 3-8. Summary of selected key input assumptions for biomass and biomethane. (Based on Tables A.2.1, A.2.11 and A.2.17 in the IA.)

Parameter	Domestic biomass	Non-domestic biomass	Biomethane
Capacity	20 kW	4 MW (1 MW-8 MW)	6 MW
CAPEX (£/kW)	850 (695-1,110)	250 (150-800)	20% lower than the Biomethane review
OPEX (£/kW)	5	10 (6-23)	As per Biomethane review
Design efficiency (%)	84% (72.5-90%)	75% (70%-85%)	
Lifetime (yrs)	20	20	
Heat load factor	14% (11%-19%)	20% (15-35)	85.5%
AD efficiency	n/a	n/a	90%
Fuel price	4.8 p/kWh	4 p/kWh	£0/t

Dependencies on other evidence sources: A key dependency for biomethane is the 2014 Biomethane injection to grid tariff review (see section 3.3.1).

[65] https://www.gov.uk/government/consultations/the-renewable-heat-incentive-a-reformed-and-refocused-scheme

[66] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/505132/Consultation_Stage_Impact_Assessment_-_The_RHI_-_a_reformed_and_refocussed_scheme.pdf

[67] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/505972/The_Renewable_Heat_Incentive_-_A_reformed_and_refocussed_scheme.pdf

[68] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/315608/Biomethane_Review_Final_-_FOR_PUBLICATION.pdf

Quality rating analysis: The data included in the IA is considered to be best in-class for the UK for the technologies covered. It is based on a combination of sources, including RHI scheme data and market intelligence. However, the IA does not provide fully transparent references. Specific examples include, “AEA data” (Non-domestic biomass CAPEX data), “Sutherland tables” (Domestic biomass fuel prices) and “Sweet (2013)” (Domestic CAPEX data). In addition, the majority of the assumptions for biomethane are not included in the IA itself.

Relevance rating analysis: Up-to-date cost (CAPEX, OPEX and fuel) and operational data is provided (central and low/high ranges) and the data is UK specific. As such the data are considered to be very relevant.

3.2.4 Technology Innovation Needs Assessment: Bioenergy (refresh) (E4tech for DECC, Unpublished)

See section 2.2.10.

3.2.5 Bioenergy Value Chain Model (E4tech for ETI, 2011-2017)[69]

Plain English description of evidence: The Bioenergy Value Chain Model (BVCM) toolkit is a spatially explicit, flexible optimisation framework linking a large library of biomass resource, logistics and conversion technology data. BVCM supports analysis and decision-making around optimal land use, biomass utilisation and different pathways for bioenergy production in the UK to 2050. It does this by optimising based on economic, emissions or energy production objectives, or with these objectives in combination, to produce optimised scenario data out to 2050.

How the work was undertaken: The initial model development was led by E4tech in collaboration with Agra CEAS, Black & Veatch, EIFER, Forest Research, Imperial Consultants, Rothamsted Research, and the University of Southampton. Black & Veatch and Imperial contributed most of the technology data, Southampton contributed SRC data, Rothamsted the Miscanthus data, and Forest Research the forestry data. EIFER provided waste data and GIS mapping support to create BVCM data for 157 grid cells across the UK, and Agra CEAS provided agricultural data on food crops. Imperial built the overall BVCM interface, using the AIMMS software environment. E4tech sourced most of the system boundary information, and logistics data.

E4tech and Imperial are continuing to update and improve the functionality of and data behind BVCM, with a major piece of 2015 work that added the emissions from soil carbon changes due to crop transitions. Earlier work expanded the technology database to include a large number of BECCS options. Recent work has focused on producing multiple scenario runs under different starting conditions, and exploring the reasons behind the different model choices, as part of an ETI bioenergy road-mapping exercise.

Key assumptions taken and scenarios modelled: The BVCM input data is combined with user choices regarding bioenergy demands (for electricity, heat, hydrogen, methane and transport biofuels), budget limits, emission targets and CO_2 prices. The model then optimises for a user-defined mix of economic, emissions and/or energy objectives, meeting the system requirements in each decade to 2050, and balancing resource flows in each of the 157 square cells across the UK. BVCM is typically run to meet a set of objectives as determined by the outputs of the ETI’s EMSE model. This means meeting a minimum energy demand from bioenergy in each decade to 2050, whilst achieving a set of decadal GHG emissions targets (usually strongly negative by 2050), and at least cost. Figure 3-1 shows example screenshots from the BVCM study.

[69] http://www.eti.co.uk/library/overview-of-the-etis-bioenergy-value-chain-model-bvcm-capabilities

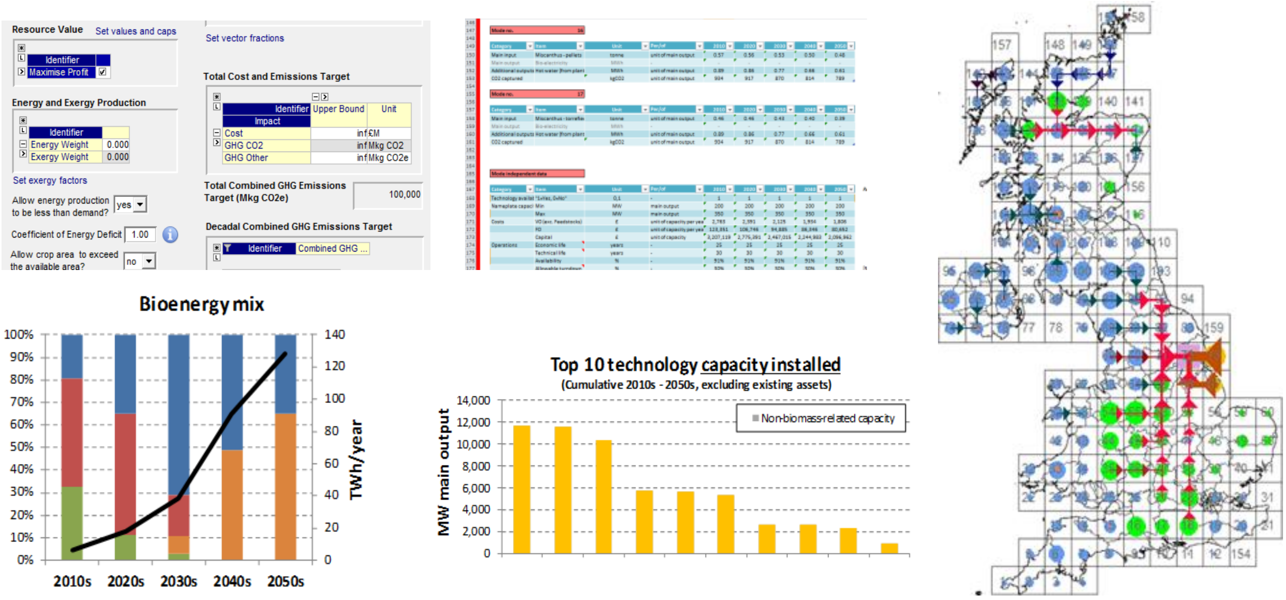

Figure 3-1. Example screenshots from BVCM.

The technology data is for overnight costs in each decade (e.g. the 2010s meaning 2010-2019), with exogenous learning over time assumed (cost and efficiency improvements are linked to the current TRL level). Technology costs are step-wise, i.e. they do not smoothly vary with scale, based on an exponential function, but rather are fixed £/MW values within the min-max capacity ranges given, with up to three different scales of the same technology present in the database. This was a requirement of the linear optimisation in AIMMS.

CO_2 capture and compression is considered within the technology costs, and the costs of downstream CO_2 distribution are included (if required) to get the CO_2 to one of six sequestration points in the UK. However, the costs of CO_2 sequestration are out of scope.

Importantly, the system boundary for BVCM differs according to the end vector. The boundary stops at the gas grid (with the production of biomethane or biohydrogen), and does not consider the final use of gases. Similarly, biofuels stop at the production plant gate, as does biomass electricity. By contrast, the final use in heating is the output of the boiler.

Key report outcomes: The ETI and its members have already used the results of BVCM to help commission further research and field-work on pre-treatment technologies, biomass characterisation and biomass logistics; and will continue using it to identify technologies with system-wide importance, and hence opportunities for technology acceleration. ETI are currently unable to share the results of the recent BVCM runs that were conducted for their road-mapping exercise, but previous insights generated via BVCM have been published by ETI.

Dependencies on other evidence sources: The input data to BVCM includes:

- spatial distribution of land types and availability (based on UKERC land masks);
- yield, cost and GHG emission maps for 83 types of arable & energy crops, forestry & wastes (based on data from Rothamsted, Southampton, Forest Research, Agra CEAS, EIFER and ETI);
- availability of imported feedstocks at ports (based on DfT Modes 1 project data);
- sale/purchase impacts of intermediate resources at the system boundary (based on ETI ESME and supplemented by E4tech data);

- techno-economics, lifetimes, efficiencies and build rates for 103 conversion technologies (based on industrial and academic data collected by B&V, ICON and E4tech, plus BECCS data from ETI TESBIC);
- road/rail/canal/ship/pipeline networks and impacts of their use (based on ICON and E4tech data); and
- CO_2 sequestration points and storage potentials (based on ETI CCS data)

Quality rating analysis: Much of the resource and technical data is from 2011 or before, so is now fairly old, and did require transformation to fit into the BVCM format. Any older data sources are inflated and currency exchanges made to convert into 2010 GBP costs. However, the data was collected and is presented using a harmonised approach across the teams, and has been through a large number of iterations with the ETI and its reviewers. The data quality is scored from Amber to Red based on the technology in question, with the best data generally available for the more commercialised pre-processing and conversion technologies. The feedstock data is scored Green to Amber, based on the maps still containing the most realistic yields and production emissions for UK grown Miscanthus and SRC willow (better than the ELUM project) – although the SRF yields are likely too low. Cost data has been superseded by more recent ETI projects.

Relevance rating analysis: There are several directly relevant datasets. Firstly, the UK average data (from 2010 to 2050) for biomass and waste yields, costs and emissions. Secondly, the detailed techno-economic data for AD and upgrading plants, biomass boilers, biomass CHP, bioSNG, biohydrogen, bioSNG with CO_2 capture and biohydrogen with CO_2 capture are all relevant. The costs, performance and emissions data for biohydrogen and bioSNG with and without CO_2 capture are particularly relevant, as this cost differential is not available in other sources, plus other sources do not typically cover biohydrogen without CO_2 capture, or bioSNG with CO_2 capture. Thirdly, there is data on chipping, pelleting, torrefaction, torrefaction + pelleting, pyrolysis and mechanical biological treatment, but the large majority of this data has been superseded by the ETI TEABPP project. Fourthly, BCVM holds assumptions about build rate constraints, and energy crop industry ramp-up constraints are also useful. And finally, BVCM also holds a large amount of data (densities, LHV, moisture, costs, emissions factors, transport emission factors for 5 transport modes) for all the other materials input/output from BVCM and exogenous learning rates that can be applied to technology cost, based on the TRL level.

3.2.6 Small-scale generation cost update (Parsons Brinckerhoff for DECC, 2015)[70]

Plain English description of evidence: The study provides an assessment of small-scale renewable generation costs for five generation technologies that are eligible for the feed-in tariff, including AD.

How the work was undertaken: Data relating to CAPEX and OPEX were collected via questionnaires that were sent to 21 industry stakeholders, follow-up interviews and literature reviews. Where data were unclear or not in-line with other data within the same technology or capacity range, the author attempted to reach out to the questionnaire respondent to cross-check data. The quality of cost data received was assessed based on designated confidence levels.

[70] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/456187/DECC_Small-Scale_Generation_Costs_Update_FINAL.PDF

Key assumptions taken and scenarios modelled:

- Costs for domestic systems are inclusive of VAT. Costs quoted for commercial and utility scale installations are exclusive of VAT. Any inflation calculations performed are based on the Retail Price Index (RPI).
- CAPEX includes the engineering (design), procurement and construction (EPC) costs, equipment costs and civil works costs. It does NOT include owner's costs, grid connection costs or substation and/or transformer costs.
- CAPEX values were adjusted to 2014 values based on the RPI.
- OPEX includes labour, planned maintenance and lifecycle replacement costs. It does NOT include land costs, property and business rates tax costs, rental and community benefit payments.
- CAPEX and OPEX have been weighted based on year installed, project type and data source to provide a more accurate representation of the data.
- Future CAPEX was assumed to decrease by 1% until 2021 and afterwards decrease by 0.5% per year.
- Future OPEX was assumed to remain flat.

Key report outcomes: The CAPEX and OPEX related to AD were estimated for three capacity ranges: <250 kW, 250–500 kW and >500 kW[71]. The results of this study are summarised in Table 3-9 and show that both CAPEX and OPEX decrease (per unit installed capacity) with increasing AD capacity. In case of CAPEX, large variations were observed around the smaller plants, possibly due to different types of feedstock processes and thus different plant configurations.

Table 3-9. Summary of CAPEX and OPEX costs for AD at 250, 250-500kW and >500kW capacity. (Based on tables included in sections 2.5.4.7 and 2.5.6.4.)

Capacity band	CAPEX (£/kW)			OPEX (£/kW)		
	Low case	Central case	High case	Low case	Central case	High case
<250kW	3,780	5,953	8,126	268	759	1,250
250-500kW	3,685	5,804	7,922	228	645	1,062
>500kW	2,835	4,465	6,095	240	679	1,118

CAPEX costs are forecast to decrease by 1% annually until 2021, from which point onwards they are forecast to decrease by 0.5% per year. Future OPEX costs are assumed to be flat.

Dependencies on other evidence sources: Other evidence sources used in this study related to the AD assessment include: CEPA, Ricardo-AEA and the Renewable Energy Association (REA).

Quality rating analysis: Data sources are indicated in the report, however, they are not easily traceable since there is no full reference or link provided. Confidence levels are given for all the data. The updates are from 2014 and so relatively recent. The work underwent a peer review exercise by Ricardo-AEA and by DECC.

Relevance rating analysis: The data is recent and UK-specific and available at a range of plant capacities.

[71] The average capacity sizes were: 155.26 kW, 479 kW and 1,414,81 kW.

3.2.7 Best available technologies for the heat and cooling market in the European Union (JRC, 2013)[72]

Plain English description of evidence: The 2012 report describes technologies that are currently available for the generation of heat for both domestic, industrial and agricultural/fishery sectors. Critically the technologies chosen are those currently employed within EU member states and are designated as Best Available Technologies (BAT). The report is primarily descriptive and is part of a larger project which has resulted in the creation of:

- a database with description and quantification of the current status of the European heat and cooling demand market by country, useful and primary energy demand by fuel and state of the art of the technology portfolio,
- a database mapping the key technologies for improving the energy efficiency and reducing CO_2 emissions within the heat and cooling market, as well as potential technology innovation and its barriers,
- a modelling tool to develop scenarios of the evolution of the heat and cooling demand up to 2050.

Importantly for this study there is no coverage of gas to grid technologies i.e. gasification or AD.

How the work was undertaken: The European Commission's Strategic Energy Technologies Information System led and coordinated by the Joint Research Centre. The study was undertaken with two partners and examined the European heat and cooling market and its technology mix. The study was performed under the auspices of the Energy System Evaluation Unit of the Institute of Energy and Transport of the JRC. The study characterises the current heat and cooling market in each of the EU27 Member States, Switzerland and Norway, it quantifies the future heat and cooling demand, reviews end-use technologies and qualifies the technology innovation that could take place in this sector. The report gives an overview of the technologies in the database.

Key report outcomes: The key report outcomes of relevance to this study relate to the current and future heating and cooling demand forecasts within the EU up to 2050.

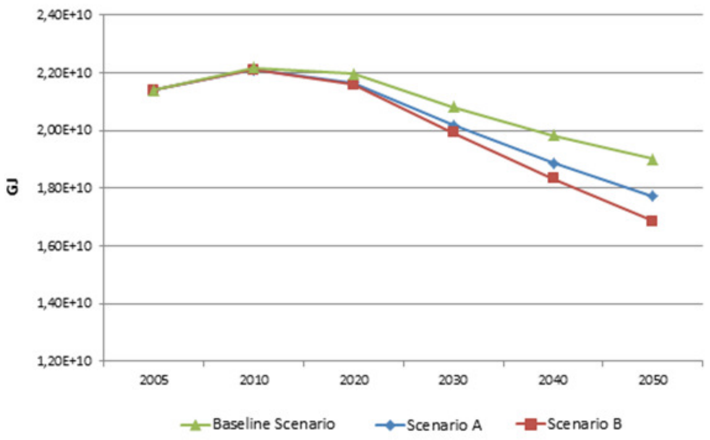

Figure 3-2. EU 27 Useful Energy for Heat Forecasts to 2050.

Dependencies on other evidence sources: The above figure is taken as an output from the heating and cooling demand model, headline outcomes shown in the summary note.[73]

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[72] http://publications.jrc.ec.europa.eu/repository/bitstream/JRC72656/eur%2025407%20en%20-%20heat%20and%20cooling%20final%20report-%20online.pdf

Quality Rating Analysis: The report is an authoritative study on heating and cooling technologies prepared on behalf of the European Commission, albeit a little old**.**

Relevancy Rating: The report does not consider gasification or biogas production technologies, hence is of low direct relevance.

3.3 Anaerobic digestion (including upgrading to biomethane)

3.3.1 RHI Biomethane Injection to Grid Tariff Review (DECC, 2014)[74]

Plain English description of evidence: This consultation document was published by DECC in May 2014 and relates to the banding and tiering of tariffs set for biomethane plants under the RHI. The consultation proposed to move away from one standard biomethane tariff to a tariff structure based on scale, to allow the market to grow further. Larger biomethane plants benefit from economies of scale, so this was also considered. A technical annex to the review (in MS Excel format) provides detailed cost and performance information for waste biomethane plants[75].

How the work was undertaken: Technical analyses use data from 2010 and are based on a reference plant of 1 MW (gross biogas capacity) as given in the report by SKM Enviros and CNG Services Ltd, commissioned by DECC and published in 2011.

Key assumptions taken and scenarios modelled: The consultation document provides the economic basis for biomethane plants at three scales (based on 1MW, 5MW and 10MW biogas output). Table 3-10 illustrates this along with an approximate conversion between the size of plant based on biogas generation capacity, the volume of biomethane injected to the grid and the electrical capacity if the biogas that was diverted to electricity generation.

Table 3-10. Conversion Table of plant biogas capacity (conversions are approximate). The data assumes a volume to volume ratio of biomethane to biogas of 0.61:1, a calorific value of biomethane of 9.96kWh/nm^3 and a gas engine efficiency of 40%. Biogas capacity (nm^3/hour) figures have been rounded to the nearest 50nm^3/hour. The conversions do not account for the parasitic load of the digester, the load factor of the upgrader or methane slippage in upgrading; these are accounted for in the full modelling of the tariffs. (Table 1 in the report.)

Biogas Capacity (MW)	Biogas Capacity (m^3/hour)	Biomethane to Grid (m^3/hour)	Electrical Capacity (MW$_{el}$)
1	150	100	0.4
5	800	500	2.0
10	1650	1000	4.0

The detailed technical annex provides disaggregated CAPEX and OPEX data in 2013 prices for arrange of capacities (1MW to 30 MW), along with key underlying assumptions

[73] https://setis.ec.europa.eu/system/files/Technology_Information_Sheet_Heating_and_Cooling.pdf

[74] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/315608/Biomethane_Review_Final_-_FOR_PUBLICATION.pdf

[75] https://www.gov.uk/government/consultations/rhi-biomethane-injection-to-grid-tariff-review

The biomethane tariff was originally set to allow internal rates of return (IRR) of 12%. Due to economies of scale the consultation document proposed to adjust the tariff for larger plants, to maintain this IRR.

Key report outcomes: The report gives the method used to derive the options and gives the underpinning evidence base. The technical annex supports the consultation document by setting out:

- The general approach undertaken by DECC in setting the original RHI biomethane tariff;
- The cost and performance evidence DECC has used to produce the illustrative policy options presented in the consultation; and
- How the illustrative policy options proposed in the consultation have been derived.

Key correlations of cost (£m) vs. scale (MW) are presented in the report, covering:

- Pre-treatment cost of AD biomethane plant
- CAPEX cost of the AD process
- CAPEX cost of biocrop plant digester
- CAPEX cost of boiler, used to provide heat to the digester
- CAPEX cost of biogas upgrader

DECC sourced evidence on biogas upgrader equipment costs across the entire capacity range from multiple sources: equipment suppliers, plant developers and a comprehensive report by the Swedish Gas Technology Centre. These estimates span the breadth of technologies used for biogas upgrading (membrane, water wash, amine, pressure swing absorption and physical scrubbing). The estimates suggest that economies of scale persist over the entire capacity range and a curve was fitted for the entire capacity range under consideration.

Injection, Metering, Odorisation, Grid ROV and Telemetry: A fixed cost of approximately £0.85m was assumed for this equipment apportioned as: £0.1m for propane storage and injection, £0.45m for metering and odorisation and £0.3m for grid ROV and telemetry equipment.

Grid Connection: These costs depend on several factors such as distance between the plant site and the grid and the grid pressure requirements. The average of the estimates obtained was approximately £0.25m and was applied to plants of all capacities.

Development & Civil Works: Development and civil works costs were added based on limited information. The average of the quotes sourced for plant development costs was approximately £1.3m and the average for civil works £0.9m. It was assumed that these costs are fixed over the capacity range.

Capital Equipment Lifetimes: For the purposes of annuitising the capital costs, these were set out in Table 2 p33 of the report. This gives a lifetime of ~17 years for annuitising the development and civil works costs.

Maintenance Costs: These were taken from SKM/CNG's evidence base and a Swedish Gas Technology Centre (2013) report and expressed as a percentage of the equipment's capital cost – see Table 3 p34 of the report.

Propane Cost: The propane cost was based upon several quotes provided to DECC in confidence which suggested approximately £60/MWh.

Electricity Costs: The electricity price has been based upon DECC's retail electricity price projection (for the services sector) which was £136/MWh at the time, based on the average real price between 2014 and 2030.

Landfill Costs: The tariff calculations compensate for the costs of disposing of rejected waste feedstock. It was assumed that approximately 10% of the feedstock (by weight) cannot be used in the digestion process. The analysis assumes waste biomethane plants pay a landfill gate fee of £25 per tonne of rejected feedstock plus landfill tax at the then level of £80 per tonne.

Digestate Disposal Costs: A disposal cost of £4.6/t of digestate was used, based on an average of estimated low and high disposal costs using cost data from WRAP's Digestate Distribution Models (2013). For biocrop plants the assumption was a zero cost of disposal (i.e. the plants can dispose of the digestate at the farms).

Labour Costs: Labour costs increase with the plant size as more full time employees (FTE) are required. The assumption used is that each FTE costs approximately £31,000 per year which is based upon the £30,000 per year figure assumed in the SKM/CNG report adjusted for wage inflation.

Insurance: Insurance costs were assumed to be 1% of capital costs as per the SKM/CNG report.

Fuel Costs (Biocrop Prices): For the analysis of the tariff required by biocrop plants, an assumption of £35/t was used which has been corroborated by industry as reflecting current prices. (An informal estimate was that biocrop prices can vary from £20-£50/t.)

Biomethane Revenue: The tariff is calculated on the basis of biomethane cost net of the revenue earned from selling the biomethane on the wholesale gas market. DECC publishes annual projections of wholesale gas prices and the average projection for 2014 to 2030 of £24.8/MWh was applied.

Dependencies on other evidence sources: A key data source is the 2011 report by SKM Enviros and CNG Services Ltd, commissioned by DECC[76]**.**

Quality rating analysis: The information has been provided in a structured way, is well referenced and reliable but some of the underlying data is slightly old so costs will require scaling to the current year.

Relevancy rating analysis: The consultation and supporting technical annex provide detailed UK-specific cost and performance data and market information on biomethane, although some of the information is superseded by the government response (see section 3.3.2).

3.3.2 RHI Biomethane Injection to Grid Tariff Review – Government Response (DECC, 2014)[77]

Plain English description of evidence: This document sets out DECC's decisions on the RHI Biomethane Injection review published in December 2014 (Government response and accompanying impact assessment), following the prior consultation (section 3.3.1).

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[76] https://www.gov.uk/government/publications/analysis-of-characteristics-and-growth-assumptions-regarding-ad-biogas-combustion-for-heat-electricity-and-transport

[77] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/384202/Biomethane_Tariff_Review_-_Government_Response_-_December_2014.pdf

How the work was undertaken: The consultation was published in relation to the adjustments to the biomethane injection to grid tariff, on 30 May 2014. It summarises key evidence, any changes to the RHI analyses and rationale behind the final decisions.

Key assumptions taken and scenarios modelled: The document is based on finalised scales of biomethane plants (producing 6, 12 and >12 MW of biomethane) and gives the associated technical and economic assumptions.

Key report outcomes: The document sets out revised biomethane injection to grid tariffs at the levels in Figure 3-3 below, which was subject to parliamentary approval.

The tariffs were modelled based on a feedstock mix of 70% unpackaged food waste and 30% energy crop. Feedback from the consultation responses indicated that it is necessary to include some energy crop in the feedstock mix to hedge against the risk inherent in short term waste contracts. In addition, respondents suggested that the gate fees used in the consultation (£35-£41/t) were unrealistically high and so, based on the evidence received, the analyses used £15/t for unpackaged food waste. The crop feedstock cost of £35/t was considered reasonable.

The industry consultees also reported that they are already incentivised to use the best available technology, to minimise methane emissions and increase their revenue and meet the Government's objective to limit GHG emissions. As such the assumption of 0.5% methane slippage/leakage was considered more realistic.

The evidence also improved understanding of the scale and capacities of biomethane plant. Overall, the tier output ranges correspond roughly to "small", "medium" and "large" plants. Figure 3-3 below (Figure 6, p28 in the document) shows the components of levelised costs before and after the consultation and the updated tariff curve.

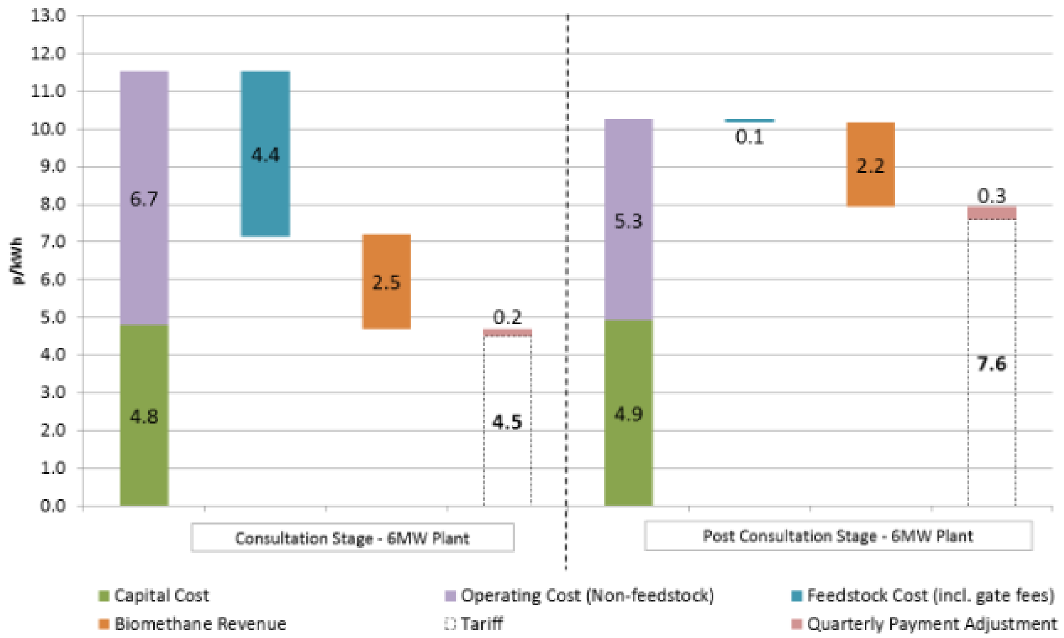

Figure 3-3. Comparison of net levelised cost components underpinning tariff for a 6MW (gross biogas) plant at consultation stage and post consultation. (Figure 6 in the report.)

Dependencies on other evidence sources: RHI Biomethane Injection to Grid Tariff Review (DECC, 30 May 2014)[78]

Quality rating analysis: The study builds on the consultation data with latest available information from UK stakeholders and is considered recent and high quality.

Relevancy rating analysis: This study provides a good basis for biomethane plant size and cost in the UK today.

3.4 Gasification

3.4.1 BioSNG Demonstration Plant - Project Close-Down Report (GoGreenGas, 2017)[79]

Plain English description of evidence: This report produced by the project partners details the design, construction, commissioning and performance of a 0.6 MWth (input) waste to bioSNG production plant in Swindon which has successfully operated for over 2500 hours over a two year period (2015-2017). The project partners outline the design of the first commercial plant currently under construction converting 10,000 tonnes of waste (RDF) into 22 GWh of low carbon bioSNG that will be injected into the local gas grid. The report provides detailed cost and performance estimates for 315 GWh first of a kind (FOAK) and 665 GWh nth of a kind (NOAK) plants, based on the experiences and learnings from the pilot and small scale plants.

How the work was undertaken: The report is the culmination of several year's work to prove the technical and economic feasibility of thermal gasification of waste and biomass feedstock to produce renewable gas, through the construction of a demonstration plant. The construction and operation of the facility and test programme has demonstrated bioSNG production and validated technical and commercial models to enable the construction of large scale commercial plants.

Key assumptions taken and scenarios modelled: The project produced outline design and financial models for future commercial waste to bioSNG plants based on the outcomes from the demonstration plant. The project provides outputs for a first and nth of a kind plants.

Key report outcomes: The project provides key characteristics and costs for a first and nth of a kind plant, as presented in Table 3-11. The following tables and figures also show: CAPEX and OPEX breakdowns for each scale of plant (Table 3-12 and Table 3-13 respectively), calculated GHG emission savings for the 315 GWh first of a kind plant (Table 3 14.) and a Sankey diagram to show the energy balance for the 315 GWh first of a kind plant (Figure 3-4).Table 3-14. GHG emissions estimate for 315 GWh first of a kind plant (HHV basis).

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[78] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/315608/Biomethane_Review_Final_-_FOR_PUBLICATION.pdf

[79] http://gogreengas.com/downloads/

	Emissions (kgCO2eq/MWh)
Electricity consumption	29.7
Gas consumption	2.5
Construction & maintenance	15.9
Avoided landfill	(151.0)
CO2 capture	(267.4)
	(370.3)
GHG emissions without landfill credit	(219.3)
GHG emissions without CO2 capture or landfill credit	48.1

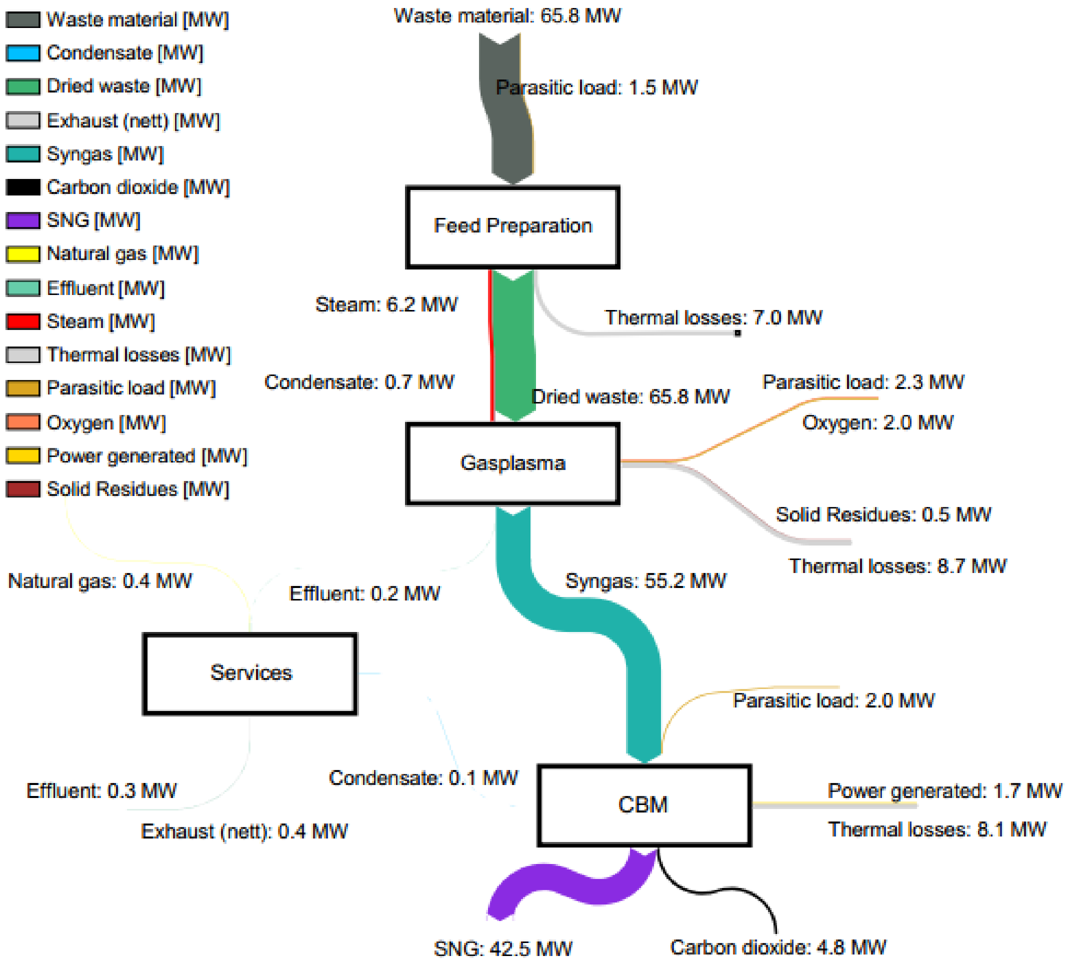

Figure 3-4. Sankey diagram showing energy balance of the 315 GWh/yr first of a kind plant.

The report estimates a 34% reduction in costs per MWh per annum between the first of a kind and nth of a kind plants and indicates that the lower costs are due to economies of scale. In addition, the report suggests that larger plant is expected to be delivered after the technology is mature and this is reflected in a smaller risk allowance and higher operating hours. A first of a kind facility is expected to operate for 7,446 hours per annum (85% availability) increasing to 7,884 hours (90% availability) for an nth of a kind facility.

The report indicates that the costs are comparable with the advanced conversion technology (ACT) waste to power costs of £5.5m per MW of power produced included in the 2016 ARUP renewable electricity generation review. A facility producing 315GWh per annum of bioSNG is equivalent to a power plant producing around 20MW of power using gas engines, which would cost £111m using the ARUP figure compared to the £108m calculated above.

Table 3-11. Process summary and estimated costs for first of a kind and nth of a kind plant (HHV basis).

	315GWh/a (1st of a kind)	665GWh/a (nth of a kind)
RDF energy input	66MWth	132MWth
RDF mass input	136tkpa	289ktpa
Footprint	3.14ha	4.95ha
Capital cost	£108m	£151m
Operating cost	£10.2m/a	£16.5m/a
Real pre-tax project return	12%	10%
Levelised cost of BioSNG	£50/MWh	£21/MWh

Table 3-12. CAPEX breakdown for each scale of plant (HHV basis).

	315GWh/a First of a kind £m	665GWh/a Nth of a kind £m
Fuel receipt and drying	4.9	7.4
Gasification	28.3	42.7
Oxygen production	7.2	10.9
Methanation	14.8	22.6
Building and civils	8.7	13.2
Install, power, controls	12.0	18.2
Grid connection	1.6	3.1
Construction management	16.8	21.2
EPC risk, overhead and profit	11.4	9.2
Other	2.2	2.2
	107.9	150.7
£ per expected MWh of annual production	348	229

Table 3-13. OPEX breakdown for each scale of plant (HHV basis).

	315GWh/a	665GWH/a
	First of a kind	Nth of a kind
	£m	£m
Labour	1.6	1.8
Power	3.0	5.3
Consumables	1.5	3.1
Maintenance	1.9	2.9
Other	2.2	3.5
	10.2	16.5
£ per expected MWh of annual production	33	25

Table 3-14. GHG emissions estimate for 315 GWh first of a kind plant (HHV basis).

	Emissions ($kgCO_{2eq}/MWh$)
Electricity consumption	29.7
Gas consumption	2.5
Construction & maintenance	15.9
Avoided landfill	(151.0)
CO2 capture	(267.4)
	(370.3)
GHG emissions without landfill credit	(219.3)
GHG emissions without CO2 capture or landfill credit	48.1

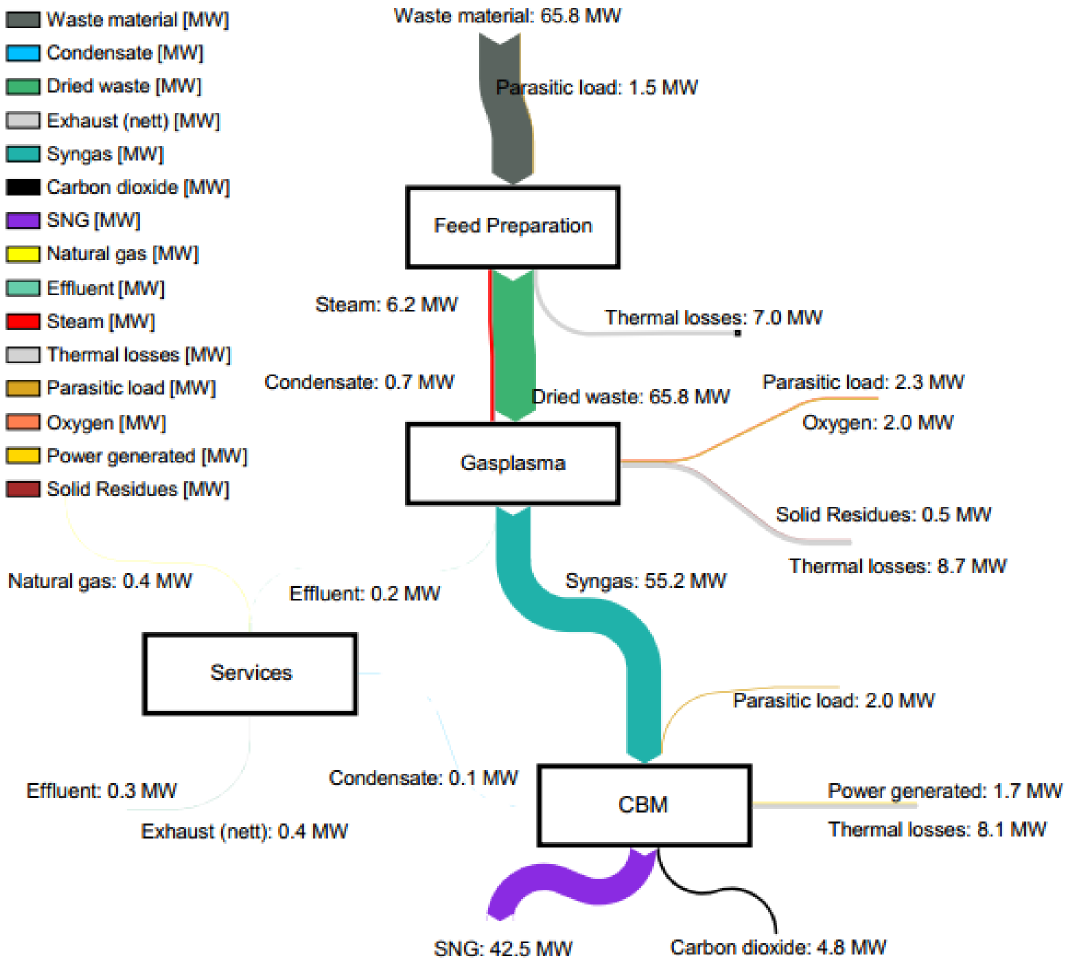

Figure 3-4. Sankey diagram showing energy balance of the 315 GWh/yr first of a kind plant.

The report estimates a 34% reduction in costs per MWh per annum between the first of a kind and nth of a kind plants and indicates that the lower costs are due to economies of scale. In addition, the report suggests that larger plant is expected to be delivered after the technology is mature and this is reflected in a smaller risk allowance and higher operating hours. A first of a kind facility is expected to operate for 7,446 hours per annum (85% availability) increasing to 7,884 hours (90% availability) for an nth of a kind facility.

The report indicates that the costs are comparable with the advanced conversion technology (ACT) waste to power costs of £5.5m per MW of power produced included in the 2016 ARUP renewable electricity generation review[80]. A facility producing 315GWh per annum of bioSNG is equivalent to a power plant producing around 20MW of power using gas engines, which would cost £111m using the ARUP figure compared to the £108m calculated above.

Dependencies on other evidence sources: The data produced in the report is primary source and model based, produced by the project team. Other interim reports are clearly referenced.

[80] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/566718/Arup_Renewable_Generation_Cost_Report.pdf

Quality rating analysis: The data is considered high quality. It is primary source and based on the outcomes from the pilot plant with detailed CAD designs for the commercial plants produced. Costs for equipment are estimated through discussion with suppliers. Operating costs have been estimated by the project partners using the mass and energy balance and current market rates. A gate fee of £33/MWh SNG for the RDF feedstock is assumed, fixed over the project lifetime[81]. Although RDF commands a gate fee today (i.e. waste producers will pay for their waste to be taken away), this may not be realistic in the long term if demand for waste feedstocks increases.

Relevance rating analysis: The data is the most relevant source available for bioSNG production from waste in the UK. It is a primary source, the latest available and UK based. It should be noted that the data is expressed on a HHV basis and therefore cannot be directly compared to the other evidence sources covered in this review (other than in section 3.4.2), which report data on a LHV basis.

3.4.2 Biohydrogen: Production of hydrogen by gasification of waste – An NIA[82] assessment of Biohydrogen production and opportunities for implementation on the gas network (Progressive Energy, Advanced Plasma Power, 2017)[83]

Plain English description of evidence: In this report project partners (Progressive Energy, Advanced Plasma Power and Cadent) seek to understand how biohydrogen may be deployed on the UK gas network. This report builds on work done by the same team who have demonstrated the ability to produce bioSNG from waste using a similar gasification process (see sections 3.4.1 and 3.4.6). The report explains the process of biohydrogen production, estimates the costs of doing so and projects the GHG savings for a nominal 50 MW_{th} waste to bioH_2 production plant which would be able to produce 375 GWh of hydrogen (bioH_2).

How the work was undertaken: This work builds on the work done on the bioSNG demonstration project. The project involved:

- Considering the commercial applications of BioH_2 and defining the appropriate scale and specifications for a commercial BioH_2 plant
- Demonstrating production of BioH_2 from waste at pilot scale
- Designing a facility to produce BioH_2 at commercial scale
- Analysing the cost and environmental impact of the technology
- Assessing routes to deployment

Key assumptions taken and scenarios modelled: A plant converting 100,000 tonnes per annum of refuse derived fuel (RDF) into around 375 GWh of hydrogen was considered because this represents a good compromise between the need to avoid excessive transport of waste and the improved economies achieved by larger scales.

The hydrogen specification modelled was developed on the basis of blending 20% by volume with natural gas in the grid whilst meeting GS(M)R Wobbe number requirements. It was assumed that this specification would be

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[81] The report does not provide the gate fee on a per tonne basis. The GoGreenGas report on BioH_2 (see section 3.4.2) assumes a gate fee of £75/t..

[82] Network Innovation Allowance - https://www.ofgem.gov.uk/network-regulation-riio-model/network-innovation/gas-network-innovation-allowance

[83] http://gogreengas.com/downloads/

acceptable for industrial users and networks completely converted to hydrogen. There were no limits for methane content in the hydrogen produced.

Plant development and optimisation was achieved by process modelling and the models were validated by laboratory experiments. The laboratory results were later validated in the pilot 50 kW bioSNG plant in Swindon.

Key report outcomes: The laboratory experiments successfully demonstrated conversion of waste derived syngas to hydrogen and removal of carbon monoxide to very low levels. The following tables and figures show: process summary of the nominal 50 MWth bioH_2 plant consuming 100,000 tonnes per annum of RDF (Table 3-15), Sankey Diagram to show the energy balance for the plant (Figure 3-5), estimated CAPEX, OPEX and GHG saving for the first of a kind plant (Table 3-16) based on previous experience gained with the previous bioSNG demonstration plant and through discussions with equipment suppliers.

Table 3-15. Nominal 50 MWth Biohydrogen Process Summary (HHV basis). (Table 19 in the report).

Inputs	Energy basis (HHV)		Mass basis
RDF feedstock	61.84MW		13.4te/h
Power	7.2MW		
Outputs			
High-purity hydrogen output	3.1MW		0.08te/h
'Grid-quality' hydrogen output	45.3MW		1.55te/h
CO_2 output			18.0te/h
Efficiency			
Overall plant efficiency	70%		
Feedstock to Biohydrogen efficiency	78%		

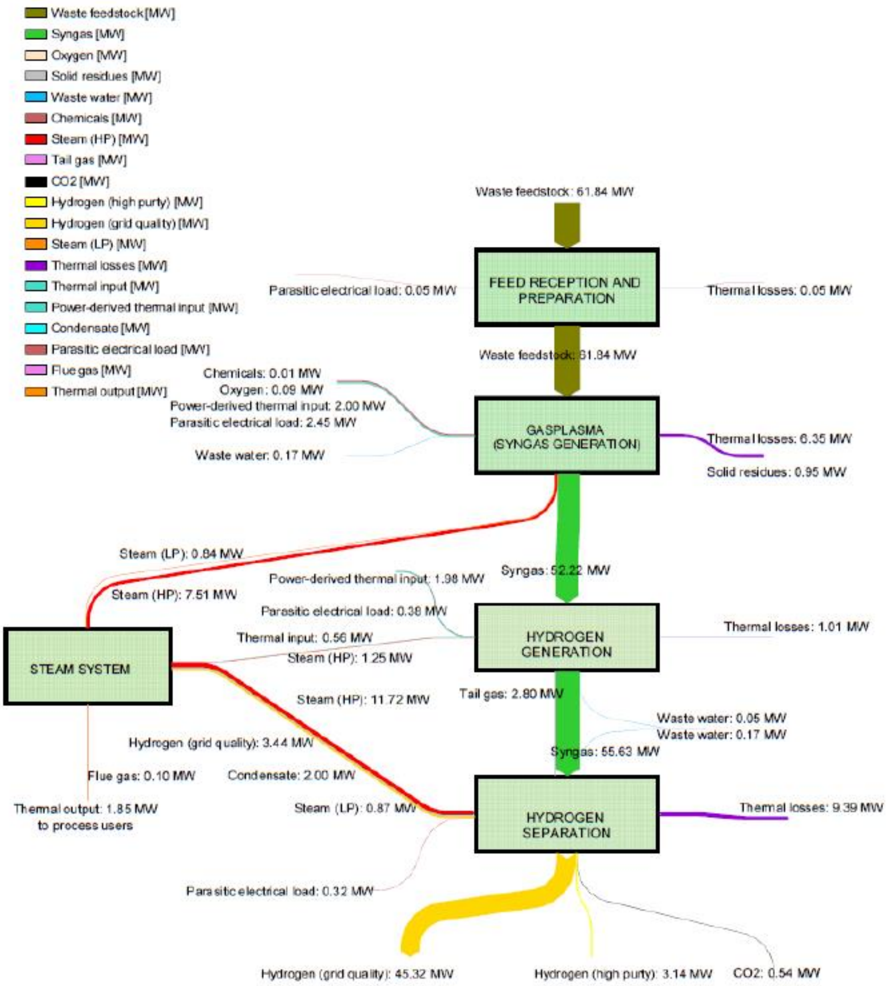

Figure 3-5. Process Sankey Diagram (HHV basis). (Figure 27 in the report.)

Table 3-16. Estimated CAPEX and OPEX and GHG savings for 50 MWth bioH_2 plant (HHV basis).

	£/MWh
Capital cost	39.5
Operating cost	52.4
Gate fee	(20.6)
Levelised cost	71.3
Market price of gas	(20.0)
Additional cost	51.3
GHG Savings (tonne CO2eq/MWh)	0.57
Cost of carbon savings (£/tonne)	91

The first of a kind plant has an estimated levelised cost of production of £71.30/MWh of bioH_2 which is projected to reduce to £42/MWh for the nth of a kind plant fitted with CCS technology.

Dependencies on other evidence sources: Performance data provided by the report is through primary source and laboratory experiment and validation work on a 50 kW demonstration plant. Budget costs are provided by equipment suppliers. Some data is referenced to the GoGreenGas bioSNG close down report (section 3.4.1) and gas quality data and GHG savings are calculated according to referenced calculation methodologies.

Quality rating analysis: The data is very recent, primary source and based on the outcomes from process modelling and pilot scale plant validated laboratory experiments. Costs for equipment are estimated through discussion with suppliers. Operating costs have been estimated by the project partners and are fully detailed and levelised. The source is the highest quality data available on bioH_2 production from waste in the UK context.

Relevance rating analysis: The data is the most relevant source available for bioH_2 production from waste in the UK. It is a primary source, the latest available and UK based. It should be noted that the data is expressed on a HHV basis and therefore cannot be directly compared to the other evidence sources covered in this review (other than in section 3.4.1), which report data on a LHV basis.

3.4.3 DECC Industrial 2050 Roadmaps - The use of gasification for industrial decarbonisation (Ecofys for DECC, 2016, Not published)

Plain English description of evidence: The report was commissioned by DECC to investigate the potential for deployment of biomass gasification technologies to replace the use of fossil fuels, principally natural gas with syngas or hydrogen in some of the UK's energy intensive industries. The report identifies the industrial sectors and processes in which syngas can replace natural gas, including a short technical barrier assessment of the capacity of natural gas fired processes to use syngas. To determine the amount of natural gas displaced, and also the projected decarbonisation across the eight Energy Intensive Industries, likely biomass gasification feedstocks were identified.

How the work was undertaken: Industry standard software (Thermoflow[84] version 25.0) was used to model the conversions of biomass and biomass based feedstocks to synthetic gas using the most common gasifier technologies and their candidate fuels to determine gas conversion efficiencies, how much syngas would be produced per GJ of feedstock, its energy density and hence the required amount of biomass feedstock required. Detailed energy conversion data sheets were compiled for each of the chosen feedstocks.

Key assumptions taken and scenarios modelled: A range of potential biomass feedstocks was selected for modelling; wood (virgin and used), energy crops, SRC willow and biogenic fraction waste. The following modelling assumptions were used:

- Fuel flow = 1.0 kg/s (3.6 t/hr)
- Cold Gas Lower Heat Values corrected to 25°C
- Carbon conversion = 98.5%
- Gasifier heat loss = 1.5%
- Gasifier ash/slag cooled to 100°C
- Cold Gas Efficiency $\frac{LHV gas \times V gas}{LHV fuel \times M fuel} \times 100(\%)$

Where *V gas = Fuel Mass Flow* × *Gas Production.kg fuel*

Key report outcomes: The key modelling outputs are summarised in Table 3-17**.**

[84] https://www.thermoflow.com/#

Table 3-17. Principle modelling outputs per feedstock and gasifier type.

Feedstock type	Feedstock name	Gasifier type(s)	Gasifier temp ^{0}C	Fuel moisture %	Gas flow rate kg/hr	LHV input KJ/kg	Cold gas efficiency %	LHV output KJ/kg
Biomass Wood	Woodchips	Fixed Bed, BFB, CFB	750	20	10,110	14,632	77.55	4,041
Biomass Wood	Woodchips	Fixed Bed BFB, CFB	750	40	9,516	10,364	70.4	2,760
Biomass Wood	Woodchips	BFB, CFB	850	40	10,100	10,364	65.17	2,407
Biomass Energy Crop	Miscanthus	Fixed Bed Downdraft	650	20	9,311	14,632	81.38	4,604
Biomass Energy Crop	Miscanthus	Fixed Bed Downdraft	650	40	8,630	9,432	73.85	2,906
Biomass Energy Crop	Straw pellets	Fixed Bed Downdraft	550	16	6,556	13,399	86.4	6,357
Biomass Energy Crop	Straw briquettes	BFB, CFB	850	16	10,080	13,399	72.59	3,473
Biomass SRC	Willow	BFB, CFB	850	30	10,530	12739	70.13	3,054
Biomass SRC	Willow	BFB, CFB	850	51.1	9,935	8161	56.49	1,671
Waste Wood	C&D type waste wood	Downdraft, BFB, CFB	850	20	10,210	13375	72.36	3,413
Waste	Meat & Bone Meal	BFB, CFB	850	12	12,060	14596	70.74	3,082
Waste	Refuse Derived Fuel	BFB, CFB	725	34.5	8,858	10304	72	3,015
Waste	Solid Recovered Fuel	BFB, CFB	725	4.9	10,309	17619	80.96	4,943
Agriculture Waste	Poultry Manure	BFB, CFB	725	35	9,991	11595	72.65	3,035

Dependencies on other evidence sources: Results were produced using Thermoflow, Version 25 thermodynamic software standard gasification models. Gas consumption data for the energy intensive industries were taken from The Direct Application of Renewable and Low Carbon Heat in Industry, DECC (2014)[85].

Quality rating analysis: The report focusses primarily on the production capabilities of raw syngas from biomass using detailed chemical analyses of the various biogenic feedstocks and identifies types of gasifier that are most appropriate to process different types of biomass feedstock. Industry standard thermodynamic mass balance software was used to model the energy conversion efficiencies (rather than experimental data).

[85] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/372992/RHI_Evidence_Report_-_Direct_Applications_of_Renewable_Heat.pdf

Relevance rating analysis: The report is relevant in that it provides a detailed study on the suitability of different gasifier types to gasify biomass feedstock and it provides conversion factors for gas output from biomass input for different types of biomass and different types of gasifier. The data can be used to sense check data reported from other sources. However, it is important to note that the report focused on lower quality syngas suitable for combustion in an industrial context in reciprocating engines or combusted to produce direct process heat and not bioSNG or $bioH_2$ suitable for injection to the grid. The report did not include an economic assessment.

3.4.4 Biomass Gasification Technology Assessment Consolidated Report (Harris Group Inc for NREL, 2012)[86]

Plain English description of evidence: The report was commissioned by the US National Renewable Energy Laboratory (NREL) to assess gasification and tar reforming technologies. The technology assessments assist NREL in understanding the economic, technical and global impacts of renewable technologies.

The goal of the technology assessments was to solicit and review the technical and performance data of gasifier systems to produce syngas capable of further treatment to liquid fuels and to develop preliminary capital cost estimates for the core equipment.

How the work was undertaken: Three base technologies were assessed:

Technology no.	Gasifier	Tar reformer
1	Direct or autothermal bubbling fluidised bed design	Solid (blocks) catalyst filled reactor design
2	Indirect or allothermal circulating fluidised bed design	Bubbling fluidized bed design
3	Direct or autothermal bubbling fluidised bed design	Design not revealed by vendor

The objectives of this study were twofold:

- Review technical and performance data, determine the engineering requirements of applicable gasifier systems and summarise those findings.
- Prepare preliminary capital cost estimates for the core gasification system equipment.

Model Design: NREL's need for a technology model to analyse the impact of gasification system design on capital costs for various design parameters (e.g. system capacity, reactor pressures, design temperatures, etc.) led to the development of four Microsoft Excel models.

1. CFB Gasifier Model - based on a circulating fluid bed design with an allothermal[87] circulating fluid bed gasification system and an allothermal circulating fluid bed syngas reforming system. The model does not include biomass feed equipment.
2. BFB Gasifier Model - based on a bubbling fluid bed design with an autothermal bubbling fluid bed gasification system. The model does not include a syngas reforming system or biomass feed equipment.
3. High Pressure Biomass Feed Model - based on a two bin design with a lock hopper as the first bin and a metering bin as the second bin.

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[86] https://www.nrel.gov/docs/fy13osti/57085.pdf

[87] "Allothermal" means that the biomass is heated by external sources, whereas in an "autothermal" system heat is provided via exothermal chemical reactions in the gasifier itself.

4. Low Pressure Biomass Feed Model - based on a single metering bin design with a rotary valve providing the pressure lock between the metering bin and the gasifier.

Key assumptions taken and scenarios modelled: Only bubbling fluid bed and circulating fluid bed designs were reviewed for this report. Fixed bed and high temperature slagging gasifiers were not reviewed as they are not suited to gasification of biomass.

Key report outcomes: From a set of input parameters entered into Design Criteria Input Tables (Excel), the models produce the following output documents, all in Excel:

- Material Balance
- Material Balance Flow Diagrams
- Equipment List
- Equipment Drawings
- Drawing List
- Detailed Capital Cost Estimate

The report assessment indicates that fixed-bed gasifiers are not ideal for producing a syngas of sufficient quality for conversion to liquid hydrocarbons, and such gasifier technology was not included in the study. Further commentary discussed the impact of feedstock quality and particle sizing for the three selected technologies.

CAPEX formed part of the assessment, however the accuracy of valuation was wide ranging. Estimated total installed capital cost for an installation with the capacity to process 1,000 oven dry metric tons per day biomass gasification and tar reformer system (in 2011 dollars) are shown below (technologies as per the table above):

- Technology 1: $71,497,300
- Technology 2: $60,529,800
- Technology 3: $71,622,900

A detailed breakdown of costs, for each technology, is included in the appendices.

The study also provides a detailed review of gasifier manufactures and the current (2012) progress on syngas production from biomass.

Quality Rating Analysis: NREL commissioned Harris Group Inc. (HGI) to provide a ‘state of the art’ review, this involved discussions with manufacturers to assess progress of the technology and CAPEX and other operational issues. HGI also cited a number of academic papers as sources, including previous NREL studies. A large number of appendices indicate the level of research, and a broadening of the original brief to determine the accuracy of the conclusions. The report is thorough, detailed and well referenced, however the data is by now quite old.

Relevancy Rating: The study mainly examines current (2012) technologies for production of syngas. The study provides a review of gasifier technologies and gasifier suppliers with information on pilot, proposed and existing process plants. The overall conclusions and analysis are detailed but suggest minimal progress in biomass gasification to syngas. The underlying gasification and syngas data is relevant to this study, despite being a little old, produced in the US context and also produced in the context of gasifying biomass to be converted into a liquid fuel.

3.4.5 The potential for bioSNG production in the UK, final report (E4tech/NNFCC for DECC, 2010)[88]

Plain English description of evidence: This study assesses the potential of bioSNG routes in the UK, in terms of the techno-economic feasibility, air quality benefits, market potential, and drivers for and barriers to bioSNG production and use. The report focuses on technologies and feedstocks that could be used, based on existing bioSNG technology developments, rather than research at an earlier stage.

How the work was undertaken: The report reviews the potential for bioSNG production and use in the UK, in terms of suitable technologies, feedstocks and plant locations, potential for economic competitiveness when used in heat and CHP applications, and local emissions impacts. It also considers the policy climate for bioSNG production and use, barriers to production and use, and makes recommendations to overcome them. The work represents a detailed desktop and literature research of the biomass gasification sector together with the author's in-house knowledge and expertise of the UK National Gas Grid, gasification and gas treatment technology and UK policy as regards to gas production and distribution.

Key assumptions taken and scenarios modelled: The report outlines the thermochemical route to convert biomass into bioSNG. It then focusses on each of the stages in detail and provides referenced detailed information on each stage together with technology development status where necessary. The study also examines the environmental implications of biomass boiler systems deployment on UK air quality and quantifies the potential benefits of biomass being used to produce SNG for injection into the gas grid for urban use. Detailed economic assessments were made covering 30 MW_{bioSNG} and 100 MW_{bioSNG} plants using 2005 industry sourced prices (not referenced) converted to 2010 equivalents and compared to known operational plant costs. End-use modelling data used is referenced comprehensively in Annex B of the study.

Key report outcomes: The study estimated that the first commercial UK plant could be operational after 2018 at a capacity of around 20 MW_{th}, Future plants are expected to fall in the range 30-100 MW_{th} operating on clean wood. The main technical challenges for bioSNG are indicated as being:

- the scale-up to commercial size, especially gasification and tar removal;
- demonstrating and optimising the critical gas cleaning steps for removing unsaturated hydrocarbons, tars and organic sulphur found in real gases, i.e. beyond the existing limited testing at lab and pilot scale;
- optimising methanation catalysts to handle specific contaminants (sulphur, unsaturated and saturated hydrocarbons), and conducting long-term testing for increased bioSNG efficiency; and
- the optimisation of plant configurations / the overall system to ensure each plant will be technically and economically viable.

The report explains that should biomass use be constrained in urban areas due to air quality concerns, its use to produce bioSNG for injection to gas grid could offer a low-emission and low-carbon fuel for heating, that fits with existing infrastructure which would also have carbon benefits from decarbonising the gas grid.

Basic Technical Parameters:

- Raw feedstock to bioSNG LHV efficiency: 74%

[88] http://www.e4tech.com/wp-content/uploads/2016/01/BioSNG-final-report-E4tech-14-06-10.pdf

- Annual operation (equivalent peak load hours): 7,000 hours
- Plant lifetime: 20 years

The following figures taken from the report show the CAPEX (investment cost) and OPEX (feedstock and other operating cost) breakdowns for a 30 MW_{bioSNG} plant and the breakdown of bioSNG production cost components for a 30 MW_{bioSNG} and100 MW_{bioSNG} plant.

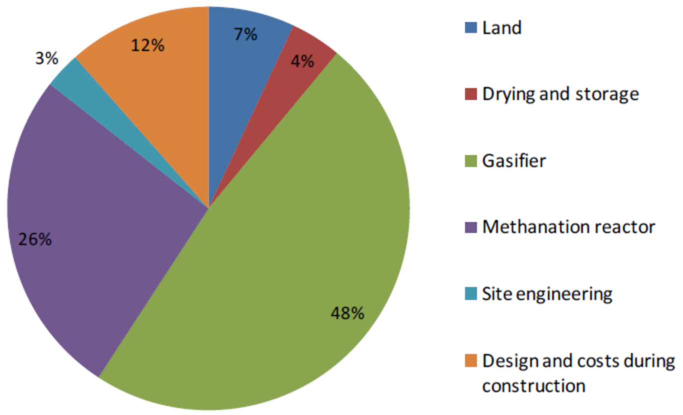

Figure 3-6. Investment cost breakdown for a 30 MW_{bioSNG} plant. (Figure 13 in the report.)

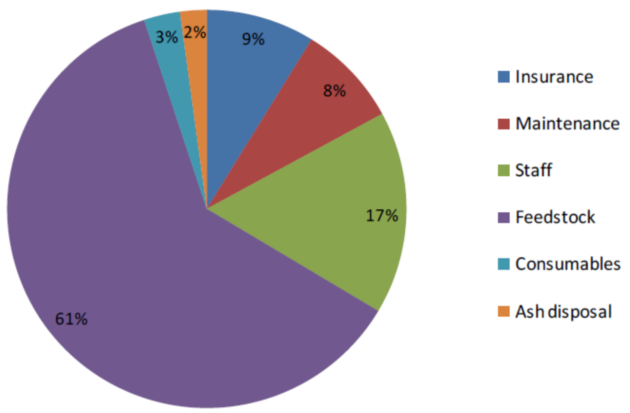

Figure 3-7. Breakdown of feedstock and operating costs for a 30 MW_{bioSNG} plant. (Figure 14 in the report.)

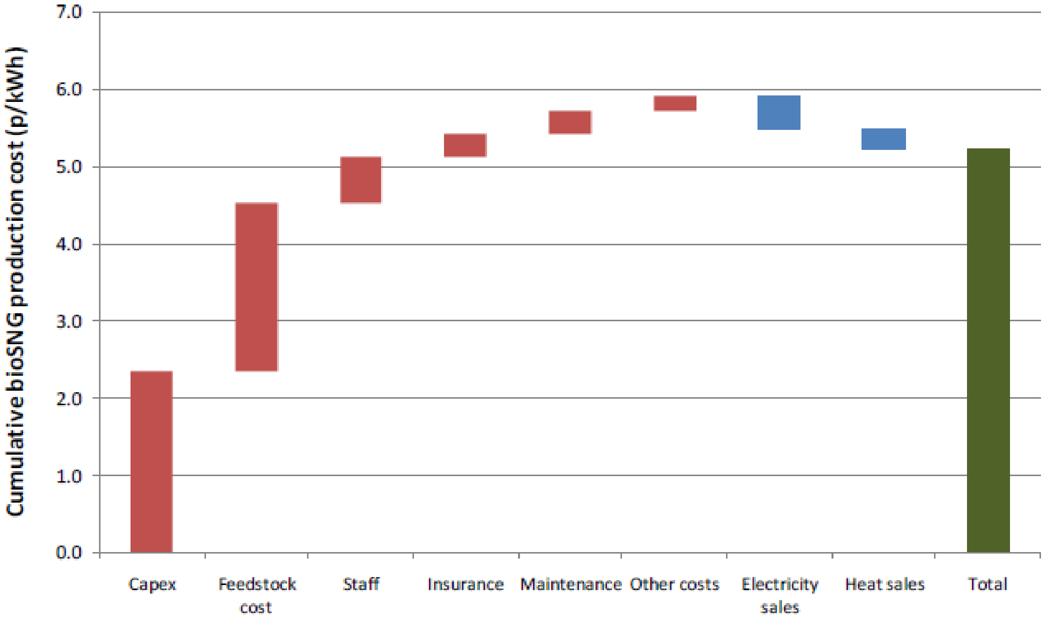

Figure 3-8. BioSNG production cost breakdown for a 30 MW_{bioSNG} plant. (Figure 15 in the report.)

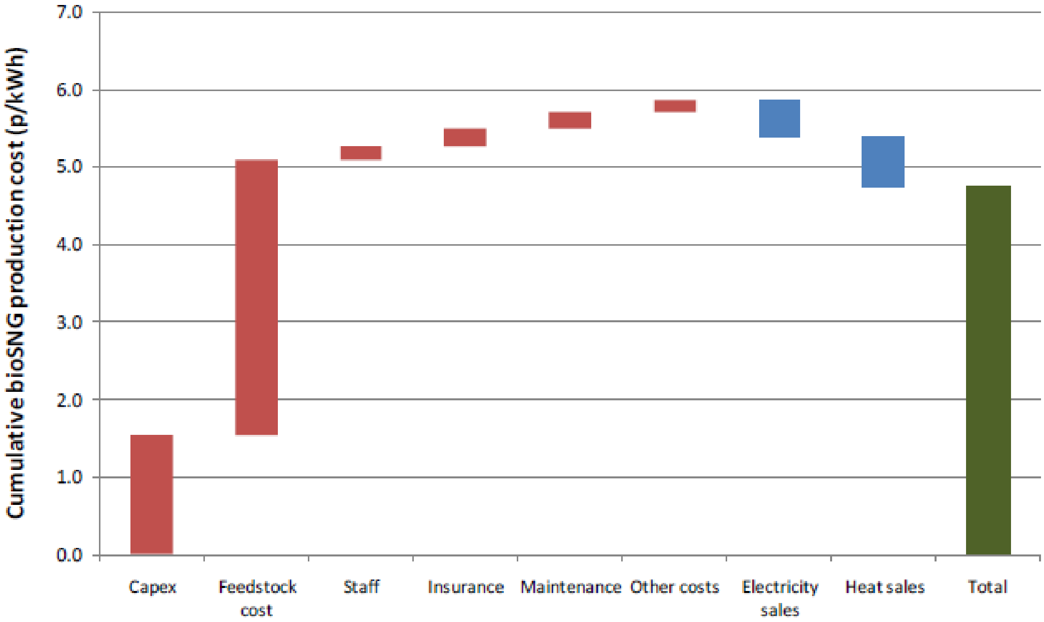

Figure 3-9. BioSNG production cost breakdown for a 100 MW_{bioSNG} plant. (Figure 16 in the report.)

Dependencies on other evidence sources: The document is comprehensively referenced throughout with nearly all references being recently produced some one or two years prior to the report's publication (2010). At the time, the most advanced process design was that of the 1 MW_{bioSNG} demonstration plant in Güssing (Austria). This is the design that was used as the basis for the Gazobois feasibility study on which the economic analysis in the E4tech/NNFCC report was based. Although modelling costs used were based on 2005 data, indexed to 2010, they resulted in reasonable alignment with quoted plant costs for the GoBiGas project and with other academic studies at the time of the report.

Quality rating analysis: The report is comprehensive in scope and covers all aspects of bioSNG production through gasification. Data and references used were mostly recent to the report, albeit they are now several years old, and costs associated with bioSNG production for 2020 projection clearly set out in tabular form.

Relevance rating analysis: The report is highly relevant for bioSNG production in the UK. Project costs and revenues are presented clearly, however they are based on the Güssing demonstration plant running at the time, so data should be applied to the UK context with care.

3.4.6 Bio SNG Feasibility Study. Establishment of a Regional Project. (Progressive Energy & CNG Services, 2010)[89]

Plain English description of evidence: This report provides a critical appraisal of the opportunity afforded by bioSNG, building on a review of the issues associated with biomass sourcing, a detailed analysis of the technology options and applicability for injection into the UK grid, as well as a financial appraisal.

It draws on benchmarking data to demonstrate the full lifecycle CO_2 savings and demonstrates that the bioSNG route is a very cost effective route for decarbonisation compared with other renewables. It provides proposals for implementation pathways, specifically how a bioSNG demonstration could be established in the North East of England.

How the work was undertaken: A review of technologies, fuel feedstock types, a risk and financial assessment and impact studies on carbon offsets, were undertaken to establish a baseline project capacity.

Key assumptions taken and scenarios modelled: Two representative scales of facility are analysed at 50 MWth and 300 MWth input. These would produce approximately 230 GWh and 1,400 GWh of bioSNG per annum respectively based on assumed process efficiencies.

The feedstock price is assumed to be £7/GJ for imported wood pellets, £5/GJ for a mix of imported and indigenous woodchip and -£1.50/GJ for processed Solid Recovered Fuel (SRF) from mixed waste streams. The feedstock prices are 2010 figures, based on biomass prices for large scale electrical generation plants and industry knowledge of SRF produced by Mechanical Biological Treatment with a biogenic energy content of ~60%.

Key report outcomes: The assumed investment cost for a 50 MW_{th} plant is ~£65 million (2010 prices) for a wood based facility. The experience with waste gasification is limited and there are a number of reasons why waste gasification is more challenging; the fuel is heterogeneous and therefore may need enhanced material handling; the nature of waste imposes requirements on the gasification unit itself; the fuel contains a wider range of chemical contaminants and therefore the gas processing must handle this. For this analysis it is assumed that a waste-based system (assuming offsite preparation of the municipal solid waste to SRF) will cost 15% more than the pure biomass one, i.e. £75 million (2010 prices).

Table 3-18 shows key plant operating assumptions in terms of inputs and outputs for the 50 MWth and 300 MWth plants. Table 3-19 shows estimated CAPEX (investment cost) for a 300 MWth (input) facility, running on either pure

[89] http://www.biogas.org.uk/images/upload/news_7_Bio-SNG-Feasibility-Study.pdf

biomass (£215 million) or waste fuel (£250 million). Figure 3-10 shows indicative breakdown of the project investment costs.

Table 3-18. Project operating assumptions. (Table 6.1 in the report.)

Parameter	Small	Large
Input		
Energy rating (energy per hour)	$50MW_{th}$ (180GJ/hr)	300MWth (1080GJ/hr)
Input fuel energy per annum	$0.4TWh_{th}$ (1.3PJ)	2.4 TWh_{th} (8.6PJ)
Biomass fuel (pellets, 16GJ/te) pa	81,000 te pa	486,000 te pa
Biomass fuel (Woodchip, 13GJ/te) pa	100,000 te pa	600,000 te pa
Solid Recovered fuel (18GJ/te) te pa	72,000te pa	432,000 te pa
Operation Load factors (hrs pa)	7200	7200
Baseline Efficiency to SNG[44]	65%	65%
Output		
Bio-SNG MWth	32.5MWth	195MWth
Bio-SNG GJ/Hr	117	702
Bio-SNG therm/hr	1110	6,650
Bio-SNG Nm^3/hr	3330	20,000
Bio-SNG energy per annum	0.23 TWh_{th} (0.84PJ)	1.40 TWh_{th} (5.05PJ)
Equivalent Households	~15,000	~100,000
Equivalent Passenger Vehicles	~25,000	~150,000
Comparative Electrical facility (no SNG)	12MWe (24% efficiency assuming gas engines)	90MWe (30% efficient based on an IGCC configuration)

Table 3-19. Investment cost assumptions. (Table 6.2 in the report.)

Assumed investment cost	Small (£000)	Large (£000)
Energy rating (energy per hour)	$50MW_{th}$	300MWth
Pure biomass	£65,000	£215,000
Waste Fuel	£75,000	£250,000

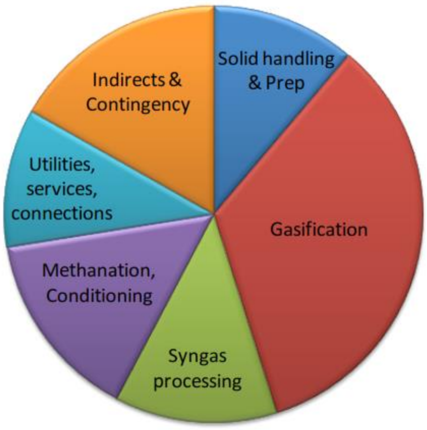

Figure 3-10. Project investment costs and breakdowns for the large SRF facility. (Figure 6.1 in the report.)

In addition, the report analyses fixed and variable operating costs (Table 3-20). Feedstock assumptions are shown in Table 3-21.

Table 3-20. Operating cost assumptions. (Table 6.3 in the report.)

Costs £000s	Small (£000)	Large (£000)
Fixed costs		
Labour,	£1,000	£1,000
Maintenance	£1,300	£4,300
Insurance	£400	£1,300
Land Lease	£100	£200
Rates, permitting, Monitoring, Connections	£500	£1,500
Total	**£3,300**	**£8,300**
Oxygen (over the fence with power supplied FOC)	£650 £25/te excl power (3.5te/hr)	£2,300 £15/te excl power (21te/hr)
Consumables	£250	£1,000
Consumables SRF	£500	£2,000
Disposal costs biomass	£0	£0
Disposal costs SRF	£600 £40/te & 15,000 te pa (20% ash)	£3,600 (£40/te & 90,000 te pa (20% ash)
Total Biomass	**£4,200**	**£11,600**
Total SRF	**£5,050**	**£15,200**

Table 3-21. Feedstock assumptions. (Table 6.4 in the report.)

SRF	Woodchip	Pellet
18 GJ/te 60%energy Bio	13 GJ/te 100%energy Bio	16 GJ/te 100%energy Bio
-£27/te	£65/te	£112/te
-1.5 GJ/te	5.0 GJ/te	7 GJ/te

The report contains an analysis of CO_2 emissions and cost of carbon abated from conversion of SRF waste to bioSNG, and offers comparisons with other heating technologies, as shown in Figure 3-11 and Figure 3-12 respectively.

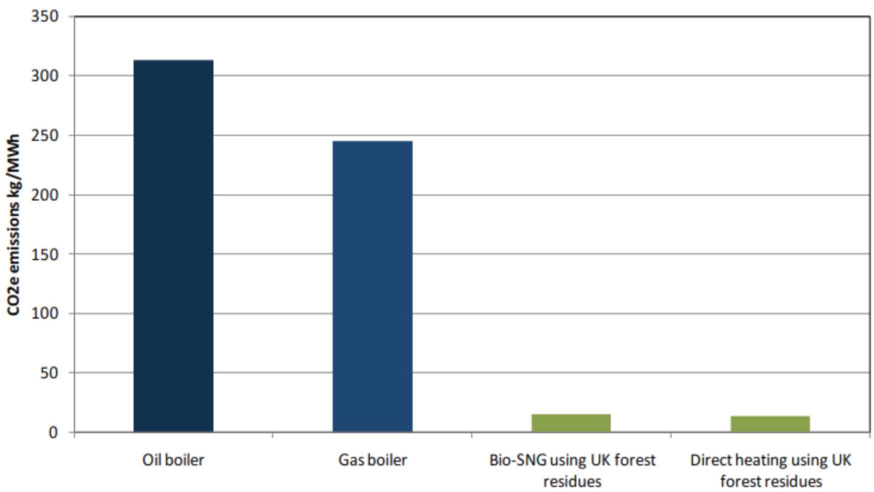

Figure 3-11. CO_2e emissions in the heating sector compared with fossil fuel alternatives (EU RED methodology) (Figure 7.3 in the report)

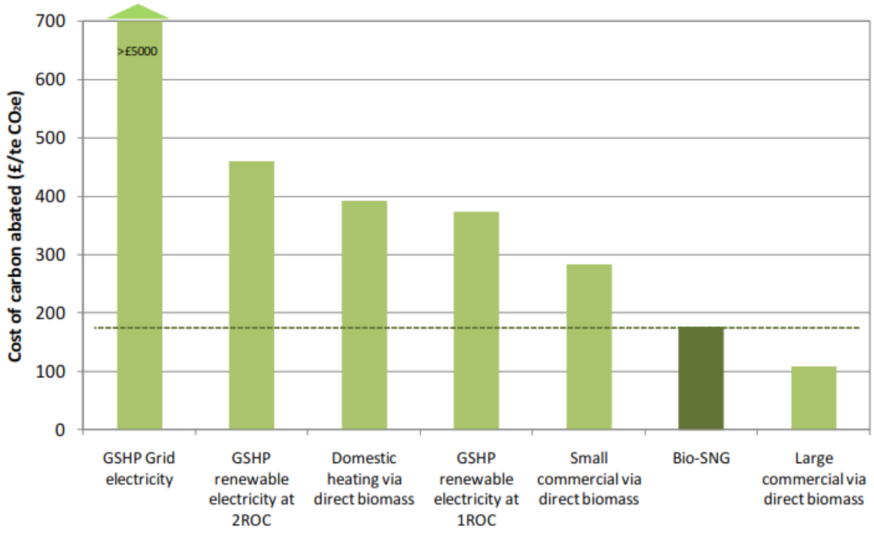

Figure 3-12. Cost of carbon abated for heating applications (Figure 7.4 in the report)

Dependencies on other evidence sources: The report uses UK and international data sources (e.g. gasification cost data published by Choren, Enerkem and GobiGas), along with the latest price (2010) UK information (e.g. wood fuel prices) using UK definitive sources e.g. RHI/RO.

Quality rating analysis: The report provides detailed analysis, engineering expertise and outcomes to provide a firm foundation to assess the practicalities of bringing biomass and waste (Solid Recovered Fuel) to SNG conversion technology onto the market. The report focuses on demonstration and full commercial scale plants. However the data is now more than 7 years old (2010).

Relevance rating analysis: The market assessment using investment criteria to determine a viable SNG process, demonstration and scaled, and subsequent return on investment does provide valuable information covering a wide range of available inputs. Much of the cost and plant performance data is directly relevant.

3.4.7 Review of technologies for the gasification of biomass and wastes (E4tech/NNFCC for DECC, 2009)[90]

Plain English description of evidence: The report aimed to provide a consistent comparison of gasification technologies suitable for liquid fuels production in the UK. Included, for information purposes, is a general overview on gasifier types and operating principles followed by an introduction and explanation of syngas to liquid fuels methods.

How the work was undertaken: To establish which gasifiers could be suitable for liquid fuels production, the requirements of the different technologies that will use the syngas produced were first established. This analysis was then used to narrow down the generic gasifier types covered by the report as follows:

[90] http://www.e4tech.com/wp-content/uploads/2016/01/gasification2009.pdf

- Providing a review of current and emerging specific gasifier technologies. A review of the gasifier technologies that are currently commercially available, or planned to be available in the short-medium term, for biomass feedstocks relevant to the UK was made. Further details on each gasifier are given in the annexes
- A comparison of generic types of gasifier to assess their status, feedstock requirements, scale and costs was undertaken.
- Conclusions on which generic types might be most suitable for fuel production in the UK were made.

Key report outcomes: The report includes a number of useful tables and figures, a few of which are listed below:

- Table 1: Gasifier types
- Table 2: Syngas to liquids efficiency
- Table 3: Syngas requirements for FT, methanol, mixed alcohol syntheses and syngas fermentation
- Figure 1: Gasifier technology capacity range
- Table 4: Entrained flow gasifier technologies from principle developers
- Table 5: Bubbling fluidised bed technology developers
- Table 6: Circulating fluidised bed technology developers
- Table 7: Dual fluidised bed technology developers
- Table 8: Plasma gasifier technology developers
- Table 11: Syngas composition of gasification technologies

Feedstock types and preparation methods were also discussed, with particular reference to suitability for gasifier types.

Dependencies on other evidence sources: The research undertaken has been based on a significant number of academic papers, gasifier developers and others. The research and references are detailed throughout the report.

Quality rating analysis: The report, although more than 7 years old, is thorough in its approach to develop and provide an understanding of gasifier types and relevance to biomass feedstocks. The report details and conclusions are considered to be largely valid at this present time.

Relevancy rating analysis: The report highlighted issues, valid at this present time, of the importance of fuel types and feedstock preparation. Report is focussed on biofuel production not bioSNG and hydrogen, but contains much relevant upstream analysis of system needs.

3.4.8 Gasification of non-woody biomass, economic and technical perspectives of chlorine and sulphur removal from product gas (ECN, 2006)[91]

Plain English description of evidence: This report investigates the economic and technical perspectives for the replacement of woody biomass with non-woody biomass in a biomass gasification process. Non-woody biomass fuels like straw, manure and sludge are cheap fuels characterised by an increased chlorine, sulphur and ash content. The economic perspectives of the study are focused on the estimation of additional costs for the removal of chlorine and sulphur compounds associated with non-woody biomass.

[91] http://www.royaldahlman.com/renewable/assets/Uploads/Gasification-of-non-woody-biomass2.pdf

How the work was undertaken: The CAPEX and OPEX costs were determined based on the mass and energy balance and the process flow diagram defined in the report. The total capital costs and operational costs are given on a Euro per tonne biomass basis. Comparison of the total additional gas cleaning costs with the price of woody biomass gives the economic perspectives for the application of non-woody biomass.

Key assumptions taken and scenarios modelled:

- The investment estimate in this chapter is done on conceptual design level and has an accuracy of approximately ±40% and should, therefore, be used only as an indicative figure
- The costs were corrected for inflation
- Interest rate = 6%
- Depreciation time: 15 years
- Yearly operating time: 8,000 hours

Key report outcomes: The economic perspectives are positive for the proposed gas cleaning systems. The total additional gas cleaning costs for the removal of chlorine and sulphur compounds are approximately 30 €/tonne biomass (dry and ash free) for the boiler application, 28 €/tonne biomass for the gas engine application and 20 €/tonne biomass for the fuel cell application. The total capital investment costs and the sorbent costs (purchase and disposal) have a similar contribution to the total additional gas cleaning cost. (See Tables 5.1 to 5.7 of the study.)

Dependencies on other evidence sources: Not relevant.

Quality rating analysis: The investment costs were estimated with ±40% accuracy, and thus are only indicative figures. Standard cost factors were used to estimate Capex costs. Costs were corrected for inflation. A number of industrial companies supported the project by providing information. The data has not been reviewed in the last 3 years.

Relevance rating analysis: The CAPEX and OPEX figures only cover the additional gas cleaning process (as opposed to the cost of the gasification process).

3.4.9 Biomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly Heated Gasifier (NREL, 2005)[92]

Plain English description of evidence: The US National Renewable Energy Laboratory (NREL) undertook an evidence based study of potential products from biomass-derived syngas (Spath and Dayton, 2003). The outcome showed that hydrogen would be an economically suitable product. NREL developed a modelling and costing process to determine the hydrogen selling price.

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92 https://www.researchgate.net/publication/255200854_Biomass_to_Hydrogen_Production_Detailed_Design_and_Economics_Utilizing_the_Battelle_Columbus_Laboratory_Indirectly-Heated_Gasifier

Two process designs were examined in this study. They were based on the current (2005) operation and performance goals of the catalytic tar destruction and heteroatom removal work at NREL. Each process design broadly consists of:

- feed handling,
- drying,
- gasification,
- gas clean up and conditioning,
- shift conversion,
- and hydrogen purification,
- integration with a steam and power generation cycle.

How the work was undertaken: The gasifier was modelled using correlations based on run data from the Battelle Columbus Laboratory (BCL) 9 tonne/day test facility. The data and correlations for the gasifier can be found in Bain (1992). The experimental runs were performed for several different wood types including Red Oak chips, Birch and Maple chips, Pine chips, sawdust, and other hard and soft wood chips.

NREL produced initial process flow diagrams and extensive research information to hypothesize plant and equipment types and capacities necessary to successfully produce hydrogen. The results were further refined by the addition of CAPEX and O&M variables. NREL have provided Excel based spreadsheets (PS0410a_bhG, PS0410a_bhC, PinchTool_PS0410a_bhC) among other output documentation. NREL was able to determine a minimum hydrogen selling price.

Key assumptions taken and scenarios modelled: Two process designs were modelled each processing 2,000 dry tonnes of biomass per day based on run data from the BCL 9 tonne/day test facility using oven dried wood chips at 12% moisture content.

Key report outcomes: Utilising scaled up data from Gasifier tests and (2005) pricing information NREL produced a hypothetical price for hydrogen based on a 2,000 dry tonne/day biomass input. All values are in 2002 prices:

- **Case 1 Hydrogen Production Process Engineering Cost Analysis**
  Design Report: Current Case 2,000 Dry Metric Tonnes Biomass per Day
  BCL Gasifier, Tar Reformer, Sulphur Removal, Methane Reformer, HTS & LTS, PSA, Steam-Power Cycle
  Minimum Hydrogen Selling Price ($/kg) $1.38
  Current case cost - $153,600,000 Total Project Investment
  Total Variable Operating Costs - $36,230,000 including feedstock, consumables and electricity
  Total Fixed Costs - $10,190,000 including salaries, O/H maintenance, maintenance and insurance/taxes
  Annual Capital Charges - $27,030,000
- **Case 2 Hydrogen Production Process Engineering Cost Analysis**
  Design Report: Goal Case 2,000 Dry Metric Tonnes Biomass per Day
  BCL Gasifier, Tar Reformer, Sulphur Removal, HTS & LTS, PSA, Steam-Power Cycle
  Minimum Hydrogen Selling Price ($/kg) $1.24
  Goal case cost - $144,400,000 Total Project Investment
  Total Variable Operating Costs - $35,770,000 including feedstock, consumables and electricity
  Total Fixed Costs - $9,820,000 including salaries, O/H maintenance, maintenance and insurance/taxes
  Annual Capital Charges - $25,420,000

Dependencies on other evidence sources: NREL undertook its own testing at the BCL in Ohio. NREL assessed OPEX and CAPEX from commercial and Governmental sources. In addition, NREL have highlighted a number of other studies including the following:

- Mann, M. K. (1995). Technical and Economic Assessment of Producing Hydrogen by Reforming Syngas from the Battelle Indirectly Heated Biomass Gasifier. National Renewable Energy Laboratory, NREL/TP-431-8143.
- Breault, R.; Morgan, D. (1992). Design and Economics of Electricity Production Form An Indirectly-heated Biomass Gasifier. Report TR4533-049-92. Columbus, Ohio: Battelle Columbus Laboratory.
- Phillips, S.; Carpenter, D.; Dayton, D.; Feik, C.; French, R.; Ratcliff, M.; Hansen, R.; Deutch, S.; and Michener, B. (2004). Preliminary Report on the Performance of Full Stream Tar Reformer. Internal NREL Milestone report.
- Wan, E. I. and Malcolm D. F. (1990). "Economic Assessment of Advanced Biomass Gasification Systems," in Energy from Biomass and Wastes XIII, Donald L. Klass ed. Chicago: Institute of Gas Technology, pp.791-827.

Quality rating analysis: The report is sufficiently detailed and robust in its analysis, engineering expertise and outcomes to provide a firm foundation in assessing the practicalities of bringing biomass to hydrogen conversion technology onto the market although much of the data used is based on a small pilot gasification plant. However, the data are now very old.

Relevancy rating analysis: NREL have highlighted practical applications for production of hydrogen from biomass. Although the prices are as at 2002, the engineering processes adopted remain valid at this present time.

3.5 Pyrolysis

3.5.1 Techno-economic analysis of biomass liquefaction via fast pyrolysis (VTT and PNNL for NREL, 2014)[93]

Plain English description of evidence: This study reports techno-economic assessment of fast pyrolysis technology for the production of gasoline, diesel and heavy oil range hydrocarbon liquids. The pyrolysis process is based on wood biomass residues. The work was carried out as a collaboration between VTT (Finland) and PNNL (USA). The study includes technical data (e.g. operation parameters, feedstock physical/chemical characteristics, oil compositions, etc.) and economic data (e.g. CAPEX, OPEX, feedstock cost, catalyst cost, etc.).

How the work was undertaken: The assessment is an extension of other similar studies carried out previously within the IEA bioenergy agreement during the 1980's, and intended to make an assessment with higher confidence than during prior evaluations, due to the recent abundance of experimental research data and industrial activities available. Aspen Plus software was used to simulate the conceptual models for the conversion of biomass via fast pyrolysis. All data are based on literature or prior works that were carried out by the project partners (VVT, PNNL).

[93] http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23579.pdf

Key assumptions taken and scenarios modelled: The capital costs were estimated by aggregating equipment costs (for available equipment sizes) and applying appropriate scaling factors (not shown in this report), which were derived from primary sources. Operation costs include fixed and variable costs:

Fixed operating costs include:

- Operating labour (which is a function of plant size, 5 shifts assumed, 6 persons per shift)
- Maintenance labour: 1% FCI[94] assumed
- Overheads: 2% FCI assumed)
- Maintenance materials: 3% FCI assumed
- Taxes, insurance: 2% FCI assumed
- Other fixed costs: 1% FCI assumed

Variable operating costs include:

- Feedstock cost
- Natural gas
- Electricity consumption
- Catalyst costs
- Waste handling

Other assumptions for economic calculations are:

- Plant capacity: 2,000 tonne/day
- Construction period: 2 years
- Annual operating time: 7,000 hrs/year
- Plant life: 20 years

Key report outcomes: The report shows estimated cost of a pioneer plant and a mature plant. Tables 19 and 20 in the PNNL report summarise the results for capital cost and production cost estimates, respectively. These tables are shown below in Table 3-22 and Table 3-23 below.

Table 3-22. Fast pyrolysis and upgrading capital costs estimation for a 2 kt/day refinery (costs in USD).

Process Section	*PID*	*Installed*	*Uninstalled*	
Feedstock Handling and Prep	A100	$ 21.4	$ 8.7	6%
Fast Pyrolysis	A100	$210.0	$ 61.9	59%
Hydrotreating	A310	$ 76.3	$ 35.6	21%
Hydrogen Plant	A400	$ 41.1	$ 21.4	11%
Utilities	A700	$ 9.2	$ 3.2	3%
Total		**$358.0**	**$130.8**	**100%**

[94] Financial Conditions Index

Table 3-23. Fast pyrolysis production cost estimations for a 2 kt/day refinery (costs in USD).

	Fast Pyrolysis			Upgrading		
	M $/a	$/t	$/GJ	M $/a	$/t	$/GJ
FIXED OPERATING COST						
Operating labor	1.1	3	0.2	0.3	2	0.1
Maintenance labor	2.3	6	0.4	1.3	9	0.2
Overheads	4.6	11	0.8	2.5	18	0.4
Maintenance materials	6.9	17	1.1	3.8	27	0.6
Taxes, insurance	4.6	11	0.8	2.5	18	0.4
Others	2.3	6	0.4	1.3	9	0.2
Total	21.9	52	3.6	11.7	84	2.0
CATALYST COST						
Hydrogen plant catalyst				0.2	2	0.0
Stabilizer catalyst				4.6	33	0.8
1st HDO catalyst				10.4	75	1.8
2nd HDO catalyst				4.3	31	0.7
Total				19.5	138	3.3
VARIABLE OPERATING COST						
Feedstock	35.0	84	5.8	96.7	694	16.5
Electricity	5.8	14	0.9	7.3	53	1.3
Waste water treatment	0.0	0	0.0	0.1	1	0.0
Natural gas	0.0	0	0.0	0	0	0.0
Total	40.8	98	6.7	104.2	747	17.8
CAPITAL CHARGES	34.0	81	5.6	18.6	134	3.2
PRODUCTION COST	96.7	231	16.0	153.9	1103	26.3

Dependencies on other evidence sources: The equipment cost estimates were derived from Jones et al. (2003); scaling factors were derived from Harris Group (2011), SRI PEP 2007 Yearbook (2007) as well as Aspen Capital Cost Estimator.

Quality rating analysis: The data is global and not UK specific. The data is collected from publicly available literature. The underlying data for the cost estimates is presented in a very transparent way and clearly linked to their respective sources. The report is older than 3 years (from 2014) and uses other sources that include older data (2007 to 2013).

Relevance rating analysis: The report includes cost figures (capital, fixed and variable operating costs) technical data (operating parameters, compositional analysis, process design) and information about the plant (plant construction period, depreciation time, etc.). The data requires minor transformation (e.g. currency conversion from US dollar to UK pound). The pyrolysis oil production and product value are not relevant for this study, however, as a feedstock pre-treatment the pyrolysis process and its related costs are relevant.

3.5.2 Techno economic analysis of biomass fast pyrolysis to transport fuel (NREL, 2010)[95]

Plain English description of evidence: This study was conducted by NREL (the US National Renewable Energy Laboratory) with support from ConocoPhillips. The study models techno-economic assessment of biomass conversion to a mixture of gasoline and diesel blend stock via fast pyrolysis and subsequent pyrolysis oil upgrading using hydrogen (hydrocracking and hydrotreating processes). For the upgrading operation, the study compares the economics of two scenarios: i) hydrogen is produced onsite by reforming of aqueous fraction of pyrolysis oil, ii) hydrogen is purchased from an external source. Detailed cost figures are provided in this study, including equipment, CAPEX and OPEX costs as well as technical data including operation conditions (temperature, pressure, flow rates, etc.) and compositional analysis of the pyrolysis products.

How the work was undertaken: A computational model was developed, based on Aspen plus software, to calculate the mass and energy balances and economic costs related to the processes. Also, Aspen Icarus software was used to estimate equipment costs. The results based on this methodology have an accuracy within 30%. The process design and all the underlying data in this study were exclusively based on public domain literature.

Key assumptions taken and scenarios modelled: Cost calculations were performed for a mature plant (n^{th} of a kind) and then were adjusted to the first of a kind plant. The other important assumptions for the economic analysis are:

- Feedstock is modelled based on proximate and elemental analysis,
- Pyrolysis oil composition was modelled based on previous NREL data and USDA data,
- Present value: zero,
- Internal rate of return: 10% over 20 years,
- Plant capacity: 2,000 tonne/day of dry corn stover, employing multiple 500 tonne/day reactors,
- The online time: 328 days/year (90% of the capacity),
- Construction time: less than 24 months,
- Start-up period: 25% of the construction time,
- Contingency for the nth plant: 20% of the total installed equipment,
- Contingency for the 1st plant: 30% of the installed equipment,
- Feedstock costs (including delivery costs): $75/ dry tonne,
- Catalyst replacement costs: $M 1.77 /year
- General overhead: 60% applied to the total salaries and covers items such as safety, general engineering, general plant maintenance, payroll overhead, plant security, janitorial and similar services, phone, light, heat and plant communications,
- The general plant depreciation: 7 years

Key report outcomes: Sensitivity analysis of key process variables finds fuel conversion yields to have the most impact on the final cost of transportation fuel. Biomass cost and bio-oil yield are found to have a significant impact on the final cost of the fuel produced.

[95] http://www.nrel.gov/docs/fy11osti/46586.pdf

The cost data are given in Tables 12 to 18 and Tables A-1 and A-2 in the NREL report. Appendix B in the NREL report includes mass and energy balances. The main results of the study are presented below in Table 3-24 and Table 3-25.

Table 3-24. Capital costs estimated for 2000 tonne/day fast pyrolysis plant (n^{th} plants of its kind); the estimated capital costs include onsite hydrogen production.

Capital Costs (millions $)	
Hydroprocessing	$48.7
Combustion	$47.3
Pyrolysis and Oil Recovery	$28.0
Pretreatment	$20.2
Utilities	$9.1
Storage	$5.8
Total Equipment Installed Cost	**$159.1**
Indirect Costs	$46.9
(% of TEIC + IC)	20%
Project Contingency	$41.2
Total Project Investment (TPI)	$287.4
Installed Cost per Annual Gallon	$4.50
Total Project Investment per Annual Gallon	$8.12
Lang Factor	5.46

Table 3-25. Operating costs estimated for 2000 tonne/day fast pyrolysis plant (n^{th} plants of its kind); the estimated capital costs include onsite hydrogen production.

Operating Costs (cents/gal product)	
Feedstock	153.8
Electricity	16.4
Solids Disposal	5.1
Catalyst	5.1
Fixed Costs	32.5
Co-Product Credits	-31.9
Capital Depreciation	33.6
Average Income Tax	26.4
Average Return on Investment (10% IRR)	63.5
Total	309.4
Operating Costs (millions $/yr)	
Feedstock	$54.4
Electricity	$5.8
Solids Disposal	$1.8
Catalyst	$1.8
Fixed Costs	$11.5
Co-Product Credits	-$11.3
Capital Depreciation	$11.9
Average Income Tax	$9.3
Average Return on Investment	$22.5
Total	$109.5

Dependencies on other evidence sources: A previous NREL report (2006) was used as the basis for compositional analysis of pyrolysis oil and gas products; USDA report (2010) was used as the basis for pyrolysis product distribution; the Peters and Timmerhaus method was used for estimation of project expenditure investment (2003).

Quality rating analysis: The data is global and therefore not UK specific. The data is collected from publicly available literature. Equipment costing data and installation factors were collected from direct quotations, published data, and Aspen Icarus software evaluation. If process changes were made and the equipment size changed, the equipment was re-costed using a scaling equation. Estimates are typically accurate within 30%. The underlying data for the cost estimates is presented in a very transparent way. All the assumptions for the calculations are given. Although the report is older than 7 years (data is from 2010), it is thorough in its approach to develop and provide an understanding of fast pyrolysis process and feedstock pre-treatment. The report conclusions are considered to be largely valid at this present time.

Relevance rating analysis: The report includes cost figures (capital, fixed and variable operating costs, equipment costs), technical data (operating parameters, compositional analysis, process design) and information about the plant (plant construction period, depreciation time, etc.). The data requires minor transformation (e.g. currency conversion from US dollar to UK pound). The pyrolysis oil production and product value are not relevant for this study, however, as a feedstock pre-treatment, the pyrolysis process and its related costs are relevant.

3.6 Pre-processing technologies

3.6.1 Techno-Economic Assessment of Biomass Pre-Processing (E4tech for ETI, finalised September 2017)[96]

Plain English description of evidence: The ETI's Techno-Economic Assessment of Biomass Pre-Processing (TEABPP) study is delivering process modelling for a selected set of bioenergy value chains, comparing the costs, performance and emissions of supply chain configurations with and without pre-processing. Optimal chain designs will be derived, highlighting areas of the supply chain with greatest potential for improvement, and circumstances when different pre-processing choices are most beneficial.

The study is comprised of 6 main deliverables:

- D1: Benchmarking report with a detailed technology review and horizon scanning
- D2: Excel model of the full chain costs
- D3: Report summarising down-selection process to pick 10 chains
- D4: Process model in gPROMS modelling environment
- D5: Process model user guide
- D6: Final report with analysis and recommendations

The TEABPP study therefore has detailed cost, performance and emissions data for five UK biomass feedstocks, 12 transport types, seven storage types, 15 pre-processing technologies, and 32 end conversion technologies generating either hot water, electricity, CHP or syngas. The pre-processing technologies in scope are:

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[96] http://www.eti.co.uk/programmes/bioenergy/techno-economic-assessment-of-biomass-pre-processing

- Water washing
- Field washing
- Chemical washing
- Drum drying
- Belt drying
- Screening
- Chipping
- Briquetting
- Pelleting
- Pyrolysis
- Torrefaction
- Torrefaction + pelleting
- Torrefaction + briquetting
- Steam explosion + pelleting
- AFEX + pelleting

How the work was undertaken: E4tech are leading a contractor team of Black and Veatch (B&V), PSE, CMCL innovations, Imperial College, University of Sheffield and University of Leeds. Desk-based research was used for D1, with the data collected using an aggregation of confidential industrial sources, published white papers, a number of supplier quotes and interviews (mostly conducted by B&V), and academic literature for the less developed technologies (mostly sourced by Sheffield, Leeds and Imperial). D2 pooled this cost and performance data into a consistent format, allowing the user to select thousands of combinations of feedstocks, transport, storage, pre-processing and conversion options. These options were narrowed down in D3 to just 10 chains, via a series of meetings with ETI and their expert reviewers. The live process model in D4 was developed by PSE, using their software modelling toolkit gPROMS to translate the Excel analysis into code, and add in GHG emissions and blending considerations that were missing from D2. PSE also authored the D5 user guide. CMCL are conducting a sensitivity analysis of each chain using their internal MoDS software, before identifying cross-over conditions where pre-processing has benefits over chains without pre-processing.

Key assumptions taken and scenarios modelled: The scope of the work was clearly defined to only collect and present data for new build/greenfield, dedicated biomass conversion plants, without any CO_2 capture. Costs are presented in present day values (GBP), levelised at a commercial discount rate where necessary – there is no forecasting into future years. Profit margins are not considered. The model and data are not spatially explicit.

Ten chains were taken forward for further study. A chain is defined as a fixed choice of pre-treatment technology, conversion technology and end vector. Biomass feedstocks and other chain parameters (including the scale and performance of pre-treatment and conversion technologies) are allowed to vary within a chain, and these key parameters are varied in the sensitivity analysis to explore the impact of uncertainties.

Five feedstock types are in scope – Miscanthus, SRC willow, SRF (both coniferous and deciduous) and imported LRF wood pellets. Waste wood, MSW and other biomass feedstocks are out of scope.

Key report outcomes: The project outcomes were not finalised at the time of writing.

Dependencies on other evidence sources: The TEABPP study uses a very wide range of industrial and academic literature for the 15 pre-processing and 32 conversion technologies in scope. Detailed information about the background sources is included in the D1 report chapter (contains 389 references) and the D2 Excel tool.

Quality rating analysis: This study is the latest and most comprehensive study covering clean biomass pre-processing technologies. The data was collected and is presented using a harmonised approach across the teams, and has been through several review iterations with the ETI and its reviewers. Costs from older data sources are inflated to present day costs and currency exchanges made to convert into today's GBP costs. The underlying data sources often present a wide spread of values (e.g. differing CAPEX costs at the same scale), and hence base case averages are presented for each parameter, along with a likely minimum and maximum value to explicitly consider this uncertainty. In general, the data quality is good or medium, with the best data available for the more commercialised pre-processing and conversion technologies.

Relevance rating analysis: The techno-economic and emissions data for each of the pre-processing technologies are based on the current state-of-the-art, and are very relevant for this project. There is some data on energy crop prices, emissions and densities of each form. The data for the conversion technologies are less relevant, as there are no biomethane or biohydrogen options. However, the additional D1a work that was done by B&V on small-scale biomass heating boilers (summarising the status and costs of manually fed, automatic fixed bed and automatic moving bed systems, to supplement the medium-scale underfed stoker and moving bed boilers in D1) is relevant, particularly if moisture, scale and air quality impacts are considered.

4 Greenhouse gas emission evidence

This chapter includes information on the key evidence sources reviewed relating to the estimation of GHG emissions for bioenergy supply chains (most recent studies first). The scope of this review is to identify and assess evidence that provides data on supply chain emissions (i.e. arising from cultivating, harvesting, processing and transporting the biomass), in-line with the European Commission's Renewable Energy Directive (RED) GHG emission calculation methodology. As such, reports that assess the carbon impact of land management practices or forestry operations are not covered in the review.

4.1 Key evidence sources assessed

Table 4-1. Summary of greenhouse gas emission sources assessed

Title	Author	Publication date	Timescale	Geographical coverage
UK and Global Bioenergy Resource Model	Ricardo (for BEIS)	2017	2015-2050	Global (UK-focus)
Solid biomass and biogas carbon calculator (B2C2)	E4tech (for DECC)	2015	Current	Global (UK-focus)
Solid and gaseous bioenergy pathways: input values and GHG emissions	JRC	2014	Current	Global (EU-focus)

4.1.1 UK and Global Bioenergy Resource Model (Ricardo for BEIS, 2017) [97]

Plain English description of evidence: The UK and Global Bioenergy Resource Model allows users to estimate the potential sustainable bioenergy resource that may be available to the UK to 2050. The 2017 version is an update to a model originally developed in 2011 (see section 2.2.1 and 2.4.1). In the updated model, the GHG intensity can be used to vary the estimated resource available for solid and gaseous biomass used for heat and power (in the previous version of the model this was only possible for biofuels for transport).

How the work was undertaken: The model includes default GHG values per feedstock and standard GHG savings thresholds that must be achieved. In addition, both of these variables can be adjusted by the model user.

Key assumptions taken and scenarios modelled: Five GHG emissions intensities are defined per feedstock (in chip/bale and pellet forms), varying linearly from low to high. In addition, three distribution profiles are included to determine the percentage of the total feedstock which has emissions at that level: central (square distribution), low weighted and high weighted. These two factors can be combined and compared to a GHG saving threshold, currently set at the level implemented in the RO and RHI, but that can also be varied by the user per 5-year period.

[97] https://www.gov.uk/government/publications/uk-and-global-bioenergy-resource-model

A placeholder field is also included for indirect land-use change (ILUC) emissions to be included. This is currently set at zero as there are no internationally agreed ILUC factors.

Key report outcomes: GHG estimates for different feedstocks are detailed in the model worksheet “Sustainability data”. Data are hard-coded (although they can be overwritten).

Dependencies on other evidence sources: “Data on emissions associated with feedstock production for solid and gaseous feedstocks are taken from a variety of sources, but principally a spreadsheet used previously by DECC, and data from the UK Solid and Gaseous Biomass Carbon Calculator.” (p11, User Guide: UK and Global Bioenergy Resource Model v8.09)

Quality rating analysis: The underlying data uses reputable data sources (i.e. “DECC spreadsheet” and B2C2 calculator), but is not transparent. Specifically, it is not stated which data sources are used for which biomass feedstocks. It is also unclear what the “spreadsheet used previously by DECC” is. Furthermore, the model does not provide any information on the assumed supply chains, input data or emission factors that were used in calculating the GHG emissions.

Relevance rating analysis: The model provides high level GHG emission data for bioenergy chains relevant for bio-derived gas for heat in the UK.

4.1.2 Solid biomass and biogas carbon calculator, B2C2 (E4tech for DECC, 2015)[98]

Plain English description of evidence: The Solid and Gaseous Biomass Carbon Calculator (B2C2) is a GHG emissions calculator tool. The tool was developed to assist companies and individuals calculate the GHG intensity of solid or gaseous biomass fuel chains for use in sustainability reporting under the RO and RHI schemes. The GHG calculation methodology applied is fully aligned with the requirements of these schemes and applies the recommendations set out in the European Commission report (SEC(2010)65-66) on the impact assessment of the use of solid and gaseous biomass for the production of heating, cooling and electricity.

The tool was developed by E4tech, who retain the Intellectual Property Rights to the tool. Project partners were DECC, the UK Environment Agency and NNFCC, with Concepto providing the software coding and model interface.

How the work was undertaken: The tool’s default values were developed based on literature review and in consultation with stakeholders. The B2C2 has been through several iterations, including new assumptions on AD chains and manure emissions, until maintenance support was stopped by Ofgem in late 2016.

Key assumptions taken and scenarios modelled: The feedstocks for which default GHG intensities have been developed include dedicated energy crops (SRC, forestry and energy grasses), food/feed crops, and a number of wastes and residues including forestry residues, agricultural residues, sawmill residues, end-of-life timber and RDF. End use sectors covered include heating, power generation, CHP and biomethane grid injection. A number of countries/regions, biomass forms and process options are included in the tool – the list below is non-exhaustive:

[98] https://www.ofgem.gov.uk/publications-and-updates/uk-solid-and-gaseous-biomass-carbon-calculator

Country/region of feedstock origin options:

- UK
- Europe
- North America
- Russia
- Tropical / subtropical

Biomass forms:

- Bales
- Briquettes
- Cakes, meals
- Chips
- Pellets
- Biogas
- Biomethane
- RDF

Process options:

- Drying
- AD
- Gasification (of woody biomass)
- Mechanical biological treatment (of RDF): Bio-drying, aerobic digestion, anaerobic digestion
- Wood pellet production: Bulk drying, continuous drying (with biomass (natural gas)

The tool includes ‘typical’ input data and calculated outputs for each supply chain step (covering cultivation and harvesting, processing and transport emissions). An uplift factor of 1.4 was applied to the processing input data to set the GHG emissions at a more conservative level.

Methane losses during AD are estimated as 0.2 g CH_4 / MJ biogas output.

Key report outcomes: The tool does not include a summary of the default values of the available supply chains. The GHG emissions results for wood pellets produced from different feedstocks, regions and processes are shown in Figure 4-1 below, and then further below in Figure 4-2, GHG emissions results for biogas production from different crops. These figures show the GHG emissions results in unit of gCO_2e/MJ of the final fuel.

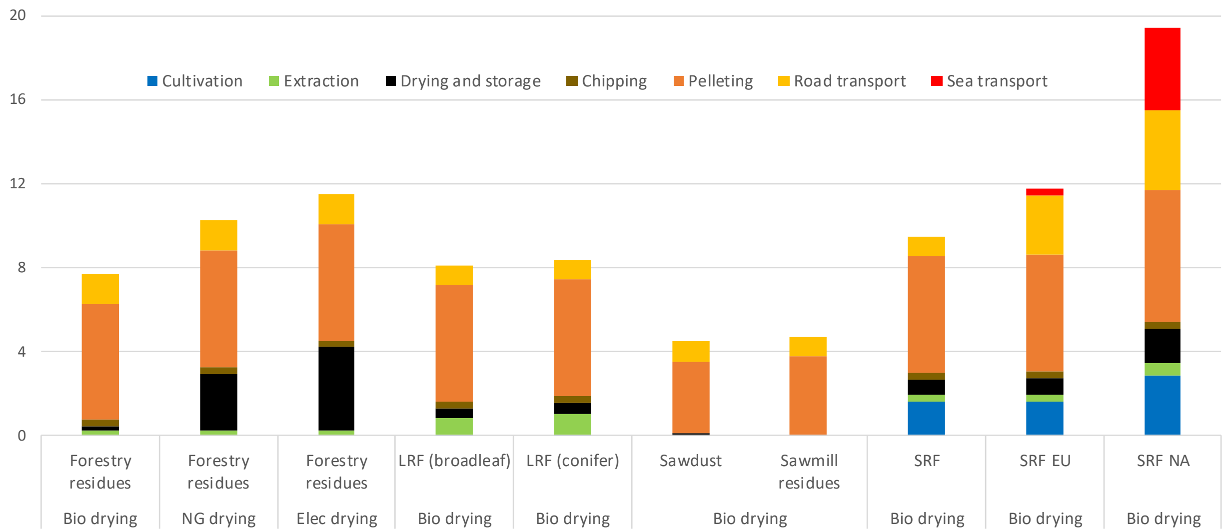

Figure 4-1. GHG emissions for wood pellet production from various biomass sources. Units are in gCO_2e/MJ of the final fuel. (Source: UK B2C2 - prepared by Ecofys.)

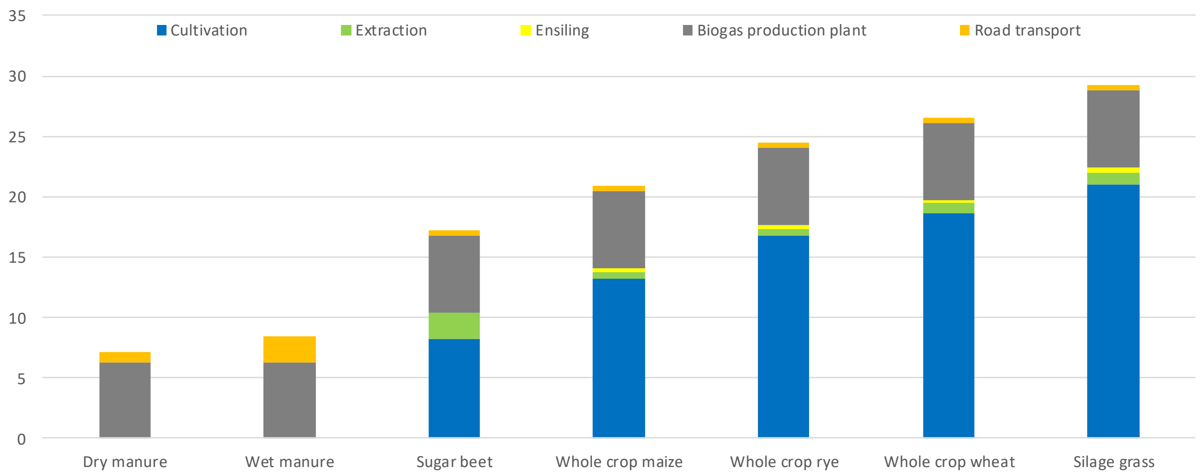

Figure 4-2. GHG emissions for biogas production from various biomass sources. Unit is in gCO_2/MJ of the final fuel. (Source: UK B2C2 - prepared by Ecofys.)

Dependencies on other evidence sources: Multiple literature sources were used to derive standard data and input values. These can be accessed directly via the tool using the "Options, Default and constant values for current chain" selection. Individual references for data sources can also often be found in the yellow panel at the base of the B2C2 interface when the user hovers over a value within one of the chain modules. The estimated data variability is also typically provided for the input values (e.g. +50%).

Quality rating analysis: The tool applies the GHG emission calculation methodology published by the Commission in 2010, and not the updated 2014 methodology. The references used in the report are in some cases quite old. Furthermore, although the references used in the tool are provided they are not specific to pathways and therefore it is difficult to check what the basis for individual input assumptions are without hovering over input values in the chain modules. Industry stakeholders were able to provide input to develop the model's input assumptions. The model defaults were last updated in September 2015. A detailed user manual accompanies the tool.

Relevance rating analysis: The tool is specifically designed for the calculation of GHG emissions for solid and gaseous biomass in production of heating, electricity and biomethane in the UK. The tool has been approved by the UK Government for use by operators to calculate and report GHG emissions under the RHI and RO. The tool provides default GHG intensities for a comprehensive set of UK specific biomass, biogas and biomethane (via gasification) supply chains. (GHG emissions relating to biomethane injection to the grid is not covered.) However, it should be recognised that individual supply chains may be very variable and as such the default intensities should be viewed as informative estimates rather than definitive calculations.

4.1.3 Solid and gaseous bioenergy pathways: input values and GHG emissions (JRC, 2014)[99]

Plain English description of evidence: This report was published by the Joint Research Centre (JRC) of the European Commission to provide information on the methodologies used for the GHG emissions calculations of solid and gaseous biomass used for electricity, heating and cooling. The report also provides input values for stakeholders to evaluate GHG emissions of specific bioenergy pathways and also by regulatory bodies as a basis for policy implementation. (An updated report was published in November 2017 which served as input for the Commission's legislative proposal for a recast of the Renewable Energy Directive (RED II) (COM(2016) 767).[100])

JRC conducted this work by order of the European Commission's Directorate-General for Energy (DG Energy) to update the list of pathways and the relative input database, published in the Staff Working Document (SWD(2014) 259), to account for the scientific, technological and economic developments in the solid and gaseous bioenergy sector.

How the work was undertaken: The input values reported in this document were calculated after consulting with technical experts and various stakeholders. The input data proposed by JRC were presented to technical experts and stakeholders and previewed by them during two workshops:

- Expert workshop held in November 2011 in Ispra (Italy)
- Stakeholder workshop held in May 2013 in Brussels (Belgium)

Detailed comments were collected after both meetings and taken into consideration by the JRC to finalise the dataset and the calculations. Detailed questions and comments from stakeholders along with JRC's responses are included in Annexes 2 and 3 of this document.

Key assumptions taken and scenarios modelled: For the calculation of the GHG emissions and related savings, the report applies the following equation which is based on the methodology published in (SWD(2014) 259). The methodology follows a simplified attributional life cycle assessment approach and it accounts only for direct GHG emissions associated with the production and combustion of the bioenergy carriers. Land use emissions, biogenic

[99] https://ec.europa.eu/energy/sites/ener/files/documents/Solid%20and%20gaseous%20bioenergy%20pathways.pdf

[100] https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/solid-and-gaseous-bioenergy-pathways-input-values-and-ghg-emissions-calculated-according-0

carbon removals and emissions of CO_2 from biomass fuel combustion are not included in the methodology and in the calculations. Neither are other indirect impacts on other markets (displacement).

$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} – e_{ccs} - e_{ccr}$

where

E = total emissions from the production of the fuel before energy conversion;
e_{ec} = emissions from the extraction or cultivation of raw materials;
e_l = annualised emissions from carbon stock changes caused by land use change;
e_p = emissions from processing;
e_{td} = emissions from transport and distribution;
e_u = emissions from the fuel in use, that is greenhouse gases emitted during combustion;
e_{sca} = emission savings from improved agricultural management;
e_{ccs} = emission savings from carbon capture and geological storage; and
e_{ccr} = emission savings from carbon capture and replacement.

It should be noted that the methodology includes some significant changes compared to the EC's previous recommendations. These include:

- A bonus of 45 gCO_{2eq}/MJ manure can be applied for improved agricultural and manure management (e_{sca}) if animal manure is used as a feedstock to produce biogas and biomethane. The bonus can be applied because the methane (CH_4) and nitrous oxide (N_2O) emissions from treating manure via AD are avoided. This bonus leads very high GHG emission savings (> 100%) for AD pathways using manure as a feedstock.
- The credit for exporting excess electricity from a CHP plant (formerly e_{ee} in the formula) is no long applicable. Allocation of GHG emissions to power and heat produced simultaneously in CHP plants is based on 'exergy' and takes into account the temperature of the heat (which reflects the usefulness (utility).
- For biogas and biomethane, the methodology has been updated to include rules for calculating GHG emissions for the co-digestion of multiple feedstocks (i.e. mixtures of different feedstocks going into an AD plant), which is common practice but was difficult to calculate. Previously, emissions were calculated for each individual feedstock. Calculating the GHG emissions for the entire mixture within a given biogas plant results in higher GHG saving performance, which is particularly relevant for crop-waste feedstock mixes.
- Non-CO_2, long-lived GHG emissions from the combustion of solid biomass and biogas are included in the calculations (i.e. CH_4 and N_2O). Typical emissions from end-use combustion are negligible in the case of solid biomass (< 1 g CO_{2eq}/MJ), but more significant in the case of biogas (8.9 g CO_{2eq}/MJ).

Various assumptions (e.g. fertiliser type, moisture content of biomass, transport mode and distance) were used for the calculation of each of elements in the above equations. These assumptions can be found in respective sections of the report. However, for the calculation of default values the following general assumptions were used:

- Emissions from the manufacture of machinery and equipment are not considered
- For the biogas pathways, a credit for the use of manure is applied
- Emission savings from carbon capture and geological storage and from carbon capture and replacement are assumed to be zero

The GHG emissions for the solid biomass pathways were calculated for three scenarios:

- **Case 1:** Pathways in which a natural gas boiler is used to provide the process heat to the pellet mill. Process electricity is purchased from the grid.
- **Case 2a:** Pathways in which a boiler fuelled with pre-dried wood chips is used to provide the process heat to the pellet mill. Process electricity is purchased from the grid.
- **Case 3a:** Pathways in which a CHP, fuelled with pre-dried wood chips, is used to provide heat and power to the pellet mill.

Similarly, the GHG emissions for the gaseous pathways were also calculated for three scenarios:

- **Case 1:** Pathways in which power and heat required in the process are supplied by the CHP engine itself.
- **Case 2:** Pathways in which the electricity required in the process is taken from the grid and the process heat is supplied by the CHP engine itself.
- **Case 3:** Pathways in which the electricity required in the process is taken from the grid and the process heat is supplied by a biogas boiler. This case applies to some installations in which the CHP engine is not on-site and biogas is sold (but not upgraded to biomethane).

Key report outcomes: The outcomes of the report for solid and gaseous pathways are shown in figures and data tables:

- **Solid biomass pathways:** The total typical and default GHG emissions are summarised in Tables 86–89, disaggregated GHG emissions are further summarised in Tables 90-93; they are also illustrated in Figures 3 to 5 of the report. The GHG emissions savings are summarised in Tables 94-97 and illustrated in Figure 6. The results for the solid biomass pathways are shown below in Figure 4-3 and Figure 4-4.
- **Biogas and biomethane pathways**: The total typical and default GHG emissions for biogas pathways are summarised in Tables 98-99, disaggregated GHG emissions are further summarised 100-101 of the JRC report; they are also illustrated in Figures 7 and 8 of the report. The GHG emissions savings are summarised in Tables 102-103 and illustrated in Figure 9. The results for the biogas pathways are shown below in Figure 4-5, Figure 4-6 and Figure 4-7.

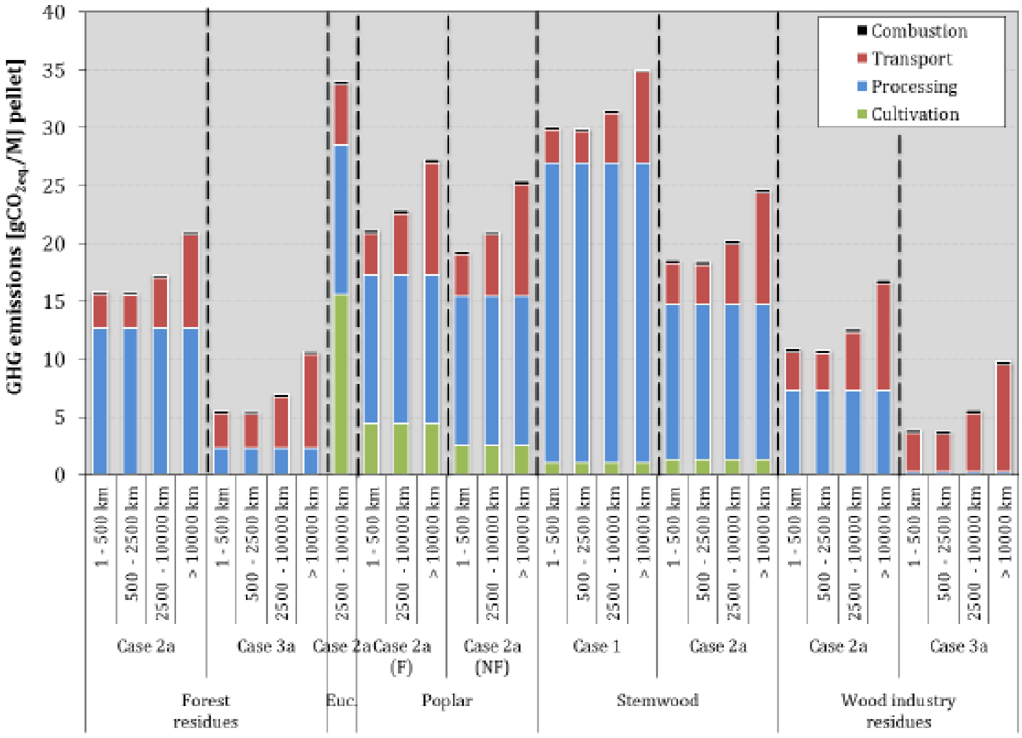

Figure 4-3. Default GHG emissions for a selection of wood pellets pathways. The contribution of the emissions from various steps in the supply chain is also indicated. (Figure 4 in the report.)

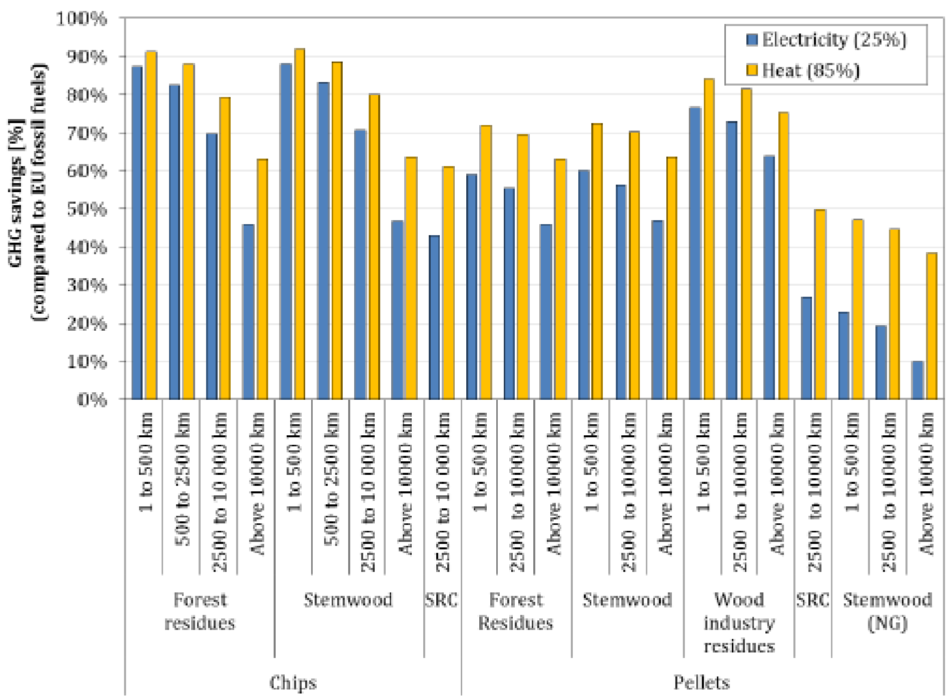

Figure 4-4. Default GHG savings for forest based solid biomass pathways based. The calculations are based on GHG data from eucalyptus cultivation in tropical areas. NG refers to natural gas. (Figure 6 in the report.)

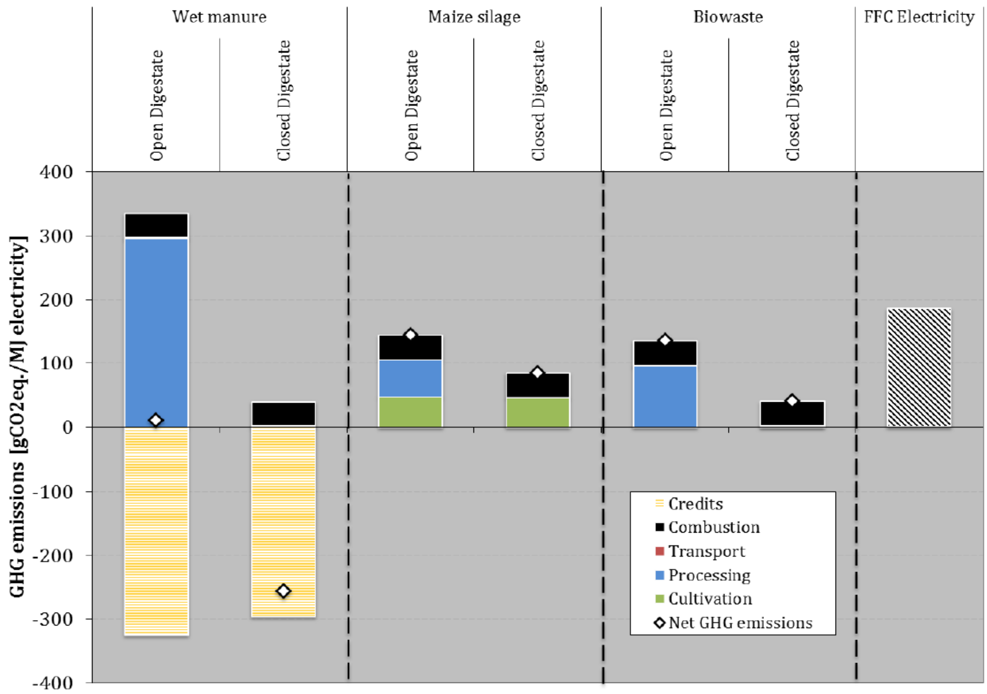

Figure 4-5. Default GHG emission values calculated for electricity production from raw biogas; the results are shown for different digester configurations and for using different substrates as feedstock. The contribution of the emissions from various steps in the supply chain is also indicated. (Figure 7 in the report.)

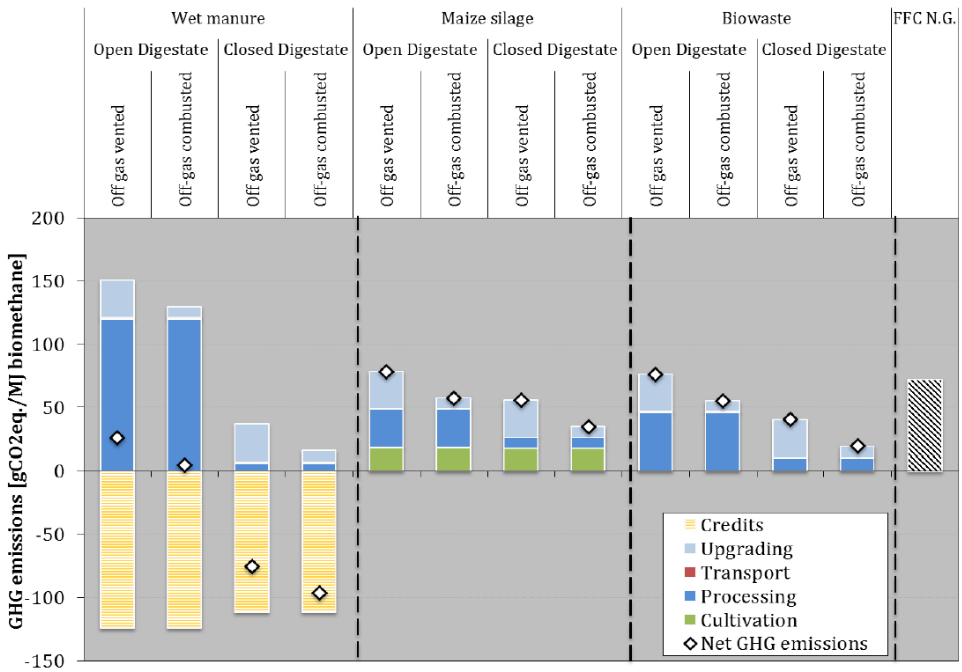

Figure 4-6. Default GHG emission values calculated for the production of biomethane (upgraded biogas); the results are shown for different upgrading configurations and for using different substrates as feedstock. The contribution of the emissions from various steps in the supply chain is also indicated. (Figure 8 in the report.)

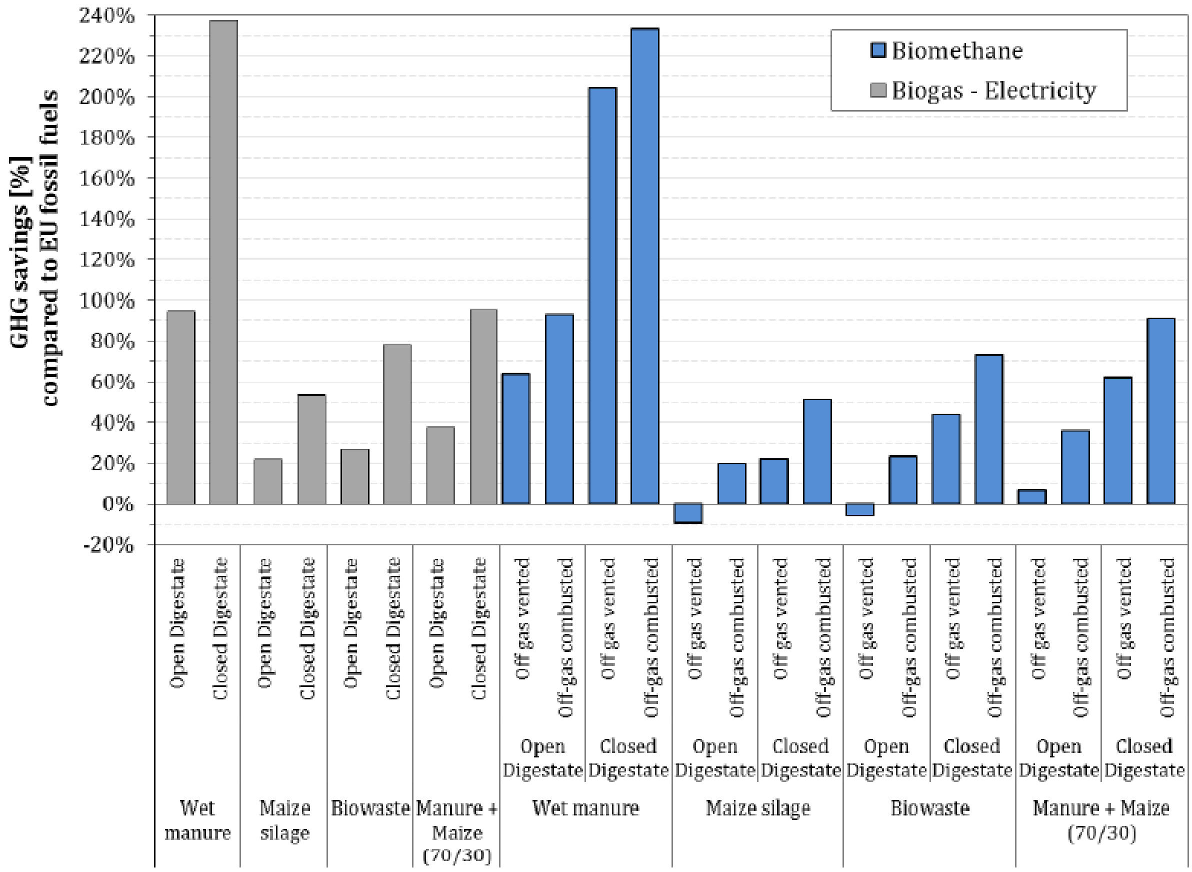

Figure 4-7. Default GHG savings for the most representative biogas and biomethane. Values for biogas – electricity represent the Case 1. Values higher than 100% represent systems in which credits from improved agricultural management more than offset any supply chain emission. Values lower than 0% indicate systems which emit larger amounts of GHG than the fossil fuel comparator. For illustrative purposes, values obtained for the co-digestion of a mixture of 70% (wet mass) manure and 30% (wet mass) maize are also included. (Figure 9 in the report.)

Dependencies on other evidence sources: The Commission Staff Working Document on biomass sustainability (SWD(2014) 259) was used as the basis for the GHG calculation methodology. Data were derived from reports and databases of emission inventories produced by international organisations, such as the Intergovernmental Panel for Climate Change (IPCC) and European Environment Agency (EEA), LCA databases, peer-reviewed journal publications as well as proprietary data provided by stakeholders and industrial associations.

Quality rating analysis: The report uses the latest European Commission methodology for the calculation of GHG emissions for solid and gaseous biomass pathways. The data presented are very transparent, including both the underlying input assumptions and disaggregated calculated outputs. A consistent methodology was used for GHG calculation of all the pathways and all the assumptions and references used are clearly indicated. However, the report acknowledges that there are several possible sources of uncertainty and data variation.

- Geographical variability of some processes (e.g. cultivation techniques and land productivity): As the data are aimed at being valid throughout the whole EU, the dataset may not necessarily represent each specific condition. (This is indicated as being the main factor of uncertainty.)

- Technological differences: The values and pathways were disaggregated to represent the most common technological options (e.g. for biogas upgrading pathways).
- Data: For some processes there is a lack or scarcity of data. In some cases the references used are old (from 2005 to 2010).

Relevance rating analysis: The report includes GHG emissions for EU-specific rather than UK-specific supply chains. However, the methodology used in this report is, to our best knowledge, the most complete available methodology for the calculation of GHG emissions from biomass pathways for use in heat, electricity and cooling. The report outputs served as the basis for the calculation of the default values published by the European Commission in 2014. The updated 2017 version served as the basis for the calculation of the RED II default values (although the calculated outputs are not fundamentally different).

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