BIOENERGY HEAT PATHWAYS TO 2050 - RAPID EVIDENCE ASSESSMENT

SUMMARY REPORT

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Acronyms

AD	Anaerobic digestion
B2C2	UK Solid and Gaseous Biomass Carbon Calculator
ARA	Amsterdam-Rotterdam-Antwerp region
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
CH_4	Methane
CO_2	Carbon dioxide
CAPEX	Capital expenditure
CCC	Committee on Climate Change
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CFB	Circulating Fluidised Bed (gasifier type)
DECC	Department for Energy and Climate Change
Defra	Department for Environment, Food and Rural Affairs
DFT	Department for Transport
EBA	European Biogas Association
ESME	(ETI) Energy System Modelling Environment
ETI	Energy Technologies Institute
EUR	Euro
FAOSTAT	United Nations Food and Agriculture Organisation Corporate Statistical Database
GB	Great Britain
GHG	Greenhouse gas
H_2	Hydrogen

HHV	Higher Heating Value
ICCT	International Council on Clean Transportation
IEA	International Energy Agency
IRENA	International Renewable Energy Association
JRC	Joint Research Council (of the European Commission)
kt	Kilo tonne
LHV	Lower Heating Value
LRF	Long rotation forestry
MSW	Municipal Solid Waste
Mt	Million tonnes
odt	Oven dried tonne
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
t	Tonne
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
UK	United Kingdom
VAT	Value Added Tax
WRAP	Waste & Resources Action Programme
yr	Year

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1 Introduction and evidence review scope

BEIS has commissioned a series of projects to review and consolidate evidence to help consider the long-term options to decarbonise heat. This report describes the findings from a Rapid Evidence Assessment (REA) that was conducted to review the available evidence on biomass heating. The focus was on evidence on the **potential, cost and greenhouse gas (GHG) emissions** of biomass pathways to decarbonise the gas grid to 2050.

The evidence review considers the whole bioenergy value chain (from feedstock production to gas or heat production), focusing on those pathways that are most relevant to decarbonising heat in Great Britain (GB) to 2050, and in particular, options that lead to decarbonisation of the gas grid using **biomethane, bio-synthetic natural gas (bioSNG), or biohydrogen (bioH$_2$)**.

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

This report presents an overview of the quality of the current evidence base on biomass-derived gas options. The aim is to identify where evidence is strong and where it is weak, including where weaknesses could be solved by additional research and where there will always be inherent uncertainty in the data (e.g. willingness of land owners to plant energy crops). The findings are categorised by **feedstock** (Chapter 2), **conversion technology** (Chapter 3) and **GHG emissions** (Chapter 0). The key evidence sources are described in more detail in a Technical Annex to this report. The outputs from this project will feed into the Government's considerations as they take the next steps towards decarbonising the heating sector. Note that this evidence review does not consider the impacts of biomass on air quality. A cross-departmental review is being conducted into the role of biomass in future policy for low carbon electricity and heat, focusing on the air quality impacts. The proposed way forward will be set out in the final Clean Air Strategy, due for publication in December 2018.

1.1 Evidence review scope

The evidence review focuses on the technologies expected to have the ability to contribute most significantly to decarbonising a gas grid in 2050. The bioenergy feedstock scope is guided by the technology choice. This evidence review focuses specifically on routes to biomass-derived gases, but it is important to note that these routes would not be used in isolation and could contribute heat alongside more conventional bioenergy routes such as direct combustion of wood pellets, as well as other routes to low carbon heat such as hybrid heat pumps or non-biomass routes to hydrogen. Furthermore, the same biomass sources and conversion technologies could be applicable to other forms of energy or bioeconomy end uses. These alternative uses are not explicitly considered in the scope of this review.

Feedstock scope

The most suitable feedstocks to produce gas for use in the gas grid infrastructure are "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$_2$. In this review, we therefore focused on the following feedstocks:

- Wet wastes (Food waste (domestic, commercial and industrial), wet manure, sewage sludge);
- Dry wastes (Municipal solid waste (MSW) and wood waste);
- Agricultural and forestry residues (e.g. cereal straws from the UK and bark, branches, tops, thinnings, arboricultural arisings and small roundwood);
- Industrial wood processing residues (sawdust and wood chips from sawmills);
- Perennial energy crops (Miscanthus, Short Rotation Coppice (SRC) and Short Rotation Forestry (SRF)).

During the review evidence was also found on the potential for macro-algae (seaweed) as a feedstock for AD. Micro-algae was not included in the evidence review as this is more suited to producing oils for transport fuel or for other bioeconomy uses.

Heat needs to be generated close to demand, but this does not preclude biomass feedstocks being imported. The scope of the feedstock potential review was therefore global, but from the perspective of heat production in GB. We assumed that only the higher energy density feedstocks would be imported, for example wood-based pellets but not wet feedstocks for AD. Therefore, wet wastes and macro-algae were not assumed to be imported and as such the scope of the potential review was domestic production only (in practice defined as the wider UK, rather than GB only). We also did not consider imported dry wastes within the feedstock evidence review. There is currently some limited international trade in these materials, however it was assumed that the primary policy aim in the 2050 context should be to decrease waste production and treat wastes that are produced more locally.

Agricultural and forestry residues, industrial wood processing residues and perennial energy crops could, in theory, be imported from any world region (as long as the appropriate phyto-sanitary requirements[1] are met; in practice this usually means that the material will be pelletised, which also has the advantage of improving energy density and handleability, thus decreasing the cost of long-distance transport). The agricultural residues listed above are typical UK feedstocks. Suitable agricultural residues from outside the UK could include a wide range of materials, such as nut or seed shells or olive pits. Similarly, the energy crops listed above are the most likely to be cultivated in the UK context. Outside the UK and Europe, other crops or tree species may be more suitable, such as Eucalyptus in South America.

The evidence review focuses on feedstock potential studies that cover a wide range of countries, with additional effort also to review evidence from key world regions that are expected to have the potential to become significant exporters to the UK, including North and South America and South East Asia. North America is already a source of solid biomass for the UK market. South America and South East Asia are a significant source of biomass for transport biofuel in the UK and Europe and are also significant producers of the types of solid biomass that could be exported to the UK for gasification in the future. Biomass could be transported by sea from all these countries to the UK, which has a relatively low cost and GHG impact compared to land-based transport (road or to a lesser extent rail). By contrast, Russia also offers a large potential solid biomass source, but the logistics of transportation are more challenging as a significant volume of this resource is located in remote regions and would have to be transported over land, so is less attractive for the UK to access both economically and from a GHG perspective.

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[1] Forestry Commission (2015) Importing woodchip. Requirements for landing regulated material into Great Britain. https://www.forestry.gov.uk/pdf/fcph006.pdf/$file/fcph006.pdf

Technology scope

The evidence review focuses on routes to biomass-derived gases. More conventional bioenergy routes such as direct combustion of wood pellets were not included in the review (although in some cases the same feedstock types would be suitable for either route). We therefore focus on biomass conversion technologies that offer greatest overall potential for decarbonising the gas grid in GB to 2050, namely:

- Anaerobic Digestion (AD) 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 with methane (CH_4) synthesis (with and without CO_2 capture), to produce bio-synthetic natural gas (bioSNG);
- Thermal gasification with hydrogen (H_2) synthesis (with and without CO_2 capture) referred to as bio-hydrogen (bioH_2).

Pyrolysis is included in the evidence review in the context of a pre-processing step that could produce a bio-oil suitable for off-grid heating. Gas produced as a co-product is typically assumed to be used to fuel the pyrolysis process so is not considered to provide a useable bio-derived gas that can be fed into the gas grid.

GHG scope

The evidence review focussed on the GHG emission calculation methodology relevant to solid and gaseous biomass that is applied in the UK/EU and typical supply chain emissions (i.e. arising from cultivating, harvesting, processing and transporting the biomass).

Out of scope

The evidence review focused on assessing the evidence relating to the potential, cost and GHG emissions of biomass routes to decarbonise the gas grid in GB. Aspects not in the scope of the review include:

- Biomass potential pathways relating to transport biofuels, non-energy applications (e.g. bio-based plastics and furniture) and electricity/electric heating;
- Biomass potential pathways relating to imported gas (biogas, biomethane, syngas, bioSNG or bioH_2);
- Renewable electricity and/or renewable hydrogen routes to renewable methane, such as waste CO_2 methanation, or waste CO catalysis;
- GHG emissions savings other than specified in the UK legislation[2] (i.e. no consideration of waste counterfactual emissions via consequential lifecycle analysis);
- GHG impacts of land-use change (direct or indirect – including the concept of “carbon debt”) – it is assumed that any biomass used for heat in the UK would have to meet some sort of sustainability criteria that would prevent (negative) direct land-use change. Indirect land-use change emissions are not currently in the scope of the sustainability legislation for operators;
- Co-product revenues (e.g. revenues from selling digestate from AD plants for fertiliser);

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[22] Specifically, the sustainably requirements included in the Contracts for Difference (CfD), Renewable Heat Incentive (RHI) and Renewables Obligation (RO).

- Costs associated with gas grid infrastructure, gas grid conversion, end-use appliance costs (e.g. boilers) or their conversion (e.g. from natural gas to hydrogen); and
- Downstream costs of CO_2 distribution and sequestration.

2 Feedstock evidence sources

Summary

There is a substantial body of research into the potential availability of feedstocks that are suited to producing biomass-derived gases in Great Britain, both current availability and potential estimates to 2050. The evidence review identified a range of UK specific studies, most importantly the Ricardo UK and Global Bioresource Model, a review of UK feedstock potential for bioSNG led by Progressive and conducted by Anthesis and E4tech, several detailed studies funded by the Energy Technologies Institute (ETI) that has invested significant sums in developing sophisticated models capable of modelling biomass use for energy purposes in the UK out to 2050 and in detailed studies related to UK energy crops. There are also a range of national statistics on feedstock availability from e.g. the Forestry Commission or Defra and the Waste and Resources Action Programme (WRAP) for wastes. Key European or global studies include e.g. a study by Ecofys on waste and residue potential for the German, Dutch and Danish governments and the "Wasted" study led by the International Council on Clean Transportation (ICCT), and global bioenergy supply and demand study by the International Renewable Energy Agency (IRENA). National statistics are available for some feedstocks, both from the UK and from other countries, e.g. for wastes, forestry materials. For global agricultural residues, the potential is often calculated based on national statistics on cereal production, which are collated internationally by e.g. the United Nations Food and Agriculture Organisation Corporate Statistical Database (FAOSTAT), multiplied by a residue yield assumption.

This review focused on evidence that collates data from a range of other sources in a consistent manner. There are further individual country or feedstock specific studies that were identified, but these are of more varying quality and detail and are often difficult to compare on a consistent basis. Key differences include, for example, the level of sustainability assumed or how this is implemented in feedstock potential estimates.

Underlying data is strong for current UK feedstock availability but projections are inherently less certain.

- **Agricultural and forestry residues** are traded in the UK today and estimates of availability are good quality and based on national statistics, even if they are based on statistics of production of the main crop multiplied by a residue yield assumption and assumptions on the sustainable removal rate. The key uncertainty into the future is the level of competing uses.
- **Perennial energy crops** offer a significant potential into the future, but the area planted today is very limited and current planting rates are below even recent projections. There is good quality evidence on current planting and availability and detailed studies on characteristics and land areas that could be used. The key uncertainty is delivery (achievable planting rates).
- Good quality data is available on current **waste arisings**, per sub-region within the UK, but waste collection differs locally so the composition of waste arisings varies widely and official projections on waste arisings are lacking. Wastes can provide an important low cost, low emission source of bioenergy feedstock, but their availability is ultimately limited.
- **Macro-algae** (i.e. seaweed) could offer a reasonable potential for AD in the future, if investment is made to farm the feedstock, but no macro-algae is cultivated commercially today for energy purposes. Current

evidence on availability and cost is highly uncertain, but better evidence is expected from the results of the SEAGAS project.

For global feedstocks, there is reasonable data available on agricultural and forestry residue availability and on land areas for energy crops. As with the UK, the key uncertainty is delivery of energy crop potential.

- For **global agricultural residues** there are existing markets. FAOSTAT publishes data on the availability of various agricultural residues per country, which is often based on national statistics on agricultural and forestry materials. This is the key organisation that collates data such as this in as consistent a manner possible across the world and it is unlikely that there is a better overview of the current availability of these feedstocks globally, although it could be possible that organisations within a country have a closer insight into more local level availability, for example local sustainable removal rates. Studies often assume one sustainable removal rate as a simplifying assumption.
- For **global energy crops**, potential estimates are similarly based on estimates of abandoned land availability multiplied by yield. Estimates for global abandoned land availability often reference the same two academic studies, Hoogwijk (2005) which was built on by van Vuuren (2009) which estimated the amount of abandoned land that would be unsuitable for growing crops (e.g. because it is too severely degraded or because of water scarcity). These are both well respected reports and are cited widely in bioenergy potential studies. The reports have not been updated in recent years, although the same team at Utrecht University (Netherlands) continues to work on the IMAGE ecological-environmental model that was used by Hoogwijk. The global energy crop potential to 2050 is significant, but as in the UK, existing planting for energy purposes is currently low. Realising the global potential will rely on actions taken in third countries, over which the UK has less control to incentivise planting.

Overall, reasonable quality data are available on **current feedstock prices.** All biomass feedstock markets are immature relative to other energy commodities and data often has to be sourced via contacts in industry. Some feedstocks are beginning to be traded as commodities (e.g. imported wood pellets or straw) and there are examples of price data being publicly available via price indices, but these are the exception rather than the rule. **There are no credible forward projections of feedstock price beyond the next 2-5 years**. The current gate fee for waste feedstocks (i.e. the negative prices) make them attractive to use, especially in the short term, and so supply chains using wastes might develop, but if demand increases, the gate fee could quickly change to a feedstock cost.

Data could be improved in the following areas:

- Alternative competing uses for feedstocks, especially from within the energy sector. Ultimately this is heavily reliant on policy decisions which impact on the commercial viability of alternatives, and therefore will remain inherently uncertain where Government has not set a specific ambition for bioenergy use in that sector.
- Investigating more local level “sustainable removal rates” for agricultural and forestry residues systems in the UK and nations with significant residue production which are more in line with the variation in removal rates per crop and according to local conditions such as soil quality.
- National publication of UK waste arisings specifying the extent to which food waste and dry waste will be mixed or available as separate streams. Future projections would be improved through further policy direction.

- The potential for the use of crops that form part of a standard crop rotation or intercropping but cause no net reduction in food production (e.g. “Biogasdoneright” concept[3]) could be further investigated in a UK context.
- Revisit estimates of current global planting and land availability for perennial energy crops, also including the expected impacts of climate change on yields. Further investigation into how to remove the barriers to energy crop planting would also lead to further insights into the likely future potential.

The following aspects are **likely to remain uncertain** due to inherent difficulties in predicting how policy and markets will develop in the future:

- For global feedstocks, there is an inherent uncertainty in the amount of feedstock that will be available to be imported to the UK. This will be dependent on the UK’s willingness to pay for biomass compared to other countries into the future and the openness of global trade. No good reference currently exists for that. Assumptions are generally based on proxies such as the UK’s projected share of global GDP, projected population or the projected size of the UK energy sector relative to other countries.
- Feedstock price projections into the future. As markets develop, prices may diverge from the underlying costs of producing feedstocks. This can be the case for all biomass, but is especially the case for wastes, which currently command a gate fee (i.e. the biomass user is paid to take the waste away) but this could flip and become a market price as demand for the feedstock emerges. This can be mitigated by assuming conservative prices and not assuming gate fees for wastes beyond the short term.
- UK and global energy crop potential in as far as it relies on land owners’ appetites to plant the crops. There is no good reference for the rate at which energy crop planting could happen in the future, given that this is entirely dependent on farmers’ response to policy and the market. This is likely to remain a key uncertainty.

Realising feedstock potential estimates will also only be possible if the conversion technologies are available that demand those feedstocks. For example, wastes and residues will be produced in the absence of a bioenergy industry, but they will only be collected if there is a demand to do so. Equally the available feedstock and its characteristics can influence the development of the different technologies. For example, the availability of a biomass stream with consistent characteristics throughout the year will influence the location and design of a gasification plant and any associated biomass pre-processing.

Realising an increase in energy crops will only be achieved with policy action to stimulate production. A supportive policy environment with clear and stable sustainability criteria is needed and a focus on the removal of barriers and stimulating planting. Long term bioenergy vision is especially needed for energy crops because of the time needed to establish crops before harvest.

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[3] CIB (2016) Biogagasdoneright and Soil Carbon Sequestration. The Italian Agricultural Revolution. http://www.ieabioenergy.com/wp-content/uploads/2016/05/P11-Biogasdoneright-and-soil-carbon-sequestration-Gattoni.pdf

2.1 Overall feedstock potential

BEIS published an updated version of the **UK and Global Bioresource Model**[4] in 2017. The model takes a detailed, well-structured and transparent approach to estimating potential feedstock supply to 2050. The model covers both UK and global feedstock potential. The feedstock coverage is highly relevant for producing bio-derived gas in the UK, and the model covers the time period to 2050 in 5-year time periods, making it a very suitable source of information for these purposes. The evidence source is a model with underlying data, which allows users to choose key variables, such as the level of competing *non-energy* uses, GHG thresholds that should be applied and the extent to which barriers to deployment are overcome. Competing *energy* uses within the UK are not considered (i.e. the model does not distinguish whether feedstocks are used for electricity, heat or transport fuel). The Ricardo model includes GHG data (set at default values which can be overwritten), but no detailed feedstock cost data. There are individual evidence sources that provide better data for individual feedstocks or geographies, but given the breadth of feedstock coverage, the ability to adjust key variables in a transparent and consistent manner and the timeframe of the model, the Ricardo model is considered to provide the most up-to-date and consistent framework for feedstock potential data for producing biomass-derived gas in Great Britain to 2050.

For the purpose of comparison in this report, when we quote UK feedstock potentials from the Ricardo model, we have defined a low scenario as the amount of feedstock available for bioenergy at a feedstock price of £4/GJ with no constraints overcome and competing feedstock demands also met (which is consistent with the feedstock deployment data used in UK TIMES[5], BEIS's main in-house model of the UK energy system) and a high scenario as the amount of feedstock available for bioenergy at a feedstock price of £10/GJ with all barriers overcome and competing feedstock demands also met.

During the course of this review, Progressive Energy published a study (financed by Cadent Gas Ltd and conducted by E4tech and Anthesis[6,]) to review how much renewable gas 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 bioSNG and bioH_2 from gasification, so the same scope as this study, but focusing on domestic feedstocks only. The study produced three scenarios of UK potential (low, medium and high). The study findings are generally consistent with the Climate Change Committee (CCC) UK biomass feedstock estimates in their 2011 Bioenergy Review and with the Ricardo 2017 model. The main difference is that the Progressive Energy report has a reduced estimate of UK energy crop potential by 2050 due to the lack of current planting.

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[4] Ricardo (2017) UK and Global Bioenergy Resource Model. https://www.gov.uk/government/publications/uk-and-global-bioenergy-resource-model (see sections 2.2.1 and 2.4.1 of the Technical Annex)

[5] UCL Energy Institute (2014) UK TIMES Model Overview. http://www.wholesem.ac.uk/documents/uktm-documentation (see sections 2.2.3 and 3.2.1 of the Technical Annex)

[6] Anthesis and E4tech (2017) Review of Bioenergy Potential. https://cadentgas.com/getattachment/About-us/The-future-role-of-gas/Renewable-gas-potential/Promo-Downloads/Cadent-Bioenergy-Market-Review-SUMMARY-Report-FINAL.pdf and https://cadentgas.com/getattachment/About-us/The-future-role-of-gas/Renewable-gas-potential/Promo-Downloads/Cadent-Bioenergy-Market-Review-TECHNICAL-Report-FINAL.pdf ((see sections 2.2.4 of the Technical Annex)

2.1.1 UK Agricultural residues

The main UK agricultural residue considered in the evidence review was straw. Straw can be burnt directly in boilers to generate electricity and/or heat, a practice which is already occurring in the UK[7], or otherwise could be gasified to produce bioSNG or bioH_2. Agricultural residues could also include other dry field residues, such as husks, seeds or shells, or wet residues such as poultry litter. Both are also combusted directly for heat or power in the UK today, and could in theory be gasified, but the total potential is relatively low so they were not the focus of the review.

Overall, there is good quality data on the current availability of UK agricultural residues. Several studies have examined straw potential, using a similar approach. A study by Stoddart & Watts[8] published in 2012, estimated the UK straw potential based on 2011 Defra statistics on cereals and oilseed rape production multiplied by the "harvest index" of the specific crops (the ratio between the grain yield and the total crop weight at harvest). An estimate of existing non-energy uses of straw is also provided, which can be used to estimate the amount of straw that might be available for the energy market. Ecofys (2013)[9] took a similar approach to estimate the straw potential and existing non-energy uses of straw in selected EU Member States, including the UK. The estimate was based on 2002-2011 EUROSTAT data and applied crop-specific straw to crop production ratios based on correlations proposed by Scarlat et al. (2010)[10]. Importantly, the Ecofys study also considered the "sustainable removal rate" of straw in each country, which is the quantity of straw that can be harvested or collected in a sustainable way without comprising soil quality. The sustainable removal rate varies by location, according to soil type and quality, but it was found to typically vary between around 33-50% of straw that can be removed (either each year or 100% of straw removed every 2-3 years), with the remainder being ploughed back into the land to maintain soil quality. Without consideration of the appropriate sustainable removal rate, straw quantity may be overestimated or straw harvesting could lead to a loss of soil quality and/or increased inorganic fertiliser requirements to maintain crop yields. The approaches used in these studies are considered to be robust and offer a good approach to estimate sustainable straw potential, especially in the absence of actual harvested straw statistics.

The straw availability estimates applied in the Ricardo model (2017) are from a paper published by the Agriculture and Horticulture Development Board (AHDB) in 2014 and are based on (2008-2012) data published by ADAS. The data were calculated based on regional estimates of actual straw yield and crop area (in 2008-2012), rather than crop yield and standard harvest indices. As such, they are considered to be a good basis for current UK straw availability, also taking into account regional differences in straw yield (although not site-specific sustainable removal rates). The Ricardo model (2017) also includes an estimate for poultry litter and seed husks and hulls under the category dry agricultural residues. As such, Ricardo (2017) is considered to be a good representative data source for this feedstock category.

Out of these studies, the Ricardo model is the only one to project UK agricultural residues to 2050, although the projection is fixed at a total unconstrained resource of 10 Mt/yr dry agricultural residues to 2050, of which 7.7 Mt/yr is straw and the remainder poultry litter and (1.1 Mt/yr) and seed husks and hulls (1.2 Mt/yr). Competing non-energy

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[7] For example, the 38MW straw fired power station in Sleaford that has been operating since 2014. http://sleafordrep.net/

[8] Stoddart & Watts (2012) Energy potential from UK arable agriculture: Straw – what is it good for? http://www.etaflorence.it/proceedings/index.asp?detail=8129 (see section 2.2.13 of the Technical Annex)

[9] Ecofys (2013) Low ILUC potential of wastes and residues for biofuels. Straw, forestry residues, UCO, corn cobs. https://www.ecofys.com/files/files/ecofys-2013-low-iluc-potential-of-wastes-and-residues.pdf (see section 2.3.5 of the Technical Annex)

[10] 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

uses are estimated to be 4.9 Mt/yr, so the accessible potential for UK agricultural residues is estimated to be 5.1 Mt/yr. As this is an estimate of residues from other industries, it is reasonable to assume that bioenergy demand should not increase the supply of these residues, certainly for materials like seeds and husks for which the ratio of the main material to the residue is relatively fixed. However, for straw there could be some potential for farmers to plant varieties of the main crop with higher straw to grain ratios, if straw demand leads to an increase in value, which could increase this potential to 2050 slightly.

2.1.2 UK Forestry residues and Industrial wood processing residues

Forest residues comprise brash, stumps and small roundwood not suitable for other purposes. Additional potential is available from the wood processing industry; specifically, clean wood residues such as wood chips, slabs, sawdust and bark. Wood processing residues have existing uses including, animal bedding and panel board manufacture. In contrast, forest residues largely remain under-utilised.

The forest residue potential can vary widely depending on the tree type and in particular between softwood and hardwood species. It is also important to consider the 'sustainable removal rate' when estimating the potential of forestry residues, which takes into account the quantity of residues that can be harvested or collected in a sustainable way without comprising soil quality and biodiversity. The "Wasted" study[11], published by the ICCT (2014), assume that 24% of the above-ground biomass is available as residues in the EU and that it is sustainable to harvest 50% of the available residues if combined with good land management practices. Ecofys (2013) assume a more conservative sustainable removal rate of 20%, but also indicate that there are no specific thresholds for the maximum permitted removal rate in the UK.[12]

Ricardo (2017) is considered to represent the best data source for estimating the potential of these feedstocks to 2050. These estimates are based on data published by Forest Research[13] (of the Forestry Commission), including the CARBINE and CSORT models[14] and Forestry Statistics 2014[15]. The potential assumes that 50% of the forest residue potential in the UK is required to fulfil other functions such as the maintenance of the environment of the forest and structural stability of soil. Similarly, around 50% of the wood processing resource is assumed to be utilised for panel board manufacture.

The Forestry Commission's "Forestry Statistics" publication is considered to be the most robust and comprehensive evidence source covering the UK forestry sector and related industries. The statistics are published annually, the latest version of which was published in September 2017[16]. They indicate that the total woodland area in the UK in

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[11] ICCT (2014) Wasted: Europe's untapped resource. https://www.theicct.org/publications/wasted-europes-untapped-resource (see section 2.3.2 of the Technical Annex)

[12] Ecofys (2013) Low ILUC potential of wastes and residues for biofuels. Straw, forestry residues, UCO, corn cobs. https://www.ecofys.com/files/files/ecofys-2013-low-iluc-potential-of-wastes-and-residues.pdf (see section 2.3.5 of the Technical Annex)

[13] Forest Research. https://www.forestry.gov.uk/forestresearch

[14] https://www.forestry.gov.uk/fr/infd-633dxb, https://www.forestry.gov.uk/forestry/infd-889hsz (CARBINE is a carbon accounting model that estimates the carbon stocks of stands and forests (in living and dead biomass and soil), and any associated harvested wood products. The model is applicable at the stand, forest and national level. CSORT has been developed as a successor to the CARBINE model.)

[15] Forestry Commission (2014) Forestry Statistics 2014. https://www.forestry.gov.uk/website/forstats2014.nsf/LUContentsTop?openview&RestrictToCategory=1

[16] Forestry Commission (2017) Forestry Statistics and Forestry Facts & Figures. https://www.forestry.gov.uk/forestry/infd-7aqdgc (see section 2.2.5 of the Technical Annex)

2017 was 3.17 million hectares, which is equivalent to 13% of the total land area in the UK[17]. Of this, 1.39 million hectares (44%) are independently certified as sustainably managed. Just 7,000 hectares of new woodland were created in the UK in 2016-17.

The statistics, furthermore, indicate that a total of 11 Mt of UK roundwood (95% softwood and 5% hardwood) were delivered to primary wood processors in 2016, of which around 2 Mt 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 to pellet manufacturers). This represented around 21% of the total supply of sawmill co-products. The statistics, however, do not include data on forestry residue deliveries.

E4tech (2014)[18] estimate the UK potential for forestry residues as 6.7 Mt/yr (wet basis) in 2020, before any competing uses for the feedstock are considered. This is based on 3.4 Mt/yr of bark, branches and leaves and 3.3 Mt/yr of small round wood. A further potential of 1.6 Mt/yr of sawdust and cutter shavings were estimated. The specific data sources used to derive these estimates are not transparently indicated.

2.1.3 UK Perennial energy crops: Short Rotation Coppice and Miscanthus

Perennial energy crops, such as Miscanthus or Short Rotation Coppice (SRC), offer a significant potential for domestic feedstock for gasification[19]. Miscanthus is a high yielding energy grass that can be harvested annually once the crop is established, which normally takes up to three years. SRC is densely planted poplar or willow. It is normally ready for harvest after four years, depending on climatic conditions, after which it can be harvested every three years. Miscanthus and SRC can achieve high biomass yields with relatively low agricultural inputs (and therefore low cultivation GHG emissions) compared to annual crops.

Unlike data on agricultural crops or wastes and residues for which there are existing markets, estimates of energy crop availability are based on projections of the potential land area available multiplied by the projected crop yield. The amount of land that will be used in the UK for energy crop planting is a question of the best use of land which is subject to many varied economic, social and political factors as well as sustainability considerations.

Defra publish an annual report with actual energy crop production (Miscanthus, willow, straws) annually, going back to 2007[20]. This also includes yields and a discussion of which sectors are using which feedstocks. Current area planted and planting rates are very low and in the UK the total area planted has even decreased since the Energy Crops Scheme grant funding stopped. Total planting of perennial energy crops in the UK stood at less than 7 kha for

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

[18] E4tech (2014) Advanced Biofuel Feedstocks – An Assessment of Sustainability. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/277436/feedstock-sustainability.pdf (see section 2.2.11 of the Technical Annex)

[19] For further information on the crops and planting techniques and expected yield development, see Ecofys and E4tech (2018) Innovation Needs Assessment for Biomass Heat, Chapter 5.

[20] Defra (2016) Crops Grown for Bioenergy in England and the UK: 2015. https://www.gov.uk/government/statistics/area-of-crops-grown-for-bioenergy-in-england-and-the-uk-2008-2015 (see section 2.2.7 of the Technical Annex)

Miscanthus and under 3 kha SRC willow in 2015. The Technology Innovation Needs Assessment (TINA) 'bioenergy refresh'[21] uses this Defra data as a starting point for UK energy crop projections.

Several literature sources provide estimates for land area that could be used in the UK for perennial energy crops to 2050. The Climate Change Committee (CCC) Bioenergy Review (2011)[22] modelled three scenarios for UK perennial energy crop potential, which assumed 0.3 Mha total land used for perennial energy crops by 2050 in the constrained land use scenario, 0.6 Mha in the extended land use scenario and 0.8 Mha in the further land conversion scenario.

The ETI commissioned several studies that look in detail at energy crop potential in the UK, also on the expected spatial distribution of UK energy crops that would inform the optimal gasification plant location, configuration and design. The **ETI Refining Estimates of Land for Biomass** (2015) study gives a meta-analysis of land availability studies for energy crops (although the study does not estimate supply potentials over time). The **ETI Biomass Value Chain Model - BVCM[23]** (2011-2017) does not include feedstock deployment as an input – UK energy crop, forestry, straw, wastes and import scenarios arise an output of the cost-optimisation and demands set by the user. However, the underlying data does include land availability constraints and resource maps.

The Review of Bioenergy Potential report (Anthesis and E4tech, 2017)[24] was commissioned to review the CCC scenarios to 2050 in the context of bioSNG in the UK. The study reviewed and built on the CCC work and complemented the high scenario with data from BVCM to come up with the following estimates for land availability for perennial energy crops in the UK. **Low: 0.3 Mha, Medium: 0.6 Mha, High: 1.15 Mha.** Planting rates and therefore overall deployment of energy crops in 2050 in this report is, however, considered to be lower than in the CCC scenarios due to the lack of current planting witnessed in the UK. The UK and Global Bioresource Model (Ricardo, 2017) includes a maximum estimate of 1.85 Mha for unconstrained land area that could be available for perennial energy crops in the UK. For context, current total utilised agricultural area in the UK is 17.1 Mha, of which 5.9 Mha is arable.

Which specific crops are grown on the available land is also an important consideration (although the yields of Miscanthus and SRC in energy terms are broadly similar, their characteristics as a feedstock are different). The Ricardo (2017) model assumes a default ratio of 70:30 of land used for Miscanthus to SRC out to 2050 (in line with the Defra 2015 ratio of land used[25]). The ETI has conducted several projects which look into UK energy crops, costs, yields, spatial distribution and barriers to uptake in significant detail (although much of this detail has not been available to this review). Relevant ETI projects include: **Energy Crop Competitiveness and Uptake** (2013), **Energy crop business models** (2014), **Ecosystem Land Use Modelling** (ELUM, 2015) and **Refining Estimates of Land for Biomass** (RELB, 2015).

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[21] E4tech (2015) Technology Innovation Needs Assessment: Bioenergy (refresh). Unpublished (see section 2.2.10 of the Technical Annex)

[22] CCC (2011) Bioenergy Review. https://www.theccc.org.uk/publication/bioenergy-review/

[23] E4tech (2011-2017) Bioenergy Value Chain Model. http://www.eti.co.uk/library/overview-of-the-etis-bioenergy-value-chain-model-bvcm-capabilities (see section 3.2.5 of the Technical Annex)

[24] Anthesis and E4tech (2017) Review of Bioenergy Potential. https://cadentgas.com/getattachment/About-us/The-future-role-of-gas/Renewable-gas-potential/Promo-Downloads/Cadent-Bioenergy-Market-Review-SUMMARY-Report-FINAL.pdf and https://cadentgas.com/getattachment/About-us/The-future-role-of-gas/Renewable-gas-potential/Promo-Downloads/Cadent-Bioenergy-Market-Review-TECHNICAL-Report-FINAL.pdf ((see sections 2.2.4 of the Technical Annex)

[25] Defra (2016) Crops Grown for Bioenergy in England and the UK: 2015. https://www.gov.uk/government/statistics/area-of-crops-grown-for-bioenergy-in-england-and-the-uk-2008-2015 (see section 2.2.7 of the Technical Annex)

There is broad agreement between the studies in the range of estimates of land area that could be made available for perennial crop planting and that these estimates could be significant and could be hundreds of thousands of hectares compared to the thousands of hectares planted today. In general, the land use studies that form the basis of these estimates are considered to be sound and do take into account sustainability requirements. However, whether the scenarios manifest themselves in practice is speculative and will remain so. Achieving the high estimates of potential requires market conditions to become more favourable and a willingness to invest from potential growers. Future projections could be improved by linking the energy crops estimates to detailed analysis of reducing the barriers.

Concerted effort is required to establish energy crops plantings and to increase planting rates to realise the potential estimates. There is no good reference for the rate at which energy crop planting could happen in the future, or the split of different energy crops planted, given that these are entirely dependent on farmers' response to policy and the market. This is likely to remain a key uncertainty.

2.1.4 UK Short Rotation Forestry

SRF consists of trees grown as conventional, single stems, harvested at approximately 8-20 years old. Some of the studies that look into perennial energy crops also consider SRF, although in general it has been less studied than Miscanthus and SRC. SRF could be planted on lower quality land than other perennial energy crops.

The Ricardo model (2017) assumes that planting starts at 1,000 ha/yr from 2017, increasing the planting rate by 40% from 2019 to a maximum planting rate of 10,000 ha/yr from 2025. If a 15 year rotation is assumed, the first harvest would be in 2031. A yield of 90 odt[26]/ha is assumed, which equates to 6 odt/yr on a 15 year rotation (12 t fresh at 50% moisture content). The maximum land use for SRF is assumed to be 1.8 Mha, which assumes 10% of permanent pasture and 20% rough grazing land could be converted, mainly in the west, north west Scotland and upland areas in north, west and south west England. These assumptions are based on a study by ADAS on behalf of the NNFCC (2008)[27]. However, currently (2017) there is no planting of SRF in the UK. Therefore, as above, planting rates and achievement of the total potential are speculative. Planting rates are the key uncertainty here. There is no good reference for the planting rates that could be achieved.

Given the lead time between planting of SRF and first harvest, and the fact that no SRF is planted in the UK today, harvesting any SRF before the early 2030's is very unrealistic.

2.1.5 UK Waste arisings

Good quality data is available on **current waste arisings**, per sub-region within the UK, but waste collection differs locally so the composition of waste arisings varies widely and **official projections on waste arisings are lacking**. Data on commercial and industrial waste arisings is more limited because of the often privatised nature of the market.

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[26] odt denotes "oven dry tonnes", i.e. feedstock at 0% moisture content.

[27] ADAS (2008) Addressing the land use issues for non-food crops, in response to increasing fuel and energy generation opportunities. https://www.forestry.gov.uk/pdf/NNFCC_ADAS_Addressing_the_land_use_issues_for_non-food_crops_in_response_to_increasing_fuel_and_energy_generation_opportunities_2008.pdf

WRAP (2016)[28] provides the most recent and detailed data on current **UK waste arisings**. The Ricardo model bases waste arisings on data from WRAP and Defra and includes both domestic and commercial and industrial wastes. In some cases there is a more recent WRAP report available, but the data source is updated to at least WRAP 2015 so is still considered high quality and highly relevant. Personal communication with Defra officials during the course of the evidence review indicates that there are no official UK waste projections to 2050, although the Clean Growth Strategy[29] sets an ambition to work towards zero avoidable waste by 2050. The Clean Growth Strategy also commits the government to work on a new Resources and Waste Strategy, which should inform both around how total waste arisings and recycling and recovery rates will develop.

The Ricardo model **food waste** arising data is based on relatively recent (2013-2014) detailed (by source and by devolved administration) actual arisings data from WRAP on total waste arisings and the percentage that is food waste, and from Defra on recycling rates. The Ricardo model projects total waste arisings to increase out to 2050, which is in line with current trends that suggest economic growth is not completely decoupled from waste arisings. The Ricardo model projects recycling rates to increase and reach a maximum of 60% in England, 70% in Scotland and Wales and 50% in Northern Ireland, which is in line with current targets. This leads to an overall increasing food waste resource, which would reach 10.7 Mt/yr in 2050. By contrast, a recent report by ReFood Saria[30] quotes figures from WRAP 2011 that total UK food waste currently is 14.8 Mt/yr, of which 9 Mt/yr is avoidable and 5.8 Mt/yr is unavoidable. Assumed waste reduction rates and food waste recovery rates are both key assumptions that act in opposing directions to impact actual food waste availability for AD. In a scenario with ambitious food waste reduction, it could therefore be envisaged that food waste available for AD is lower than the estimate in the Ricardo model and closer to the unavoidable food waste estimate of 5.8 Mt/yr. The Ricardo model estimates the available potential for commercial and industrial waste to be around 11 Mt/yr in 2050.

Estimates of UK waste wood arisings vary significantly (although the potential of the feedstock overall is relatively small). Anthesis published a report on waste wood in 2017[31], which shows publicly available UK waste wood estimates varying from 4.1 to 10.6 Mt/yr. The 2017 Anthesis study derives a consensus figure of 5.7 Mt/yr wood waste currently, which is slightly higher than the consensus figure used in the underlying Ricardo model data of 5 Mt/yr. A different 2017 study by Anthesis for Cadent[32] reviewed UK waste availability to 2050 in the context of bioSNG in the UK. The scenarios of wood waste availability from 2020-2050 estimate availability of wood waste for bioSNG to be in the range 4.5-4.6 Mt/yr in 2020 to 5.2-5.6 Mt/yr in 2050, which is broadly in line with the data used in the Ricardo model. The availability of wood waste for bioenergy will depend on policies to separate the resource out of waste arisings, which is dependent on broader waste policy. The volume of wood waste also varies according

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[28] WRAP (2017) Estimates of Food Surplus and Waste Arisings in the UK. http://www.wrap.org.uk/sites/files/wrap/Estimates_%20in_the_UK_Jan17.pdf (see section 2.2.8 of the Technical Annex)

[29] HM Government (2017), The Clean Growth Strategy Leading the way to a low carbon future. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/651916/BEIS_The_Clean_Growth_online_12.10.17.pdf

[30] Vision 2020 UK roadmap to zero food waste to landfill, available from www.vision2020.info, https://www.saria.co.uk/pdfs/vision2020_roadmap.pdf

[31] Anthesis (2017) The UK wood waste to energy market. https://anthesisgroup.com/wp-content/uploads/2017/02/Anthesis_Wood-Waste-to-Energy-Report_February-2017.pdf

[32] Anthesis and E4tech (2017) Review of Bioenergy Potential. https://cadentgas.com/getattachment/About-us/The-future-role-of-gas/Renewable-gas-potential/Promo-Downloads/Cadent-Bioenergy-Market-Review-SUMMARY-Report-FINAL.pdf and https://cadentgas.com/getattachment/About-us/The-future-role-of-gas/Renewable-gas-potential/Promo-Downloads/Cadent-Bioenergy-Market-Review-TECHNICAL-Report-FINAL.pdf (see sections 2.2.4 of the Technical Annex)

to economic activity, with most waste coming from the construction and renovation industry, which is inherently challenging to predict.

The current waste wood utilisation in the UK is significantly lower than the potential, although this is growing year on year. In 2016, an estimated that around 1.6 Mt of recycled wood were used for woodfuel, an increase of 7% from the 2015 estimate. The estimates are included in the Forestry Commission's Forestry Statistics dataset[33], and are provided by the Wood Recyclers' Association.

There is an ongoing study for the ETI on waste gasification which may also provide analysis of waste arisings in the UK in the context of those that would be suitable for gasification, although this is a long running project so may not necessarily be based on more recent data than the recent Anthesis studies.

2.1.6 UK Macro-algae

Macro-algae (i.e. seaweed) is a wet feedstock that could offer a reasonable potential for AD in the future, if investment is made to farm the feedstock for the purpose. No macro-algae is cultivated commercially today for energy purposes. Macro-algae potential is not included in the Ricardo 2017 model and there are few studies currently available that have estimated the potential. Data on the potential for macro-algae farming in the UK is best covered in the 2011 bioenergy TINA[34], in which similar assumptions were used as in the DfT Modes 1 study[35], the precursor to the Ricardo model. The underlying data comes from Ecofys (2008)[36] and is in line with the DECC 2050 Calculator. The underlying data is old, and the sector has not grown in the past 7 years since 2010, however the underlying assumptions have not changed. The low scenario in the TINA assumes no development to 2050. The medium scenario assumes cultivation of macro-algae equal to half the area currently occupied by Scotland's natural standing reserves (563 km^2) by 2050 and the high scenario assumes land area for macro-algae cultivation is Scottish reserve plus an additional area of offshore development equal to the area proposed for the Hornsea Round Three Offshore Wind development area (4,735 km^2). The TINA states that "*Future detailed analysis from the Crown Estate is expected to offer further insights into the area of the UK seabed which macroalgae could be farmed on. Initial insights from this indicate that significantly greater production might be possible, by a factor of two or three. However, increased production will not necessarily mean greater use as an energy source, owing to the higher profitability of macroalgae in pharmaceutical, chemical and food markets*."

Cost data included in the TINA report is highly uncertain, given that there is no commercial scale production of macro-algae for bioenergy purposes.

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[33] Forestry Commission (2017) Forestry Statistics and Forestry Facts & Figures. https://www.forestry.gov.uk/forestry/infd-7aqdgc (see section 2.2.5 of the Technical Annex)

[34] E4tech and Carbon Trust (2011) Technology Innovation Needs Assessment: Bioenergy. http://www.lowcarboninnovation.co.uk/working_together/technology_focus_areas/bioenergy/ (see section 2.2.9 of the Technical Annex)

[35] 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, Study for the UK Department for Transport. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/3238/modes-1.pdf

[36] Ecofys (2007) Worldwide potential of aquatic biomass. https://www.ecofys.com/files/files/ecofys-2008-worldwide-potential-of-aquatic-biomass-revision-2014.pdf

The SEAGAS[37] project started in 2015 and aims to develop a process which will use seaweed for energy via AD. The Crown Estate is working together with Queen's University Belfast, Newcastle University, SAMS, CPI, CEFAS and Eunomia. The project is due to produce first results in 2018 and is likely to be a valuable evidence source once the project is finalised on the potential and cost of macro-algae for bioenergy in the UK. There is also an ongoing trial in Sweden for macro-algae for broader bioeconomy and bioenergy use, called SEAFARM[38]. This project may come with new insights on the potential for macro-algae use for energy, although the study looks at macro-algae's potential from a biorefinery perspective. As such, biogas is primarily considered as an application for the wastes from the biorefinery, rather than for the whole macro-algae crop. The research team will investigate whether biogas production is most effective when the full crop is used for AD or only when the waste from the biorefinery is used.

2.1.7 Global agricultural residues

Different reports consider different feedstocks within the category of **global agricultural residues**. Imports of agricultural residues were originally scoped out of the evidence review, on the basis that straw is not economically viable to transport long distances (without pre-processing) because of its relatively low energy density. However, several reports were identified that quantify different agricultural residues that have a higher energy density than straw and may be more economically viable to transport longer distances. The Ricardo model (2017) covers the potential for 11 different global agricultural residues[39] transparently and in detail. The Ricardo approach sums the current availability from the top ten countries per feedstock, based on statistics from FAOSTAT. The FAOSTAT data is in most cases based on official national statistics and is therefore considered to be robust. This is the key organisation that collates data such as this in as consistent a manner possible across the world and it is unlikely that there is a better overview of the current availability of these feedstocks globally, although it could be possible that organisations within a country have a closer insight into more local level availability, for example local sustainable removal rates. The total world data from FAOSTAT is also included in the underlying datasheets, for comparison. The top ten countries make up between 75% and 97% of the global potential, depending on the feedstock.

The "Wasted"[40] study also provides a useful reference for agricultural residues[41] in Europe to 2030 based on EU's 12 most produced crops using data from (FAOSTAT covering 2002-2011). The study estimates an unconstrained potential of 417 Mt/yr and a sustainable potential of 139 Mt/yr in 2030. 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). Availability to 2030 is estimated using extrapolation, based on 2012 projections of increased agricultural production to 2022.

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[37] http://seagas.co.uk/

[38] http://www.seafarm.se/

[39] Ricardo (2017) includes bagasse, olive residues, palm oil residues, nut shells (from shea nuts, groundnuts and walnuts), husks (cocoa, oats and soya), corn cobs and sunflower pellets. Many of these feedstocks are traded internationally already, although we would question the feasibility of international trade in bagasse which is most often used onsite for energy production.

[40] ICCT (2014) Wasted: Europe's untapped resource. https://www.theicct.org/publications/wasted-europes-untapped-resource (see section 2.3.2 of the Technical Annex)

[41] The "Wasted" study includes different types of agricultural residues from EU's 12 most produced crops: wheat, barley, maize, rapeseed, sugar beet, triticale, rye, oats, sunflower, rice, soybeans, olives (ordered in terms of volume).

Ecofys (2013) provide detailed information on steady state **straw** availability in 12 key straw producing Member States, of which the UK is one.[42] The study investigated the average sustainable removal rate for straw in each of these countries, which ranged from 33% to 50% (see section 0 for further discussion).

The 2014 IRENA Global Bioenergy Supply and Demand study[43] uses high quality underlying data from FAO and covers 118 countries. It gives a high level estimate low/high range of feedstock availability to 2030. However, it uses fixed assumptions for sustainable potential/uses for all countries (e.g. 25% of the potential was assumed to be recoverable, based on a 50% sustainable removal rate and the assumption that 50% can be collected economically), and crop-specific residue coefficients are based on a study from 2004. Although the fixed assumptions are considered to be at a reasonable level, so the overall figure could be a reasonable estimate, 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. There will be variation per crop and per country, so the data should not be relied upon at a detailed country or crop level.

2.1.8 Global woody biomass

For **global energy crop availability**, the Ricardo (2017) approach focuses on an estimate of global abandoned land availability multiplied by a yield assumption (appropriate woody perennial crop and therefore appropriate yield figure is varied for each of 17 world regions, annual yield increase modelled as low, Business as Usual (BAU) or high). It is not fully transparent what the different crops assumed are in the 17 world regions, just the respective yields are included in the underlying worksheets. The amount of land is an estimate of spare agricultural land available, which includes “abandoned agricultural land” and “abandoned pasture (rest) land”. The underlying source for the land availability is relatively old (Hoogwijk (2005)[44] supplemented with Van Vuuren (2009)[45] which estimated the amount of abandoned land that would be unsuitable for growing crops, e.g. because it is too severely degraded or because of water scarcity). These sources are widely cited in bioenergy literature as few alternatives exist. The 2017 Ricardo model uses updated land scenarios as compared to the 2011 version, but is also based on the same IMAGE ecological-environmental model from Utrecht University (Netherlands) 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.

Overall the approach in the Ricardo model to estimating land availability is relatively conservative from a sustainability perspective. The 2017 version of the model is based on the same underlying land availability data as the earlier version, but makes more conservative sustainability assumptions. The resulting land availability is therefore significantly lower than the estimate in the 2011 version of the report. The 2017 version of the model also

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[42] The report also covers woody residues (bark, branches, leaves, sawdust and cutter shavings) and corn cobs (quick scan only).

[43] IRENA (2014) Global Bioenergy Supply and Demand Projections: A working paper for REmap 2030. https://www.irena.org/remap/IRENA_REmap_2030_Biomass_paper_2014.pdf (see section 2.4.3 of the Technical Annex)

[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, Energy Policy, Volume 37, Issue 11, November 2009, Pages 4220-4230.

makes conservative assumptions about the surplus energy crops that could be available to trade, assuming high levels of domestic use of any energy crops grown.

For all global feedstocks (global agricultural residues and global woody biomass), users of the Ricardo (2017) model can define the **percentage of global feedstock trade that could come to the UK**. The default level is set at 10% of the global traded feedstock in 2015 and 2020 that could come to the UK, declining to 2% in 2050 (based on assumptions used in the medium supply scenario in DECC's Bioenergy strategy, 2012). This is a crucial sensitivity and makes a very large difference to the assumed potential of feedstock that could come to the UK. Of course, even changing the assumption from e.g. 2% to 4% in 2050 would double the amount of biomass that is assumed that could come to the UK. According to the International Energy Agency (IEA) Task 40[46], the UK currently imports around 25% of the global traded pellet market (6.5 Mt out of 26 Mt) and if companies are proactive and successful in signing long term international supply deals, the UK could continue to import a high share of the global market. However, it is also reasonable to assume that on a 2050 timescale, demand for bioenergy from other countries will increase and the international market will become more competitive, meaning that the UK share of the global market would decrease (although if the size of the overall market increase, this would not necessarily mean a decrease in imports in absolute terms). In reality the percentage of the global market that the UK can access will be based entirely on the UK's future willingness to pay for biomass compared to other countries (i.e. the UK policy priority given to biomass use) and the openness of global trade, and will not necessarily be related to proxies such as the UK's share of global GDP, or population or the energy sector size (which the 2% in 2050 in the Ricardo model is calculated from).

For **global forestry residue availability**, the Ricardo model (2017) draws data from a number of robust sources including FAOSTAT (2015) for industrial wood production and the UK Forest Research CARBINE model data for estimating the maximum sustainable availability of forest co-products. It should be noted that as forest residues are a residue from other industries, in a high investment scenario, the Ricardo model assumes that a large share of forestry and industrial wood processing residues are used by industries other than bioenergy (e.g. construction) so the estimated potential of these feedstocks is actually lower in a high investment scenario than a BAU scenario.

The 2014 IRENA Global Bioenergy Supply and Demand study[47] provides potential estimates for global forestry products, but applies the assumptions from Smeets and Faaij (2007). This was a high quality bottom-up study on forestry product availability, but based on data that is now quite old (pre-2000 in some case). Furthermore, the IRENA study makes a high level assumption that 25% of the total wood logging residue and 75% of the total wood processing residue and wood waste could be sustainably recovered, which is reasonable and should not over-estimate the total potential but it is an oversimplification as this will vary locally. IRENA's 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), which again is reasonable but an oversimplification. As with global agricultural levels, this study gives a good top-down estimation of the total global potential, but the data should not be relied upon at a detailed level.

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[46] IEA Task 40 (2017) Global Wood Pellet Industry and Trade Study 2017. http://task40.ieabioenergy.com/wp-content/uploads/2013/09/IEA-Wood-Pellet-Study_final-july-2017.pdf

[47] IRENA (2014) Global Bioenergy Supply and Demand Projections: A working paper for REmap 2030. https://www.irena.org/remap/IRENA_REmap_2030_Biomass_paper_2014.pdf (see section 2.4.3 of the Technical Annex)

Ecofys (2013) provide detailed information on steady state EU forestry residue and wood processing residue availability, with underlying data available at the Member State level. This study did explore sustainable removal rates for forest residues in selected Member States through interviews with Member State experts. For example, in Sweden and Finland, a forest residue removal of 70-80% could be considered appropriate, but this should only be from an individual forest stand with good soil conditions, and not within “high value natural forests”. This level of residue removal will not be sustainable or technically feasible from all forest stands. An appropriate removal rate will always have to be determined at the forest stand level as the local nutrient conditions must also be taken into consideration.

The Ecofys study quotes an European Climate Foundation report[48] that estimates that currently around 3% of forestry residues in the EU are harvested. The report states that, on the basis of interviews with country experts, the majority of forestry residues in Europe today are left in the forest, as there is little demand for the material from the conventional wood-based industries. Only in Scandinavia is there significant level of industrial forestry residue collection, estimated to be up to 40% of technically harvestable logging residues in Sweden. This suggests a significant potential for increasing forest residue collection – and therefore potential for bioenergy – across Europe.

For **global forestry products**, FAO publishes an Annual Market Review of forest products[49]. This report provides a comprehensive overview of global forest product markets. Although the scope of this report is broader than woody biomass for bioenergy it nonetheless serves as an important reference source, using largely official national statistics as the underlying data.

2.2 Feedstock prices

Overall, reasonable quality data are available on **current feedstock prices.** All biomass feedstock markets are immature relative to other energy commodities and data often has to be sourced via contacts in industry. Some feedstocks are beginning to be traded as commodities (e.g. imported wood pellets or straw) and there are examples of price data being publicly available via price indices, but these are the exception rather than the rule. Argus, for example, publishes good quality data on the current market price of wood pellets.[50] Defra used to publish statistics on straw prices[51], although the series has been discontinued since March 2016. Other feedstock markets are less mature and price estimates are only accessible via specific research reports or by contacting individuals involved in the industry. Contracted feedstock prices naturally tend to be confidential.

Several studies considered in this review look at the *cost* of feedstock production, notably the ETI studies on energy crops. This is key to understanding the relative costs of different feedstocks and which ones are likely to be most cost-effective to produce. However, it should be noted that gasification plants – and AD plants to the extent that they are not using wastes or feedstocks produced on-site – will pay the market *price* for their feedstocks, i.e. feedstock production cost plus transportation and pre-processing costs (e.g. chipping and/or pelletising) plus a margin for the feedstock producer. For international wood pellets, in particular, we already see some convergence towards one

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[48] European Climate Foundation (2010) Biomass for heat and power – Opportunity and Economics. http://www.europeanclimate.org/documents/Biomass_report_-_Final.pdf

[49] FAO (2016) Forest Products Annual Market Review 2015-2016. https://www.unece.org/fileadmin/DAM/timber/publications/fpamr2016.pdf

[50] Argus Biomass Markets. http://www.argusmedia.com/bioenergy/argus-biomass-markets/

[51] Defra (2016) Commodity Prices. Prices for selected agricultural and horticultural produce. https://www.gov.uk/government/statistical-data-sets/commodity-prices

market price (e.g. for wood pellets delivered to the Amsterdam-Rotterdam-Antwerp (ARA) region), which therefore does not necessarily reflect the actual cost of production of those pellets, but rather the willingness to pay for the pellets.

A study by DeltaEE for BEIS (unpublished)[52] on UK **wood pellet prices** completed during the course of this evidence review includes data on wood pellet prices in the commercial and domestic sectors. This is a very recent (2017) primary evidence source, based on engagement with customers, industry and the UK Pellet Council. The study indicates that typical prices are currently £135-165/t at factory gate/port (ex-VAT) in the wholesale market, £169-248/t (average £204/t) delivered for bulk blown pellets and £210-257/t delivered for bagged pellets on pallets. The prices for the bagged pellets are broadly consistent with those listed on the Wood Pellet Guide website and Forest Fuels a leading UK wood pellet supplier[53]. Price data for pellets purchased in larger volumes (e.g. by power companies) are confidential since they are often the subject of long term bilateral contracts which are not made public. The IEA indicates that the likely range is 100-150 EUR for pellets delivered in the ARA region. Pellet price developments for other large scale consumers are available via subscription from Argus.

Agricultural residue prices respond to the success of harvests and also fluctuate during the course of the year if purchased on the “spot” market. Straw prices are typically lowest in July to September following harvest and peak in spring. The UK power sector typically pays less for straw compared to other markets, such as the livestock sector, as the straw is sold through long-term contracts (e.g. ten years). UK supply contracts are typically based on a moisture content of 16-25%, and the lower the moisture content the higher the price.[54] The Defra statistics on straw prices show that the average wheat straw price (big square baled) was £34/t over 2015/16, with barley straw trading at a £5/t premium. Our understanding is that the price is broadly representative at this time.[55] **Forestry** is less affected by annual harvest fluctuations, but natural events such as disease or forest fires can have a dramatic impact on availability of forestry feedstocks for energy. Feedstocks that are residues from other industries (e.g. agricultural residues, sawmill residues etc) tend to command a lower price than the primary agricultural or forestry products, but their availability is dependent on the performance of other industries so their availability is harder for energy policy to influence. The cost of production for such residues relates to collection (e.g. straw baling) and pre-processing only.

Perennial energy crops are, in theory, not expensive crops to grow compared to annual crops, as they have relatively low fertiliser and diesel input requirements compared to annual crops. Despite this, they currently only provide around half the annual net margins of conventional crops such as wheat, due to the high relative cost of planting the material (particularly in the case of Miscanthus) and crop establishment. Energy crops, particularly SRC, also require specialised harvesting equipment. The payback time on the initial investment is a risk, and the time between establishment and first payments can lead to cash flow problems. Miscanthus takes a full three years to reach an economically viable yield for harvesting while SRC takes up to four years with subsequent harvesting every three years. A payback period of five or more years is unattractive for a farmer used to annual income. These concerns where highlighted in a 2011 study which found that 30 out of 36 surveyed farmers did not consider planting

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[52] DeltaEE (2017) BEIS UK pellet market report. https://www.delta-ee.com/delta-ee-blog/can-wood-pellets-set-the-heating-market-alight.html

[53] http://woodpelletguide.uk/wood-pellet-prices.html, https://www.forestfuels.co.uk/wood-fuel-price-comparison/

[54] Ecofys (2013) Low ILUC potential of wastes and residues for biofuels. Straw, forestry residues, UCO, corn cobs. https://www.ecofys.com/files/files/ecofys-2013-low-iluc-potential-of-wastes-and-residues.pdf (see section 2.3.5 of the Technical Annex)

[55] Personal communication with industry sources.

energy crops citing the long-term commitment and time to payback as key concerns.[56] The industry therefore needs a boost to give land owners the confidence to invest in and plant such crops. Potential growers need the confidence that there will be a market for their crops into the future and that they will receive a consistent income. This is especially the case if growers are to establish longer rotation feedstocks such as SRF, which can take up to 15 years before any feedstock is harvested.

The ETI has conducted a large number of detailed studies into UK energy crops (the detail of which has not all been publicly available during the course of this review). A key evidence source for the determination of current energy crop costs is the **Characterisation of biomass feedstocks database** (Forest Research/Uniper, 2017[57]). The database provides "as is" 2015/2016 production costs for Miscanthus, SRC poplar/willow and SRF and their pelletised versions, broken down into growing, harvesting etc, based on field tests and laboratory analysis. The ETI **Energy Crop Competitiveness and Uptake** (2013) project produced an **Energy Crop Cost Calculator** covering Miscanthus and SRC. This was later used in the ETI **Refining Estimates of Land for Biomass** project for case studies, but the data was specific to only three individual farms, so the original calculator is considered to provide a better UK average. The report also quantifies the "on-farm yield data" seen between model predictions and real-world cultivation. The ETI **Energy Crop Business models** (2014) project provides qualitative information on barriers facing the UK industry, tonnage data on current key users and locations around the UK, and past/current areas planted. The ETI BVCM contains data on likely energy crop ramp up constraints, based on the findings from the **Energy Crop Competitiveness and Uptake** (2013) project. This project can also be useful for UK average biomass/waste yields, costs and emissions to 2050. Spatial data is part of the project, but is not publicly available. All forestry data within the project is confidential. The previous ETI projects also have more recent Miscanthus and SRC costs than in BVCM. (Note that BVCM includes feedstock costs for UK feedstocks, but market prices for imports.) The ongoing ETI **Biomass logistics** project includes "factory gate" feedstock costs (including logistics, transport, processing) from a variety of sources – some provided by e.g. Drax and stakeholder interviews. The project also includes projected costs out to 2050, but these are not published at the time of writing. The project may also be a useful source of more general transport and logistics assumptions, including costs and GHG emissions. The feedstock scenarios are based on BVCM.

Waste feedstocks, such as waste wood, food waste and refuse derived fuel (RDF), typically command a gate fee today (i.e. waste producers will pay for their waste to be taken away), but if demand grows for waste feedstocks, this could easily flip so that the waste feedstocks command a price. This has already been seen for several waste feedstocks used in the transport biofuel market, e.g. used cooking oil.[58] A large increase in bioenergy deployment *could* be highly disruptive in terms of current feedstock prices, therefore caution should be applied if assuming negative prices in the long term for waste feedstocks. An exception might be for certain wet feedstocks for AD, such as sewage sludge or wet manures, which are not economical to transport over long distances (given their very low energy density) so they will typically be treated onsite (e.g. at a water treatment plant or on-farm), or otherwise close to where they are produced, and are therefore unlikely to be widely traded.

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[56] Wilson, P., Glithero, P. and S. Ramsden (2011) "Agricultural Economics and the LACE Programme: Farm Systems Assessment of Second Generation Biofuel Production". Presentation at UKERC workshop "The Economics of Land Use and Energy", 25-26 October 2011, Oxford, available at: www.ukerc.ac.uk/support/tiki-download_file.php?fileId=2064

[57] Forest Research/Uniper (2016) Characterisation of biomass feedstocks database. http://www.eti.co.uk/programmes/bioenergy/characterisation-of-feedstocks (see section 2.2.6 of the Technical Annex)

[58] Ecofys (2013) Trends in the UCO market. Input to the Draft PIR. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/266089/ecofys-trends-in-the-uco-market-v1.2.pdf

Key evidence sources for the determination of current prices of waste feedstocks are the WRAP Gate Fees reports[59] (for wood waste and food waste) and the Let's Recycle price series (for waste wood and RDF produced from waste[60], which is the form that waste would be fed into a gasifier). These evidence sources do not provide any future price forecasts.

Feedstock cost data in UK TIMES is several years old, being based on 2009-2011 sources or simplified estimates. For example, all wastes are assumed to be £0 cost over the period 2010 to 2050. No rationale is provided other than the assumption was *"based on discussion with the Committee on Climate Change"*. It may have been assumed that prices will decrease over time so gate fees turn into positive prices in later years, averaging out at £0 over the period 2050. Sawmill residues are also assumed to be £0 cost, which is not the case in the market today, as their current price in the UK is understood to be up to £100/odt delivered[61]. UK TIMES is not therefore considered to be a directly relevant evidence source for obtaining feedstock cost estimates.

For **macro-algae**, costs are estimated in the bioenergy TINA 2011[62]. These are currently the best available UK data and the underlying assumptions are still considered to be valid. However, the data is considered to be highly uncertain, given that there is no commercial scale production of macro-algae for bioenergy purposes.

Whilst good quality data are generally available on current feedstock prices, very few studies predict prices into the future and therefore there is an **absence of data on long term price projections** (beyond the next 2-5 years) or any consensus on how the market might develop as demand and supply for different feedstocks develop. Average cost data for generic biomass feedstock in the 2016 RHI impact assessment[63] is projected to remain flat going forward to 2020. This is not likely to be realistic in the medium to long term beyond 2020. The DeltaEE study on pellet prices in includes projections for wood pellet prices, but only to 2021. The study author's assert that *"the wood pellet market is set up to be a high volume, low-margin market. Therefore, if demand increases it is unlikely prices will rise significantly, and market forces themselves will have a limited impact."* The IEA (2017) suggest that future pellet prices in the industrial sector will depend on global market conditions (i.e. demand trends and supply capacities). Demand markets are still influenced to a large extent by policy framework providing incentives in different forms to biomass combustion. So far, supply capacities have reacted to policy and demand projections (i.e. the pellet market is not supply driven).[64]

Will costs fall over time as global supply chains scale-up, and yields improve, or will prices increase as pressure on global resources increases?[65] Underlying costs to produce feedstocks could decrease with economies of scale, increasing yields and efficiencies and better handling methods, but they may also increase because increased demand for feedstocks may mean that harder to access feedstocks are required (e.g. harder to collect forest

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[59] WRAP (2011-2016). Gate Fee Reports. http://www.wrap.org.uk/collections-and-reprocessing/recovered-materials-markets/reports/gate-fee-reports

[60] Let's Recycle (2014-2017) Prices. EfW, landfill, RDF. https://www.letsrecycle.com/prices/efw-landfill-rdf-2/efw-landfill-rdf-2017-gate-fees/

[61] Personal communication with industry sources.

[62] E4tech and Carbon Trust (2011) Technology Innovation Needs Assessment: Bioenergy. http://www.lowcarboninnovation.co.uk/working_together/technology_focus_areas/bioenergy/ (see section 2.2.9 of the Technical Annex)

[63] DECC (2016) Consultation Stage IA: The Renewable Heat Incentive: A reformed and refocused scheme. https://www.gov.uk/government/consultations/the-renewable-heat-incentive-a-reformed-and-refocused-scheme

[64] IEA Task 40 (2017) Global Wood Pellet Industry and Trade Study 2017. http://task40.ieabioenergy.com/wp-content/uploads/2013/09/IEA-Wood-Pellet-Study_final-july-2017.pdf

[65] Note that under some climate scenarios, yields now get worse. This is not modelled in Hoogwijk (2005), which is the study that underlies many of the land availability and yield assumptions.

residues or waste streams that require additional processing to separate). There is no consensus on this in the literature. Note that once feedstocks are traded widely as commodities for energy, the price fluctuations may become more aligned to energy markets (as was seen with vegetable oil prices). Price projections for all feedstocks to 2050 are likely to remain a key data uncertainty, given the complexity and the policy uncertainty.

3 Conversion technology evidence sources

Summary

There is good research into conversion technologies that could produce biomass-derived gases in GB, but it is a developing industry. **The evidence base is stronger for commercially deployed technologies of AD to biogas and biomethane, as compared to gasification to bio-synthetic natural gas (bioSNG) and biohydrogen (bioH$_2$)**. Gasification is not new, but deployment for bioSNG or bioH$_2$ production is still very limited.

Evidence on AD cost and operational performance and market data is good. As part of this review, there was only a limited search on data directly from industry and individual AD plants, as this would have been very time consuming and we know that often the basis for stating costs is not consistent. The review focused on industry statistics and studies by the trade association, ADBA, the European Biogas Association, the International Energy Association (Task 37), as well as publications by UK government in the context of the RHI and FIT, which are considered to be representative for the industry.

For gasification, we did not review all studies available on biomass gasification projects embarked upon in the UK, the EU and globally, but focused on those that are of the most relevance technically and that provide most detailed cost information. Many of the studies identified use somewhat dated information, only cover certain aspects of the process (i.e. the upstream process elements; feedstock handling, gasification, syngas clean up) or are focused on gasification to alternative products such as biofuels.

The studies identified by NREL and ETI are very detailed and considered robust evidence sources, and the data from the GoGreenGas consortium (Progressive Energy, Cadent, Advanced Plasma Power) are based on an actual demonstration plant in the UK. **Overall the available data on gasification to bioSNG and bioH$_2$ are good quality and highly relevant, but the data are based on very few example demonstration scale plants, so appropriate caution should be used when extrapolating the data to estimate costs for a whole potential future bioSNG industry**.

All technologies could be combined with carbon capture and sequestration (CCS), which could lead to potential negative emissions (i.e. net removals). This was not a core focus of the evidence review as the development of CCS options is independent from the development of AD or gasification of biomass. Due to the location and typical small-scale, CCS is not considered to be realistic for wide-scale deployment coupled with AD. However, larger scale gasification plants, especially those that are located close to ports to make use of imported biomass, and that are also close to potential CCS storage sites, present a better opportunity. CCS deployment is uncertain and heavily impacted by policy decisions.

AD is an established technology and the potential for cost reduction is limited compared to emerging technologies like gasification. A number of the evidence sources assessed do include learning rates from a first of a kind to nth of a kind plant, but these will always be subject to uncertainty. **Learning rates are identified as a key uncertainty in the evidence.**

Data could be improved in the following areas:

- Limited number of studies on pre-processing but good quality evidence. With the exception of chipping and pelletising which are needed to transport feedstocks, the benefits of further pre-processing are difficult to characterise in terms of potential, cost and GHG emissions which are the subject of this review.
- For AD the future uncertainties in the data primarily centre on the feedstock cost (i.e. level of gate fees), the potential revenue streams for digestate and the extent to which a market will develop for CO_2.
- There is variation in gasification cost estimates, and not always clear whether this is due to different plant configuration or technology assumptions or extent of what is included in cost estimates. Further investment in larger scale research and demonstration gasification facilities to prove the full system and projected learning rates in practice will improve data availability and enable better insights into potential for innovation and future cost projections.
- Compression cost data for CO_2 captured for “local scale” plants.

The following aspects are likely to remain uncertain due to inherent difficulties in predicting how policy and markets will develop in the future:

- There is good evidence on existing number of plants in UK, but projections are always speculative.
- CCS deployment which is impacted by policy decisions, which are to some extent independent from heat policy and gasification of biomass.

3.1 Feedstock pre-processing

Biomass and waste pre-processing refers to activities and processes that may be used to densify, improve handling, homogenise or clean-up raw biogenic feedstocks with the aim of improving their subsequent thermal treatment. Such processes include amongst others, drying, chipping, pelletising, torrefaction, washing, fast pyrolysis etc. Drying, chipping and pelletising are all commercially deployed technologies and commonly practiced today in biomass supply chains to improve the handling and transporting qualities of feedstocks.

The evidence review identified a very limited number of techno-economic studies on biomass pre-processing. The main study identified is the £0.5m ‘**Techno-Economic Assessment of Biomass Pre-processing**’ (TEABPP), commissioned by the ETI in 2015[66]. Once completed, this will be by far the most comprehensive study on biomass pre-processing, analysing and comparing different pre-processing options in a detailed, systematic and consistent way. The 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. The study covers pre-processing of woody and ligno-cellulosic crops e.g. Miscanthus grass, SRC, SRF, but does not cover processing of waste or waste derived materials. Fifteen pre-processing technologies are covered, including chipping, pelleting, torrefaction (several variants), pyrolysis, washing (chemical and water) and drying (belt, drum). Final results are not

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[66] E4tech et al. (forthcoming) Techno-Economic Assessment of Biomass Pre-processing. A techno-economic assessment of the costs and benefits associated with pre-processing biomass. http://www.eti.co.uk/programmes/bioenergy/techno-economic-assessment-of-biomass-pre-processing

available at the time of writing, but the ETI were able to share the Excel deliverable with the underlying data, along with the background report, during the course of the evidence review.

The review also identified a key report by the **IEA Task Force 40** covering **wood pellets**[67]. This is a very recent source and considered high quality. The study provides a detailed overview of the wood pellet market in Europe, North America and Asia (by country), including information on trade flows and wood pellet prices. A summary of developments in biomass **torrefaction**[68] is also included.

The UK has very limited pellet production of wood pellets. According to the Forestry Commission, the production in 2016 stood at 323,000 tonnes (a 6% reduction compared to 2015).[69] This compared to a global market of 26 million tonnes in 2015 according to the IEA Task Force 40 study. The USA is the largest pellet producer with 6.3 Mt production. Other significant producers are Canada (2.4 Mt), Germany (2.2 Mt) and Sweden (1.5 Mt). The UK is the largest wood pellet consumer with 6.7 Mt pellets in 2015, followed by the USA (2.9 Mt), Denmark (2.8 Mt) and Italy (2.1 Mt). The largest pellet plants globally are located in the USA (South East), with several exceeding 500,000 tonnes per year in capacity. Examples include plants run by Georgia Biomass and Enviva. Drax Power also operates two facilities in the USA.[70]

The IEA Task 40 report cites several advantages of torrefaction over standard wood pellets. Torrefaction makes the biomass feedstock handle in a similar manner to coal (i.e. grindability characteristics) so there has been particular interest in the technology from parties interested in co-firing biomass with coal. Torrefaction also makes the biomass resistant to water (hydrophobic) and minimal biodegradation so it can be stored outside, which saves storage costs. The material furthermore offers significant cost reductions in transport given the very high energy density of the material. Torrefied material reportedly combusts and gasifies “easier and cleaner”. There are many torrefaction initiatives being undertaken globally, with a number of these at the commercial scale (>2t/h). These include the 80,000 tonnes/yr New Biomass[71] plant in Quitman, Mississippi (USA). However, the IEA indicate that torrefaction is more expensive compared to standard pelletising and there has been little import of torrefied pellets into the UK to date.

Pyrolysis has been reviewed in the context of a pre-processing step rather than as a gasification technology. Two key techno-economic studies have been published by the US National Renewable Energy Laboratory (NREL) in 2010[72] and Pacific Northwest National Laboratory (PNNL) in 2014[73]. Fast pyrolysis is also included in the forthcoming TEABPP study for the ETI. There is interest in pyrolysis in the UK, often in the context of processing

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[67] IEA Task 40 (2017) Global Wood Pellet Industry and Trade Study 2017. http://task40.ieabioenergy.com/wp-content/uploads/2013/09/IEA-Wood-Pellet-Study_final-july-2017.pdf

[68] Torrefaction is a thermal pre-treatment technology in which biomass is heated to a temperature between 250-350°C in an atmosphere with low oxygen concentrations, so that almost all of the moisture is removed. The process can be likened to the production of charcoal or roasting of coffee beans.

[69] Forestry Commission (2016) Forestry Statistics 2017, Chapter 2: UK-Grown Timber (section 2.10.2) https://www.forestry.gov.uk/pdf/Ch2_Timber_FS2017.pdf/$FILE/Ch2_Timber_FS2017.pdf (see section 2.2.5 of the Technical Annex)

[70] https://www.gabiomass.com/; http://www.envivabiomass.com/about/; https://www.draxbiomass.com/plant-port-journey-compressed-wood-pellet-2/

[71] http://newbiomass.com/

[72] NREL (2010) Techno-Economic Analysis of Biomass Fast Pyrolysis to Transportation Fuels. http://www.nrel.gov/docs/fy11osti/46586.pdf

[73] PNNL (2014) Biomass Direct Liquefaction Options: Techno Economic and Life Cycle Assessment. http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23579.pdf

wastes, in particular difficult to process wastes such as tyres[74] or plastics. Pyrolysis outputs include an oil (pyrolysis oil) and a syngas. The process can be optimised towards the desired ratio of oil to gas output, but the oil is the dominant product, so pyrolysis is considered to be of limited interest from the perspective of decarbonising the gas grid. Pyrolysis could be interesting in the context of producing a bio-oil (or waste derived oil) suitable for the off-grid heating sector.

3.2 Anaerobic Digestion

AD is a commercially available and widely used biological process for converting biomass into biogas in the absence of oxygen. Typical feedstocks for AD are wet organic waste materials such as manures, sewage sludge, food wastes as well as crops such as maize. Crops (primarily maize) are currently deployed for AD in the UK, but are limited by sustainability concerns in terms of land use and GHG savings. Initiatives such as "Biogasdoneright"[75] which looks at intercropping could, however, go some way to mitigate these concerns by producing additional feedstock for AD on existing agricultural land, without displacing the current food production on the land.

The end products of the AD process are biogas (a gas containing around 50-70% CH_4 and 25-50% CO_2[76], water vapour and trace amounts of other gases, such as oxygen, nitrogen and hydrogen sulphide (H_2S)[77]) and a solid fraction called digestate, consisting of what is left from the treated substrate (typically around 85% of the input material). The digestate is a nutrient rich substance that can be spread to fields as fertiliser, either on-farm or sold on the market. The British Standards Institution (BSI) PAS 110 standard specifies the minimum quality level for the use of digestates on soil in the UK[78]. It would otherwise need to be disposed of, incurring a cost (estimated to be £5/t in analysis undertaken by DECC[79]).

AD plants tend to be developed at a local scale because of the nature of wet feedstocks, which are costly to transport long distances. According to the Anaerobic Digestion and Bioresources Association (ADBA), the average UK plant size is around 1 MW_{el}, although sizes vary largely depending on the type of feedstock processed. The larger AD plants tend to be located at sites that have access to a large and consistent wet waste stream such as sewage treatment plants, waste collection plants or food processing plants. Smaller AD plants (up to 250 kWh_{el}) tend to be on-farm, processing wet manure (often supplemented with crops such as maize to boost the calorific value of the feedstock mix).

The biogas produced in the AD plant can be used to generate electricity or heat, or both outputs in a CHP system. The electricity can either be used on-site or exported to the grid. A portion of the biogas produced is generally used to generate on-site energy requirements for the plant itself (heat and electricity). Biogas can be used as an

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[74] http://www.mishergas.co.uk/developments/

[75] CIB (2016) Biogagasdoneright and Soil Carbon Sequestration. The Italian Agricultural Revolution. http://www.ieabioenergy.com/wp-content/uploads/2016/05/P11-Biogasdoneright-and-soil-carbon-sequestration-Gattoni.pdf

[76] Different feedstocks will produce biogas with different methane contents. A representative composition is considered to be 60% CH_4 and 40% CO_2 by volume. This equates to around 35% CH_4 and 65% CO_2 by mass.

[77] EBA (2013) EBA's BIOMETHANE fact sheet. http://european-biogas.eu/wp-content/uploads/files/2013/10/eba_biomethane_factsheet.pdf

[78] BSI PAS 110 - Producing quality anaerobic digestate. http://www.wrap.org.uk/content/bsi-pas-110-producing-quality-anaerobic-digestate

[79] BEIS (2016) Review of support for Anaerobic Digestion and micro-Combined Heat and Power under the Feed-in Tariffs scheme. https://www.gov.uk/government/consultations/review-of-support-for-anaerobic-digestion-and-micro-combined-heat-and-power-under-the-feed-in-tariffs-scheme (see section 3.2.6 of the Technical Annex)

alternative to natural gas, but it has a lower caloric value (due to the lower CH_4 content) and may cause corrosion and mechanical wear of the equipment in which the biogas is used (due to the presence of H_2S) unless scrubbers are deployed. These include ferric chloride dosing, the installation of activated carbon filters and biological treatment[80].

Biogas can also be upgraded to biomethane, a process in which the CO_2, water and other trace gas impurities are removed. Biomethane has an additional advantage that it can be injected into existing gas infrastructures. This can be the national high pressure gas transmission grid or a local low pressure gas distribution network. Proximity to the gas network is cited by Northern Gas Networks as a key factor in determining the viability of a biomethane project[81]. Biogas must be enriched ("spiked") with (bio)propane prior to injection to homogenise the calorific value in order to meet the Gas Safety (Management) Regulations (GS(M)R). (The level of spiking according to the UK Renewable Energy Association is typically 5-12% by energy[82].) The GB gas grid specifications are likely to be reviewed in the period to 2050, especially in the context of gas grid decarbonisation, and so this requirement and the level of spiking may change in the future.

The process of upgrading biogas to biomethane removes CO_2, which could be compressed and transported for sequestration, further improving the GHG balance of the plant. There are several types of carbon removal technology that can be deployed, of which the more prevalent types in the UK are membrane (45%) and waste washing (22%)[83]. Currently the CO_2 is typically vented. The distributed and relatively small nature of AD plants and the relatively small volumes of CO_2 involved compared to industrial plants mean that CCS is unlikely to be practical as the costs of establishing the CCS infrastructure will be prohibitively expensive. CO_2 could otherwise be captured, liquefied and bottled/tankered for subsequent use (Carbon Capture and Use, CCU, e.g. in beverage carbonation or greenhouses), but the same practical issues of location and scale mean that CCU is likely to be restricted to niche situations. Also, our understanding is that end use demand for CO_2 is typically restricted to plants using crop-based feedstocks because of the negative perception of using gas produced from waste, even though this CO_2 source would be permitted to be used in food supply chains[84]. Limited recent publicly available UK evidence on the CAPEX cost of CO_2 compression was identified. A report published by the IEA was identified that provides high level information, however the underlying data relates to studies undertaken in 2011[85].

There is a large body of research and industry data available on AD, including industry statistics and studies by the ADBA, the European Biogas Association (EBA), the IEA (Task 37)[86] (technical studies, country reports and case studies) as well as publications by UK government. As part of this review, there was only a limited search on data directly from industry and individual AD plants, as this would have been very time consuming and we know that often the basis for stating costs is not consistent. AD plants are often quite bespoke and there can be a variety of reasons

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[80] http://www.allison.co.uk/product-guide/biogas-analysers/biogas-scrubbers-technical-review/

[81] Northern Gas Networks Biomethane (2015) A producer's handbook. http://biomethane.northerngasnetworks.co.uk/wp-content/uploads/2015/11/NGN-Biomethane-Full-document-low-res.pdf

[82] REA (2010) CV Enhancement (1). https://www.ofgem.gov.uk/ofgem-publications/47872/rea-ofgem-6-aug-10pdf

[83] CNG Services (2017) UK Biomethane Market. Market Update and the Capacity Question. http://www.cngservices.co.uk/images/BiomethaneDay/2017/John-Baldwin--UK-Biomethane-Market--the-Capacity-Question.pdf

[84] Ecofys (2017) Assessing the potential of CO_2 utilisation in the UK. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/665580/SISUK17099AssessingCO2_utilisationUK_ReportFinal_260517v2.pdf

[85] Ecofys (2013) Potential for biomethane production with carbon dioxide and storage. http://ieaghg.org/docs/General_Docs/Reports/2013-11.pdf

[86] IEA Bioenergy. Task 37: Energy from Biogas. http://task37.ieabioenergy.com/

for individual plants having different costs. The data from the trade association, ADBA, and the government's RHI impact assessment are considered to be representative for the industry.

ADBA publishes annually a detailed review of the UK AD market[87], which is considered to be the most complete evidence source covering market information (dating back to 2012). The 2017 report indicates that a total of 557 plants were in operation in 2016. Of these 466 were generating electricity/CHP, 6 heat and 85 biomethane, with a combined capacity of 491 MW_{el}, 0.1 MW_{th} and 61,320 m^3/hr respectively. The UK market has seen rapid growth in recent years, largely driven by the introduction of the tariffs available under the RHI and FIT. It peaked in 2014/2015 with around 100 plants commissioned, but has since slowed. The ADBA project a further slowdown in the market in the period to 2019 (to around 10-40 plants per year), which is reflected in the reduction in the number of planning applications for new plants.

According to the EBA over 17,000 biogas and 459 biomethane plants were in operation across Europe in 2015, almost 11,000 (60%) of which were located in Germany and a further 1,555 (9%) in Italy[88]. The UK market represented around 3% of the total biogas plants and 6% of the biomethane plants in 2015.

The ADBA estimate that around 38 million tonnes of wet feedstock will be processed through AD plants in 2017/2018, 24 Mt (64%) of which is sewage sludge and a further 6 Mt from liquid effluents from food and drink processing industries (16%). Energy crops (such as maize), food waste and farm waste each represent around 2 Mt (6%) of the total. In the UK, 84% of sewage sludge is now processed through AD plants.

The ADBA estimate that 1 MW_{el} of AD capacity costs £4.3m on average to build and that the average load factor across the industry was 73% in 2016, up from 46% in 2011. The most comprehensive evidence sources for UK cost and operational data for AD and biomethane are considered to be the consultations and impact assessments published by DECC/BEIS in the context of the RHI and FIT (sections **Error! Reference source not found.**, **Error! Reference source not found.**, and **Error! Reference source not found.**). The RHI and FIT tariffs have reduced since the publication of these reports, but this was due to planned degression of the tariffs rather than evidence of cost reductions. The underlying evidence base was not updated by BEIS for the purpose of the tariff degression. We consider the data in these evidence sources to still be largely representative of the current position. Future uncertainties in the data primarily centre on the feedstock cost (i.e. level of gate fees), the potential revenue streams for digestate and the extent to which a market will develop for CO_2.

3.3 Gasification

Thermal gasification is a process whereby a solid feedstock is heated in a reduced concentration atmosphere comprising air, oxygen or steam to produce a synthetic gas (syngas). Gasification is not a new technology and there are many examples of gasifiers operating around the world, but mainly based on the gasification of coal. There are globally only around 100 to 150 biomass and/or waste gasifiers in operation, however only a small subset of these are targeting bioSNG or bioH_2 production.[89]

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[87] ADBA (2017) Anaerobic digestion Market Report 2017. http://adbioresources.org/adba-market-policy-reports

[88] EBA (2016) EBA launches 6th edition of the Statistical Report of the European Biogas Association. http://european-biogas.eu/2016/12/21/eba-launches-6th-edition-of-the-statistical-report-of-the-european-biogas-association/

[89] Global Syngas Technologies Council (no date) The Gasification Industry. http://www.globalsyngas.org/resources/the-gasification-industry

The quality of syngas produced is dependent on the feedstock quality and consistency and the medium in which the feedstock is thermally treated. The synthetic gas produced can be used in a variety of ways to produce heat, power and/or chemicals depending on the downstream processing. It is possible to convert biogenic feedstocks – either clean biomass or wastes – into syngas and subsequently bioSNG or bioH_2 for injection into the gas grid. Although the gasification of biomass to syngas for power and/or heat generation is a proven technology, the further synthesis of syngas into bioSNG or bioH_2 is not. Clean biomass to bioSNG is most advanced at TRL level 7, while waste to bioH_2 is considered to be at TRL level 5.

There are several types of gasifier which can be used for production of syngas from biomass, but only a subset of these are appropriate for integration with a downstream methanation process, which ideally requires: minimal tar production, high methane concentration in the syngas, high H_2:CO ratio, high pressure operation and no nitrogen dilution of the syngas.

A 2016 report by Ecofys for DECC[90] on the use of gasification for industrial decarbonisation provides a recommendation on gasifier suitability per feedstock type. The report recommends **bubbling fluidised bed (BFB)** and **circulating fluidised bed (CFB)** as the most appropriate types of gasifier able to thermally treat most solid biogenic feedstocks. The evidence review therefore focused mainly on studies that used these types of gasifier.

Entrained flow gasifiers can also be considered, especially as they have potentially higher output capability than fluidised bed gasifiers (up to 2 GW_{th} biomass input), however they operate at higher temperatures and are prone to slagging. Entrained flow gasifiers are sensitive to fuel quality and consistency and, due to the short fuel residence times, require small particle sizes to ensure efficient gasification. They have the most stringent fuel parameters of the gasifiers considered in the report, which is challenging when using biomass feedstocks and could reduce feedstock choice, which impacts security of supply, and increases the requirement for feedstock pre-processing which adds cost and GHG emissions. Coal gasification typically uses entrained flow gasification technology.

Fluidised bed gasifiers, as compared to fixed bed and entrained flow gasifiers, are considered most appropriate for larger scale gasification of biomass particularly if pressurised. Fluidised bed gasifiers offer lower temperature operation and are therefore better able to process higher ash materials (e.g. wastes) which may contain alkali metals such as potassium (oxide), and which would otherwise be prone to slagging. They can handle variable particle size, have a greater tolerance of moisture, lower requirement for feedstock pre-processing and offer better possibilities to process blended (heterogeneous) materials. Fluidised bed biomass gasifiers have been built up to around 150 MW_{th} biomass input to-date, and it is likely that pressurised fluidised bed gasifiers would be able to operate up to around 350MW_{th} biomass input.[91]

Pressurisation enables higher feedstock flowrates and larger capacities of gasifier, hence higher gas outputs. However, it also promotes hydrogen production and therefore reduced methane content in the syngas. The constituents of syngas are H_2, CO/CO_2, CH_4 and other trace compounds. More H_2 and CO/CO_2 and reduced CH_4 leads to a higher calorific value gas, but of course the optimal balance of gases depends on the gas output the system is aiming to produce. Equipment costs are a key consideration with a pressurised system as the gasifier,

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[90] Ecofys (2016) DECC Industrial 2050 Roadmaps - The use of gasification for industrial decarbonisation (unpublished). (see section 3.4.3 of the Technical Annex)

[91] E4tech (2009) Review of technologies for gasification of biomass and wastes. http://www.e4tech.com/reports/review-of-technologies-for-gasification-of-biomass-and-wastes/ (see section 3.4.7 of the Technical Annex)

upstream pressurisation and downstream clean up equipment must all be designed to handle syngas at pressure and will be costlier for higher pressure systems.

The main studies identified in the evidence review that cover gasification of biomass to bioSNG or bioH_2 are summarised below. These studies do not constitute all biomass gasification projects and studies embarked upon in the UK, the EU and the US, but they are those that are of the most relevance technically and that provide most detailed cost information. The studies by NREL and ETI are very detailed, and the data from the GoGreenGas consortium (Progressive Energy, Cadent, Advanced Plasma Power) are based on an actual demonstration plant in the UK. Overall the available data on gasification to bioSNG and bioH_2 are good quality and highly relevant, **but the data are based on very few example demonstration scale plants, so appropriate caution should be used when extrapolating the data to estimate costs for a whole potential future industry**.

An important consideration when comparing data reported in the different studies is the assumption on whether syngas produced in the process is used to generate electricity for the process (and whether surplus electricity is exported to the grid), or whether imported grid electricity is used to drive the process. The choice of assumption has a direct impact on the operational efficiency and emissions performance of the process. Specifically, using syngas for electricity generation lowers the overall biomass to bioSNG/bioH_2 production, but improves the GHG emissions performance (particularly if electricity is exported to the grid as this generates a GHG emission “credit”). In contrast, using imported grid electricity results in higher overall bioSNG/bioH_2 production but also results in increased process GHG emissions, although this impact will decrease as the electricity grid decarbonises to 2050.

Furthermore, although most of the studies reviewed (such as ETI’s BVCM model) present data on a Lower Heating Value (LHV) basis for the output gas, the studies published by the GoGreenGas consortium present data on a Higher Heating Value (HHV) basis. The relative difference between the HHV and LHV bioSNG and bioH_2 is around 1.11 and 1.18 respectively[92]. Therefore, data expressed on an HHV basis will show higher process efficiency and lower cost per unit output gas in comparison to LHV data, and this impact is more pronounced for bioH_2 compared to bioSNG.

There is a selection of other publicly available studies on biomass gasification to SNG or H_2, including detailed engineering studies published by the US Government’s National Renewable Energy Laboratory (NREL), however these are not recent (2010 or older). In addition, several other pilot, demonstration and commercial scale plants have been commissioned globally. Cost data is available for some of these plants, although it is often not sufficiently granular or transparent (e.g. costs also include a 5 MW district heating system in the case of the GoBiGas[93] project in Sweden); and in some cases the plants have not yet been built or are no longer operational.

3.3.1 Waste (RDF) gasification to bioSNG

A key message from a recent ETI insights paper on gasification for power production[94] is that waste gasification is more efficient at a “town scale” (<10 MW_{el}). A key benefit is that the waste heat generated can be readily integrated in district heating networks. In addition, waste production is concentrated in conurbations and so developing waste

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[92] The LHVs and HHVs for bioSNG and bioH_2 are 49.9/55.4 GJ/t and 120/141.9 GJ/t respectively.

[93] https://gobigas.goteborgenergi.se/English_version/Start

[94] ETI (2017) Targeting new and cleaner uses for wastes and biomass using gasification. http://www.eti.co.uk/insights/targeting-new-and-cleaner-uses-for-wastes-and-biomass-using-gasification

gasification plants at a town scale makes sense from a feedstock resource perspective. The gate fee currently assumed from wastes is useful to make projects work economically in the short term to get the technology started, although as discussed in section 0, as demand for wastes increases it could be expected that the waste materials command a price rather than companies paying to take the waste away. The short term development of town scale gasification from waste projects could provide a stepping stone to larger scale biomass gasification. Larger projects could also be combined with CCS to achieve negative emissions, which will be needed on a 2050 timescale.

There are two known detailed data sources covering the gasification of waste derived material, both of which relate to the same demonstration project located in Swindon, UK:

- 'BioSNG Demonstration Plant Project Close-Down Report' (GoGreenGas, 2017)[95]
- 'BioSNG: Feasibility Study, Establishment of a Regional Project' (Progressive Energy and CNG Services, 2010)[96]

The 2017 report was produced by the GoGreenGas consortium of partners involving Progressive Energy, Cadent (formerly National Gas Grid Distribution) and Advanced Plasma Power, who have constructed a demonstration plant in the UK that has successfully generated bioSNG from waste in the form of RDF. The plant is based on gasification of mixed wastes using an Outotec oxygen-blown BFB gasifier to produce syngas, and then a plasma torch for gas cleaning. The methanation process uses Amec Foster Wheeler's VESTA technology. The data contained within the 2017 project close-down report is current, supersedes the 2010 report, and is validated by the demonstration plant's construction and operation and represents the best data for a future commercial plant technical and economic performance. However, as this is a first of a kind demonstration plant, it represents just a single data point and as such should be used with appropriate caution (as discussed above).

The study reports CAPEX costs of £107.8m for a 42 MW_{th} capacity "first of a kind plant" (136 kt of RDF fuel input) and £150.7m for a 84 MW_{th} capacity "nth of a kind plant" (both without carbon capture), which represents a 34% decrease on a per MWh basis. Reported OPEX costs are £10.2m/yr and £16.5m/yr respectively, which represents a 24% decrease on a per MWh basis. Around 30% of the OPEX costs relate to power consumption. A plant efficiency of 64% is assumed for both capacities. The plant configuration assumes net electricity import from the grid, along with natural gas use for the preheating of equipment. All data published in the 2017 report are on an HHV basis.

A commercial bioSNG plant in Swindon is currently being developed and constructed by the consortium to process 10,000 tonnes per annum to produce 22 GWh of gas for injection to grid (equivalent to about 2-3 MW_{th}) during 2018 which will provide further insights into the costs, performance and economic viability of producing bioSNG for grid injection.

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[95] GoGreenGas (2015) BioSNG Demonstration Plant. Project Close-Down Report. http://gogreengas.com/wp-content/uploads/2015/11/BioSNG-170223-1-Project-Close-Out-Report.pdf (see section 3.4.1 of the Technical Annex)

[96] Progressive Energy and CNG Services (2010) Bio SNG Feasibility Study. Establishment of a Regional Project. http://www.biogas.org.uk/images/upload/news_7_Bio-SNG-Feasibility-Study.pdf (see section 3.4.6 of the Technical Annex)

3.3.2 Clean biomass gasification to bioSNG

In contrast to the gasification of *waste* to bioSNG, there is no definitive report which covers the gasification of *clean biomass* to bioSNG that is based on the project outcomes of a UK demonstration plant. This evidence review has identified three key reports:

- Biomass Value Chain Model – BVCM (ETI, 2011-2017)[97]
- The potential for bioSNG production in the UK (E4tech, 2010)[98]
- Biomass Gasification Technology Assessment Consolidated Report (NREL, 2012)[99]

ETI's BVCM contains information and data drawn from the second report and includes cost, performance and emissions data for bioSNG, with and without CO_2 capture out to 2050. This data is presented in a consistent format and although slightly old is considered to the best data source available covering the conversion of clean biomass (including clean waste wood) to bioSNG using thermal gasification. Data are based on an indirectly heated duel fluidised bed gasifier type at 60 MW_{th} and 200 MW_{th} capacity.

BVCM assumes that a portion of the syngas is used to generate the process electricity, with surplus electricity exported to grid (for both the with and without CO_2 capture configurations). An additional process output is hot water, although its potential use to provide a heat source will be site specific depending on the heat demand in the local vicinity of the plant. A plant efficiency of 64% in 2010 is assumed rising to 70% in 2050 at 200 MW_{th} capacity, with a 2% reduction in efficiency for the 60 MW_{th} capacity configuration (all date is expressed on a LHV basis). A 4% efficiency penalty is applied for SNG with CO_2 capture. The BVCM model also includes exogenous cost learning rates to 2050[100].

In the usual bioSNG production process, a relatively pure CO_2 stream is produced, which could potentially be captured, compressed and stored with minimal additional processing, achieving negative CO_2 emissions. As the CO_2 must already be separated, little additional technology is required for integration of bioSNG with carbon capture. Carbo et al. estimate that in a bioSNG plant based on indirect gasification, around 20% of the initial carbon is emitted as CO_2 in flue gas, 40% as methane in bioSNG and 40% as a high-purity CO_2 stream that could be captured, compressed and stored[101]. Directly-heated gasifiers, which do not have a separate combustion chamber, do not have a separate flue gas stream. The BVCM model assumes that around 0.2 t CO_2 is sequestered per MWh of bioSNG output.

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[97] Bioenergy Value Chain Model. http://www.eti.co.uk/library/overview-of-the-etis-bioenergy-value-chain-model-bvcm-capabilities (see section 3.2.5 of the Technical Annex)

[98] E4tech (2010) The potential for bioSNG production in the UK, final report http://www.e4tech.com/wp-content/uploads/2016/01/BioSNG-final-report-E4tech-14-06-10.pdf (see section 3.4.5 of the Technical Annex)

[99] NREAL (2012) Biomass Gasification Technology Assessment Consolidated Report. https://www.nrel.gov/docs/fy13osti/57085.pdf (see section 3.4.4 of the Technical Annex)

[100] These are calculated based on the technology TRL, technology category (e.g. gaseous fuel), the project categorisation (e.g. large complex plants vs. modular manufacturing line units) and whether the base costs represent the current costs or nth of kind plants costs. The learning rates can be applied to different technologies.

[101] Carbo et al. (2010), Bio energy with CO_2 capture and storage (BECCS): conversion routes for negative CO_2 emissions. http://tu-freiberg.de/en/fakult4/iec/evt/04-1-bio-energy-with-co2-capture-and-storage-beccs-conversion-routes-for-negative-co

A point to note is that although the 2017 GoGreenGas report deals specifically with the conversion of waste (RDF) to bioSNG, much of the post-gasification data is also relevant to clean biomass gasification to bioSNG, so could potentially be used in conjunction with data from BVCM.

3.3.3 Waste (RDF) gasification to bio-hydrogen

The evidence available covering the production of bioH_2 is limited and restricted to the following two sources:

- Biohydrogen: Production of hydrogen by gasification of waste – An NIA assessment of Biohydrogen production and opportunities for implementation on the gas network (Progressive Energy/Advanced Plasma Power, 2017)[102]
- Biomass Value Chain Model – BVCM (ETI, 2011- 2017)[103]

Importantly a 2017 study has been produced in the UK by the GoGreenGas consortium investigating the practicalities, qualitative, quantitative and cost issues of producing grid quality hydrogen suitable for blending with natural gas and injecting into the gas grid (bullet 1 above). The work is based on the development and operation by GoGreenGas of the demonstration plant in Swindon producing bioSNG from waste.

The waste to bioH_2 plant development and optimisation undertaken by the consortium 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. Performance data in the report is from primary sources and laboratory experiments and validation work on the 50 kW demonstration plant. Budget costs are provided by equipment suppliers. Some data is referenced to the 2017 GoGreenGas bioSNG close down report and gas quality data and GHG emissions are according to referenced calculation methodologies. Appropriate caution should be used when extrapolating the data to estimate costs for a potential future industry as this data is based on one plant.

The study reports a CAPEX cost of £99m for a 48.4 MW_{th} capacity “first of a kind plant” (100 kt of RDF fuel input) and £138.1m for a 96.8 MW_{th} capacity “nth of a kind plant” (both with carbon capture), which represents a 30% decrease on a per MWh basis. CO_2 compression costs are £1.5m to £2.3m, which corresponds to around 1.5% of the total CAPEX costs. Reported OPEX costs are £19m/yr, of which £5.4m relates to CO_2 sequestration and £4.95m for power import. A gate fee for the waste feedstock of £75/t is assumed in the modelling. A plant efficiency of 78% is assumed for both capacities. All data published in the report are on an HHV basis.

There is also data available from the BVCM model, although this specifically focusses on clean (non-waste) biomass based gasification to bioH_2.

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[102] GoGreenGas (2017) Biohydrogen: Production of hydrogen by gasification of waste – An NIA assessment of Biohydrogen production and opportunities for implementation on the gas network. http://gogreengas.com/wp-content/uploads/2015/11/Biohydrogen-Cadent-Project-Report-FINAL-3.pdf (see section 3.4.2 of the Technical Annex)

[103] Bioenergy Value Chain Model. http://www.eti.co.uk/library/overview-of-the-etis-bioenergy-value-chain-model-bvcm-capabilities (see section 3.2.5 of the Technical Annex)

3.3.4 Clean biomass gasification to bio-hydrogen

Evidence covering the use of clean biomass feedstocks to produce bioH2 is provided by three sources, however two of these sources are dated 2005 or older:

- Biomass Value Chain Model – BVCM (ETI, 2011- 2017)[104]
- Biomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly Heated Gasifier (NREL, 2005)[105]
- Techno-Economic Analysis of Hydrogen Production by Gasification of Biomass (US Department Of Energy, 2002)[106]

The NREL report is sufficiently detailed and robust in its analysis, engineering insights and outcomes in assessing the practicalities of converting biomass to hydrogen but much of the data used is modelled, based on a small laboratory scale (9 tonne/day) test facility using oven dried wood chips. The report is now very dated, with CAPEX and OPEX cost data from 2002. Similarly, the US Department of Energy report is considered to be robust, but now also dated. The report furthermore concerns the gasification of bagasse, switchgrass and a nutshell mix (40% almond nutshell, 40% almond prunings and 20% walnut shell), feedstocks that are not directly relevant to the UK.

The ETI's BVCM model contains cost, performance and emissions data for bioH_2 production, with and without CO_2 capture out to 2050. This data is presented in a consistent format and although slightly old is the best data source available covering the bioH_2 production gasification technology. Data is provided at both 50 MW_{th} (CFB gasifier) and 250 MW_{th} (entrained flow) capacities. The BVCM model assumes that a portion of the syngas is used to generate the process electricity. In contrast to clean biomass to bioSNG, the BCVM model assumes no surplus electricity or hot water export. A plant efficiency of 55% in 2010 is assumed rising to 59% in 2050 at 250 MW_{th} capacity, with a 2% reduction in efficiency for the 50 MW_{th} capacity configuration (all data is expressed on a LHV basis).

As with bioSNG production, CO_2 must be removed from the gas streams, meaning that integration with CO_2 capture should only require minimal modifications to the process. The cost of adding a CO_2 compression unit is not significant in terms of the additional CAPEX required, but the additional OPEX can be significant (resulting from increased electricity usage to run the CO_2 compressor) unless it is assumed that a portion of the bioH_2 output is used. BVCM assumes the latter, and applies a 4% efficiency penalty for doing so.

In contrast to bioSNG production, where there are CO_2 emissions at the point of combustion of the bioSNG (in the end application), in bioH_2 production all of the carbon contained in the biomass is released at the production plant, so a much higher percentage of the initial biogenic carbon can be captured and stored. BioH_2 therefore offers significant negative GHG emission potential if combined with CO_2 capture. The BVCM model assumes that around 0.6 t CO_2 is sequestered per MWh of bioH_2 output, compared to only 0.2 t CO_2 for SNG.

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[104] Bioenergy Value Chain Model. http://www.eti.co.uk/library/overview-of-the-etis-bioenergy-value-chain-model-bvcm-capabilities (see section 3.2.5 of the Technical Annex)

[105] NREL (2005) Biomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly Heated Gasifier. https://www.researchgate.net/publication/255200854_Biomass_to_Hydrogen_Production_Detailed_Design_and_Economics_Utilizing_the_Battelle_Columbus_Laboratory_Indirectly-Heated_Gasifier (see section 3.4.9 of the Technical Annex)

[106] DOE (2002) Techno-Economic Analysis of Hydrogen Production by Gasification of Biomass. https://www.osti.gov/servlets/purl/816024

In contrast to AD, the larger scale of biomass gasification plants, and in particular gasification to produce bioH_2 which is producing large volumes of carbon, is likely to lend itself more readily to the practical challenges of CCS, although the costs and logistics of CO_2 compression, transport and sequestration may still be prohibitive. Large scale gasification plants located near CCS hubs, located near to ports to receive biomass imports, would be a logical starting point for gasification with CCS.

4 GHG emission evidence sources

Summary

All supply chains in the scope of this review could offer significant GHG abatement potential when following the GHG methodology implemented in the RO and RHI. When used in combination with carbon capture, the conversion technologies could lead to significant negative emissions (i.e. net removals), but this relies on carbon sequestration to be implemented in the UK.

The EU Renewable Energy Directive 2009/28/EC (RED) provides a good basis for calculating direct supply chain GHG emissions for solid and gaseous biomass pathways. The RED (and the underpinning technical reports prepared by the JRC), along with the UK Solid and Gaseous Biomass Carbon Calculator (B2C2) provide good evidence on typical direct supply chains emissions in the UK/EU context and based on input from stakeholders. However, these evidence sources do not represent the potential range of input data seen in actual supply chains, and the impact this has on the variability in typical GHG emissions. This aspect was not explicitly reviewed as part of this study, but could represent significant increase or decrease in the GHG emissions estimates. Furthermore, how GHG emissions may develop into the future, or how grid decarbonisation might impact supply chains and processing choices was also not assessed.

Another important dimension is how GHG emissions will develop into the future as more feedstock is sourced, particularly for imports. For example, using marginal land may lead to more fertiliser application (if the land is of poor quality) or accessing further afield or harder to reach feedstocks may result in higher transport or energy requirements, and resulting GHG emissions. Alternatively, some land use change could result in a carbon sequestration through a net build-up of carbon stocks above or below ground. The evidence review did not focus on these aspects because there is limited literature available. Neither was the evidence review able to identify literature on how innovation may impact GHG emissions, beyond efficiency improvements.

In terms of indirect effects, this is an area of ongoing research, however the latest EC research shows that solid and gaseous biomass have lower indirect effects than annual crops and indirect effects could even be positive for perennial energy crops and short rotation plantations.

A key uncertainty for gaseous biomass supply chains is the level of methane leakage in AD plants. GHG emissions in biogas operation can be significantly reduced by taking measures such as application of a gas tight cover of digestate tank, frequent maintenance of the gas engine and monitoring of methane concentrations in the exhaust.

The EU Renewable Energy Directive 2009/28/EC (RED) includes a methodology for the calculation of GHG emissions for biofuels. The European Commission report, SEC(2010) 65 final[107], includes additional information relevant to solid and gaseous biomass – which is the subject of this review – as well as "default" GHG intensities[108] for a number of pathways[109]. A further update to the methodology and default values was put forward by the Commission in Staff Working Document SWD(2014)259[110], based on technical input provided by the Joint Research Council (JRC). The Commission's legislative proposal for a recast of the RED (RED II, COM(2016) 767[111]) proposes to formalise this methodology in mandatory criteria that would apply for solid and gaseous biomass used within the EU from 2021. The Renewables Obligation (RO) and Renewable Heat Incentive (RHI) schemes have implemented the methodology included in SEC(2010) 65 final, but not the 2014 update. For biomass fuels to receive support under the RO or RHI, they must demonstrate at least a 66%/60% GHG saving compared to fossil fuel respectively, using the 2010 methodology.

GHG emissions from the whole fuel chain are included in the RED methodology, from the cultivation (including any emissions from direct land-use change) or production of the feedstock, through any processing and transport steps to the use of the fuel. GHG emission "credits" for improved agricultural management (such as the use of manure in AD[112]), CCS and CCU can be taken into account. Any emissions from direct land use change are taken into account in the RED methodology. Indirect emissions from indirect effects, such as substitution effects and indirect land use change (ILUC), are not included in the RED or RED II GHG methodology. Indirect emissions can be significant, although the 2015 GLOBIOM study for the EC showed that the modelled indirect emissions from typical solid and gaseous biomass supply chains were much lower than starch and oil crops typically used for biofuels, and in the case of perennial energy crops and SRC and forestry the indirect emissions could even lead to a net decrease in emissions.[113]

Several reports and GHG calculator tools are available that implement the RED GHG methodology and also include standard assumptions and input values. The **UK Solid and Gaseous Biomass Carbon Calculator (B2C2)**[114] is a GHG emissions calculator tool that was developed to assist companies and individuals to calculate the GHG intensity of their actual solid or gaseous biomass fuel chain for use in sustainability reporting under the RO and RHI schemes. The B2C2 tool includes a number of default value pathways that can be loaded and adapted to fit the

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[107] EC (2010) SEC(2010) 65 final. COMMISSION STAFF WORKING DOCUMENT IMPACT ASSESSMENT. Accompanying document to the Report from the Commission to the Council and the European Parliament on sustainability requirements for the use of solid and gaseous biomass sources in electricity, heating and cooling. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=SEC:2010:0065:FIN:EN:PDF

[108] "Default values" are conservative GHG intensities for common bioenergy pathways that companies can use to report to Member States. Alternatively, companies can report "actual values" which reflect the actual GHG intensity of their pathway.

[109] Specifically: Biogas from dry/wet manure, Biogas from wheat and straw (wheat whole plant), Biogas from maize as whole plant (maize as main crop) and Biogas from maize as whole plant (maize as main crop) – organic agriculture.

[110] EC (2014) SWD(2014) 259 final. COMMISSION STAFF WORKING DOCUMENT State of play on the sustainability of solid and gaseous biomass used for electricity, heating and cooling in the EU. https://ec.europa.eu/energy/sites/ener/files/2014_biomass_state_of_play_.pdf

[111] EC (2016) COM(2016) 767 final/2. ANNEXES to the Proposal for a Directive of the European Parliament and the Council on the promotion of the use of energy from renewable sources (recast). https://ec.europa.eu/energy/sites/ener/files/documents/1_en_annexe_proposition_part1_v6_0.pdf

[112] A credit of -45 gCO_{2eq}./MJ manure used is available.

[113] In the context of feedstocks suitable for solid and gaseous biomass, the GLOBIOM study modelled cereal straw, forestry residues, perennial energy crops, short rotation plantations and maize silage: Ecofys et al. (2015) The land use change impact of biofuels consumed in the EU. https://ec.europa.eu/energy/sites/ener/files/documents/Final%20Report_GLOBIOM_publication.pdf

[114] The UK Solid and Gaseous Biomass Carbon Calculator. https://www.ofgem.gov.uk/publications-and-updates/uk-solid-and-gaseous-biomass-carbon-calculator (see section 4.1.2 of the Technical Annex)

company's actual biomass supply chain(s). 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, and therefore represents a reliable data source for typical GHG intensities of UK-specific bioenergy pathways. The tool was developed by E4tech. Project partners were DECC, the UK Environment Agency and NNFCC.

An additional key data source is the "**Solid and gaseous bioenergy pathways: input values and GHG emissions report**" published by the JRC[115]. JRC prepared the work on behalf of the European Commission's Directorate-General for Energy (DG Energy) to update the list of pathways (and input values) published in SEC(2010) 65 final, to account for the scientific, technological and economic developments in the solid and gaseous bioenergy sector. The updated default values are included in the SWD(2014) 259. The input values were calculated after consultation with technical experts and various stakeholders at two stakeholder workshops. Detailed questions and comments from stakeholders along with JRC's responses are included in Annexes 2 and 3 of this document. An updated report was published by the JRC in November 2017[116], which served as input for the Commission's draft RED II proposal (COM(2016) 767).

The **BioGrace II** GHG calculation Excel tool[117] applies the input data and pathways for a selection of pathways included in the JRC report (specifically those included in the SWD(2014) 259). As with the B2C2, the input data can be adapted by companies with more specific actual data and used by companies to calculate the GHG intensity of their specific biomass pathways.

Collectively, these sources are considered to represent the best starting point for available evidence on typical direct supply chain GHG emissions for solid and gaseous biomass pathways following the RED methodology. They consider a wide range of feedstock sources and data sources, have been peer reviewed and scrutinised by all Member States and furthermore apply an internationally recognised methodology in a consistent manner. These sources do not, however, present the potential range in GHG emissions across specific supply chains. Additional sources provide more specific technology data. In particular, the GoGreenGas consortium reports provide detailed input data for bioSNG and bioH_2 respectively (see below).

The supply chain GHG emissions from different routes to biomass derived heat or gases differ significantly depending on the biomass type and the level of processing that is applied. For example, in the case of woody biomass fuels the calculated emissions will vary, for example, according to how far the biomass is transported and by what mode of transport and whether the biomass is in chip or pellet form.

Many of the feedstocks included in this review are waste or residue materials (e.g. tree tops and branches, straw, manure, food waste, MSW). The RED methodology assumes that wastes and residues have zero life-cycle GHG emissions up to the process of their collection. This means that emissions from the collection and any subsequent processing of the waste or residue need to be included, but not emissions for the production of the material in the

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[115] JRC (2015) Solid and gaseous bioenergy pathways: input values and GHG emissions. Calculated according to the methodology set in COM(2010) 11 and SWD(2014) 259. https://ec.europa.eu/energy/sites/ener/files/documents/Solid%20and%20gaseous%20bioenergy%20pathways.pdf (see section 4.1.3 of the Technical Annex)

[116] JRC (2017) Solid and gaseous bioenergy pathways: input values and GHG emissions: Calculated according to methodology set in COM(2016) 767: Version 2. 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 (see section 4.1.3 of the Technical Annex)

[117] http://www.biograce.net/biograce2/

first place (as those emissions are allocated to the main product – e.g. the timber, the grain, or the food before it became a waste). As wastes and residues are considered to have zero emissions, such fuel chains tend to offer high GHG savings. For example, according to the B2C2 carbon calculator UK forestry residue wood chips and UK straw bales can achieve over 90% GHG emission savings compared to fossil fuels[118].

Energy crops do have emissions associated with their cultivation, but these are generally low compared to annual crops as energy crops have relatively low input requirements, such as fertiliser. For example, according to the B2C2 carbon calculator the combined N, P, K fertiliser input for Miscanthus is less than 20 kg/ha and just 8 kg/ha, compared to over 100 kg/ha for maize. Furthermore, perennial energy crops have higher above and below ground carbon stocks compared to annual crops, so a change from cropland to perennial crop land results in an increase in carbon stored over their lifetime. The (original) RED took this account in the calculation of GHG emissions from carbon stock change due to land-use change calculation, but the 2015 amending ILUC Directive now considers cropland and perennial crop land to be one land category for the purposes of the calculation. If the ILUC Directive is fully implemented then this may underestimate the potential GHG benefits.

Pre-processing of feedstocks, such as pelletising, can add to the GHG intensity of the fuel, but not if biomass is used as the drying or processing fuel as this is considered to be carbon neutral. However if fossil fuels are used in such plants this can significantly add to the GHG intensity. For example, according to the RED II typical values, UK forestry residues wood pellets achieve 92% GHG emission savings if a CHP run on wood chips provides both process heat and electricity to the pellet mill. This drops to a 57% saving if a natural gas boiler is deployed and electricity is imported from the grid. Pelletising is, however, considered a necessary step if feedstocks are going to be transported a long distance as it improves the energy density and the handling properties and therefore also reduces the GHG emissions from transporting the feedstock.

Long distance transport also clearly adds to the GHG intensity of a biomass fuel, but sea transport has relatively low emissions per tonne kilometre (0.07 MJ/t.km for a “Supramax" bulk carrier running on fuel oil transporting pellets). In contrast, long distance road transport quickly adds to the GHG intensity of a fuel as the emissions per tonne kilometre are high (0.88 MJ/t.km for a 40 tonne truck running on diesel transporting pellets); this is an important consideration for biomass supply chains to ensure that the GHG intensity limits are met.[119]

The RED II typical values indicate that the GHG emissions for gaseous biomass can vary across a wide range. Key factors that influence the emissions performance include: feedstock type (e.g. waste feedstock such as manure vs. crop), whether digestate is stored in an “open” or “closed” (i.e. gas tight) system[120], whether a CHP or boiler is utilised to provide process heat and electricity and for biomethane whether “off-gases” are combusted. The typical GHG emission savings for electricity production range from 246% savings for manure using a closed system (heat and electricity are supply via a CHP) to just 28% for maize using an open system (electricity required in the process is taken from the grid and the process heat is supplied by a biogas boiler).

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[118] Assuming 85% conversion efficiency to heat and a fossil fuel comparator for heat of 80 gCO_2 /MJ heat. The supply chain emissions are 2.2 and 5.1 g CO_2/MJ fuel for wood chips and straw respectively.

[119] The fuel efficiencies are taken from BioGrace II GHG calculation Excel tool. See “Standard values” worksheet.

[120] Open storage of digestate accounts for additional emissions of methane and N_2O following the AD process. The additional biogas released during closed storage is considered to be recovered for production of additional electricity or biomethane.

A recent study published by the **IEA Task 37 on “Methane emissions from biogas plants”**[121] cited a number of factors that can have a significant impact on the GHG emission balance. (The global warming potential of methane is considered to be around 25 times that of CO_2 and consequently methane emissions can greatly impact the overall performance of gaseous biomass supply chains.[122]) These are characterised by structural (the technologies deployed) and operational (plant management) factors. The most relevant ones include: open storage or composting of the digestate; the CHP engine; leaks; and the pressure release valve. The report indicates that the results available show a large variability in the level of emissions and that it is very difficult to give typical numbers for emissions from components or complete biogas plants. There is insufficient data for a general assessment of the sector, but trends indicate which components should be monitored and which measures are useful to minimise the amount of released methane. GHG emissions in biogas operation can be significantly reduced by taking measures such as application of a gas tight cover of digestate tank, frequent maintenance of the gas engine and monitoring of methane concentrations in the exhaust.

The gasification process can add directly to the GHG intensity, but this is dependent on whether it is assumed that a portion of the gas output is used to run the process after initial start-up, or if imported natural gas or electricity is instead used. ETI’s BVCM model assumes the former, while the GoGreenGas consortium studies assume the latter. Use of the gas produced decreases the overall gas output of the process, but does not lead to additional GHG emissions arising from the fuel or electricity use. The impact of using grid electricity as a process fuel will decrease in the longer term, as the UK electricity grid decarbonises and consequently has less impact on the GHG intensity. GoGreenGas assumes a UK grid intensity of 204.5 $kgCO_{2eq}$/MWhe and 174 $kgCO_{2eq}$/kWh for bioSNG and $bioH_2$ respectively (average of carbon intensities given in National Grid’s 2016 Future Energy Scenarios). It should be noted that these factors are significantly lower than the current UK electricity grid emission factor of 412 $kgCO_{2eq}$/kWh[123].

The addition of carbon capture to biomass supply chains can even lead to significant <u>negative</u> GHG emissions as long as the carbon is sequestered. $BioH_2$ can offer most significant GHG abatement potential if combined with carbon capture and sequestration because all the carbon from within the biomass is removed to make hydrogen. The GoGreenGas consortium estimates that $bioH_2$ production results in GHG emissions of 46 $kgCO_{2eq}$/MWh $bioH_2$ without carbon capture and a net GHG emission removal of 322 $kgCO_{2eq}$/MWh $bioH_2$ with carbon capture (resulting in GHG emission savings of 81% and 232% respectively against natural gas (using an average EU grid mix value of 243 $kgCO_{2eq}$/MWh). These compare with figures for bioSNG of 48 $kgCO_{2eq}$/MWh GHG emissions without carbon capture (80%)

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[121] IEA Bioenergy Task 37 (2017) Methane emissions from biogas plants. Methods for measurement, results and effect on greenhouse gas balance of electricity produced. http://task37.ieabioenergy.com/files/daten-redaktion/download/Technical%20Brochures/Methane%20Emission_web_end.pdf

[122] Note that the science around global warming potentials is constantly evolving. It is possible that the GWP of methane may be further increased to 28 times that of CO_2,

[123] https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2016

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