Biomass for energy

A framework for assessing the role of domestic feedstocks in the UK's energy transition.

Technical report to support summary document.

Final

May 2022

Executive summary

A shifting energy and climate context

- Global, national, and corporate emissions targets have undergone a revolution since 201 - with a deeper understanding by business and policy makers of the need for rapid and deep decarbonisation by 2050.
- Negative emissions and associated technologies, such as Bioenergy Carbon Capture and Storage (BECCS) have become integral to many climate models. If carbon capture and storage (CCS) becomes operational at scale, then this presents a potential new argument for the expansion of bioenergy crops.
- There has been a significant fall in the cost of non-biomass renewable technologies and the emergence of battery technologies. Biomass costs have not fallen.
- Land-intensive bioenergy systems face a significant risk of being seen as a ’legacy’ fuel by 2050 – and so it will be critical to avoid physical, institutional, and behavioural lock-in when setting biomass policies in the 2020s.
- The concept of the ‘circular economy’ and increasing demand for biomaterials is ratcheting up demand for biomass resources and further challenging the idea that valuable resources should be burnt for energy. The quantity of bioenergy will depend, in the end, on the priority given to bioenergy products versus other products obtained from these finite resources.
- Increasing pressures on land have led to calls for a more strategic approach to land use recognising that we must ensure that food, climate mitigation, nature – and other requirements – are met sustainably.
- Finally, with Russia’s invasion of Ukraine and the associated focus on energy security and independence, there is a need to objectively examine how different types of biomass feedstock can support - or potentially hinder - energy security.

Bioenergy use in the UK

- Renewable energy has gained significant traction in recent years with some record outputs and significant milestones passed.
- Except for landfill gas, energy supply from most bioenergy sources has grown significantly since 2010 - with the largest upturn apparent from plant biomass (imported and domestic).
- Bioenergy and waste make up 11% of the total UK primary energy supply, and are the largest source of renewable power after wind.
- Solid biomass contributed 33% of total renewable demand, with approximately two thirds being used in electricity generation and the remaining to produce heat.
- Approximately a third of existing bioenergy feedstock/fuel demand (across the power, heat, and transport sectors) comes from imports.

Future biomass availability

- New research on the technical, constrained, and sustainable potential of biomass energy supply in the UK, Europe and globally has been undertaken in recent years by researchers, industry, and NGOs.
- These studies tend to see static or reducing supply in the most sustainable sources of biomass (i.e., residues and waste) over next 30 years due to increase in competing uses, policy pressures to support the circular economy and reduce waste.
- The greatest differences between models are the extent to which energy crops (e.g., short rotation coppice) and stemwood are used.
- The degree to which non-energy sectors compete with energy for use of bio-resources has increasingly been included in modelling. Historically this has been overlooked. These competing uses further constrain the quantity of resource available for the energy system.
- The models with most significant sustainability constraints assume stemwood and energy crops are limited in use and only on degraded/marginal land.
- There is reasonably good alignment between studies in levels of waste and residues (lower risk) feedstocks which are likely to be available in coming decades. Based on data reported in these studies, we estimate this to be between 0.35 and 0.40 exajoules of primary energy in 2050 (c. 4% of primary energy demand).
- Whilst the extent to which usage of 'lower risk' feedstocks might align on models, other models (for example the Climate Change Committee) continue to recommend 'higher risk' feedstocks (for example dedicated energy crops).

Challenges in defining bioenergy sustainability

- Bioenergy systems have well documented potential for both positive and negative social, economic, and environmental impacts. These include greenhouse gas emissions, water, biodiversity, and wider resource competition with other sectors.
- Defining 'sustainability' of feedstocks is extremely challenging due to differences in the chosen impact weighting of some issues, or different assumptions on life cycle impacts, future economic trends and agricultural productivity.
- We identify four aspects of biomass systems and sustainability assessment approaches that contribute to significant uncertainty: Land use thresholds and constraints; Unintended consequences and system complexity; Carbon neutrality and biogenic carbon accounting; Rapidly changing socio-economic context.
- To deal with these challenges we propose the establishment of clear quota or land budget for the most land-intensive bioenergy sources. This is the only way to ensure that bioenergy – or indeed bioenergy carbon capture and storage – does not transgress ecological limits.

Framework for assessing biomass sustainability and implementing controls

- Rather than relying on a 'preference' expressed via hierarchy or by using a limited number of indicators to assess sustainability we propose the development of a framework that assesses biomass sustainability risk across all feedstock types and then uses the results of this assessment to implement differential controls for each feedstock.

- The framework encourages feedstocks that: have low land competition risk; have low resource competition risk with other sectors; deliver additional sustainability benefits (or avoids other sustainability risks); deliver high climate mitigation effectiveness over a short time horizon.
- The application of this scoring approach resulted in a range of biomass feedstock sustainability risk scores – from low to very high. The lowest risk feedstocks were landfill gas and renewable fractions of waste. The highest risk feedstocks were stemwood combustion and biomass from crops.
- Managing an appropriate level of adoption for land-intensive bioenergy will require an unusual mix of policies and incentives that encourage appropriate utilisation in the short term but minimise lock-in in the longer term.
- We recommend using a framework such as the one presented in this section to enable differentiated controls on feedstocks that present different sustainability risks. Each of these will call for different types of general and feedstock-specific policy responses: feedstock use quotas; production standards; increased transparency/due diligence; and carbon intensity performance thresholds.

Exploring UK-level scenarios based on sustainability risk

- Based on the feedstock scores developed, and availability data from the BEIS UK and Global Bioenergy Resource Model, it was possible to explore the likely availability of feedstocks of different risk levels.
- UK availability of biomass of low or moderate risk is relatively stable over the period (c. 0.27EJ in 2030 and 0.29EJ in 2050).
- We found a reasonably good alignment with other data sources reviewed both in terms of overall scale of low/moderate risk resource.
- Overall, these models show that low or medium risk domestic biomass could supply c. 4% of primary energy supply – just above the levels currently supplied by all biomass. Current dominant projections utilised by policymakers (for example from the Climate Change Committee and the UK's Net Zero Strategy) include a significant quantity of high-risk feedstocks.

Recommendations

Based on the research and analysis summarised in this report we recommend the following are addressed within the forthcoming Biomass Strategy:

- The upcoming Biomass Strategy should seek to develop a risk-based assessment framework similar to the one explored in this report. It should be an approach that 1) can be applied to all feedstock categories consistently 2) consider a broad set of sustainability risks – in particular land use and resource competition; and 3) identify higher risk feedstocks that should have greater controls applied to them. Although environmental risks were the focus of this project, any framework should also consider social risks.

- For lower risk feedstocks, further analysis is required to identify mechanisms to encourage sustainable supply, where barriers exist (for example to incentivise the supply of arisings from genuine conservation management).
- For the highest risk feedstocks, explicit quotas or budgets should be established for the UK and devolved regions, ensuring alignment with a broader UK or devolved administration land use strategy. A precautionary principle should be taken with these feedstocks, and regulation should ensure supply should not be incentivised beyond these limits.
- It is also important that the complete accounting of GHG implications of biomass is taken into account when assessing biomass sustainability – including full accounting of biogenic emissions. Overall, sustainable biomass should deliver energy in line with carbon intensities that are aligned to 1.5°C emissions pathways for the energy sector with a short “carbon payback period”. Full accounting of greenhouse gases should largely prevent the use of stemwood to be used for bioenergy.
- Given the variability in biomass feedstocks and sustainability, the Biomass Strategy should establish – or seek to establish - a transparent, complete, and consistent set of feedstock categories with clear definitions. This would ensure a more consistent and coherent approach to feedstock assessment and use. The categorisation of feedstocks should be sufficiently granular to enable differentiation on the basis of key sustainability criteria.
- Given biomass sustainability is influenced by broader economic and technological contexts, any assessment of feedstock sustainability needs to be reviewed regularly (for example every 3-5 years).
- Given the radically different political and market context, the Biomass Strategy should also explore the potential of different biomass sources to deliver energy security and independence, reducing reliance on imports and our overseas footprint. We expect biomass systems that are highly dependent on imported raw materials unlikely to deliver significant energy security dividends at the scales they are used, as well as posing significant challenges to sustainability monitoring.
- Significant users of biomass should be required to report in detail on the precise nature of biomass being used, with greater chain-of-custody and transparency for feedstocks. Learnings from ‘due diligence’ requirements on deforestation within the UK Environment Act 2021 should be drawn upon to develop strong requirements on due diligence of biomass feedstocks, so as to reduce risks identified in this report.
- The government should seek to incentivise energy demand reduction as a priority, alongside innovation and research into new technologies that compete against biomass (e.g., heating and energy storage). Low carbon, sustainable negative emissions technologies should also be incentivised to avoid BECCS overreliance (e.g., Direct Air Capture).

Contents

1 Introduction

1.1 Bioenergy definition and use

Bioenergy is energy produced from renewable, biological sources (such as biomass). It covers a range of traditional and modern technologies including liquid biofuels for transport, anaerobic digestion and combustion of wood fuel.[1]

Globally, approximately three-quarters of renewable energy use involves bioenergy, including a significant amount of traditional biomass use, such as the combustion of wood and manures.[2] Bioenergy and wastes make up 11% of the total UK primary energy supply and are the largest source of renewable power after wind generation. Approximately a third of total bioenergy feedstock and fuel supply is imported.[3]

In recent years demand for biomass has increased across Europe, where biomass power generation has increased five-fold and the use of biofuels in transport 25-fold since 2000.[4] These trends have been in response to policies that have incentivised biomass and waste combustion and anaerobic digestion – such as the Renewables Obligation and Renewable Heat Incentive.

This document focuses on domestic biomass feedstocks described at the end of this section.

1.2 Biomass use

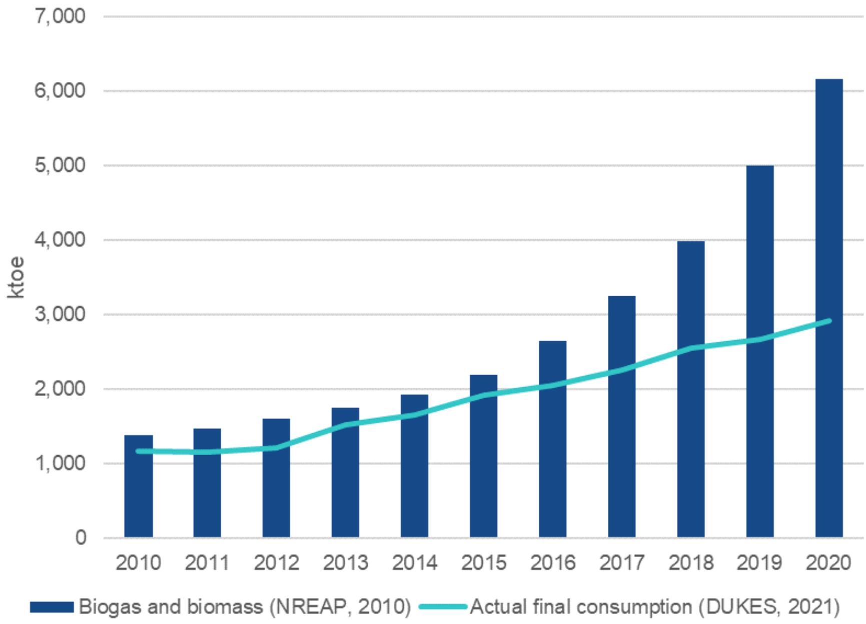
Between 2010 and 2020, the quantity of primary energy supplied from biomass in the UK increased by less than was anticipated in the UK's Renewable Energy Action Plan published in 2010 (see

[1] IRENA (2022) Bioenergy Data https://www.irena.org/bioenergy
[2] IRENA (2022) Bioenergy Data https://www.irena.org/bioenergy
[3] BEIS (2022) Digest of UK Energy Statistics 2021
[4] Material Economics (2021), EU Biomass Use in a Net-Zero Economy - A Course Correction for EU Biomass.

Figure 1 below). Actual biomass energy supply in 2020 was also below levels that the 2012 Biomass Strategy concluded would be available (8% and 11% of primary energy respectively). This is likely due to biomass's relative risks and costs compared to competing technologies – a topic that is explored in the next section.

The most notable change in biomass supply over the past 10 years has been a significant increase in imported plant biomass for use in power generation and increases in energy from waste and animal biomass.

Figure 1: UK REAP vs. actual biogas and biomass final consumption, 2010-2020[5]



1.3 Bioenergy sustainability

The environmental and social impacts of different bioenergy technologies have been the subject of much debate and research over the past two decades.[6,7,8,9] These include:

- Greenhouse gas emissions - including direct and indirect land-use change impacts.
- Competition with other sectors and uses (e.g., food, biomaterials) - with implications for food prices, food security, and delivery of the wider bioeconomy.
- Other environmental impacts of production (e.g., biodiversity, water, and air quality).

Defining the sustainability of bioenergy feedstocks has remained challenging due to the inherent complexity and uncertainties of the socio-ecological systems involved, and differences in the methodologies used to assess sustainability impacts, trade-offs, and thresholds.[10, 11] As a result, published estimates of the scale of 'sustainable' biomass available differ widely.[12] The reality is that these uncertainties place limitations on how

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[5] Based on UK data downloaded from EU JRC "NREAPs and progress reports Data Portal" - and DUKES 2021 Final consumption figures for Renewables and Waste commodity balances. Assumes biodegradable fraction of waste is 62.5%.

[6] Jeswani Harish K. Chilvers Andrew and Azapagic Adisa (2020) Environmental sustainability of biofuels: a review Proc. R. Soc. A

[7] Food and Agriculture Organization (2013) Biofuels and the sustainability challenge: a global assessment of sustainability issues, trends and policies for biofuels and related feedstocks. Rome, Italy: Food and Agriculture Organization of the United Nations

[8] Calvin, K., Cowie, A., Berndes, G., Arneth, A., Cherubini, F., Portugal-Pereira, J., Grassi, G., House, J., Johnson, F. X., Popp, A., Rounsevell, M., Slade, R., & Smith, P. (2021). Bioenergy for climate change mitigation: Scale and sustainability. GCB Bioenergy, 13, 1346– 1371.

[9] Humpenöder F et al (2018) Large-scale bioenergy production: how to resolve sustainability trade-offs? Environmental Research Letters, Volume 13, Number 2

[10] Energy Transitions Commission (2021) Bioresources within a Net-Zero Emissions Economy – Making a Sustainable Approach Possible

[11] Wang J et al (2018) Sustainability Assessment of Bioenergy from a Global Perspective: A Review

[12] Energy Transitions Commission (2021) Bioresources within a Net-Zero Emissions Economy – Making a Sustainable Approach Possible

precise we can be about the availability of biomass and land resources – or pinpoint when detrimental impacts outweigh benefits.[13,14] Any framework for assessing and managing biomass sustainability at a national level needs to be able to work within this context.

We have identified four aspects of bioenergy systems and sustainability assessment approaches that contribute to significant uncertainty. These are the focus of this report:

- Land use thresholds and constraints
- Carbon neutrality and biogenic carbon accounting
- Unintended consequences and system complexity
- Rapidly changing socio-economic context and technologies

1.4 Research context

In 2022 the UK Government intends to publish a Biomass Strategy that will set out in detail how it believes biomass can best contribute towards net zero across the economy. It will outline the policies needed to deploy biomass in the priority areas for net zero, alongside the frameworks to support these policies, such as sustainable supply of resources, air quality requirements, and greenhouse gas accounting.

This Biomass Strategy development comes at a time when new and urgent concerns are being raised over the UK's energy security and as a 'cost of living' crisis emerges, due to energy and food price inflation. Energy policy was evolving at pace during the final stages of this research as a result of the impacts of Russia's invasion of Ukraine. The recommendations therefore take into account this new operating context.

1.5 Research objectives & scope

The goal of this research was to build on work commissioned by the RSPB in 2011 to assess the availability of sustainable domestic biomass (see box below).[15] This has been done by examining new data and research on domestic availability of biomass and by refining the "environmentally responsible biomass hierarchy" framework proposed in the original report. The evolved approach needed to consider a range of sustainability definitions and criteria that would properly reflect the complexity of issues that affect the use of biomass for energy. Finally, the research needed to identify policy recommendations that would incentivise or restrict domestic feedstock supply to align with the sustainability criteria.

It is important to note that, like the original IEEP report, this new research only focuses on bioenergy produced from UK sourced biomass. It also concentrates on solid and gaseous biomass and not on liquid biofuels (see feedstock categories in Table 1 below). The rationale behind looking purely at domestic potential of biomass stems from the evidence that international supply chains are frequently less transparent and so harder to safeguard from a

[13] Calvin K et al (2021) Bioenergy for climate change mitigation: Scale and sustainability
[14] Energy Transitions Commission (2021) Bioresources within a Net-Zero Emissions Economy – Making a Sustainable Approach Possible
[15] IEEP (2011) Securing Biomass for Energy - Developing an environmentally responsible industry for the UK now and into the future

sustainability perspective.[16] The exploitation of domestic bioenergy sources, by contrast, has the merit that their environmental impacts are more readily observed, better understood, and more easily regulated.

Table 1: Feedstock names and descriptions grouped under the term 'biomass' in this project

Feedstock	Description
Landfill gas	Gas that is produced under anaerobic conditions in a landfill
Renewable fraction of wastes	The fraction of energy produced from waste incineration that can be classed as renewable (organic element).
Biogas from food waste	Food that was originally meant for human consumption but for various reasons is removed from the human food chain.
Arboricultural arisings	The cut wood left after tree surgery that may either be removed, burnt, or left on the site chipped, logged for firewood. Typically subcategorised as either 'green', 'brash' or 'heavy timber/round wood'. Covers conservation-management related arisings, including reeds/rush. This is a very diverse category and so may warrant further sub-categorisation in policymaking, to ensure definitions reflect comparable materials (for example roundwood will have different climate profile to rush).
Sawmill co-products	Sawmills recover ~50% of the input material as sawn product, with the balance being coproduct in the form of bark, sawdust, and woodchip.
Marine resources	Macro-algae could also be used in anaerobic digestion plants to produce biogas for combustion or production of biomethane
Waste wood	Wood, which is not virgin timber (that is, wood that has already been used for another purpose) and associated residues such as off-cuts.
Biogas from sewage sludge	Sewage sludge is a semi-solid residue, or by-product, arising from the treatment of municipal wastewater.
Forestry residues	Forestry residues are a by-product from forest harvesting- consisting of branches, leaves, bark, and other portions of wood. We have not included whole tree thinnings in this category (see notes below in Stemwood section).
Dry agricultural residue	Crop residues left in an agricultural field after the crop has been harvested. These residues include stalks and stubble, leaves and seed pods - mainly wheat straw in UK.
Biogas from livestock manures	Organic matter, mostly derived from animal faeces and urine, but normally also blended with plant material (often straw). Often collected from animal bedding/housing that has absorbed the faeces and urine. Can be in a solid or liquid form.
Short rotation forestry	Short rotation forestry (SRF) consists of planting a site and then felling the trees when they have reached a size of typically 10-20 cm diameter at breast height. Depending on tree species this usually takes between 8 and 20 years.
UK perennial energy crops	Crops which are grown for combustion. Short Rotation Coppice (SRC) species such as willow and poplar to 'grassy' energy crops such as Miscanthus.
Stemwood	The wood of the stem(s) of a tree, i.e., the above ground main growing shoot(s). Stemwood includes wood in main axes and in major branches of a given diameter and length. To be conservative we have included whole tree thinnings in the 'Stemwood' rather than 'Forestry residues' category. While thinning can be beneficial for biodiversity and be an inevitable, low value co-product of a well-managed forest system, there is some evidence that bioenergy demand can stimulate excessive thinning with no climate change benefit[17]. The definitions and requirements set for forestry residues and thinnings require particular attention in any framework for assessing sustainability of feedstocks
Biogas from crops	A plant grown for use in the generation of energy or the production of fuels such as bioethanol.

[16] Blair J et al (2021) Contribution of Biomass Supply Chains for Bioenergy to Sustainable Development Goals
17 Buchholz, T et al (2021) When Biomass Electricity Demand Prompts Thinnings in Southern US Pine Plantations: A Forest Sector Greenhouse Gas Emissions Case Study. Frontiers in Forests and Global Change. Vol 4; Brack D. et al (2021) Greenhouse gas emissions from burning US-sourced woody biomass in the EU and UK

Box: IEEP "Securing Biomass for Energy" report for RSPB

The original IEEP report was produced in the context of a potential expansion of the bioenergy sector. The UK Energy Roadmap (2011) and a forthcoming Bioenergy Strategy imminent from DECC would highlight the significant role of bioenergy and specifically biomass in meeting the UK's low carbon objectives.

One of the nearer term goals that would have an influence on the uptake of bioenergy sources was the introduction of the Renewable Energy Directive that required an increase in share of renewable energy in national supplies from 3.3% in 2010 to the target of 15% in 2020. At the time of the IEEP report the expectation was that the UK Government's plans translated into a more than three-fold increase in bioenergy supply between 2010 and 2020 implying that bioenergy would contribute around 50% to the UK renewable energy. Furthermore, it was anticipated that of the total bioenergy supply in 2020, imports would account for around 40%.

The IEEP report proposed a sustainability hierarchy to guide the approach for exploiting the UK's domestic bioenergy resource. They adopted a modified version of a hierarchy previously developed by Gove et al[18] as the main approach to assessing the environmental benefits of the different bioenergy resources and determining the extent to which various resources could be utilised. The hierarchy order of preference was:

1 Genuinely residual wastes
2 Arisings produced by habitat conservation and landscape management
3 Agricultural and forestry co-products and residues
4 Biomass harvested from new and existing woodlands
5 Dedicated energy crops.

The overarching policy recommendations formulated in the IEEP report focussed particularly on introducing environmental safeguards and exploiting the potential for environmental benefits, with a view to routing the bioenergy sector on an "environmentally responsible path into the future".

The recommendations on UK energy policy were fostered around the driving forces in that sector at the time (Renewables Obligation) and the expected implementation of additional new schemes (Renewable Heat Incentive). They highlighted that these schemes should be adapted to ensure there are positive incentives for environmentally preferable feedstocks and safeguards on the production of these feedstocks.

[18] Gove, B, Flower, K A and Bradbury, R B (2010). A review of environmental consequences of biomass production for UK energy consumption. RSPB Research Report No. 38, Sandy: RSPB.

2 A shifting energy and climate context

Key messages:

- When revisiting the question of biomass sustainability, it is critical to understand the wider energy and climate context.
- Global, national, and corporate emissions targets have undergone a revolution since 2011 - with a deeper understanding by business and policy makers of the need for rapid and deep decarbonisation by 2050.
- Negative emissions and associated technologies, such as Bioenergy Carbon Capture and Storage (BECCS) have also become integral to many climate models. If carbon capture and storage (CCS) becomes operational at scale, then this presents a potential new argument for the expansion of bioenergy crops.
- There has been a significant fall in the cost of non-biomass renewable technologies and the emergence of battery technologies. Biomass costs have not fallen
- Land-intensive bioenergy systems face a significant risk of being seen as a 'legacy' fuel by 2050 – and so it will be critical to avoid physical, institutional, and behavioural lock-in when setting biomass policies in the 2020s.
- The concept of the 'circular economy' and increasing demand for biomaterials is ratcheting up demand for biomass resources and further challenging the idea that valuable resources should be burnt for energy. The quantity of bioenergy will depend, in the end, on the priority given to bioenergy products versus other products obtained from these finite resources.
- Increasing pressures on land have led to calls for a more strategic approach to land use recognising that we must ensure that food, climate mitigation, nature – and other requirements – are met sustainably.
- Finally, with Russia's invasion of Ukraine and the associated focus on energy security and independence, there is a need to objectively examine how different types of biomass feedstock can support - or potentially hinder - energy security.

Since the IEEP report was published in 2011, the environmental, economic, and social context of energy and climate policy has moved on significantly. This has major implications for how the UK should think about the role and sustainability of biomass in a modern energy system. These themes are expanded on in the rest of the document and provide the basis for how biomass sustainability is defined and assessed within this research.

2.1 Deep decarbonisation needed by 2050

Since 2011, the concept of 'net zero' has become established in policy and corporate climate commitments. The science regarding the need to decarbonise the economy rapidly and deeply by mid-century has strengthened.[19]

Soon after the previous IEEP report was done the IPCC Fifth Assessment report (AR5) was published and made clear that limiting global temperature change meant limiting cumulative CO_2 emissions in the atmosphere.[20] To eventually stop global warming net anthropogenic additions of CO_2 and other GHGs into the atmosphere would have to reach zero. Two years later the Paris Agreement was agreed, stating that "parties aim to reach global peaking of greenhouse gas emissions as soon as possible … so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of the century".[21]

In 2018, the IPCC's Special Report on 1.5°C concluded that "limiting temperature rise to around 1.5°C and preventing the worst impacts of climate change implies reaching net zero emissions of CO_2 by mid-century along with deep reductions in non-CO_2 emissions".[22] The next year, the UK became the first G7 economy to legislate for net zero by 2050. As of March 2022, 136 countries have made net zero pledges, covering 88% of emissions.[23]

The IPCC Sixth Assessment (AR6) Working Group II report published in 2022 concluded that the evidence of observed impacts, projected risks, levels and trends in vulnerability, and adaptation limits, demonstrate that worldwide climate resilient development action is more urgent than previously assessed in their AR5. They stated with very high confidence that "global warming, reaching 1.5°C in the near-term, would cause unavoidable increases in multiple climate hazards and present multiple risks to ecosystems and humans". Furthermore, "if global warming transiently exceeds 1.5°C in the coming decades or later (overshoot), then many human and natural systems will face additional severe risks, compared to remaining below 1.5°C".[24] The report highlighted concerns over the use of bioenergy (see Box below).

Box: Concern over biomass use in IPCC AR6

The IPCC's AR6 Working Group II highlighted major risks of bioenergy and BECCS to biodiversity, water and food security: *"afforestation of naturally unforested land, or poorly implemented bioenergy, with or without carbon capture and storage, can compound climate-related risks to biodiversity, water and food security, and livelihoods."* and "*severe impacts on species were likely if bioenergy were a major component of climate change mitigation strategies … BECCS has profound implications for water resources" and "can significantly impact food prices via demand for land and water", with impacts including "dispossession and impoverishment of small-holder farmers, food insecurity, food shortages, and social instability*".

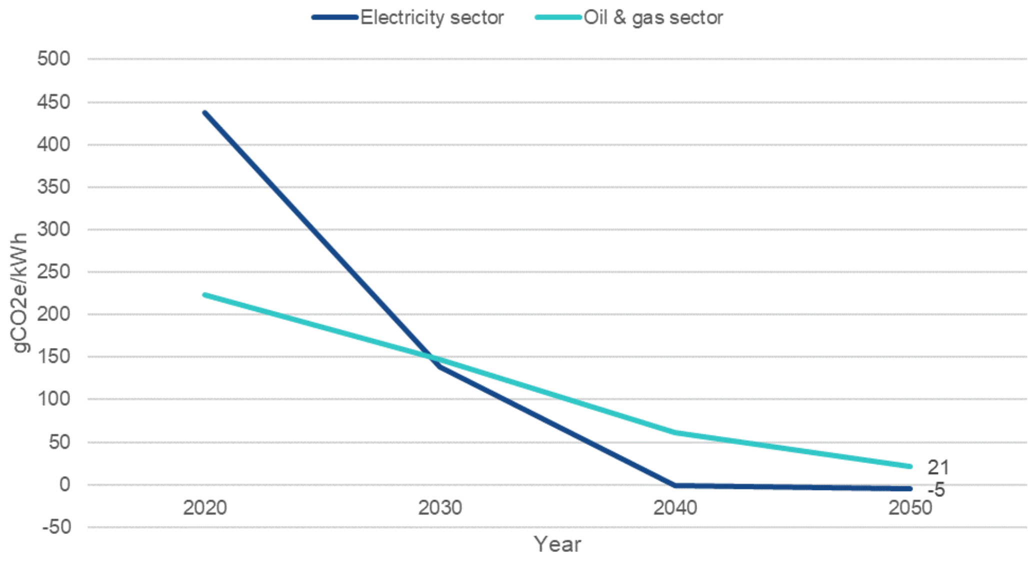
[19] IPCC (2022) Climate Change: Impacts, Adaptation and Vulnerability
[20] IPCC (2013) Fifth Assessment Report. https://www.ipcc.ch/assessment-report/ar5/
[21] Paris Agreement Article 4.1
[22] IPCC (2018) Special report: Global warming of 1.5C
[23] Energy & Climate Intelligence Unit Net Zero Tracker: https://zerotracker.net/
[24] IPCC (2022) Sixth Assessment Report – Working Group II – Summary for Policy Makers Headline Statements

Most recently, the IPCC Sixth Assessment Working Group III report, published in 2022, underlined the current status of the global challenge: "*Without immediate and deep emissions reductions across all sectors, limiting global warming to 1.5°C is beyond reach*".[25]

Overall, there is a clear understanding that greenhouse gas emissions need to be reduced ***rapidly and deeply*** to stay within 1.5°C temperature goals. This means that all aspects of the economy must seek to be as low carbon as possible – including energy sources. Ultimately energy systems need to decarbonise by >90% to be considered sustainable (i.e., delivering energy at 21gCO_2e/kWh or less (see Figure 2 below for transition pathway carbon intensities for electricity and oil and gas sectors).

For these reasons, we assume within this report that sustainable biomass should deliver energy in line with carbon intensities that are aligned to 1.5°C emissions pathways - and those emissions reductions should be delivered in the short term (i.e., they should have a short "carbon payback period").[26,27]

Figure 2: Electricity sector and oil & gas sector emissions intensities needed to meet Paris Agreement[28]



Carbon neutrality of biomass and payback periods

Under the United Nations Framework for the Convention on Climate Change (UNFCCC) guidance, bioenergy is allowed to be classed as 'zero carbon' in the energy sector. This ignores the biogenic CO_2 emissions (the "stack emissions") which are released when

[25] IPCC (2022) Sixth Assessment Report – Working Group III – News post
[26] "The carbon payback period is the time period before the cumulative carbon flux of a bioenergy system equals a fossil-fuel reference system, taking into account biomass regrowth
[27] Reid, WV, Ali, MK, Field, CB. The future of bioenergy. *Glob Change Biol*. 2020; 26: 274– 286.
[28] Adapted from data in Transition Pathway Initiative (2022) TPI Sectoral Decarbonisation Pathways. For "oil and gas" Scope 1, 2 and 3 (use of sold product) greenhouse gas emissions from energy products sold externally in units of grams of CO2 equivalent (gCO2e) per mega joule (MJ). "Energy products sold externally" is defined as the total net calorific energy supply from all fuels including hydrocarbons, biomass and waste, plus energy supplied as electricity generated from fossil fuels, nuclear or renewables.

biomass is burnt for energy as well as upstream biogenic CO_2 emissions. This is done on the understanding that these carbon emissions are accounted for in the Land, Land Use Change and Forestry (LULUCF) sector of the harvesting country.

Accounting for these emissions in the land sector is appropriate for country-level carbon balance sheets (provided this accounting is done to appropriate baselines, which often does not occur), however it does not mean that that biomass energy is in fact carbon neutral or that its biogenic emissions should be disregarded.

According to some researchers, if these impacts are included the combustion of woody biomass can ultimately end up as a more polluting energy source than coal.[29] It should therefore be recognised that the approach to energy from woody biomass sources should be distinctly different to the approach to other renewable sources. This topic is explored in more detail in Section 6 and 7.

2.2 Negative emissions technologies have become key part of climate mitigation modelling

The adoption of the net zero concept has also focused attention on carbon dioxide removals (CDR) and associated ‘negative emissions technologies’ (NETs) - ranging from existing ‘nature-based solutions’ (such as afforestation/reforestation) to emerging carbon capture and storage (CCS) technologies.[30] Most emission pathways that are compatible with the temperature goals of the Paris Agreement goals are heavily reliant on negative emissions technologies, especially biomass energy with carbon capture and storage (BECCS).[31]

More than 85% of previous IPCC climate scenarios assume that BECCS is used to meet climate goals.[32] Greater reliance on biomass - and BECCS - is seen in IPCC indicative pathways that see mid or late decarbonisation (see pathways 3 and 4 and Figure 3 below).

Despite this there are many studies that highlight issues with overreliance on BECCs in Impact Assessment Models (IAMs). Notably, Grant et al. conclude that the low carbon pathway in the 2020’s is extremely sensitive to assumptions around carbon capture systems. They demonstrate that accounting for the uncertainty in future CDR deployment provides a strong argument to significantly increase rates of mitigation in the 2020s.[33]

This is reinforced in work done by the European Academies Science Advisory Council (EASAC), who observed in its analyses of negative emission technologies, that relying on future technologies such as BECCS to compensate later for inadequate emission reductions today places significant risks on future generations, since failure to deliver the removals anticipated would intensify climate change and require even more extreme measures to

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[29] Brack, D. (2017) Woody Biomass for Power and Heat Impacts on the Global Climate. Chatham House

[30] Royal Society (2018) Greenhouse gas removal

[31] Gough C, Garcia-Freites S, Jones C, Mander S, Moore B, Pereira C, Röder M, Vaughan N, Welfle A (2018). Challenges to the use of BECCS as a keystone technology in pursuit of 1.5ºC. Global Sustainability 1, e5, 1–9. https://doi.org/10.1017/sus.2018.3

[32] Muri, H. (2018) The role of large—scale BECCS in the pursuit of the 1.5°C target: an Earth system model perspective Environ. Res. Lett., 13, 044010

[33] Grant et al (2021) Confronting mitigation deterrence in low-carbon scenarios. Environ. Res. Lett. 16

contain it.[34] They summarise that CDR technologies remain highly uncertain, and mitigation remains the priority to urgently reduce global emissions.

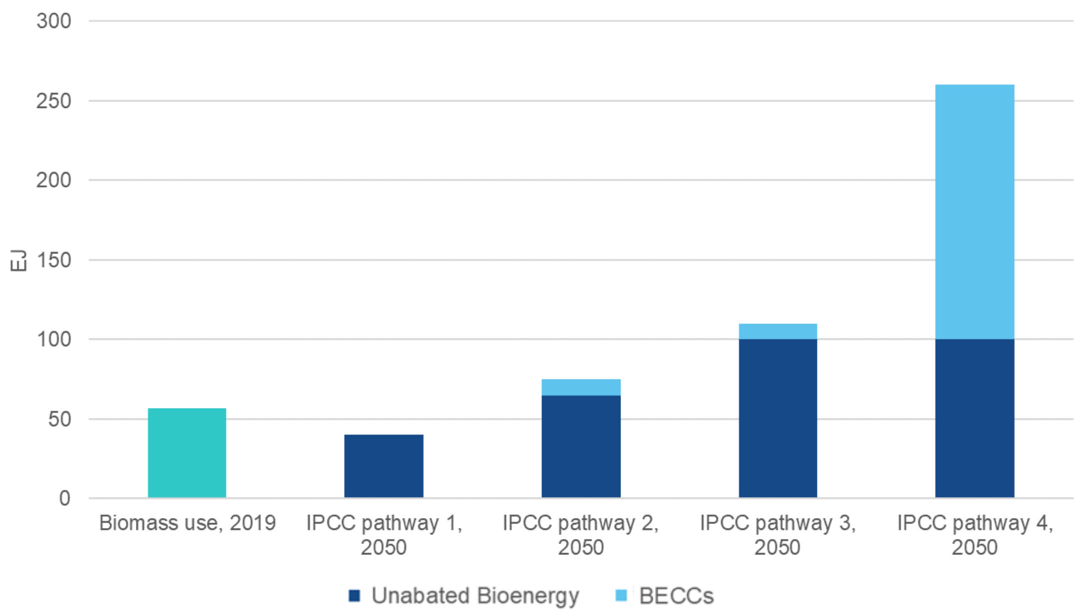
EASAC also recommend that, to avoid the ‘moral hazard’ of displacing climate risks to future generations, investing in the support of future technologies should not be allowed to reduce immediate mitigation measures, and that mitigation and CDR should be treated separately in national and international targets.

CCS has become part of the UK’s overall Net Zero Strategy.[35] The strategy anticipates the need to develop the capacity to capture c. 20-30 $MtCO_2$ per year by the early 2030s across the economy. It expects that by the middle of the century, deployment of engineered removals of between 75 and 81 $MtCO_2$ per year, will be needed to help compensate for residual emissions from sectors such as agriculture and aviation.[36]

As part of its advice to government, the Climate Change Committee suggests that by 2050, between 20 and 65 $MtCO_2e$/year could be sequestered through BECCS in the UK. This is equivalent to up to around 15% of current UK CO_2e emissions.[37]

Overall, carbon dioxide removal has now become the third ‘use’ of biomass alongside energy and biomaterials. BECCS could become the primary rationale for promoting biomass-based energy as arguments over its energy security, climate mitigation and energy storage benefits fall away due to the performance and availability of alternatives (see next sub-section). How BECCS is considered in the sustainability assessment of biomass is explored further in Section 6.

Figure 3: Primary energy supply from biomass in IPCC pathways, compared to 2019.[38]



[34] EASAC (2022) Forest bioenergy update: BECCS and its role in integrated assessment models
[35] Net Zero Strategy: Build Back Greener - HM Government (Oct 2021)
[36] Climate Change Committee (2019) Net Zero – The UK’s contribution to stopping global warming
[37] The Committee on Climate Change (2018): Biomass in a low-carbon economy
[38] IPCC data derived from IPCC (2018), Special Report on Global Warming of 1.5°C (SR1.5). Biomass use in 2019 based on World Bioenergy Association (2021) Global Bioenergy Statistics 2021

2.3 Significant fall in non-biomass renewable costs – and emergence of battery technologies

There have been significant reductions in the price per kWh of renewable energy technologies (see Figure 4 below).[39] Between 2010 and 2020, solar PV cost per kWh fell by more than 80%. It is expected to halve again by 2050.[40]

Since 2010, biomass energy costs per kWh have remained the same. Some researchers see this trend continuing, with many current applications of bioenergy being uncompetitive against clean electrification options.[41] Increasing demand for biomass and constrained sustainable supply could actually drive prices up in the future.[42] Element Energy and Vivid Economics note that the cost of biomass fuel is highly uncertain over the medium-to-long term as the global woody biomass market grows.[43] They identified a range of risks for BECCS including market risks related to the costs of feedstock. Feedstock supply chains and biomass prices were frequently raised as an area of concern from stakeholders consulted in industry and the financial community.

There is the expectation that the value of biomass will be affected as the social cost of carbon and value of carbon reduction increases. The Climate Change Committee estimates that 2050 carbon values would increase the value of biomass by approximately 100-500% from today's prices for wood pellets.[44] This is supported by integrated assessment model outputs published by the Network of Central Banks and Supervisors for Greening the Financial System (NGFS), which project an increase in EU biomass prices of approximately 200-300% by 2050 in some scenarios where global warming is limited to 2°C.

In addition to cost reductions in competing power generation, the last ten years have seen a similar revolution in battery storage technologies that is likely to further disrupt power system planning and influence the relative attractiveness of different technologies. Reid W. et al argue that, rather than being a substitute for 'baseload' power production, by mid-century bioenergy will be competing with other energy sources to supply this "firm" power for inter-day and seasonal load balancing.[45] For several reasons, Reid et al. conclude it is unlikely that bioenergy will comprise a significant portion of this energy mix.[46]

Overall, given the relative cost of biomass – and the increasing attractiveness of alternatives, it is likely biomass will rely on market demand created by policy.[47] *Land-intensive bioenergy systems face a significant risk of being seen as a 'legacy' fuel by 2050 – and so it will be*

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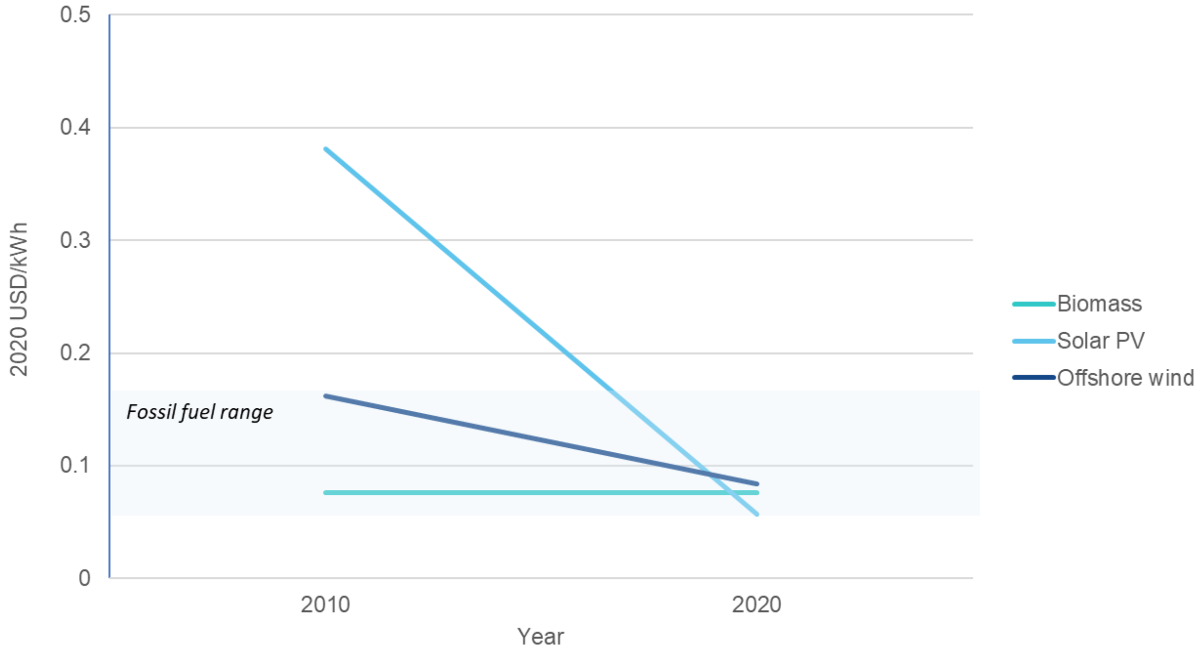
[39] IRENA (2021) Renewable Power Generation Costs in 2020
[40] Energy Transitions Commission (2021) Bioresources within a Net-Zero Emissions Economy – Making a Sustainable Approach Possible
[41] Energy Transitions Commission (2021) Bioresources within a Net-Zero Emissions Economy – Making a Sustainable Approach Possible
[42] Energy Transitions Commission (2021) Bioresources within a Net-Zero Emissions Economy – Making a Sustainable Approach Possible
[43] Element Energy and Vivid Economics (2021) Investable commercial frameworks for Power BECCS. Report to BEIS
[44] The Sixth Carbon Budget. The UK's path to Net Zero – Climate Change Committee (2020)
[45] Firm power is power or power-producing capacity, intended to be available at all times during the period covered by a guaranteed commitment to deliver, even under adverse conditions.
[46] Reid, WV, Ali, MK, Field, CB. The future of bioenergy. *Glob Change Biol*. 2020; 26: 274– 286.
[47] Vivid Economics (2019) Energy Needs Innovation Assessment. Biomass and bioenergy.

critical to avoid physical, institutional, and behavioural lock-in when setting biomass policies in the 2020s.[48]

Figure 4: Change in cost per kWh for renewable energy technologies[49]



2.4 Rise of circular and bio-economy – additional demands being placed on biomass resources

Since 2011 the concept of the 'circular economy' and the 'bioeconomy' has also gained significant policy and private sector interest. Circular economy principles promote the use of renewable materials – but also encourage adoption of the waste hierarchy. Central to the approach is keeping materials cycling in the economy, and only burning them for energy as a last resort.[50]

Biomaterials (e.g., wood products, pulp, paper, fibre, etc) are a key input to several sectors of the economy – and are likely to increase in importance.[51] Given that competition for renewable materials is likely to increase in the coming decades, it will become increasingly essential to prioritise the recycling and reuse of biomaterials – and not for energy recovery.[52]

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[48] Kalkuhl, M., Edenhofer, O., & Lessmann, K. (2012). Learning or lock-in: Optimal technology policies to support mitigation. *Resource and Energy Economics*, **34**(1), 1–23.
[49] IRENA (2021) Renewable Power Generation Costs in 2020
[50] Ellen MacArtthur. The butterfly diagram: visualising the circular economy. https://ellenmacarthurfoundation.org/circular-economy-diagram
[51] EU Biomass Use in a Net-Zero Economy – A course correction for EU biomass' and 'Bioresources within a Net-Zero Emissions Economy: Making a Sustainable Approach Possible (Energy Transition Commission Nov 2021)
[52] Terlouw, T (2021) Life cycle assessment of carbon dioxide removal technologies: a critical review. Energy Environ. Sci., 2021, 14, 1701-1721

Unfortunately, many climate mitigation models that depend on significant biomass use by the mid-century *do not* fully account for competing materials use sufficiently.[53] The Energy Transition Commission estimates that if all sectors convert current energy and material demand to biomass in 2020 it would be approximately ten times the available supply they have modelled under a 'prudent' biomass energy scenario.[54] Satisfying global material use alone in 2050 (i.e., paper, plastic, and timber) would use up their low-end estimate of available sustainable biomass – even after assuming a significant (>50%) reduction in biomaterials demand through recycling and re-use.

This highlights that the quantity of bioenergy will depend, in the end, on the priority given to bioenergy products versus other products obtained from these finite resources (i.e., food, paper, bioplastics and other bio-based products).[55] For this reason, we assume within this report that 'sustainable' biomass should be only those sources with low risk of competing against alternative uses - both food and non-food. Even though this concept is not new (the waste hierarchy has been embedded in business and policy documents for many years) the principles need to be more actively supported by policymakers to ensure alignment across different policy areas.[56]

2.5 Energy and food security back on the agenda

The case for biomass has been partially made, in the past, on the potential for it to contribute to a country's energy security, particularly in the context of energy baseloads and the intermittency of some other renewables like solar and wind.[57,58,59]

Russia's invasion of Ukraine has put the topic of food and energy security firmly back on the agenda of business and policymakers. While the UK does not import much Russian gas directly (it is only 5-6% of imports), a drop in global supply from Russia will affect European and international gas markets and so will affect UK gas prices.

As a result of this volatility and reliance on gas for heating and electricity generation, bills in the UK will likely rise because of conflict in Ukraine. Cheap renewables are and will continue to help to cushion electricity price rises, though while the UK is still reliant on gas for electricity generation and home heating, there is still vulnerability to gas price volatility in the short term.

In response to the invasion and energy price inflation the UK government was rapidly developing a new Energy Security Strategy at the time that this report was being finalised.

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[53] Energy Transitions Commission (2021) Bioresources within a Net-Zero Emissions Economy – Making a Sustainable Approach Possible
[54] Energy Transitions Commission (2021) Bioresources within a Net-Zero Emissions Economy – Making a Sustainable Approach Possible
[55] Calvin K et al (2020) Bioenergy for climate change mitigation: Scale and sustainability
[56] In 2020 representatives of the recycling sector said that recent downgrading of wood recycling targets by Defra was 'collateral damage' of the Renewable Heat Incentive. Letsrecycle.com (2020) Wood sector stunned by packaging targets. https://www.letsrecycle.com/news/wood-sector-stunned-by-packaging-targets/
[57] DECC (2012) UK Bioenergy Strategy
[58] Scope (2015) Bioenergy & Sustainability: bridging the gaps
[59] Renewable Energy Association (2019) Delivering the UK's Bioenergy Potential

In the EU, similar steps are being proposed under the 'REPowerEU' plan[60], which includes a commitment to double the ambition for EU biomethane production from agricultural waste and residues by 2030.

In the International Energy Agency 10-point plan to reduce dependence on Russian gas, they point out there is limited potential to scale up biogas and biomethane supply in the short term because of the lead times for new projects. But this sector offers medium-term upside for the EU's domestic gas output.[61] They also note that the large fleet of bioenergy power plants in the EU operated at about 50% of its total capacity in 2021. So, there is potential that these plants could generate up to 50 TWh more electricity in 2022[62] if the right incentives and sustainable supplies of bioenergy are put in place. It is important to recognise that whilst there may be available capacity to increase production from bioenergy, many EU NGOs argue that the current scale of supply is already unsustainable and increasing supply from these sources may only address energy diversification from Russian gas but not improve sustainability of the energy mix.

In the context of discussions on energy security and import dependence, it is worth noting that the UK has a comparatively poor domestic biomass resource-base compared to its relative share of global GDP and energy demand (see Table 2 below). It is logical to assume that this will place constraints on the degree to which domestic bioenergy sources can offer significant energy security benefits. It should also be noted that any effective 'security' measures must rely on mitigating climate change: the expansion of highly emitting fuel sources would endanger long term national security even if energy demands are met in the short term.

Table 2: UK share of global socio-economic and resource indicators in 2020[63]

Indicator, UK share of global...	Value
GDP	3.20%
Energy demand	1.24%
Planted forest	0.95%
Cropland	0.39%
Sawn wood production	0.71%
Population	0.86%

[60] European Commission (2022) Joint European action for more affordable, secure, and sustainable energy
[61] A 10-Point Plan to Reduce the European Union's Reliance on Russian Natural Gas - IEA (2022)
[62] A 10-Point Plan to Reduce the European Union's Reliance on Russian Natural Gas - IEA (2022)
[63] Forest, cropland and sawn wood production indicators derived from FAOSTAT 2020. Energy demand derived from bp 2021 Statistical Review of World Energy. GDP and population indicators derived from the World Bank data catalogue.

3 Biomass policy overview

Key messages:

- Previous policy, such as the Renewables Obligation and Renewable Heat Incentive, have stimulated growth in the bioenergy sector through the provision of incentives for the deployment of eligible technologies.
- Key incentives promoting renewables growth, including bioenergy, have now closed to new applicants, replaced with alternative options that prioritise larger-scale capacity deployment (e.g., Contracts for Difference).
- Sustainability criteria for solid and gaseous biomass feedstocks have been tightened but are still lacking in a wider sustainability context for feedstock assessment.

3.1 Renewables Obligation and Renewable Heat Incentive

The UK has had several policy mechanisms in place to promote the deployment of low carbon energy sources including bioenergy. Generally, the objectives are to decarbonise the energy sector, bolster energy security and enhance economic development. In the bioenergy sector measures such as the Renewables Obligation (RO), the Renewable Heat Incentive (RHI), Renewable Transport Fuel Obligation (RTFO) and more latterly the Feed in Tariff (FIT) were the cornerstones to this development.

The Renewables Obligation (RO), the Renewables Obligation (Scotland) (ROS) and the Northern Ireland Renewables Obligation (NIRO) were designed to incentivise large-scale renewable electricity generation in the UK to help meet its target 15% of energy to come from renewable sources by 2020. The scheme put an obligation on licensed electricity suppliers in England and Wales, Scotland, and Northern Ireland to acquire an increasing proportion of electricity from renewable sources.

Under the Renewable Energy Directive (RED) (2009), the UK government transposed the new solid biomass recommendations into the RO in 2011. The UK went beyond the mandatory EU rules, extending sustainability criteria to solid biomass and biogas and adding in a food crop cap within the RTFO.[64] In 2015, the requirement for solid biomass to meet the sustainability criteria to receive support under the RO scheme was introduced.[65]

These policies were first introduced was to stimulate renewable energy deployment when technologies were immature, and costs were high. Providing long term incentives for renewable energy production, made the higher costs and inherent risk more palatable in the early days of deployment. Policy priorities have shifted with current emphasis on reducing the cost of energy production and, for bioenergy, imposing tighter sustainability constraints.

[64] Committee on Climate Change (2018) Biomass in a low-carbon economy
[65] Renewables Obligation: Sustainability Criteria (OFGEM) 2018

With the closure of the pre-eminent schemes of the RO and FIT and the renewables landscape dramatically changing, the shift in focus is apparent in the government's current approach to promoting low carbon electricity generation.

The replacement scheme, Contracts for Difference (CfD), aims to incentivise investment in renewable energy by providing developers with protection from volatile wholesale prices, while protecting consumers from paying high support costs when electricity prices are high.

The new scheme is still aimed at providing investment security for longer term renewable generation, but the structure of the scheme favours fewer, larger scale, developments as opposed to a more 'free for all' technology scale deployment. This is good for capacity building, and some dedicated biomass projects were successful in the first rounds of auctions under the CfD, but in the long term it could hinder deployment of certain projects and technologies that are more suited to smaller scale generation and indeed harnessing bioenergy resources at point of generation becomes less likely.

Other initiatives that could be seen to encourage the development of bioenergy deployment are linked to heat generation and delivery. BEIS has some initiatives to encourage the development of heat networks in England and Wales. The Heat Networks Delivery Unit (HNDU) and the Heat Networks Investment Project (HNIP) have been established to provide support for project development and to support capital investment in heat networks. However, these schemes are not specifically designed for bioenergy and as such most of the projects supported under these schemes are based on gas rather than bioenergy or other renewable sources. Scotland has a similar scheme in place in the Heat Network Partnership.

There are also some nuances within the devolved administrations that are important to recognise (see

Table 3 below). In Scotland and Northern Ireland, the requirement for solid biomass and biogas stations to meet the sustainability criteria was introduced in an amendment Order. The RO and ROS Orders came into effect in 2015 and the NIRO Order came into effect in 2016.

Table 3: Summary of Biomass energy status by devolved administration[66]

Nation	Policy
England	Continuation of the CfD scheme, with an increase in allocation rounds such that they are to be held annually from March 2023 – when the fifth round will be open to applicants.[67] The Waste Policy Review[68] and Anaerobic Digestion Strategy[69] set out the potential for energy recovery from waste in England, consistent with the waste hierarchy, and a set of actions to deliver it. This includes consulting this year on restrictions on waste wood going to landfill, which will aim to improve opportunities for the efficient use of waste wood (Defra) The Independent Panel on Forestry (in England) will advise on the future direction of forestry and woodland policy, which includes how woodland cover can be increased as well as options for enhancing public benefits from all woodland and forests.
Scotland	Bioenergy was identified as a strategic priority in the 2018 Energy Strategy Commitment to a bioenergy action plan that is consistent with its 2018 Climate Change Plan and 2016 Land Use Strategy. Biomass should be used for energy in heat-only or combined heat and power schemes to exploit available heat and local supply.
Wales	The Welsh Government consultation on a low-carbon pathway to 2030 did not assume significant levels of bioenergy in the Welsh power sector in future.
Northern Ireland	There is currently no policy in place to support the deployment of low-carbon heat, including biomass or biogas, following the closure of the Northern Irish RHI scheme to new applications in 2016.The scheme is currently subject to a public inquiry, An election in May 2022 may present renewed interest in renewables and bioenergy within NI but it is likely to be extremely cautious given the historical issues with previous scheme.

3.2 Bioenergy Strategy, 2012

As set out in the 2011 UK Renewable Energy Roadmap, bioenergy was an important part of the Government's plans to meet the Renewable Energy Directive objectives in 2020. In 2012 they released an important framework document in the UK Bioenergy Strategy. In summary the four key principles[70] of the strategy stated that:

- Policies that support bioenergy should deliver genuine carbon reductions that help meet UK carbon emissions objectives to 2050 and beyond.
- Support for bioenergy should make a cost-effective contribution to UK carbon emission objectives in the context of overall energy goals.
- Support for bioenergy should aim to maximise the overall benefits and minimise costs (quantifiable and non-quantifiable) across the economy.
- At regular time intervals and when policies promote significant additional demand for bioenergy in the UK, beyond that envisaged by current use, policy makers should

[66] From Committee on Climate Change (2018) Biomass in a low-carbon economy
[67] Business Update Statement made on 9th February 2022 – Kwasi Kwarteng (https://questions-statements.parliament.uk/written-statements/detail/2022-02-09/hcws600)
[68] Government Review of Waste Policy in England 2011 – DEFRA (2011)
[69] Anaerobic Digestion Strategy and Action Plan – DEFRA / DECC (2011)
[70] UK Bioenergy Strategy - DfT, DECC, Defra (2012)

assess and respond to the impacts of this increased deployment on other areas, such as food security and biodiversity.

In the overarching principles there looked to be a distinct shift away from specific targets and rules but more a system that should be able to develop with an evolving bioenergy landscape. Whilst there is certainly reference that "*clear, enforceable, transparent sustainability criteria have a key role to play across the policy landscape in distinguishing between bioenergy production and use which is consistent with these principles*".[71]

3.3 The UK Biomass Statement and Strategy, 2022

During the UNFCCC's COP26 in November 2021, BEIS published a statement to commit the UK to using sustainable biomass energy to assist the UK to meet its 2050 Net Zero target. This is a follow-up to the call for evidence run by BEIS in April; to obtain stakeholder engagement on the availability of sustainable biomass from the UK and overseas; and to examine the supply chain and the end use. The purpose of the evidence was also to seek clarification on sustainability criteria and methods for accounting for biomass emissions, and to obtain feedback on the use of carbon capture and storage.

The resulting policy statement is a first step to the release of the Biomass Strategy paper due for release in 2022 by BEIS.

The Statement sets out the principles on priority uses for biomass in the short (i.e., 2020s), medium (i.e., by 2035) and long term (i.e., by 2050) to meet net zero (see Figure 5 below). These principles are intended to support the development of a priority use framework for the Biomass Strategy (see Figure 5 from the Biomass Statement).

The Statement does not see biomass as a major source for electricity in the long run but does see it as a reliable baseload power source (for use in "peaking" units), alongside carbon capture technologies.

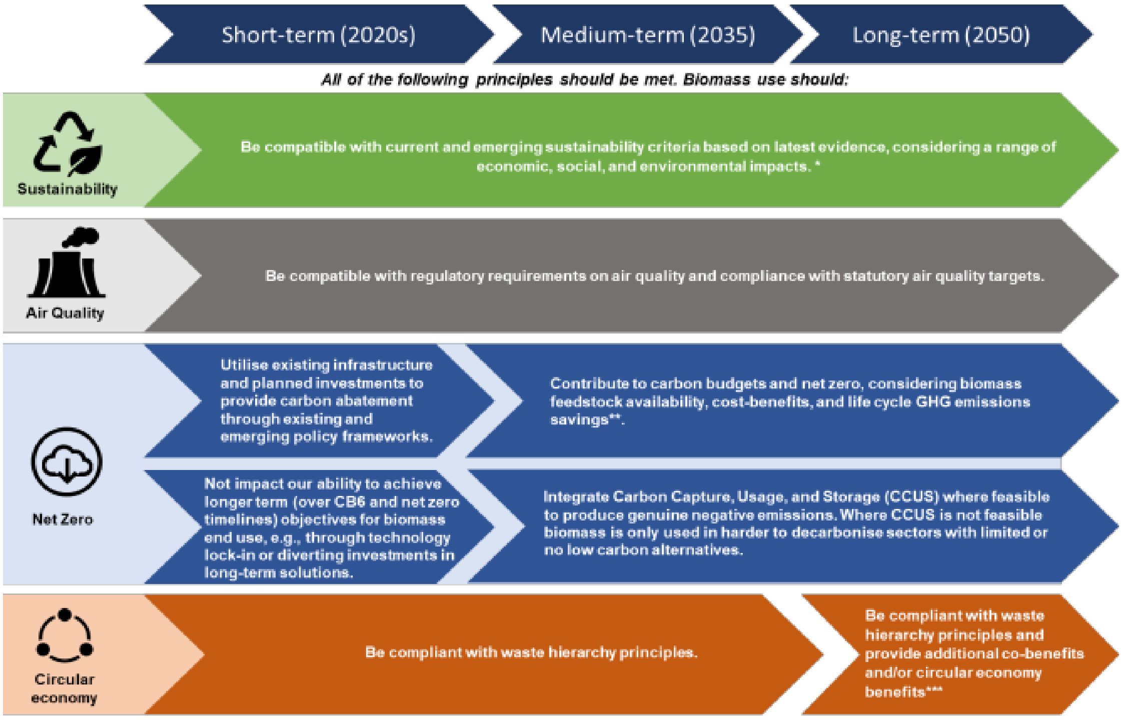
The Statement sets out the UK Government's position on the importance of bioenergy combined with carbon capture and storage (BECCS).

Existing policies and emissions markets are not designed to value negative emissions (essential if BECCS are to be deployed) and need development. The UK ETS is one long-term market-based approach to supporting biomass via BECCS, whereby the current zero-rating of biomass emissions could be adapted, however, as noted in Section 6.2 this is not without controversy.

The use of Carbon Capture, Utilisation & Storage (CCUS) clusters is also tied to the UK government "levelling up agenda" to provide jobs and reindustrialisation to economically deprived parts of the country. BECCS facilities could be co-located with such CCUS clusters to benefit from storage and transportation infrastructure.

[71] UK Bioenergy Strategy - DfT, DECC, Defra (2012)

Figure 5: Overarching priority use principles for biomass use over three timescales[72]



* Further work is being carried out to review the UK's existing sustainability criteria, including exploring ways to harmonise the criteria across sectors to promote fair competition. Details to follow in the Biomass Strategy.

** Compared to GHG emissions of appropriate counterfactuals.

*** e.g., by-products are used to make other high value products which can be utilised elsewhere in the economy.

3.4 Trends in EU policy

In the European Union we can see some policy updates that point towards the future trends we are likely to see in that region. For example, the European Commission has proposed a revision of the RED to work towards a gradual shift from conventional biofuels to advanced biofuels (those produced from non-recyclable waste and residues) and other alternative renewable fuels (e-fuels). The revised RED will strengthen the biomass sustainability criteria taking up recommendations of the Commission's Joint Research Centre.[73] The revised directive includes:

- the extension of no-go areas for forest biomass to protect, in particular primary and old-grown forests, as well as wet- and peatland.
- It also requires avoiding the use of roots and stumps and minimising large clear-cuts.

The new rules will oblige EU countries to design their support schemes in accordance with the biomass cascading principle, i.e., *woody biomass is used according to its highest economic and environmental added value.*

These policies are no longer applicable to the UK, but it does serve to highlight the direction that other nations are likely to follow in attempting to reduce reliance on fossil fuels, enhance the bioenergy sector and mitigate greenhouse gas emissions.

[72] Biomass Policy Statement - BEIS (2021)
[73] EC JRC (2020) The use of woody biomass for energy production in the EU

4 Current uses of bioenergy in the UK

Key messages:

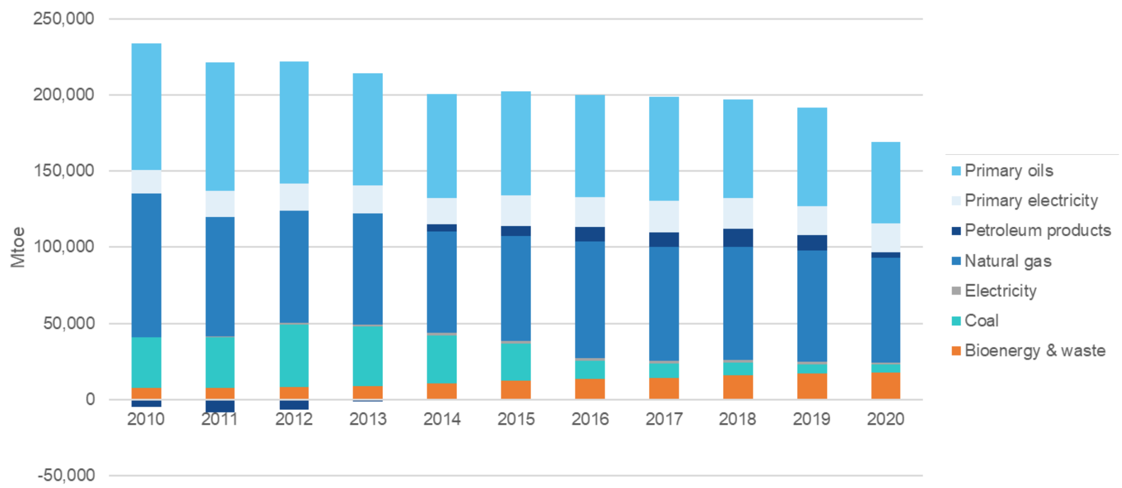
- Renewable energy has gained significant traction in recent years with some record outputs and significant milestones passed.
- With the exception of landfill gas, energy supply from most bioenergy sources has grown significantly since 2010 - with the largest upturn apparent from plant biomass (imported and domestic).
- Bioenergy and waste make up 11% of the total UK primary energy supply and are the largest source of renewable power after wind.
- Solid biomass contributed 33% of total renewable demand, with approximately two thirds being used in electricity generation and the remaining to produce heat.
- Approximately a third of existing bioenergy feedstock/fuel demand (across the power, heat, and transport sectors) comes from imports.

4.1 The UK energy supply

Total energy consumption in the UK has continued to steadily decrease since the peaks of the early 2000s (See Figure 6 below).

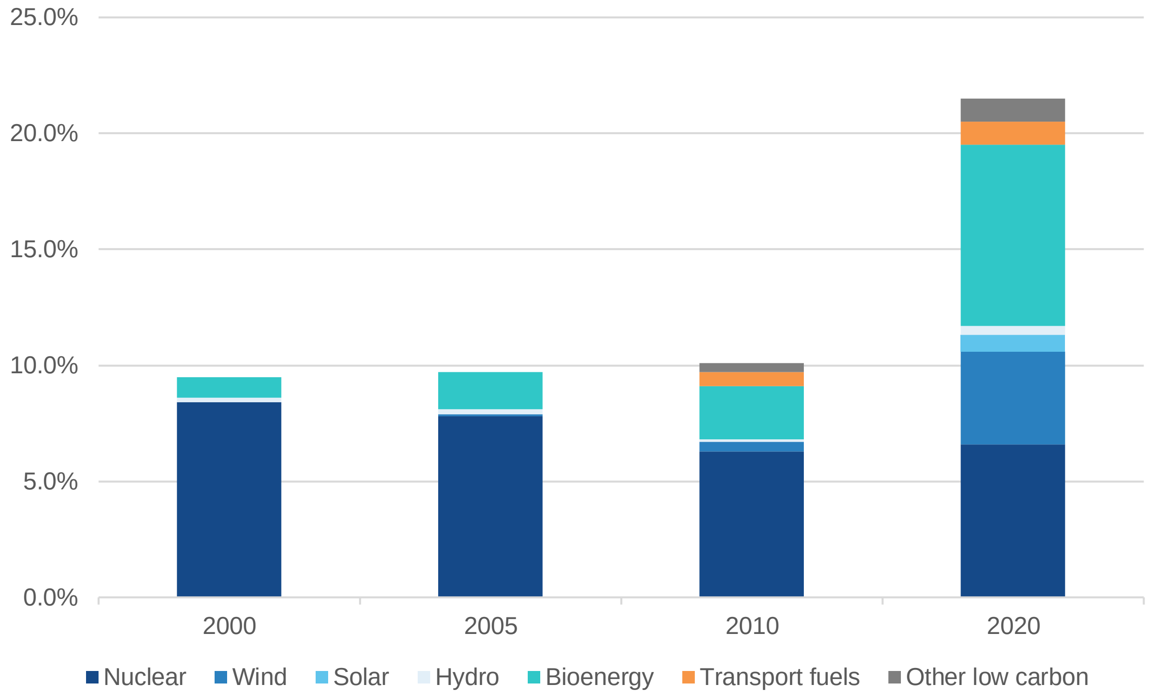
Currently, bioenergy and biodegradable waste make up 11% of the total UK primary energy supply (see Figure 7 below). Reductions in reliance on petroleum, oils and significantly coal are apparent, with a slight increase in gas use. In this period, we also see a growth in bioenergy supply, modest in terms of the overall makeup of primary energy supply. Primary electricity (nuclear, solar, wind and hydro) grew by 25% over this period.

Figure 6: Total primary supply of energy to UK – all sectors and end uses[74]



[74] BEIS (2021) Digest of UK Energy Statistics Annual data for UK, 2020. Primary electricity covers wind, hydro and solar photovoltaics and nuclear

Figure 7: Proportion of UK energy supplied from low carbon sources, 2000 to 2020[75]

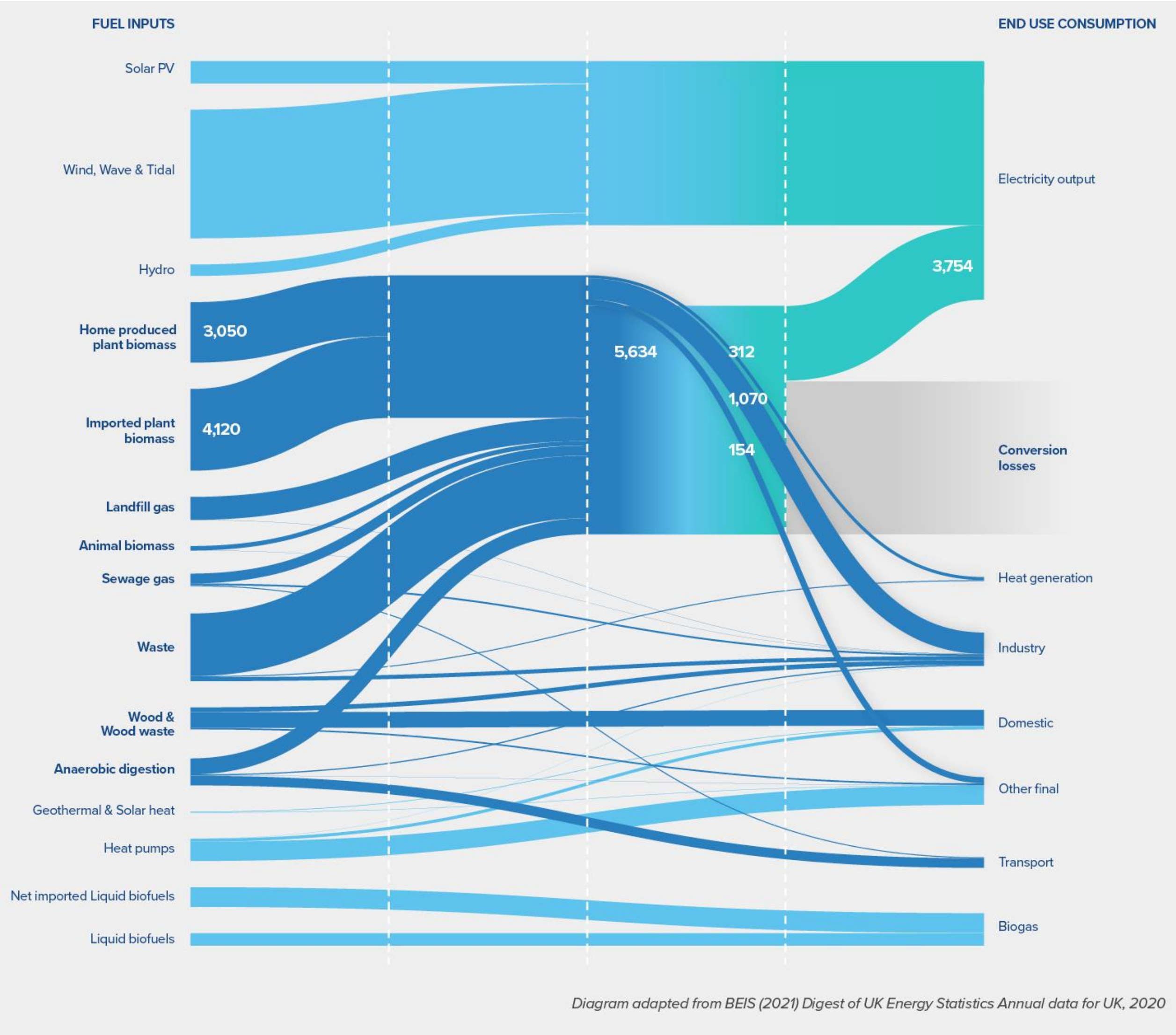


[75] BEIS (2021) UK Energy in Brief 2021

4.3 Renewables

In 2020, solid biomass contributed 33% of total renewable demand, with approximately two thirds being used in electricity generation and the remaining to produce heat (see flow diagram in Figure 8: , Figure 9 and Figure 10 below). It is worth noting that, after conversion losses, wind power contributes a much greater share of renewable *output*. This is because there are significant conversion losses in heat generation when combusting fuels.

Figure 8: UK renewable energy flow chart, 2020[76]



[76] BEIS (2021) Digest of UK Energy Statistics Annual data for UK, 2020

Figure 9: Renewable sources used to generate electricity and heat, 2020[77]

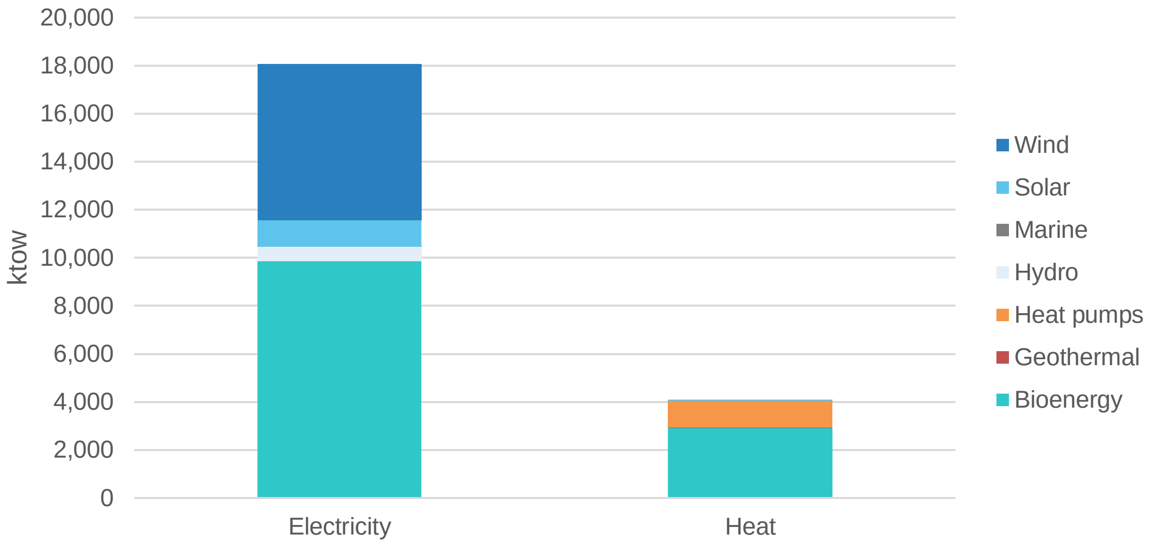
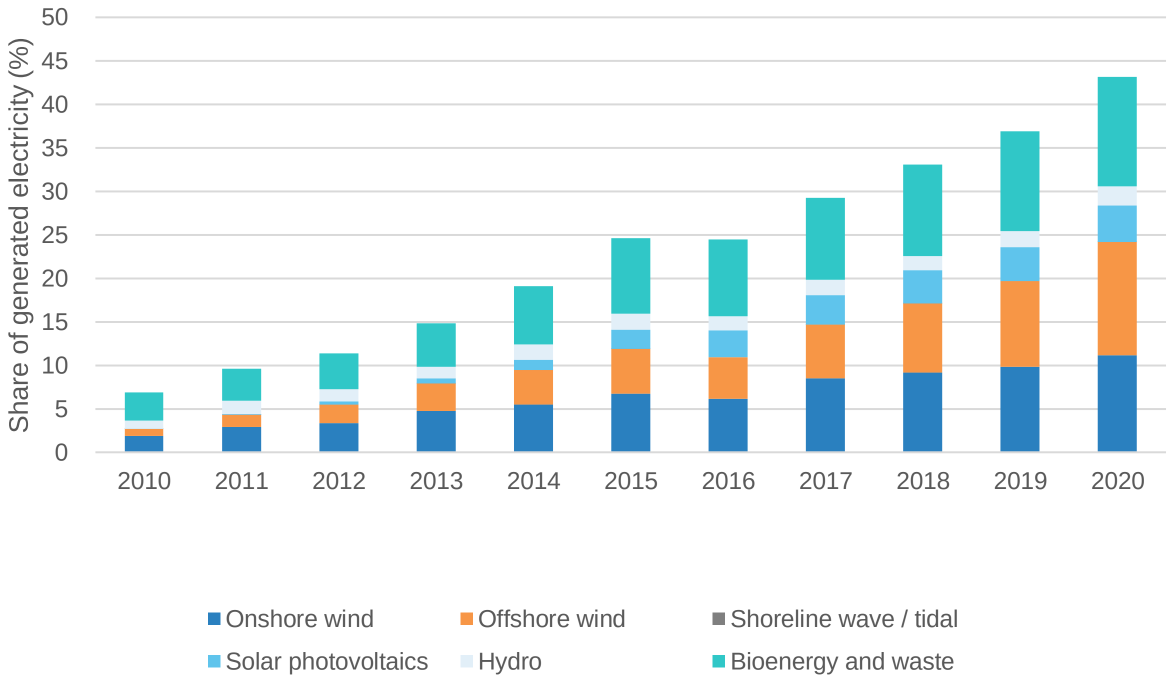


Figure 10: Renewable electricity generation, annual data[78]



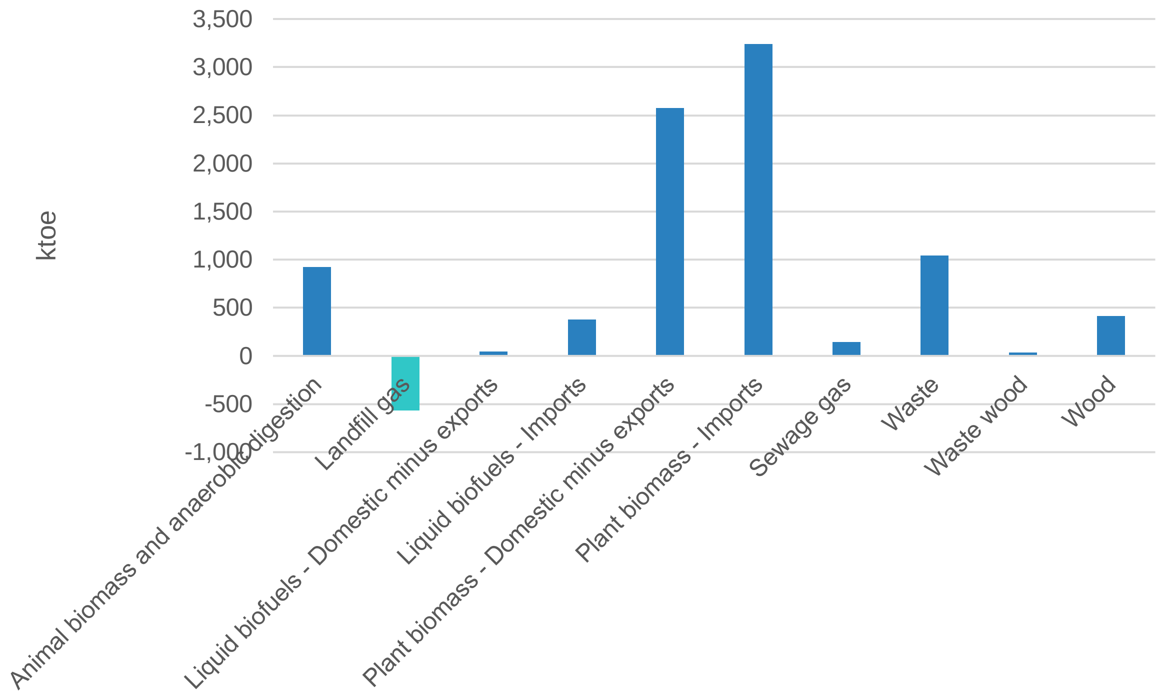
[77] BEIS (2021) Digest of UK Energy Statistics Annual data for UK, 2020. Table 6.6
[78] BEIS (2021) Energy Trends

4.5 Bioenergy

Around a third of existing bioenergy feedstock/fuel demand (across the power, heat, and transport sectors) comes from net imports, the majority of which is wood pellets produced from forestry residues that are used in low carbon electricity generation (see Figure 12 on the next page).[79] The main change in bioenergy use between 2010 and 2020 was the increase in plant biomass combustion (see Figure 11 below).

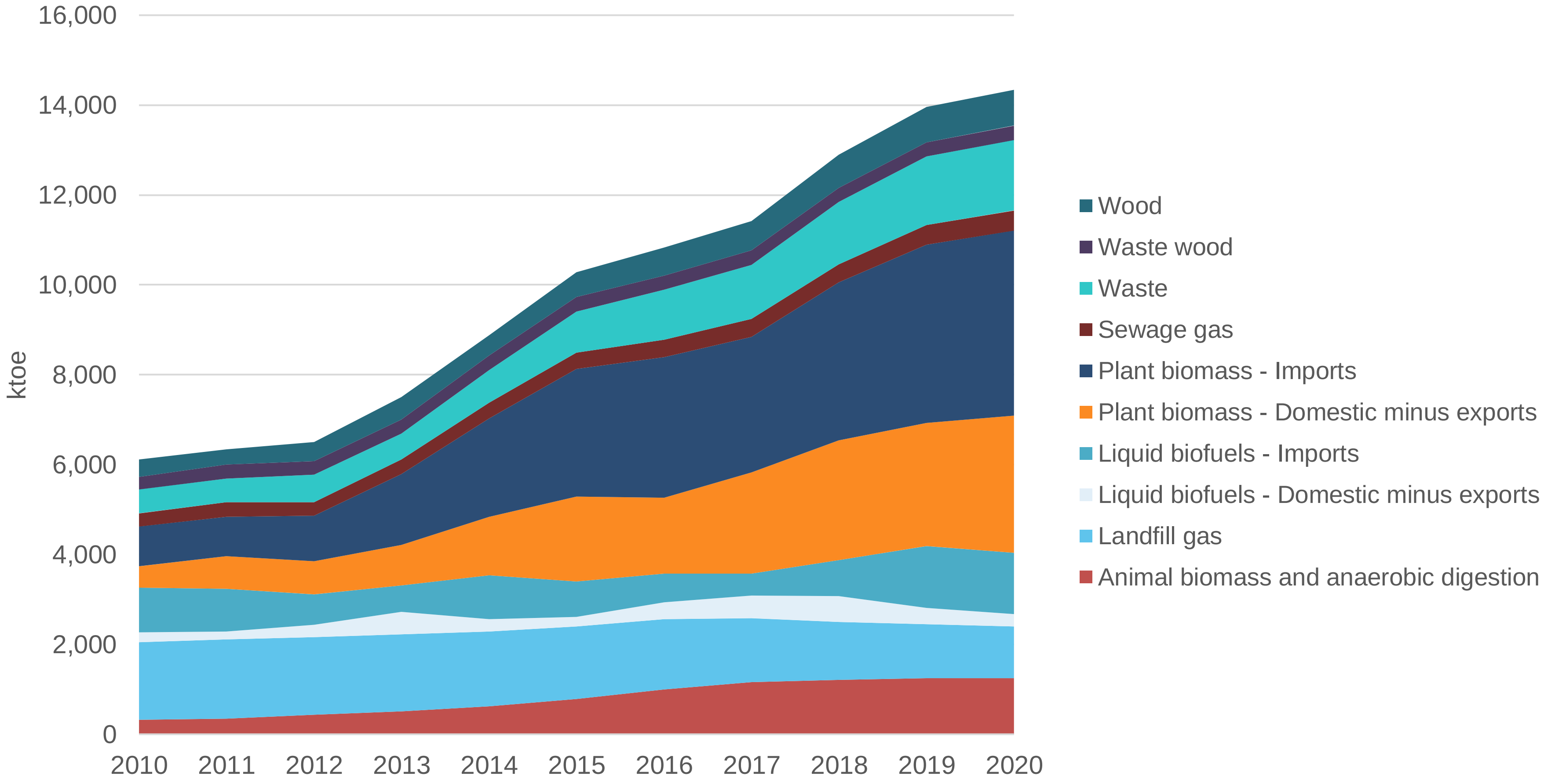
Since the start of the decade there has been a steady increase in the amount of wood pellets imported to the UK. In 2010, just 0.6 million tonnes of wood pellets were imported, compared to 7.8 million tonnes in 2018. In 2018, around 82% of wood pellets imported were from the United States and Canada.[80] US wood pellets comprised 75% of UK pellet imports in 2019.[81]

Figure 11: Change in biomass and biofuel energy supply, 2010 to 2020 (ktoe)[82]



[79] Biomass Policy Statement - BEIS (2021)
[80] ONS (2019) A burning issue: biomass is the biggest source of renewable energy consumed in the UK
[81] Chatham House (2021) Greenhouse gas emissions from burning US-sourced woody biomass in the EU & UK
[82] Derived from BEIS (2021) DUKES. Commodity balances in flat format.

Figure 12: Biomass and biofuel energy supply in UK, 2010 to 2020[83]



[83] BEIS (2021) DUKES. Commodity balances in flat format. 'Waste' adjusted to reflect biodegradable fraction only using assumption quoted in DUKES Chapter 6 that "Energy from waste plants increased their capacity in 2020 which provided an additional 0.5 TWh in generation (1.1 TWh including non-biodegradable waste)" i.e., biodegradable waste contributes 45% of energy generation.

4.6 Installed capacity

Total renewable cumulative capacity has continued to grow, with a marked rise in capacity since the 2011 IEEP report. However, year-on-year added capacity has slowed. New renewable capacity reached a peak in 2015, largely driven by the increase in solar capacity installations prior to incentive reductions (see Figure 13 below)[84] . Looking specifically at bioenergy, the largest capacity growth was in plant biomass (see Figure 14 below).

Figure 13: Renewable capacity (MW)

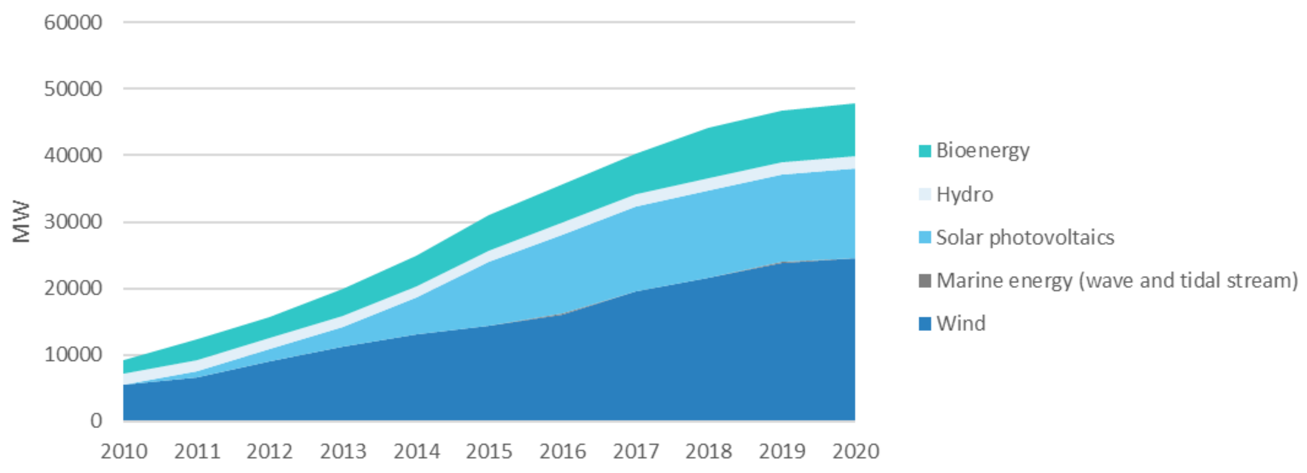
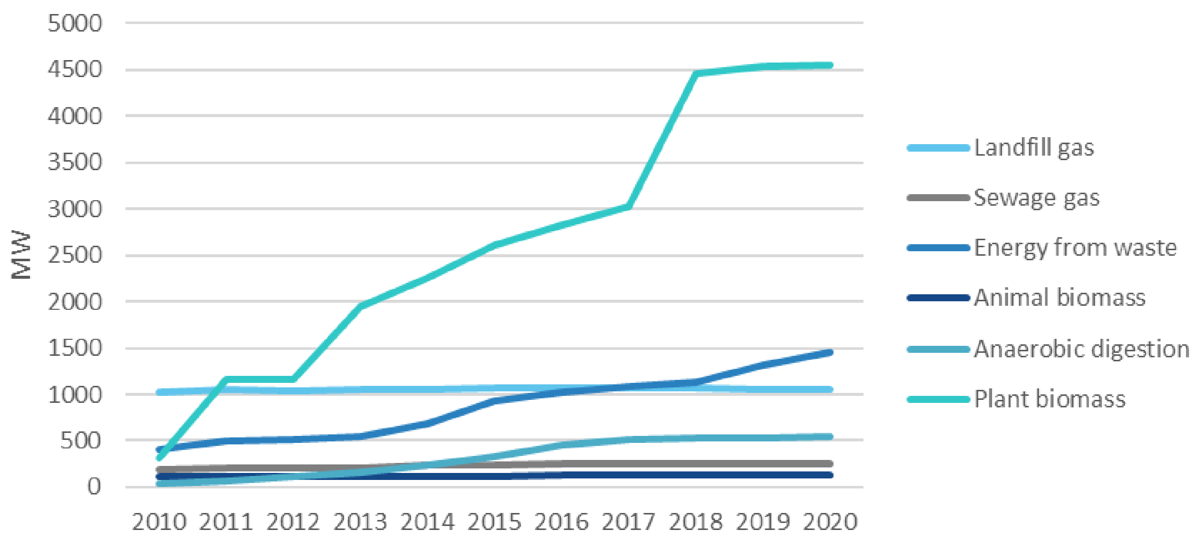


Figure 14: Bioenergy capacity growth by fuel type



[84] BEIS (2021) Digest of UK Energy Statistics

5 Future biomass availability

Key messages:

- New research on the technical, constrained, and sustainable potential of biomass energy supply in the UK, Europe and globally has been undertaken in recent years by researchers, industry, and NGOs.
- These studies tend to see static or reducing supply in the most sustainable sources of biomass (i.e., residues and waste) over next 30 years due to increase in competing uses, policy pressures to support the circular economy and reduce waste.
- The greatest differences between models are the extent to which energy crops (e.g., short rotation coppice) and stemwood are used.
- The degree to which non-energy sectors compete with energy for use of bio-resources has increasingly been included in modelling. Historically this has been overlooked. These competing uses further constrain the quantity of resource available for the energy system.
- The models with most significant sustainability constraints assume stemwood and energy crops are limited in use and only on degraded/marginal land.
- There is reasonably good alignment between studies in levels of domestic waste and residues (lower risk) feedstocks which are likely to be available in coming decades. Based on data reported in these studies, we estimate this to be c. 0.3 exajoules of primary energy in 2050 (c. 4% of primary energy demand).
- Whilst the extent to which usage of 'lower risk' feedstocks might align on models, other models (for example the Climate Change Committee) continue to recommend 'higher risk' feedstocks.

5.1 Summary of research

Since 2011 new analysis on the technical, constrained, and sustainable potential of biomass energy supply in the UK, Europe and globally has been undertaken by researchers, industry, and NGOs. A summary of the scope and findings of six such studies are summarised in Table 4 below. Data from these studies have been used to inform our later analysis of likely sustainable supply of domestic biomass for energy.

Table 4: Summary of key new analysis of biomass potential and sustainability at global and UK levels

Research	Scope	Summary	Key findings.
Energy Transitions Commission (ETC) (2021) Bioresources within a Net-Zero Emissions Economy: Making a Sustainable Approach Possible	Global	The report is an assessment of the total sustainable, low-emissions biomass supply available by mid-century. It is notable as it examines priority uses of bioresources within industrial sectors. It summarises critical industry and policy actions required during the 2020s to ensure the development of a sustainable approach to bioresources within a net-zero-emissions economy. **This analysis, which is comprehensive and takes on board competing biomass demands, has been used to inform our summary of likely biomass energy supply ranges at a global level (see subsection below).**	The authors determine a constrained role for bioenergy (~5% of final energy demand in 2050), with clean electricity as the dominant form of energy, complemented by hydrogen and fossil fuels with carbon capture and storage. They conclude sustainably sourced biomass can play a role, though its value is likely to be highest if used in materials (including in plastics feedstocks), in aviation, and in applications where it can be combined with carbon capture and storage to deliver net carbon dioxide removals.
Ricardo Energy & Environment (2017) Biomass Feedstock Availability	UK / Global	This report and model serve as an update to a 2010/11 model commissioned by DECC to estimate the potential bioenergy resources available to the UK from domestically sourced and imported feedstocks to 2030 and 2050. **This analysis, which is the most up-to-date and comprehensive view of UK biomass availability has been used to inform our analysis of sustainable sources of biomass.**	Their conclusions were that overall, the total underlying resource in 2030 is estimated to be 34% less than in the previous model developed in 2010/11. The accessible resource (after price-independent competing uses are removed) is estimated to be about 28% lower. Changes in individual feedstock resources vary, but the change in the overall total is largely driven by the fact that the short rotation forestry resource (estimated as 143 PJ in 2030 in the previous model) is now considered not available in 2030. This was based on the rationale that significant planting of this resource had not occurred in the period 2010 to 2015 as it was anticipated in the previous model. There are also significant reductions in the total waste and landfill gas resource. In terms of the accessible resource the main reduction comes in the energy crops estimate, due to more conservative assumptions about what could be planted by 2030.

Research	Scope	Summary	Key findings.
Climate Change Committee (2020) Biomass in a Low-Carbon Economy	UK	This report updates the CCC advice to Government on the role of biomass and bioenergy in decarbonising the UK economy through to 2050. It is based on the latest evidence on the circumstances in which biomass can be both low-carbon and sustainable. It sets out scenarios and requirements for the future supply of sustainable biomass and where this limited resource can be prioritised for the most valuable end-uses ('best use') to maximise greenhouse gas abatement across the economy to 2050.	The authors say there is significant potential to increase domestic production of sustainable biomass to meet between 5% and 10% of energy demand from UK sources by 2050. The lower end of this range can be delivered by fully exploiting the UK's organic waste resource (after reduction, reuse, and recycling) whilst maintaining today's level of agricultural and forest residue use. The upper end of this range requires over 1 million hectares of land to be used for energy crops (around 7% of current agricultural land) and increasing rates of tree planting (to 50,000 hectares every year by 2050).

Research	Scope	Summary	Key findings.
Welfie et al (2020) UK Biomass Availability Modelling - Supergen Bioenergy Hub	UK	The report identifies six categories of UK focused bioenergy models that have been developed to evaluate bioenergy from varying perspectives, scales, and scopes. Based on the models identified and reviewed, they compiled a list of reports that have been produced and used by key organisations in policy, strategy and research and collated estimates of biomass resource availability at global, European and UK scales.	The biomass resource models considered were found to have a relatively narrow set of environmental, economic, and social consequences of future demand pathways in relation to sustainability. The global scale central estimates for bioenergy demand demonstrate a significant divergence between models. A similar pattern is reported at the UK scale. This variation arises both through different approaches to modelling and due to underlying model assumptions, such as diet, future populations, yield improvement, and land availability and constraints. Estimates of resource availability from crops and forestry exhibit the highest variation across models, whereas there is more consistency in assumptions about the use of waste. They conclude that differences across the models reflect differing views across models of the role that bioenergy may play in the future UK energy system and uncertainties about the amount of bioenergy resource that will be available in the future given limited UK capacity for production and international competition. Some individual feedstocks, such as forestry and residues, show some consistency across different models which provides an insight into which feedstocks have growth / decline patterns that are commonly expected.

Research	Scope	Summary	Key findings.
BRE (2015) Potential and implications for using biomass for energy in the EU	Europe	This study sought to improve knowledge and understanding on the potential of sustainable biomass for energy with the objective of setting clear robust policy recommendations to ensure the sustainable use of biomass for energy in Europe.	Very limited role of stemwood and energy crops in 2030 (10% of mix in 2030). Focus on agricultural and forestry/agricultural residues. Total sustainable sources of bioenergy are <30% of technical potential after considering competing uses and sustainability criteria. For biomass they consider 'high risk' (e.g., energy crops and stemwood) they recommend that only 5%-10% of technical potential could be considered sustainable, due to competing uses.
Anthesis & E4Tech (2017) Review of Bioenergy Potential: Technical Report - For Cadent Gas Ltd.	UK	This report is a review of the UK Bioenergy Market, estimating the energy potential of renewable gas produced from waste and non-waste feedstocks, and comparing it with the data contained in the 2011 report "Bioenergy Review" by the Committee on Climate Change (CCC). The primary outcome was to generate a set of three illustrative scenarios (Low, Central and High) to 2050, combining the different UK biomass feedstocks suitable for renewable gas production, to produce new values for the total sustainable primary biomass potential. This study does not look at all categories of biomass feedstock so has not been used in this report.	They highlight a need to support development of best practices and improved sustainability frameworks, which will improve the understanding of potentials from agricultural and forestry residues, energy crops and short rotation forestry, and will provide assurance around their sustainable use.

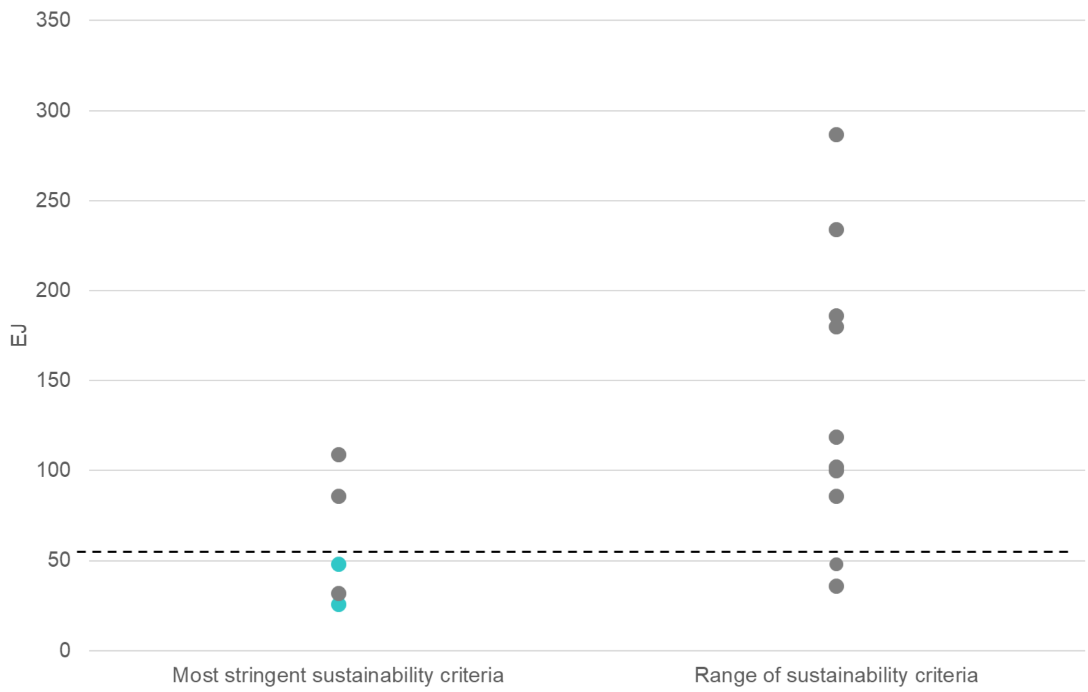
5.2 Global biomass supply – ETC review and model

The Energy Transitions Commission reviewed global biomass energy supply scenarios in fourteen studies that applied varying degrees of sustainability criteria - and more fully factored in constraints due to competing uses for biomass. The commission also contributed its own analysis of 'prudent' use of biomass for bioenergy.

Their analysis and review saw estimates for primary energy supply from biomass in 2050 differ by an order of magnitude - ranging from 30EJ to nearly 300EJ (see Figure 15, below, where blue dots are ETC's own analysis of minimum and maximum "prudent" biomass use for energy). For those studies that the ETC authors considered included the most "stringent" sustainability criteria, the range of primary energy supply was smaller: 30EJ to 109EJ, with the high end of the figures due to the inclusion of BECCS from non-food crops.

It is worth noting that the *current* total use of biomass (c 55EJ) is near the middle of the range of most sustainable scenarios in 2050. This could provide c. 9% of global primary energy supply in 2050[85] - the same contribution as in 2019.[86] The UK currently uses about 0.5 EJ of biomass for energy – with the Climate Change Committee Balanced Net Zero pathway seeing this rise to 0.8 EJ in 2050.[87]

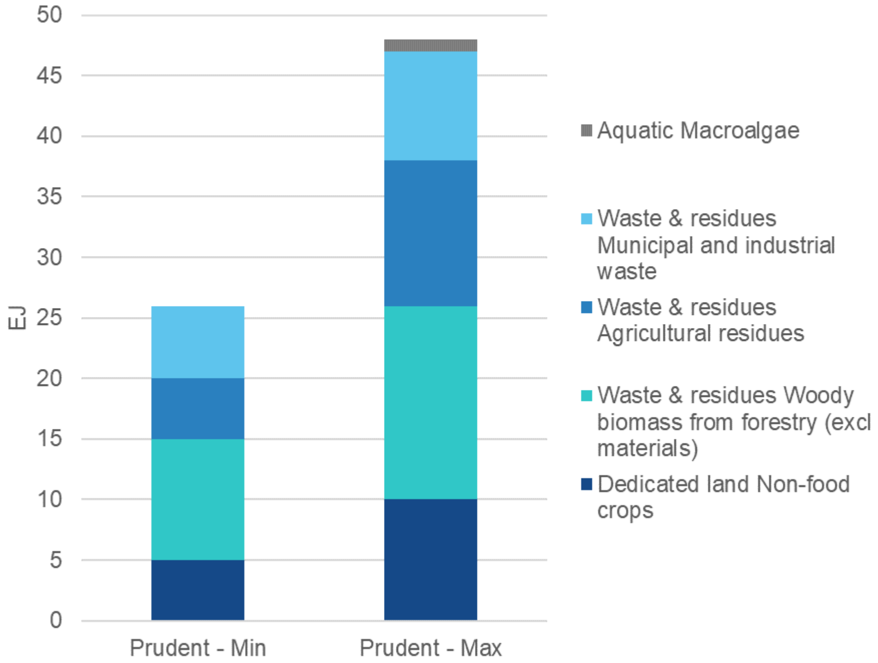
Figure 15: Range of global biomass supply estimates for 2050, from ETC (2021)[88]



[85] Assumes global primary energy supply in 2050 is 543EJ (assumption in IEA (2021) Net Zero by 2050 A Roadmap for the Global Energy Sector)
[86] Assumes solid biomass and biogas contributed 56EJ to total energy supply of 606EJ in 2019. Based on World Bioenergy Association (2021) Global Bioenergy Statistics 2021.
[87] Climate Change Committee (2020) Sixth Carbon Budget. Figure 2.8.
[88] Energy Transitions Commission (ETC) (2021) Bioresources within a Net-Zero Emissions Economy: Making a Sustainable Approach Possible. Dots highlighted in red are ETC's 'Prudent Minimum' and 'Prudent Maximum' scenarios of global primary energy supply from biomass in 2050.

In terms of the mix of feedstocks, the ETC scenarios see energy crops from dedicated land contributing c. 20% of primary bioenergy supply (see Figure 16 below). Marine sources of biomass were not expected to contribute significantly to energy supply - with the majority of biomass being from municipal, industrial, agricultural and forestry waste and residue streams.

Figure 16: Global supply of sustainable biomass in ETC illustrative scenarios[89]



Although the ETC analysis was undertaken at a global level, it is possible to 'downscale' their results to explore what this scale of sustainable biomass use could translate to from a UK perspective. Although this is approximate, this 'top down' approach provides a useful additional perspective on what the UK's share of global sustainable biomass use might be. Three approaches to downscaling were explored (see Table 5 below).

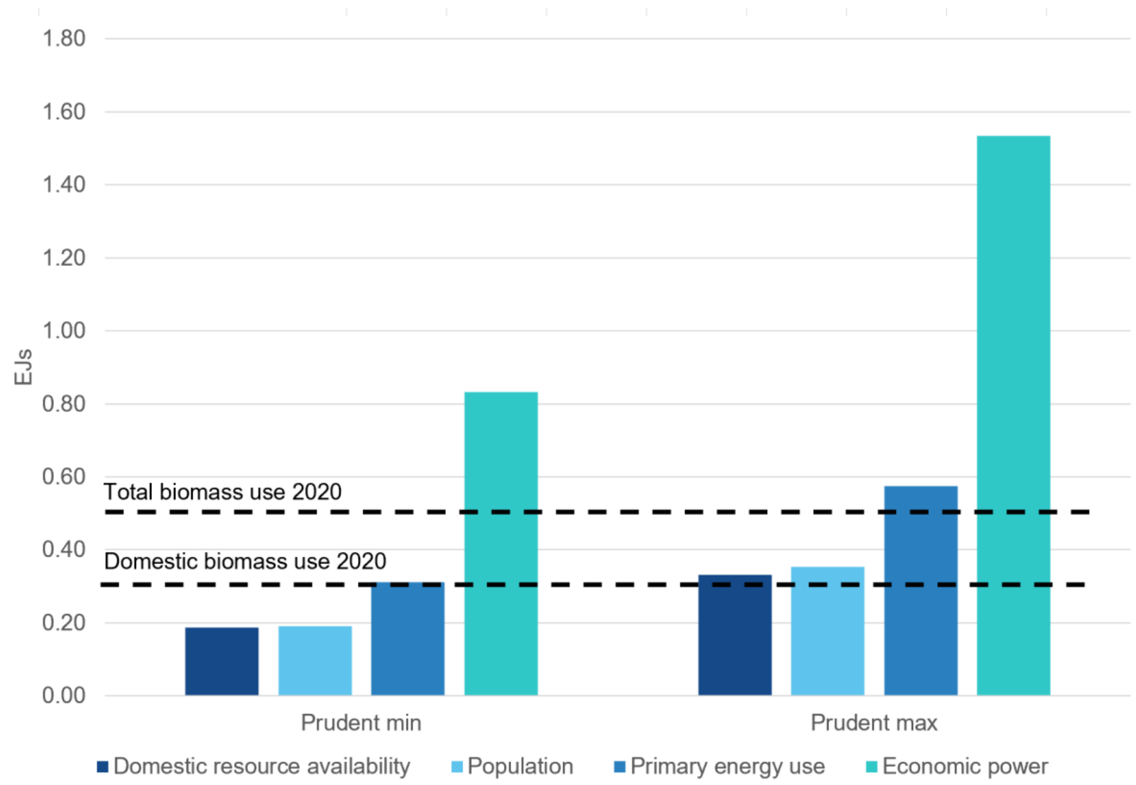
Table 5: Downscaling of ETC global analysis to UK - key assumptions

Description	Downscaling indicator	UK share of global biomass
Share based on domestic biomass resource availability	UK share of global cropland, forestry & waste, 2020	0.7%
Share based on human equity	UK share of global population, 2050	0.7%
Share based on primary energy demand (some import dependence)	UK share of global primary energy demand, 2050	1.2%
Share based on global economic power (unlimited imports)	UK share of global GDP, 2020	3.2%

[89] Energy Transitions Commission (ETC) (2021) Bioresources within a Net-Zero Emissions Economy: Making a Sustainable Approach Possible.

The results of this downscaling analysis, summarised in Figure 17 below, suggests that the UK is relatively under-resourced in domestic sustainable biomass compared to the size of its economy - due to its relative share of global cropland, planted forest, etc. Based on this analysis, domestic biomass primary supply in 2020 is of a similar scale to the UK's share of the global 'Prudent Maximum' scenario if downscaled to reflect the UK's share of global biomass resources or population, but considerably higher than UK's share of the global 'Prudent Minimum' scenario when downscaled for resource availability and population. Total biomass use (domestic and imported) is considerably higher than even the 'Prudent Maximum' scenario when downscaled for resource availability and population.

Figure 17: Downscaling of global ETC scenarios to UK based on resource availability, population GDP and energy use[90]



5.3 UK biomass resource supply – BEIS model

The most comprehensive and up to date model of potential UK bioenergy supply is BEIS's "UK and Global Bioenergy Resource Model".[91] This model and accompanying report explore the availability of bioenergy under different energy prices and constraints. The model outputs summarised in Figure 18, Figure 19 and Figure 20 below explore an example scenario where perennial crops are maximised for biomass.[92] This scenario shows that UK wastes

[90] Downscaling methodology: for share of global resources, we used data on UK share of global cropland, planted forest and population to estimate UK availability of energy crops, woody biomass, and waste streams. For the share of primary energy, we used data From BEIS and IEA.
[91] BEIS (2017) UK and Global Bioenergy Resource Model (Version 8.09)
[92] Scenario assumptions: Central energy price scenario (£6/GJ); Easy and medium barriers overcome; Maximise production perennial energy crops; BAU/continuing trends for international bioenergy

and residues available for bioenergy remain relatively flat between 2010 and 2050 (Figure 19) and replacing international biomass and agricultural residues would require ramping up of domestic dedicated perennial energy crop production (e.g., miscanthus). In Section 8 we utilise the outputs of this model to examine the sustainability of future bioenergy availability.

Figure 18: Total potential bioenergy resource available to UK – example scenario outputs from BEIS UK and Global Bioenergy Resource Model

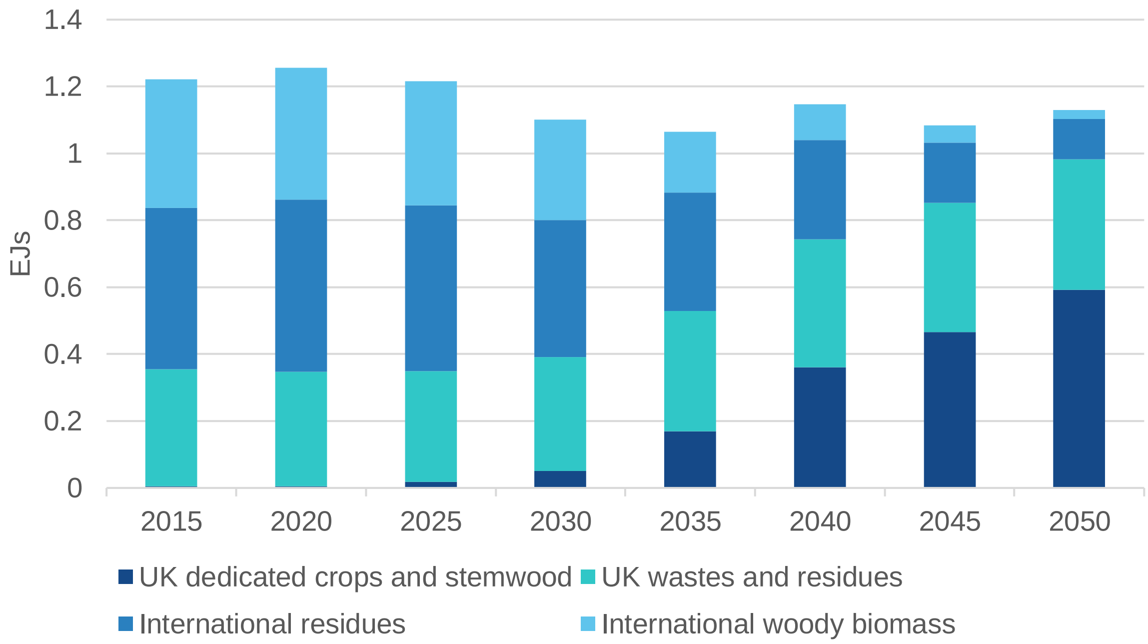


Figure 19: Total potential bioenergy resource available to UK – example scenario outputs from BEIS UK and Global Bioenergy Resource Model

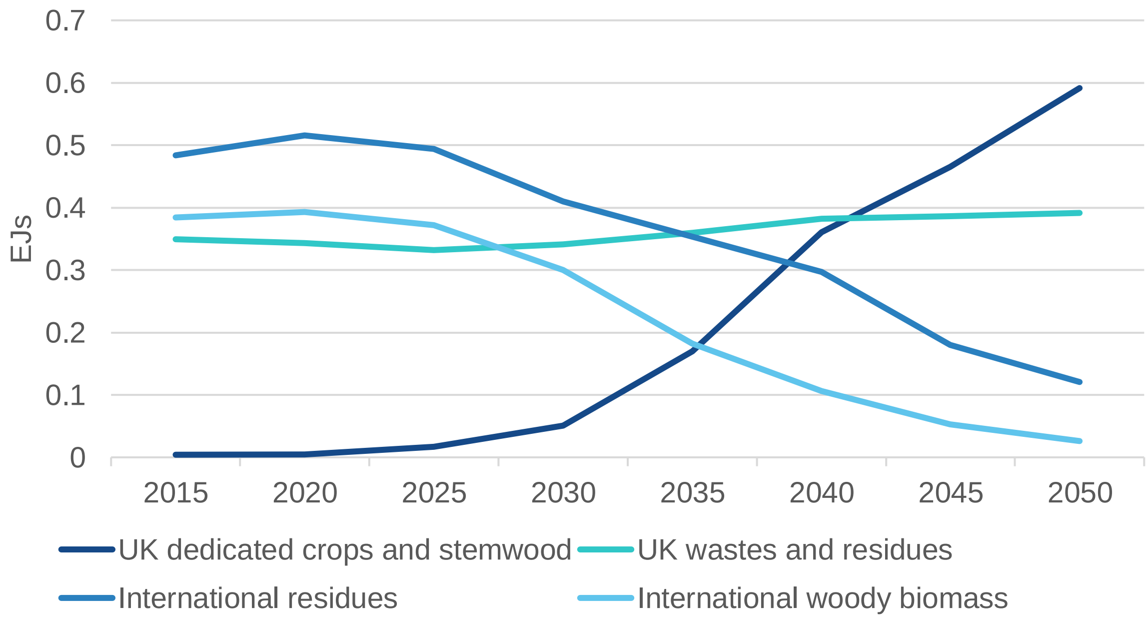
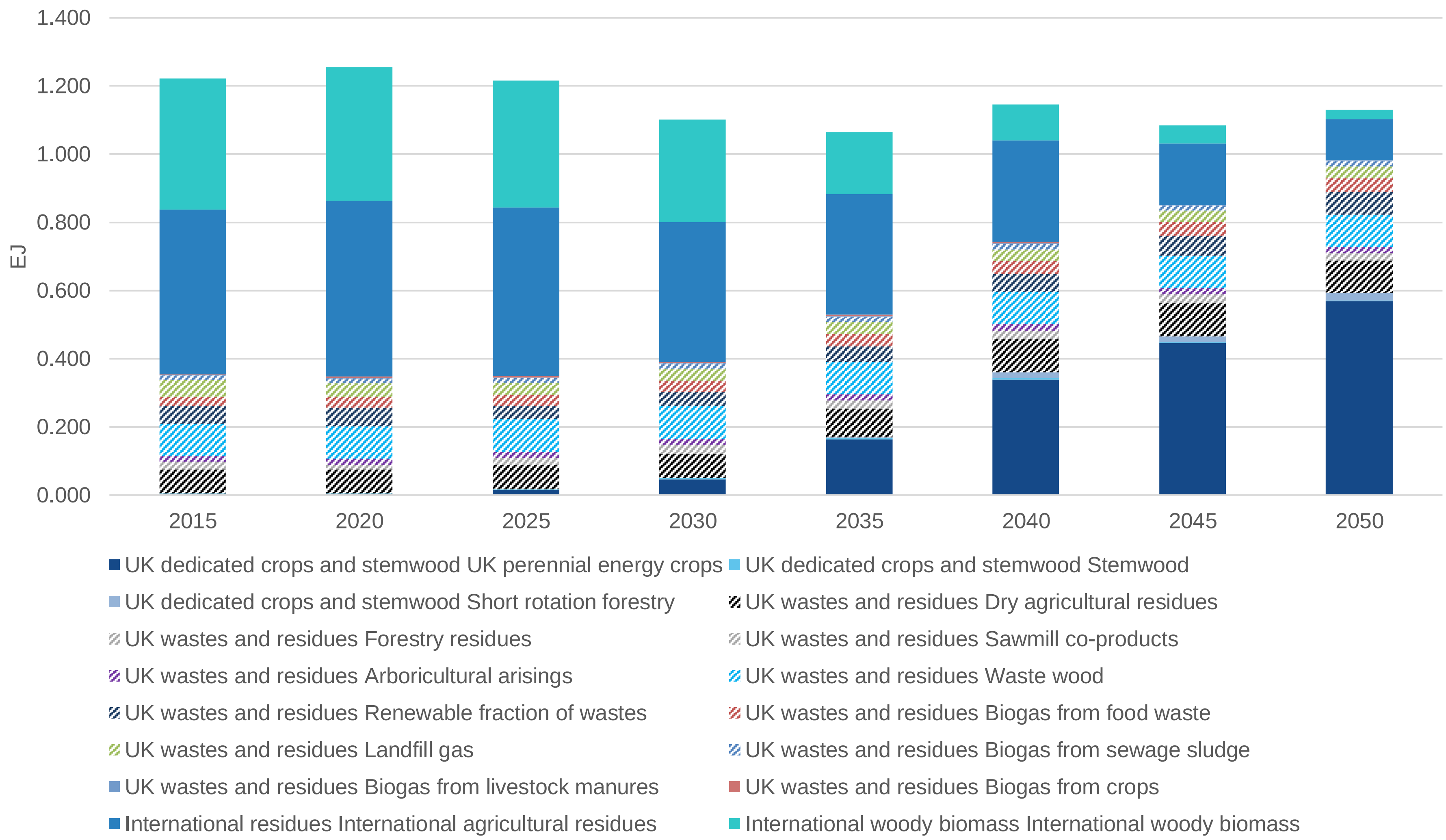


Figure 20: Total potential bioenergy resource available to UK – detailed results of example scenario outputs from BEIS UK and Global Bioenergy Resource Model



5.4 Future bioenergy use – Climate Change Committee

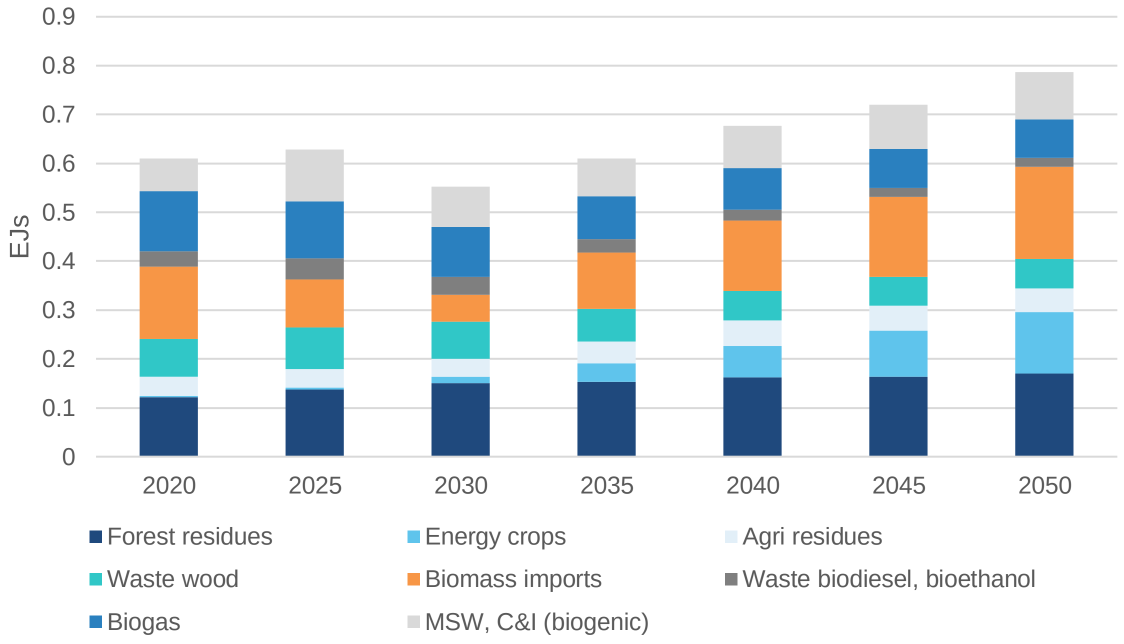
Finally, it is worth highlighting how the Climate Change Committee have integrated bioenergy into their net zero and carbon budgeting analyses. While they see a role for bioenergy in the UK's contribution to greenhouse gas reductions, they say they have been more cautious than in many scenarios assessed by the IPCC.

In the report 'Biomass in a low-carbon economy' the Climate Change Committee state there is the potential to increase the UK's use of 'sustainable' biomass to meet between 5 and 15% of UK primary energy demand by 2050.[93] Specifically noting that the lower end of this range could be achieved by maximising the potential of the UK's organic waste resource. Their Balanced Net Zero Pathway sees a c. 30% growth in biomass energy supply, principally from growth in UK energy crops (see Figure 21 below).

The upper end could be reached by expanding the growth of energy crops to around 1 million hectares of land (7% of current agricultural land), increasing the tree planting rate to 50,000 hectares per year by 2050 and by tripling current import levels. It is important to recognise that this will create direct competition with food production that needs to be addressed particularly given the current context and climate around food security due to geopolitical issues in Ukraine and Russia.

They also note that to achieve this it would rely on strong governance of biomass supply chain sustainability in both the UK and, because of the reliance on imports, worldwide.

Figure 21: Bioenergy and waste supply in Balanced Net Zero Pathway[94]



[93] The Committee on Climate Change (2018), Biomass in a low-carbon economy
[94] Based on data from Climate Change Committee (2020) 6th Carbon Budget reports. Figure 3.5e. Converted to exajoules from TWh.

6 Challenges in defining bioenergy sustainability

Key messages:

- Bioenergy systems have well documented potential for both positive and negative social, economic, and environmental impacts. These include greenhouse gas emissions, water, biodiversity – and wider resource competition with other sectors.
- Defining 'sustainability' of feedstocks is extremely challenging due to differences in the importance of some criteria, or different assumptions on life cycle impacts, future economic trends, and agricultural productivity.
- We identify four aspects of biomass systems and sustainability assessment approaches that contribute to significant uncertainty: Land use thresholds and constraints; Unintended consequences and system complexity; Carbon neutrality and biogenic carbon accounting; Rapidly changing socio-economic context.
- To deal with these challenges we propose the establishment of clear quota or land budget for the most land-intensive bioenergy sources. This is the only way to ensure that bioenergy – or indeed bioenergy carbon capture and storage – does not transgress ecological limits.

Given the nature of bioenergy systems, they have well documented potential for both positive and negative social, economic, and environmental impacts.[95,96, 97] These include:

- Greenhouse gas emissions - including direct and indirect land-use change impacts
- Competition with other sectors and uses (e.g., food, biomaterials) - with associated implications to food prices, food security, and the wider bioeconomy.
- Other environmental impacts of production (e.g., biodiversity, water, and air quality).

Defining 'sustainability' of feedstocks is extremely challenging due to differences in the chosen impact weighting of some criteria, or different assumptions on life cycle impacts, future economic trends and agricultural productivity.[98, 99] As a result, published estimates of 'sustainable' bioenergy supply can differ widely. The reality is that these uncertainties place

[95] Gough C, Garcia-Freites S, Jones C, Mander S, Moore B, Pereira C, Röder M, Vaughan N, Welfle A (2018). Challenges to the use of BECCS as a keystone technology in pursuit of 1.5ºC. Global Sustainability 1, e5, 1–9. https://doi.org/10.1017/sus.2018.3
[96] Robledo-Abad, C et al (2017) Bioenergy production and sustainable development: science base for policymaking remains limited. GCB Bioenergy (2017) 9, 541–556
[97] The Global Bioenergy Partnership Sustainability indicators for bioenergy (GBEP 2011)
[98] Energy Transitions Commission (2021) Bioresources within a Net-Zero Emissions Economy – Making a Sustainable Approach Possible
[99] Wang J et al (2018) Sustainability Assessment of Bioenergy from a Global Perspective: A Review

limitations on how precise we can be about the availability of biomass and land resources - or pinpoint when detrimental impacts outweigh benefits.[100,101]

We have identified four aspects of biomass systems and sustainability assessment approaches that contribute to significant uncertainty:

- Land use thresholds and constraints
- Unintended consequences and system complexity
- Carbon neutrality and biogenic carbon accounting
- Rapidly changing socio-economic context and technologies

In the next section we propose a framework for assessing, prioritising and incentivising feedstocks considering these challenges. We also explore if and how the rise of BECCS should – or should not - influence our view of feedstock sustainability.

6.1 Key considerations for bioenergy sustainability

6.1.1 Land use thresholds and constraints

Many forms of bioenergy are highly land intensive. Compared to solar PV, the amount of electricity that can be produced from a hectare of land from biomass is up to 100 times less.[102] As land is limited, land-intensive bioenergy or bioenergy carbon capture and storage could transform lands at a scale and to an extent that is, in the absence of protections, fundamentally unacceptable.[103]

The IPCC stresses the risks of side effects that could arise from inadequate control of bioenergy implementation – stating that "deployment of afforestation of naturally unforested land, or poorly implemented bioenergy, with or without carbon capture and storage, can compound climate-related risks to biodiversity, water and food security, and livelihoods, especially if implemented at large scales, especially in regions with insecure land tenure".[104]

While we can measure and compare the relative land use *efficiency* of different renewable or biomass feedstocks per unit of energy delivered, this does not address the core question in bioenergy sustainability of *how much land in aggregate* should be used for different purposes – for example food, energy, materials, carbon removals or nature. While the use of concepts such as 'indirect land use change' have attempted to integrate the impact of crop expansion into bioenergy climate change indicators, these measures are uncertain and do not adequately address the question of 'how much is too much'.

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[100] Calvin K et al (2021) Bioenergy for climate change mitigation: Scale and sustainability
[101] Energy Transitions Commission (2021) Bioresources within a Net-Zero Emissions Economy – Making a Sustainable Approach Possible
[102] European Academies Science Advisory Council. (2019). *Forest bioenergy, carbon capture and storage, and carbon dioxide removal: An update*. Retrieved from
[103] Reid, WV, Ali, MK, Field, CB. The future of bioenergy. *Glob Change Biol*. 2020; 26: 274– 286.
[104] IPCC (2022) Sixth Assessment Report – Working Group II – Impacts, Adaptation and Vulnerability Summary for Policy Makers

The inclusion of bioenergy or related carbon dioxide removal technologies at large scales in some IPCC or Climate Change Committee models is seen as 'needed' to reach climate goals rather than on what can be sustainably supplied within ecological boundaries. For this reason, in this report we propose the establishment of clear 'quotas' or a 'budget' for the most land-intensive bioenergy sources. This is the only way to ensure that bioenergy – or indeed bioenergy carbon capture and storage – does not transgress ecological limits.

6.1.2 Unintended consequences and system complexity

The relative environmental merit of alternative bio-energy production pathways has been the subject of many studies and much debate. Most studies have used the Life Cycle Assessment (LCA) method (or a variation upon it) to quantify the environmental burdens from bioenergy production. The methodology has several well-known limitations:

- The definition of system boundaries, the allocation of impacts, and the choice of data sources are often subjective.
- Good quality data often does not exist or may not be readily accessible.
- Spatial and temporal resolution is lost (critical for issues such as water, biodiversity). Conventional LCA is based on static modelling of GHG emissions which thereby neglects the temporal aspects of the occurrence of GHG emissions. However, the inclusion of these temporal aspects on GHG emissions could have a significant impact on the LCA results.
- Rebound effects, where environmental and cost efficiency improvements are cancelled out by greater consumption, are not considered.
- Most of the commonly used metrics identified lack context (i.e., a definition of what scale of impact is 'sustainable'). For example, the challenge of setting a blanket feedstock sustainability threshold for a 'water use' metric in m^3 per GJ, when the impact will depend on whether the production location is suffering from water stress and/or is under appropriate catchment-level management.

Bioenergy systems are highly susceptible to these shortcomings of the LCA approach and to differences in interpretation. This susceptibility arises because of the multi-scale and complex nature of biomass production and supply chains.

According to Terlouw, T. et al bioenergy technologies can exhibit substantial side effects including land use change, food and water competition and ecosystem disturbances.[105] A full understanding of these – often depending on regional, local, or even site-specific boundary conditions – is often missing from life cycle assessment studies. Scientific studies that have been conducted with the aim to model the diversion of agricultural resources towards production of biofuels and biomaterials show that there is a high degree of uncertainty regarding the magnitude of effects usually called indirect land use change (iLUC). iLUC, by definition, is impacted by changes to wider economic conditions – meaning iLUC impacts will change over time and in response to changes in dynamics such as trade or competition.

[105] Terlouw, T et al (2021) Life cycle assessment of carbon dioxide removal technologies: a critical review. Energy Environ. Sci. 14, 1701–1721

For example, although iLUC was acknowledged as a risk in the bioenergy model developed for BEIS by Ricardo in 2017, default data values were set to zero for each feedstock, as there were no widely accepted values for ILUC emissions.[106] This continues to be the case.

So, while iLUC is a real problem, single iLUC-factors (such as those used in EU renewable energy policy) are a poor guiding principle for bioenergy, land-use, and environmental policy making. To address this inherent uncertainty, industry body the Roundtable on Sustainable Biomaterials have developed Low iLUC Risk Biomass Criteria and Compliance Indicators that members can apply.[107]

For this reason, we do not think that biomass sustainability can be defined purely in terms of individual LCA-based indicators applied at feedstock level. Greater nuance is needed and the use of rules. LCA is only one of the tools to assess technologies on their (environmental) performance. Alternative assessment approaches should be used in a complementary way, such as a broader risk assessment approach explored in this report that assess wider economic and environmental risks of biomass use (e.g., resource and land competition).

6.1.3 Carbon neutrality and biogenic carbon accounting

One of the key areas of debate in bioenergy policy remains the accounting of biogenic carbon emissions from sources such as forestry: should biogenic sources of emissions be included in carbon comparisons, in the same way that fossil sources of CO_2 are? The best example of this is the conversion of Drax from the use of coal to be a significant user of wood pellets - in 2021 Drax used almost 8.5Mt of woody biomass in its operations[108] to produce approximately 12% of the UK's renewable electricity.

Drax describes its energy as 'carbon neutral' and states that with the assistance of carbon capture and storage technology it could be carbon negative. In making this claim, Drax ignores the biogenic CO_2 emissions (the "stack emissions") which are released when woody biomass is burnt for energy as well as important upstream biogenic CO_2 emissions. This is done in the understanding that these carbon emissions are accounted for in the Land, Land Use Change and Forestry (LULUCF) sector of the harvesting country and can therefore be classed as 'zero carbon' in the energy sector, to avoid double counting of emissions. The IPCC explicitly warns against representing biomass energy as producing zero emissions: "the approach of not including these [bioenergy] emissions in the Energy Sector total should not be interpreted as a conclusion about the sustainability or carbon neutrality of bioenergy."[109] In reality, biomass emissions in the LULUCF sector are often not accounted for at all or partially, depending on the land use accounting regime that countries choose to adopt.[110] Many experts have suggested that this accounting approach has been one of the

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[106] BEIS (2017) Biomass Feedstock Availability. Final report. Ricardo Energy & Environment
[107] Roundtable on Sustainable Biomaterials. (2015). *Low iLUC Risk Biomass Criteria and Compliance Indicators.*
[108] Drax Group plc Annual report and accounts 2021 - Drax (2022)
[109] IPCC (2021) Frequently Asked Questions. Available at: https://www.ipcc-nggip.iges.or.jp/faq/FAQ.pdf ("IPCC Frequently Asked Questions"). At Q2-10: "According to the IPCC Guidelines CO2 Emissions from the combustion of biomass are reported as zero in the Energy sector. Do the IPCC Guidelines consider biomass used for energy to be carbon neutral?" [C/6/185]
[110] Brack, D. (2017) The Impacts of the Demand for Woody Biomass for Power and Heat on Climate and Forests. Chatham House.

major incentives to burn biomass for energy, as it means that there is no official record in carbon accounts of the emissions released.[111]

In a complaint submitted to the UK OECD National Contact Point, a group of non-governmental organisations, including the RSPB, outlined arguments that while accounting for bioenergy emissions in the land sector is appropriate for country-level carbon balance sheets (provided this accounting is done to best practice guidance), it does not justify representations that woody biomass energy is carbon neutral or that its biogenic emissions should in some way be disregarded.[112]

Relatedly, the time lag associated with biogenic emissions and the re-growth of forests is also relevant to the topic of biomass sustainability given the short timescales needed for rapid decarbonisation (i.e., within the next 20-30 years). Conversion of land with high carbon stocks for bioenergy leads to very long carbon payback periods[113] making them less effective at delivering timely greenhouse gas mitigation.

The exclusion of biogenic CO_2 emissions from product and corporate emissions inventories is also an on-going area of method development. Many life cycle assessment studies of bioenergy systems exclude biogenic carbon from inventory data and ignore the time lag between CO_2 removals and emissions.[114] Current practice is often to exclude biogenic CO_2 emissions from main corporate greenhouse gas inventories – however that may change with the development of new guidance from the GHG Protocol.[115]

For these reasons, in the framework proposed in this research we prioritise biomass feedstocks that have short CO_2 payback periods. In our framework, this payback period is included as a proxy for assessing the overall climate mitigation effectiveness of each feedstock. This is currently omitted from the UK's sustainability criteria.

6.1.4 Rapidly changing socio-economic context and technologies

Finally, the sustainability of the supply of a biomass source will change over time. Feedstock sustainability assessments need to be updated regularly and plans should anticipate changes in supply, competing uses over time, climate change adaptation and resilience. Building an energy system around current 'sustainable' supply and use of biomass would be a mistake.

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[111] Brack, D.,& Birdsey & Walker (2021) 'Greenhouse gas emissions from burning US-sourced woody biomass in the EU and UK'
[112] Complaint submitted to the UK National Contact Point under the OECD guidelines for multinational companies in relation to the statements made by Drax Group PLC - Filed by The Lifescape Project, The Partnership for Policy Integrity, RSPB, Biofuelwatch, Conservation North and Save Estonia's Forests (2021)
[113] Gasparatos et al. (2017), Renewable energy and biodiversity: implications for transition to a green economy.
[114] Hosseinzadeh-Bandbafha et al (2021) Life cycle assessment of bioenergy product systems: A critical review. Advances in Electrical Engineering, Electronics and Energy 1
[115] GHG Protocol Land Sector and Removals Guidance https://ghgprotocol.org/land-sector-and-removals-guidance. The GHG Protocol establishes comprehensive global standardised frameworks to measure and manage greenhouse gas (GHG) emissions from private and public sector operations, value chains and mitigation actions.

6.2 BECCS and feedstock sustainability

Bioenergy Carbon Capture and Storage (BECCS) is the capture and permanent sequestration of biogenic CO_2 when biomass is processed for energy (e.g., combusted within a power plant). BECCS can theoretically result in net negative GHG emissions when the amount of CO_2 extracted from the atmosphere and permanently stored exceeds GHG emissions from the life cycle of BECCS systems, accounting for both infrastructure and feedstocks.

Despite this potential, the IPCC's AR6 Working Group II highlighted major risks of bioenergy and BECCS, such as:

- Threats to biodiversity, water and food security and livelihoods: *"afforestation of naturally unforested land, or poorly implemented bioenergy, with or without carbon capture and storage, can compound climate-related risks to biodiversity, water and food security, and livelihoods."*
- Severe impacts on species: "*severe impacts on species were likely if bioenergy were a major component of climate change mitigation strategies*."
- Food prices could rise significantly: "*BECCS has profound implications for water resources*" and "*can significantly impact food prices via demand for land and water*", with impacts including "*dispossession and impoverishment of small-holder farmers, food insecurity, food shortages, and social instability*".

Within our framework we acknowledge BECCS as a potential end-use technology for biomass and one which could drive significant increase in demand for biomass. However, we argue that – beyond improving the carbon balance of some feedstocks – a sustainable supply of a biomass resource must be assessed *independently from its end use.* The premise of BECCS is to deliver carbon negativity by capturing combustion emissions at the smokestack. However, the magnitude of carbon debt still applies in a BECCS lifecycle due to the whole system only delivering estimated negative emissions once feedstocks have grown back. Our approach also reflects the potential for failure or under delivery of CCS technology. Rather than framing these technologies as 'needed' to reach climate goals, policy must establish what can be sustainably supplied within ecological boundaries and then work to meet temperature goals by other means within these constraints (as we do on a number of other sustainability issues, such as human and animal welfare). This principle is supported by NGOs and international climate experts - for example, the IPCC states that "pathways that feature low energy demand show the most pronounced synergies and the lowest number of trade-offs with respect to sustainable development and SDGs (very high confidence)".

While some level of atmospheric carbon removal is necessary and can be achieved in synergy with other social and environmental goals, the deployment of negative emission technologies at a large scale is subject to several uncertainties and constraints, including potential adverse effects on the environment and trade-offs with other Sustainable Development Goals.

For this reason, we recommend the establishment of clear 'quotas' or a 'land budget' for land-intensive bioenergy technologies, such as BECCS. This is the only way to ensure that bioenergy carbon capture and storage does not transgress ecological limits.

6.3 Current approaches to defining biomass sustainability

Biomass sustainability is already assessed within various policy areas.

An example of this is the approach taken in the UK's Renewables Obligation (RO) laws. The Renewables Obligation and versions in devolved administrations are designed to incentivise large-scale renewable electricity generation in the UK. The scheme puts an obligation on licensed electricity suppliers in England and Wales, Scotland, and Northern Ireland to acquire an increasing proportion of electricity from renewable sources. In 2015, the Renewables Obligation Order was consolidated and the requirement for solid biomass and biogas stations to meet the sustainability criteria to receive support under the scheme was introduced. In Scotland and Northern Ireland, the requirement for solid biomass and biogas stations to meet the sustainability criteria was introduced in an amendment Order.

For example, all solid biomass and/or biogas stations ≥1MW must report against and meet "land" and "greenhouse gas" criteria to be eligible for Renewables Obligation Certificates.

For woody materials the land criteria could be met by sourcing materials produced using the Forest Stewardship Council (FSC) certificate scheme, Programme for the Endorsement of Forest Certification (PEFC) certification scheme, the Sustainable Biomass Program (SBP) or by bespoke evidence compiled by the generator. For non-woody materials the feedstock must not have been sourced from several types of land that have high conservation or carbon stock value (e.g., land that was primary forest any time after 2008).

Under the Renewables Obligation, arboricultural arisings and trees removed from an area for ecological reasons are deemed to be sustainable, and therefore meet the land criteria for woody biomass.[116] According to the regulations at least 70% of all the woody biomass used in a month must be obtained from a sustainable source (as defined in the Renewables Obligation), while the remaining 30% has to be legal but need not be sustainable.

The greenhouse gas criteria set thresholds of environmental performance that different feedstocks must meet, but this only covers the greenhouse gases generated in transport and processing of the material, not biogenic emissions released when it is combusted.

An operator of a generating station using solid biomass or biogas will need to report their average GHG emission value in grams of CO_2 per MJ of electricity. For most operators, the relevant GHG emission threshold is 79.2 gCO_2eq/MJ electricity. The threshold is slightly lower for generating stations classified as 'post-2013 dedicated biomass station' (66.7 gCO_2eq/MJ electricity). These thresholds become slightly lower over time (i.e., 50 gCO_2eq/MJ electricity by 1st April 2025). "Renewables Obligation Certificates (ROCs) are issued on a monthly basis and will be issued to electricity generated from those consignments that meet or are below the relevant GHG target that month."

The regulations set out detailed methods for calculating emissions from different types of biomass. According to the methodology, the total carbon intensity of biomass is the sum of the following, minus any 'emission savings' (e.g., from soil carbon accumulation):

[116] Ofgem. Renewables Obligation: Sustainability Criteria

- emissions from the extraction or cultivation of raw materials,
- annualised emissions from carbon stock changes caused by land use change
- emissions from processing, and
- emissions from transport and distribution.

Other methodological rules included exemptions and different calculation boundaries for different feedstocks for wastes and residues.

As noted in the analysis by Mai-Moulin et al[117] the Renewables Obligation sustainability criteria do not address all aspects of environment criteria, lacking in any recourse to 'protection of water resources, air & soil', 'ILUC' and 'LULUCF'. Whilst the Renewables Obligation does note that harm to ecosystems should be minimised, in particular by "(i) assessing the impacts of the extraction of wood from the area and adopting plans to minimise any negative impacts, (ii) protecting soil, water and biodiversity" – there are no quantifiable thresholds that would actually limit the use of a particular feedstock. By limiting sustainability criteria to LCA-type indicators and basic land exclusions/management requirements, current approaches to defining biomass sustainability do not consider broader system risks and impacts such as land and resource competition.

[117] Effective sustainability criteria for bioenergy: Towards the implementation of the European renewable directive II - Mai-Moulin et all (2021)

7 Framework for assessing biomass sustainability and implementing controls

Key messages:

- Rather than relying on a ‘preference’ expressed via hierarchy or by using a limited number of indicators to assess sustainability we propose the development of a framework that assesses *biomass sustainability risk* across all feedstock types and then uses the results of this assessment to implement differential controls for each feedstock.
- The framework encourages feedstocks that: have low land competition risk; have low resource competition risk with other sectors; deliver additional sustainability benefits (or avoids other sustainability risks); deliver high climate mitigation effectiveness over a short time horizon.
- The application of this scoring approach resulted in a range of biomass feedstock sustainability risk scores – from low to very high. The lowest risk feedstocks were landfill gas and renewable fractions of waste. The highest risk feedstocks were stemwood combustion and biomass from crops.
- Managing an appropriate level of adoption for land-intensive bioenergy will require a novel mix of policies and incentives that encourage appropriate utilisation in the short term but minimise lock-in in the longer term. We recommend using a framework such as the one presented in this section to enable differentiated controls on feedstocks that present different sustainability risks. Each of these will call for different types of general and feedstock-specific policy responses: feedstock use quotas; production standards; increased transparency/due diligence; and carbon intensity performance thresholds.

This section outlines a proposed framework for rating biomass sustainability that draws upon the findings and conclusions outlined in previous sections.

7.1 Risk framework

Rather than relying on a ‘preference’ expressed via a hierarchy (such as in IEEP, 2011) or by using a limited number of LCA-based indicators to assess sustainability we propose the development of a framework that assesses *biomass sustainability risk* across all feedstock types and then uses the results of this assessment to implement differential controls for each feedstock.

The framework consists of a set of qualitative and quantitative criteria that can be applied consistently to all feedstock types. The criteria presented in this report could be further developed and refined if adopted by government and industry – consultation on the assessment detail would be needed to increase both the credibility and consistency for each feedstock. The approach focuses on scoring feedstocks against the four areas of concern flagged in the previous section, namely that more sustainable biomass can be defined as material that exhibits the following characteristics:

- Has low **land competition** risk
- Has low **resource competition** risk
- Delivers **additional sustainability benefits (or avoids other sustainability risks)**
- Delivers **high climate mitigation effectiveness** over a **short time horizon**

The criteria used for scoring feedstock are summarised in Table 6 below.

Currently no weighting is applied to these criteria as we consider all four of equal importance when assessing biomass feedstock sustainability. This is something that could be further refined.

The framework was applied to the following fifteen categories of biomass (see Table 7). These categories were drawn from BEIS's Biomass Feedstock Availability model.

Table 6: Criteria for assessing feedstock sustainability– with scoring criteria

Criteria	Description	High (3)	Moderate (2)	Low (1)
Land competition risk	Degree to which feedstock production drives additional land use and so risks (indirect) land use change	Feedstock is primary economic output of land-based production system	Feedstock is by-product or residue of land-based system. Product has economic value.	Feedstock is waste product of land-based system – or not derived from land-based production system. Feedstock has no economic value to producer
Resource competition risk	Degree to which feedstock is used by competing value chains	Feedstock is input to significant and/or rapidly growing non-energy sector use (e.g., construction, bioplastics, pharma)	Feedstock is used as input to non-energy sector – however these are relatively low value and unlikely to be out-competed by using feedstock as energy vector	Biomass is not currently used by other non-energy sector
Wider sustainability risk	Degree to which feedstock production impacts on biodiversity and other environmental and social development goals	Feedstock production or use negatively impacts on other sustainable development goals (e.g., biodiversity, air pollution, local communities)	Feedstock production has negligible additional environmental of social impacts	Feedstock production has potential additional sustainable development benefits
Climate mitigation risk	Degree to which feedstock carbon intensity aligns with Paris Agreement transition over short term[118].	Carbon intensity not aligned to 2C or 1.5C energy pathways or has long term biogenic carbon payback (i.e., >=20 years)	Carbon intensity aligned to 2C emissions pathway for 2050 (20.3gCO_2e/MJ) **and** biogenic CO_2 has short- or medium-term pack back (<20 years, > 5 years)	Carbon intensity aligned to 1.5C emissions pathway for 2050 (5.9gCO_2e/MJ) **and** biogenic CO_2 has short payback (i.e., < 5 years)

[118] Thresholds from https://www.transitionpathwayinitiative.org/

Table 7: Feedstock names and descriptions

Feedstock	Description
Landfill gas	Gas that is produced under anaerobic conditions in a landfill
Renewable fraction of wastes	The fraction of energy produced from waste incineration that can be classed as renewable (organic element).
Biogas from food waste	Food that was originally meant for human consumption but for various reasons is removed from the human food chain.
Arboricultural arisings	The cut wood left after tree surgery that may either be removed, burnt, or left on the site chipped, logged for firewood. Typically subcategorised as either 'green', 'brash' or 'heavy timber/round wood'. Covers conservation-management related arisings, including reeds/rush. This is a very diverse category and so may warrant further sub-categorisation in policymaking, to ensure definitions reflect comparable materials (for example roundwood will have different climate profile to rush).
Sawmill co-products	Sawmills recover ~50% of the input material as sawn product, with the balance being coproduct in the form of bark, sawdust, and woodchip.
Marine resources	Macro-algae could also be used in anaerobic digestion plants to produce biogas for combustion or production of biomethane
Waste wood	Wood, which is not virgin timber (that is, wood that has already been used for another purpose) and associated residues such as off-cuts.
Biogas from sewage sludge	Sewage sludge is a semi-solid residue, or by-product, arising from the treatment of municipal wastewater.
Forestry residues	Forestry residues are a by-product from forest harvesting- consisting of branches, leaves, bark, and other portions of wood. We have not included whole tree thinnings in this category (see notes below in Stemwood section).
Dry agricultural residue	Crop residues left in an agricultural field after the crop has been harvested. These residues include stalks and stubble, leaves and seed pods - mainly wheat straw in UK.
Biogas from livestock manures	Organic matter, mostly derived from animal faeces and urine, but normally also blended with plant material (often straw). Often collected from animal bedding/housing that has absorbed the faeces and urine. Can be in a solid or liquid form.
Short rotation forestry	Short rotation forestry (SRF) consists of planting a site and then felling the trees when they have reached a size of typically 10-20 cm diameter at breast height. Depending on tree species this usually takes between 8 and 20 years.
UK perennial energy crops	Crops which are grown for combustion. Short Rotation Coppice (SRC) species such as willow and poplar to 'grassy' energy crops such as Miscanthus.
Stemwood	The wood of the stem(s) of a tree, i.e., the above ground main growing shoot(s). Stemwood includes wood in main axes and in major branches of a given diameter and length. To be conservative we have included whole tree thinnings in the 'Stemwood' rather than 'Forestry residues' category. While thinning can be beneficial for biodiversity and be an inevitable, low value co-product of a well-managed forest system, there is some evidence that bioenergy demand can stimulate excessive thinning with no climate change benefit119. The definitions and requirements set for forestry residues and thinnings require particular attention in any framework for assessing sustainability of feedstocks
Biogas from crops	A plant grown for use in the generation of energy or the production of fuels such as bioethanol.

119 Buchholz, T et al (2021) When Biomass Electricity Demand Prompts Thinnings in Southern US Pine Plantations: A Forest Sector Greenhouse Gas Emissions Case Study. Frontiers in Forests and Global Change. Vol 4; Brack D. et al (2021) Greenhouse gas emissions from burning US-sourced woody biomass in the EU and UK

7.2 Results

The summary results of the assessment of the fifteen categories of biomass feedstock are shown in Table 8 below. Full details of feedstock assessments are available in Annex 1.

A detailed summary of one of the feedstock scores – agricultural residues – is shown in Table 9. On first view, agricultural residues such as straw might be considered a waste and so presenting negligible sustainability risk if used for energy production. However, residues such as straw are a co-product of crop production and can have significant commercial and practical value to farmers. Additional demand for straw for bioenergy use is therefore likely to lead to some additional pressure on land use.

Residues can also be used as inputs to other processes higher up circular economy hierarchy e.g., fodder for animal feed, animal bedding, left to avoid soil erosion and soil improvement. If residues are used for bioenergy, then this will result in replacement of materials with inputs from other sectors.

Removal of residues can also result in wider environmental impacts. For example, straw removal can lead to higher aquatic eutrophication, due to nitrate leaching and emissions from the manufacturing process of the compensating nitrogen fertilisers.

The life cycle emissions of straw (excluding biogenic carbon) range from 6-18gCO_2e/MJ. This is classed as aligned to 'Well Below 2°C' carbon intensity for the energy sector (i.e., not aligned to levels needed for 1.5°C temperature goals in 2050). The feedstock has the benefit of being very short cycle biogenic CO_2 emissions.

Overall, the considerations above placed agricultural residues in the 'high risk' group and so warrant tighter controls on use for bioenergy as excessive use could have significant unintended consequences.

Table 8: Summary of feedstock scores from apply framework

Feedstock	Land risk	Resource risk	Other SDG risk	Climate mitigation risk	Total score	Rank	Risk rating
Landfill gas	1	1	1	2	5	1	**2. Low**
Renewable fraction of wastes	1	1	1	2	5	1	**2. Low**
Biogas from food waste	1	2	1	1	5	1	**2. Low**
Arboricultural arisings	1	2	2	1	6	4	**3. Moderate**
Sawmill co-products	1	2	2	1	6	4	**3. Moderate**
Marine resources	1	2	2	2	7	6	**3. Moderate**
Waste wood	1	3	2	1	7	6	**3. Moderate**
Biogas from sewage sludge	1	2	2	2	7	6	**3. Moderate**
Forestry residues	2	2	2	1	7	6	**3. Moderate**
Biogas from livestock manures	2	2	2	2	8	10	**4. High**
Dry agricultural residue	2	2	3	2	9	11	**4. High**
UK perennial energy crops	3	2	2	2	9	11	**4. High**
Short rotation forestry	3	3	2	2	10	13	**5. Very high**
Stemwood	3	3	2	3	11	14	**5. Very high**
Biogas from crops	3	3	2	3	11	14	**5. Very high**

Table 9: Example of scoring approach for dry agricultural residues (straw)

Criteria	Details	Score
Land competition	Straw is a co-product of crop production and can have significant commercial and practical value to farmers. Additional demand for straw for bioenergy use likely to lead to some additional pressure on land use	2
Resource competition	Residues can be used as inputs to other processes higher up circular economy hierarchy e.g., fodder for animal feed, animal bedding, left to avoid soil erosion and soil improvement.[120] If residues are used for bioenergy, then this will result in replacement of materials with inputs from other sectors	2
Wider sustainable development goal alignment	Removal of residues risks wider environmental impacts. For example, straw removal can lead to higher aquatic eutrophication, due to nitrate leaching and emissions from the manufacturing process of the compensating nitrogen fertilisers.[121]	3
Climate mitigation effectiveness	Life cycle emissions (excluding biogenic carbon) range from 6-18gCO_2e/MJ.[122] This is classed as aligned to 'Well Below 2C' carbon intensity for energy sector. The feedstock has benefit of being very short cycle biogenic CO_2 emissions.	2
Total score		**9 (High)**

7.3 Using risk assessment outputs in policy making and implementation

Ensuring an appropriate level of adoption for land-intensive bioenergy will require a novel mix of policies and incentives that encourage appropriate utilisation in the short term but minimise lock-in in the longer term.[123]

We recommend using a framework such as the one presented above to enable differentiated controls on feedstocks that present different sustainability risks. Having assessed the relative risk of different feedstocks we have grouped them into three categories: low risk; moderate risk; high/very high risk. Each of these will call for different types of general and feedstock-specific policy responses (see Table 10 below):

- **Feedstock use quotas:** Limits set by policymakers on total land areas and/or tonnages of materials that can be used in UK bioenergy generation. These are informed by an assessment of UK sustainable land use that balance competing uses, such as nature, food and materials production. Setting quotas is a key means of limiting the potential for bioenergy technologies to get locked-in[124]
- **Production standards & transparency**: Feedstock-specific requirements will need to be included to mitigate broader environmental and social risks e.g., quantified limit

[120] Monforti et al. (2015) Optimal energy use of agricultural crop residues preserving soil organic carbon stocks in Europe.
[121] Parajuli, R et al 2014
[122] Ricardo (2017) The UK and Global Bioenergy Resource Model. BEIS
[123] Reid, WV, Ali, MK, Field, CB. The future of bioenergy. *Glob Change Biol*. 2020; 26: 274– 286.
[124] Reid, WV, Ali, MK, Field, CB. The future of bioenergy. *Glob Change Biol*. 2020; 26: 274– 286.

on quantity of crop residues that can be removed from agricultural land to ensure risks of soil depletion or water pollution are minimised. This would also include requirements on excluding biomass from protected areas, etc. In addition to feedstock-specific production standards much greater transparency and due diligence is needed on the nature of medium and higher feedstocks (in particular where there is the potential for feedstocks to be assumed to be residues, when in fact they are the primary output of a production system e.g., forestry residues could be stemwood).

- **Carbon intensity performance thresholds:** Specific carbon intensity thresholds that feedstocks must meet ($kgCO_2e/MJ$). These are ratcheted-up over time and are 1.5°C pathway aligned. These should be applied to all feedstocks to ensure climate mitigation is maximised. This measure is similar to those already used in bioenergy policy.

Table 10: Policy implications of feedstock risk assessments

Feedstock risk level	Description	Feedstock use quota or budget	Production standards & transparency	Carbon intensity threshold
Very low / Low	 Growth in these feedstocks will have no additional land use pressure. They do not compete with other non-energy sectors and have limited environmental/ social issues *Example: Renewable fraction of wastes*			✓
Moderate	 Growth in these feedstocks will have some limited additional pressure on land use and materials can often compete with some, relatively low value, non-energy sectors. Additional feedstock-specific environmental or social risks may need to be mitigated. *Examples: Sawmill co-products; forestry residues*		✓	✓
High / Very high	 Growth in these feedstocks is highly likely to drive additional land use, they have strong competition for resources and frequently have longer carbon payback times or wider sustainability risks. In theory these feedstocks could drive significant land use. *Examples: UK perennial energy crops; Stemwood*	✓	✓	✓

8 Exploring UK-level scenarios based on sustainability risk

Key messages:

- Based on the feedstock scores developed, and availability data from the BEIS UK and Global Bioenergy Resource Model, it was possible to explore the likely availability of feedstocks of different risk levels.
- UK availability of biomass of low or moderate risk is relatively stable over the period (c. 0.27EJ in 2030 and 0.29EJ in 2050).
- We found a reasonably good alignment, both in terms of overall scale of low/moderate risk resource in the data sources reviewed.
- Overall, these models show that low or medium risk biomass could supply c. 4% of primary energy supply – just above the levels currently supplied by all biomass.

Based on the feedstock scores developed, and availability data from the BEIS UK and Global Bioenergy Resource Model, it was possible to explore the likely availability of feedstocks of different risk levels. Figure 22 and Table 11 below shows UK availability of biomass – low or moderate risk biomass is relatively stable over the period (c. 0.27EJ in 2030 and 0.29EJ in 2050). The increase in high/very high-risk biomass from 2030 reflects the potential for growth in UK perennial crops one of the Ricardo scenarios.

Figure 22: UK availability of domestic biomass by sustainability risk – example scenario

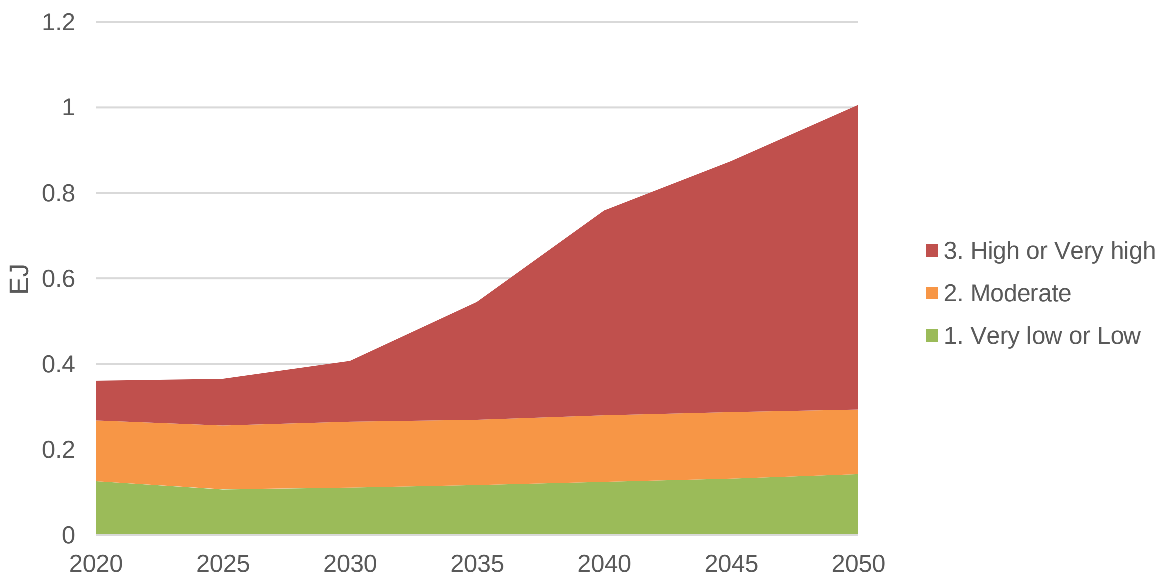
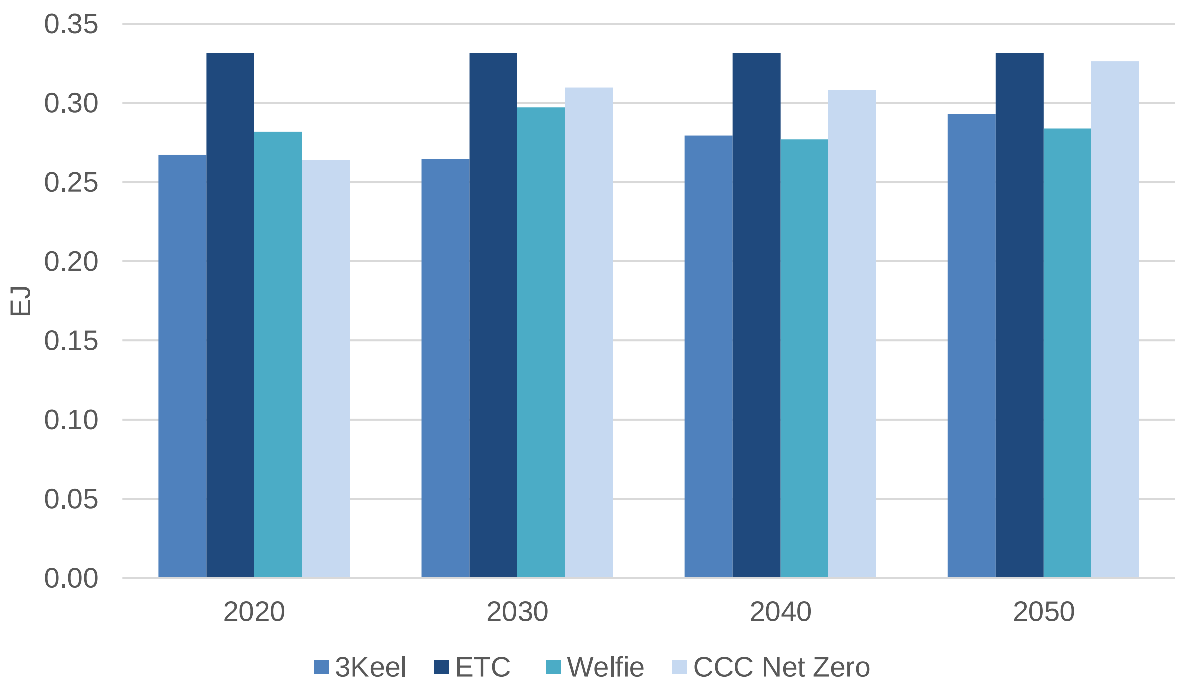


Table 11: Availability of Very low/Low or Moderate risk feedstocks, 2020-2050 (EJs)

Year	Very low or Low	Moderate	Grand Total
2020	0.14	0.13	0.27
2025	0.15	0.11	0.26
2030	0.15	0.11	0.26
2035	0.15	0.12	0.27
2040	0.16	0.12	0.28
2045	0.16	0.13	0.29
2050	0.15	0.14	0.29

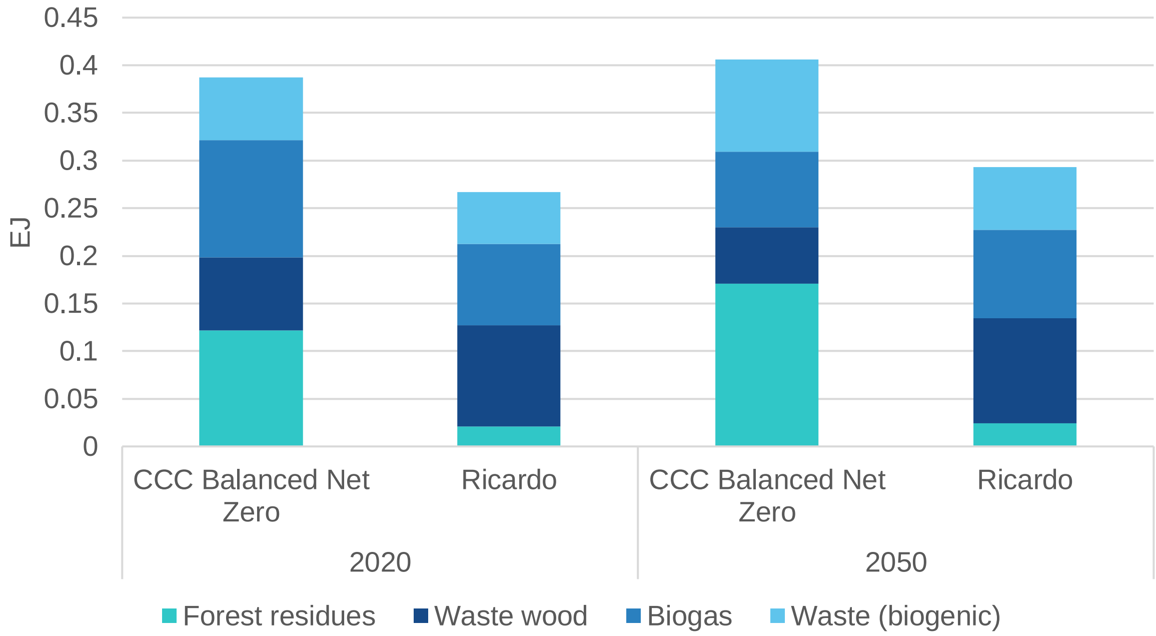
Comparing the Ricardo low/moderate risk results with comparable feedstocks in other data sources reviewed in this project we can see a reasonably good alignment both in terms of overall scale of low/moderate risk resource – and trends in production between now and 2050 (see Figure 23 below). These models show that low/medium risk biomass could supply c. 4-5% of primary energy supply – just above the levels currently supplied by all biomass. It is worth noting, the Climate Change Committee model is at the top end of this group as it assumes much greater availability of forestry residues (see Figure 24).

Figure 23: Comparison of domestic availability models ***showing only biomass feedstocks scored as low/moderate in our analysis***[125]



[125] "Ricardo" is the BEIS UK Biomass Model. "ETC (Downscaled)" is the Energy Transitions Commission model, downscaled to UK based on UK share of cropland, planted forest, etc. (see Section 5.2 for explanation). "CCC Balanced Net Zero" is from the Climate Change Committee. "Welfie" is the Supergen Bioenergy Hub UK Biomass Availability Modelling Scoping Report.

Figure 24: Comparison of Low/Moderate risk feedstock availability (2020) – CCC and Ricardo



9 Conclusions and recommendations

9.1 Key conclusions

Since the IEEP report was published in 2011, the environmental, economic, and social context of renewable energy and climate policy has moved on significantly.

There has been a significant fall in the cost of non-biomass renewable technologies and the emergence of new technologies that have the potential to compete in biomass's traditional space. Given the relative cost and risks of biomass – and the increasing attractiveness of alternatives, it is likely biomass will need to rely on market demand created by policy. Land-intensive bioenergy systems face a significant risk of being seen as a 'legacy' fuel by 2050 – and so it will be critical to avoid physical, institutional, and behavioural lock-in when setting biomass policies in the 2020s.

Meanwhile, carbon dioxide removal has now become the third 'use' of biomass alongside energy and biomaterials. The implication of this trend is that technologies such as BECCS could become the primary rationale for promoting biomass-based energy as arguments over its energy security, climate mitigation and energy storage benefits fall away due to the performance and availability of alternatives.

Methods and criteria used by policymakers for assessing biomass sustainability continue to not adequately take into account the key challenges that this technology presents – in particular: the need to establish clear limits on overall land use; take into account wider resource competition; and fully account for biogenic carbon emissions.

Existing UK biomass supply models include 'higher risk' feedstocks (such as dedicated energy crops) and do not propose any rationale for limiting their expansion on ecological grounds. Global models that apply sustainability constraints assume stemwood and energy crops are limited in use and only on degraded/marginal land.

There is good agreement between studies on the levels of domestic waste and residues (low/medium sustainability risk) feedstocks which are likely to be available in the UK in coming decades. Based on data reported in these studies, this to be between 0.35 and 0.40 exajoules of primary energy in 2050 (c. 5% of primary energy demand). These resources are unlikely to increase but stay reasonably static over the next three decades – meaning that lower risk biomass energy is unlikely to grow in significance.

9.2 Recommendations

Based on the research and analysis summarised in this report we recommend the following are addressed within the forthcoming Biomass Strategy:

- The upcoming Biomass Strategy should seek to develop a risk-based assessment framework similar to the one explored in this report. It should be an approach that 1) can be applied to all feedstock categories consistently 2) considers a broad set of sustainability risks – in particular land use and resource competition; and 3) identifies higher risk feedstocks that should have greater controls applied to them. Although environmental risks were the focus of this project, any framework should also consider social risks.

- For the highest risk feedstocks, feedstock use quotas are needed. These are limits set by policymakers on total land areas and/or tonnages of materials that can be used in the UK energy system. These should be informed by an assessment of UK land use that balances competing uses, such as nature, food, and materials production. As the UK has been a global leader on national carbon budgeting through the work of the Climate Change Committee, there is an increasingly urgent need to develop a similar UK-level 'land budget' for enabling policymakers across government to balance competing land use priorities. Setting quotas in this way is a key means of limiting the potential for energy technologies to drive unsustainable resource use[126]
- It is also important that the GHG implications of are completely accounted when assessing biomass sustainability – including full accounting of biogenic emissions. Overall, sustainable biomass should deliver energy in line with carbon intensities that are aligned to 1.5°C emissions pathways for the energy sector with a short "carbon payback period". Full accounting of greenhouse gases should largely prevent the use of stemwood to be used for bioenergy.
- Given the variability in biomass feedstocks and sustainability, the Biomass Strategy should establish - a transparent, complete, and consistent set of feedstock categories with clear definitions. This would ensure a more consistent and coherent approach to feedstock assessment and use. The categorisation of feedstocks should be sufficiently granular to enable differentiation on the basis of key sustainability criteria.
- Given biomass sustainability is influenced by broader economic and technological contexts, any assessment of feedstock sustainability needs to be reviewed regularly (for example every 3-5 years).
- Given the radically different political and market context, the Biomass Strategy should also explore the potential of different biomass sources to deliver energy security and independence, reducing reliance on imports and our overseas footprint. We expect biomass systems that are highly dependent on imported raw materials unlikely to deliver significant energy security dividends at the scales they are used, as well as posing significant challenges to sustainability monitoring.
- Significant users of biomass should be required to report in detail on the precise nature of biomass being used, with greater chain-of-custody and transparency for feedstocks. Learnings from 'due diligence' requirements on deforestation within the UK Environment Act 2021 should be drawn upon to develop strong requirements on due diligence of biomass feedstocks, so as to reduce risks identified in this report.
- The Government should seek to incentivise energy demand reduction as a priority, alongside innovation and research into new technologies that compete against biomass (e.g., heating and energy storage). Low carbon, sustainable negative emissions technologies should also be incentivised to avoid BECCS overreliance (e.g., Direct Air Capture).

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[126] Kalkuhl, M., et al (2012). Learning or lock-in: Optimal technology policies to support mitigation. Resource and Energy Economics, 34(1), 1–23.

10 Annex 1 – Individual feedstock profiles

10.1 Dry agricultural residues

Feedstock description and uses	Agricultural residues - mainly wheat straw in UK Direct combustion - Ethanol production - Gasification	
Sustainability Criteria	**Details**	**Score**
Land competition	Straw is not a waste product - and can have good value for farmers. However, it is lower value co-product compared to the main product (e.g., wheat). On this basis it presents a moderate land use risk	2
Resource competition	Residues can be used as inputs to other processes higher up circular economy principles e.g., fodder for animal feed, animal bedding, left to avoid soil erosion and soil improvement.[127]	2
Wider sustainable development goal alignment	Straw removal can lead to higher aquatic eutrophication, in particular due to nitrate leaching and emissions from the manufacturing process of the compensating nitrogen fertilizers. [128] This impact could be mitigated by integrating catch crops into a rotation. [129]	2
Climate mitigation effectiveness	Parajuli, R et al 2014 calculated straw burned in a CHP had a gross GWP of 4.31 g CO_2-eq per 1MJ of heat production. This analysis took into account a reduction in soil carbon sequestration from the residue's removal. The UK Renewables Obligation default carbon intensity figure for wheat straw is 2gCO_2e/MJ feedstock energy - one of the lowest feedstocks in their dataset. Straw production and consumption represents a very short-term biogenic carbon cycle (i.e. c. 1 year). The emissions from dry agricultural residues could range from 6-17.5gCO_2e/MJ depending on if it's in chips/bales form or pellets (BEIS Bioenergy model)	2

[127] Optimal energy use of agricultural crop residues preserving soil organic carbon stocks in Europe – F, Monforti et al (2015)
[128] Life Cycle Assessment of district heat production in a straw fired CHP plant - Parajuli, R et al (2014)
[129] Intercropping reduces nitrate leaching from under field crops without loss of yield: A modelling study – Whitmore & Shroder (2007)

Risk score		4
Risk rating		High
Availability commentary and trend	Rules surrounding burning (with no energy capture) of crop residues[130] should push this feedstock into a higher stream of usefulness. However, this may be dependent on how easily the residues are gathered as to what their best use would be - arguably leaving to avoid soil erosion / improvement may be best.	

10.2 Forestry residues

Feedstock description and uses	Forestry residues are a by-product from forest thinning and harvesting - consisting of branches, leaves, bark, and other portions of wood.	
Sustainability Criteria	**Details**	**Score**
Land competition	Forestry residues are a by-product from forest harvesting and would therefore not be the sole driver of any land use. However, there is clearly a value to this feedstock within the energy sector and others and furthermore new forestry looks to be a focus of many projections to help with contribution to Net Zero so an increase in biomass potential from this feedstock resource could influence land use change. Other options are available for the land use that may have a better environmental impact than straight forestry addition, and therefore indirectly forestry residues. (e.g., increased domestic food production)	2
Resource competition	The end use of forestry residues is primarily in bioenergy due to the nature of the mix of materials it is often not uniform enough for any other value chains. Not all forest residues should be removed, some must be left in situ to provide ecological benefits (e.g., to provide habitat, and improve soils), however, this is somewhat self-selecting as removal of the forest residues in commercial settings requires it to be economically viable to do so. Other draws on this resource would be for animal bedding, conversion to biofuels and to be left on-site for improved ecological benefits with the latter being the most preferred but providing no economic value.	2

[130] Government Guidance - Burning crop residues: restrictions and rules for farmers and land managers (https://www.gov.uk/guidance/burning-crop-residues-restrictions-and-rules-for-farmers-and-land-managers)

Wider sustainable development goal alignment	Forestry residues can provide beneficial habitat and food for species. Tarr et al projected changes over 40 years under a baseline 'business-as-usual' scenario without bioenergy production. They found that bioenergy demand had potential to influence trends in habitat availability for some species. The analysis found that shrub-associated species would gain habitat under some scenarios because of increases in the number of regenerating forests on the landscape, while species restricted to mature forests would lose habitat.[131] Additional issues can be loss of soil sediment with the complete removal of forestry residues - good litter cover reduces the ability of rain to wash the surface, which then reduces the loss of soil sediment.[132] Therefore, leaving this feedstock to avoid soil erosion and improve soil condition is a valid alternative to bioenergy.	2
Climate mitigation effectiveness	For forestry residues (treetops and limbs left over from sawtimber harvesting), burning this material as bioenergy instead of leaving it onsite to decompose adds significant net carbon to the atmosphere because burning wood emits carbon immediately, while decomposition emits CO_2 over a much longer period. No additional carbon sink appears as a consequence of the decision to burn this material, so the emissions are not uniquely offset when the wood is used for energy. The emissions from dry forestry residues could range from 2.1-15.4gCO_2e/MJ depending if it's in chips/bales form or pellets (BEIS Bioenergy model)	1
Risk score		7
Risk rating		Moderate

[131] Projected gains and losses of wildlife habitat from bioenergy-induced landscape change – N, Tarr et al (2016)
[132] Evaluation of Forest Conversion Effects on Soil Erosion, Soil Organic Carbon and Total Nitrogen Based on Cs Tracer Technique – X, Zhu et all (2019)

Availability commentary and trend	Searle and Malins and subsequently Carraro determine that total production of roundwood and therefore indirectly forestry residues is assumed to remain constant to 2050. Declining paper production could reduce roundwood harvests in future, while other factors such as renewable energy policy could increase it; overall there is no clear indication that roundwood production will change over time.[133] [134] Policy is likely to play an important role in the availability of this feedstock and as policy on trees is a devolved matter then we may see varying growth in this feedstock across the devolved nations. A clear example of this is the England Woodland Creation Offer.[135]	

[133] Waste and residue availability for advanced biofuel production in EU Member States – Searle & Malins (2016)
[134] Waste and residue availability for advanced biofuel production in the European Union and the United Kingdom - C, Carraro et al (2021)
[135] https://www.edie.net/defra-unveils-new-grant-scheme-for-woodland-creation-as-post-brexit-green-watchdog-finally-launches/

10.3 Stemwood and whole tree thinnings

Feedstock description and uses	The wood of the stem(s) of a tree, i.e., the above ground main growing shoot(s). Stemwood includes wood in main axes and in major branches of a given diameter and length. This also includes whole-tree thinning as the specific removal of some trees allowing others more space to maintain photosynthetic capacity.	
Sustainability Criteria	**Details**	**Score**
Land competition	New forestry looks to be a focus on many projections to help with contribution to Net Zero Any new forestry considerations should specifically target carbon stock, not growth rate or coverage. Other options are available for the land use that may have a better environmental impact than straight forestry addition (e.g., increased domestic food production)	3
Resource competition	Light construction purposes. According to the Forestry commissions 2020 Forestry Statistics, only 18% of the deliveries (Deliveries should not be confused with removals, which are the quantities of roundwood that is harvested from UK woodland) UK grown softwood is used for wood fuel. Conversely, 80% of UK grown hardwood is used for wood fuel. However, hardwood makes up a significantly smaller proportion of the total deliveries (<8%). Total deliveries to wood fuel (softwood and hardwood) account for approximately 23% of total deliveries. This feedstock other uses (sawmills, pulp mills, wood-based panels, fencing and exports) account then for a significant proportion of the deliveries. Some of the final end use of the other uses will ultimately end up in the energy sector but the primary use of these feedstock is non-energy related.[136]	3
Wider sustainable development goal alignment	The conclusions drawn by Calvin et al (2021) show that depending on previous land use, widespread deployment of monoculture plantations may contribute to mitigation but can cause negative impacts across a range of other sustainability criteria. Strategic integration of new biomass supply systems into existing agriculture and forest landscapes may result in less mitigation but can contribute positively to other sustainability objectives.[137] This is more applicable to other woody biomass feedstocks such as SRC and SRF where monoculture will be a greater issue, however, the same can be said for the forestry sector if biodiversity is not a key consideration in development of new forestry.	2

[136] Forestry Statistics 2020 – Forestry Commission (2020)
[137] Bioenergy for climate change mitigation: Scale and sustainability – K, Calvin et al (2021)

	Managed forestry which is less land efficient (than energy crops), producing a more limited harvest for materials and residues for energy and with longer growth periods before harvest. However, managed forests can support greater biodiversity than intensive energy crop plantations (while still far less so than natural forests) and tend to be more multifunctional.	
Climate mitigation effectiveness	The emissions from stemwood could range from 1.7-23.8gCO_2e/MJ depending on if it's in chips/bales form or pellets (BEIS Bioenergy model). Stemwood has a long carbon payback period.	3
Risk score		11
Risk rating		High
Availability commentary and trend	Based on wider policy around sustainable timber production it is important that any increase in new managed forestry and subsequent biomass harvesting is routed to the most beneficial end use which in this case would be into construction. This aligns with the Ricardo availability expectation for 2030 for Stemwood which shows a decrease in availability compared with previous models.	

10.4 Short Rotation Forestry

Feedstock description and uses	Short rotation forestry (SRF) consists of planting a site and then felling the trees when they have reached a size of typically 10-20 cm diameter at breast height. Depending on tree species, this usually takes between 8 and 20 years, and is therefore intermediate in timescale between SRC and conventional forestry.	
Sustainability Criteria	**Details**	**Score**
Land competition	Short Rotation Forestry (SRF) is specifically grown for a quicker turnaround biomass product and therefore is a significant driver for land use change. It is often seen as an attractive option compared with agricultural biomass crops as it requires the input of relatively low levels of fertiliser, pesticides and herbicides and can also be established on marginal land, thereby not competing with food production. [138] However, there are question marks over whether this would be the case if implemented at a greater scale. Additionally, SRF has the potential to deliver greater volumes of biomass from the same land area than alternative biomass crops.[139]	3
Resource competition	SRF traditionally had a significant contribution in industries like paper, packaging, tissue, paperboard, plywood, veneer, etc. More recently the focus of SRF developments would be on biomass for energy. Therefore, competition for this feedstock is likely to be relatively low.	3
Wider sustainable development goal alignment	Afforestation has proven to be an effective method for increasing C stocks, in many soil types, it should be noted that it can cause a decrease in some soil types such as deep peats, however there are wider issues linked to afforestation with economic focussed forests such as SRF. Xi Zhu et al (2019) found that the conversion of coniferous broad-leaved mixed forests into economic focussed forests aggravated soil erosion.[140] Due to the short rotation, measures are often taken to accelerate establishment and maximise growth such as highly intensive weed control and fertiliser application (Purse and Leslie 2016) that can impact on biodiversity, and soil health. Additionally, promising options for use in SRF, such as Eucalyptus, can present other negative environmental issues and in the UK can have issues with frost damage effecting their overall suitability to a	2

[138] The technical potential of Great Britain to produce ligno-cellulosic biomass for bioenergy in current and future climates – A, Hastings (2014)
[139] Short Rotation Forestry: Review of growth and environmental impacts – Helen Mackay (2011)
[140] Evaluation of Forest Conversion Effects on Soil Erosion, Soil Organic Carbon and Total Nitrogen Based on Cs Tracer Technique – X, Zhu et all (2019)

	sustainable bioenergy mix.[141] Analysis from Griffiths et al (2018) that bird and mammal biodiversity is considerably lower in SRF stands than unmanaged forests.[142]	
Climate mitigation effectiveness	The emissions from short rotation forestry (SRF) could range from 2.3-12.6gCO_2e/MJ depending if it's in chips/bales form or pellets (BEIS Bioenergy model)	2
Risk score		10
Risk rating		High
Availability commentary and trend	Whilst there has been lots of research and trials on SRF, particularly by Forestry Commission Scotland, there are very few examples of specific SRF in the UK. With the largest plantation an area of 24.2 ha of eucalypts established at Daneshill in Nottinghamshire, eastern England as an energy forest.[143] Because of the rapid growth rates and the relatively high calorific value of their timber, this feedstock still has good interest as an alternative to other dedicated uses of land for biomass production. In their balanced pathway, the CCC suggests that up to 708,000 hectares of land could be dedicated to biomass production, which has led to an increased interest in the role of perennial energy crops and SRF as biomass feedstocks to deliver GHG savings in the land use and energy sectors. Within the CCC pathways, there is no defined split between SRF and SRC so it is hard to determine the exact balance of one feedstock over another; however, it is generally thought that crops are favoured in these pathways over SRF.	

[141] A review of the suitability of eucalypts for short rotation forestry for energy in the UK. New Forests – A, Leslie et al (2019)
[142] Environmental effects of short-rotation woody crops for bioenergy: What is and isn't known – N, Griffiths et al (2018)
[143] A review of the suitability of eucalypts for short rotation forestry for energy in the UK. New Forests – A, Leslie et al (2019)

10.5 Sawmill co-products

Feedstock description and uses	Sawmill co-product is an alternative and valuable source of woody biomass.	
Sustainability Criteria	**Details**	**Score**
Land competition	The sawmill co-product is an alternative and valuable source of woody biomass. Although sawmill recoveries are improving slightly, this still represents a significant source of biomass material. As this is a co-product the main driver for any land use would be forestry for sawn timber. The competition for the co-product into different value chains does not affect the land use.	1
Resource competition	Current outlets from sawmills have been historically to the boardmill industries for the production of chipboard and MDF. Increases in levels of using recycled material have put pressure on this market, which is dominated by a few large players in the United Kingdom. Sawmills recover ~50% of the input material as sawn product, with the balance being co-product in the form of bark, sawdust, and woodchip. From the Forestry Statistics 2020 they summarised that in 2019 of the total volumes of the other softwood products sold from sawmills (excluding sawn wood) 20% was to the bioenergy industry (including pellet manufacturers), A further 8% was used internally for heat and energy. >70% is therefore destined for other uses (construction, wood processing) and would currently be considered the primary use of sawmill residues.	2
Wider sustainable development goal alignment	This is co-product so does not directly cause negative impacts. It is reliant on the UK timber industry and sawmills to ensure sustainable sourcing of products that do not have negative environmental impacts. Important to ensure that the largest proportion of felled trees make it to the highest tier of end use (in this case sawnwood). Waste should be minimised where possible and co-products should be genuine residues from the processing.	2
Climate mitigation effectiveness	The emissions from sawmill co-products could range from 4.5-11.6gCO_2e/MJ (BEIS Bioenergy model)	1

Risk score		6
Risk rating		Moderate
Availability commentary and trend	As this is essentially a by-product of the UK timber industry then policy relating to the increased use of timber in construction could have a significant impact on the availability of this feedstock. Should be noted that the existing sawmill co-products will be from UK sourced roundwood and imports (3.4 million cubic metres - UK production, 7.2 million cubic metres of sawnwood imported).[144] Domestic forestry policy in the UK is a devolved matter. Different nations will have slightly varying priorities and policies. There is a general consensus in increasing afforestation rates for carbon sequestration; increasing the use of timber in construction; improving the resilience of woodlands and forests will be a key requirement. Whilst this doesn't necessarily translate to increased sawmill residues for use in bioenergy, it is likely that the availability will at least remain constant with a potential upturn if policies are widely adopted.	

[144] UK Wood Production and Trade: provisional figures – Forest Research (2020)

10.6 Arboricultural arisings

Feedstock description and uses	The cut wood left after tree surgery that may either be removed, burnt, or left on the site chipped, logged for firewood. Typically subcategorised as either 'green', 'brash' or 'heavy timber/round wood'. Covers conservation-management related arisings, including reeds/rush.	
Sustainability Criteria	**Details**	**Score**
Land competition	Low impact as the arisings from this activity are often seen as necessary to keep area's safe (in the form of tree surgery and kerbside clearances) and promote new growth (pollarding). These are existing resources that generally could not be used for other purposes. Under the Renewables Obligation, arboricultural arisings and trees removed from an area for ecological reasons are deemed to be sustainable, and therefore meet the land criteria for woody biomass.[145]	1
Resource competition	Competition from being left onsite for biodiversity and soil regeneration, used for composting (commercial scale) Resource can and is used for a variety of other non-energy related end uses, including landscaping, composting, timber, firewood, animal bedding and left on site. A 2010 study for the Forestry Commission Scotland highlights that the end use and in particular ratio of split of end use will vary with type of organisation and sector and the importance of the Proximity Principle. Minimisation of the distances between the source of biomass arisings and the end use makes sense in economic as well as in environmental terms, as the viability of recovering woody biomass is strongly influenced by transport distances and costs, particularly for lower grade material.[146] Whilst not unsurprising this is particularly import for this type of feedstock and how arisings can be sourced in a variety of locations and complexities for extraction that could ultimately affect the level of competition of other non-energy value chains.	2
Wider sustainable development goal alignment	Arboricultural arisings are primarily from necessary processes in order to maintain good health of wildlife habitats, restoration of vegetation and to ensure safety of other infrastructures (e.g. roadside clearances). Indeed, it forms an important part of conservation management activities in a range of sectors. For example, reedbeds, where without management, natural succession will progress and the reedbed will be lost, so some form of management will be required at some stage if the reedbed is to be retained.	2

[145] Renewables Obligation: Sustainability Criteria – Ofgem (2018)
[146] Arboricultural Arisings Scotland Study, Report to the Forestry Commission Scotland - International Synergies Ltd in association with Nevin Associates Ltd (2010)

	Use of these arisings in bioenergy production is an additional benefit that can occur when economically and environmentally prudent to do so and does not drive the production of this feedstock.	
Climate mitigation effectiveness	The emissions from arboricultural arisings could range from 2.1-15.4gCO_2e/MJ depending if it's in chips/bale form or pellets (BEIS Bioenergy model)	1
Risk score		6
Risk rating		Moderate
Availability commentary and trend	The future capacity of these arisings will not be insignificant but not a huge fraction of the overall potential for bioenergy. Not expected to reduce, given the need for new housing and tree surgeries or park management in areas surrounding railways, roads and new developments and the increase spotlight on tree planting. Consideration on availability for use in bioenergy should first be given to the source of the arisings and categorisation on their best use. E.g. only removed from site if seen a danger if left in place (railways / roadsides) otherwise priority should be given to relocation and left for soil conditioning. Currently green leafy material including grass cuttings is generally seen as a subsection of this feedstock that has little value in biomass energy production. However, consideration could be given to using more for biogas production as highlighted by Ecotricity in their Save our Boilers campaign.[147] Whilst the grass harvesting suggested is at a farm level and could be considered an energy crop if it was genuine arisings then there could be merit in trying to harness energy from it. Conservation arisings could form an important area for growth for this feedstock. There are approximately 1.3 million hectares of heathland and 2.8 million hectares of open wetlands in the UK.[148] Plants that are removed from these habitats include heather, gorse, bracken, reed and rush. Yields can vary and harvesting is very dependent on location but alternatives are often burning in situ for management purposes. Additional arisings from hedgerow management, a process to substantially improve the condition of hedges and their value as wildlife habitats, is a further underutilised resource. Even if conservative estimates on availability for harvesting and modest yields are assumed, there would be significant resource available that could be utilised for bioenergy.	

[147] Ecotricity Save Our Boilers Campaign website (https://www.ecotricity.co.uk/our-news/2021/save-our-boilers)
[148] UK natural capital: land cover in the UK - ONS (2007)

10.7 Waste wood (from industry, households)

Feedstock description and uses	Waste wood that is not virgin timber. Associated residues such as off-cuts, shavings chippings and sawdust, either treated or not treated -Electricity, heat or CHP	
Sustainability Criteria	**Details**	**Score**
Land competition	Wood waste is not from virgin timber therefore land use competition is low.	1
Resource competition	There is a hierarchy of use before energy - namely use in construction as documented by the Wood Recyclers Association.[149] AeA (2011): there is competition from panel board manufacture, horticulture, agriculture and wood energy plants.	3
Wider sustainable development goal alignment	A 2016 LCA (Morris) shows that wood waste combustion is typically the least preferable management option from a combined climate, human health and ecosystems impacts perspective versus recycling into reconstituted wood products or papermaking pulp, or even versus landfilling with methane capture and flaring or use to generate electricity.[150]	2
Climate mitigation effectiveness	4gCO_2e/MJ is reported by Forest Research in UK.[151] This is based on wood pellets (10% MC starting from dry wood waste. The emissions from waste wood could range from 0.7-11.2gCO_2e/MJ depending if it's in chips/bales form or pellets (BEIS Bioenergy model)	1
Risk score		7
Risk rating		Moderate

149 Wood Recyclers Association Hierarchy (https://woodrecyclers.org/about-waste-wood/)
150 Wood Waste: Recycle, Bury, or Burn? - Morris (2016)
151 Carbon emissions of different fuels – Forest Research (https://www.forestresearch.gov.uk/tools-and-resources/fthr/biomass-energy-resources/reference-biomass/facts-figures/carbon-emissions-of-different-fuels/)

Availability commentary and trend	AEA (2011) noted that competition from panel board manufacture, horticulture, agriculture and wood energy plants could constrain arisings and gave a forecast of 4.3 Mt (2010) to 4.1 Mt (2030) available for bioenergy generation. Using these forecasts, the CCC reported 22 TWh bioenergy potential from wood waste in 2030, unchanged to 2050. The UK is a major exporter of non-hazardous wood waste with an average export of 300+ KT every year, which could also affect supply for national use.[152]	

[152] Transboundary flows of woody biomass waste streams in Europe – IEA Bioenergy (2018)

10.8 Renewable fraction of wastes

Feedstock description and uses	Energy from Waste from the renewable fraction of MSW. AeA (2011) defined residual waste as the waste left after segregation of specific wastes for recycling (such as paper, card, plastics, glass, etc.) Can be combined with CCS. - Incineration with energy recovery	
Sustainability Criteria	**Details**	**Score**
Land competition	None	1
Resource competition	None	1
Wider sustainable development goal alignment	Conversion of waste to generate bioenergy which will help to reduce environmental pollution from landfill. However, according to an LCA by Pour et al (2016)[153], eutrophication and human toxicity (non-cancer) of MSW-CCS systems have a less benign impact than Landfill gas (LFG)-CCS systems.	1
Climate mitigation effectiveness	Non-collected CH_4 from landfills becomes a major greenhouse gas emission source. MSW-CCS systems create net negative emission by around -0.7 kg CO_2, e.q. per kg of wet MSW incinerated.[154] The emissions from renewable fractions of waste could range from 7.7-11.1gCO_2e/MJ (BEIS Bioenergy model)	2
Risk score		5
Risk rating		Low

[153] A sustainability framework for bioenergy with carbon capture and storage (BECCS) technologies – N, Pour et al (2016)
[154] A sustainability framework for bioenergy with carbon capture and storage (BECCS) technologies – N, Pour et al (2016)

Availability commentary and trend	Policy drivers will be to reduce the amount of organic waste into these streams and therefore expectation should be that policy ensures this 'feedstock' reduces. Ricardo (2017) used estimates based on a Defra estimation of English baseline arisings (45Mt in 2015) and extrapolated this data to a UK baseline. The modelling assumed that all waste that is not recycled is deemed residual and available for bioenergy generation. Results were 11.0Mt in 2015 and 13.6Mt in 2050 of residual waste available for bioenergy generation.	

10.9 Food waste

Feedstock description and uses	Food meant for human consumption that ends up in food waste stream. Associated residues such as off-cuts, shavings chippings and sawdust, either treated or not treated -Conversion of organic matter into methane by bacteria then biogas is used as the energy source.	
Sustainability Criteria	**Details**	**Score**
Land competition	None	1
Resource competition	There is a hierarchy of use for food waste - there are food recovery hierarchies that demonstrate best uses for food e,g, WRAP report (2021).[155] Food waste for AD is preferred over composting. WRAP estimates that 1.9mt is used for AD/composting.	2
Wider sustainable development goal alignment	Conversion of food waste to generate bioenergy which will help to reduce environmental pollution from food waste in landfill. Priority should be given to addressing food waste in the first place – with commitments such as Courtauld 2030 that are pushing for a reduction in food waste by 50% by 2030 - this is major concern reflected both in availability and risk of incentivising food waste as a bioenergy feedstock	1
Climate mitigation effectiveness	The emissions from biogas from food waste could range from 5-15gCO_2e/MJ (BEIS Bioenergy model)	1
Risk score		5
Risk rating		Low

[155] Food surplus and waste in the UK – key facts – WRAP (2021)

Availability commentary and trend	- WRAP 2021 estimates the UK food waste (excluding green waste) at 9.5 Mt in 2018. Availability should not be relied upon with trends of reducing food waste. - WRAP is supporting the UN's Sustainable Development Goal 12.3 to halve food waste by 2030. - AeA (2011) modelled WRAP data on food and green waste availability. The report identified food and green waste arisings as 18–20 Mt/y (WRAP data). The total waste available for energy was cited as 15.8 Mt, and for 2030 estimates, no growth in these baseline arisings was assumed (Anthesis, 2017).	

10.10 Landfill gas

Feedstock description and uses	Landfill gas (LFG) is by definition the gas that is produced under anaerobic conditions from residual waste in landfill. -The collected LFG is used as fuel for industrial boilers and power generation in internal combustion engines, gas turbines and steam turbines.	
Sustainability Criteria	**Details**	**Score**
Land competition	None	1
Resource competition	Genuine waste - whilst the availability may drop as waste is reduced there is almost no competition for the gas produced and capture of this gas should be maximised where possible. Very little option on routes for use of this gas except in combustion or potential upgrade for grid injection.	1
Wider sustainable development goal alignment	Unlike other biogas production from feedstocks, this is a genuine waste gas that would otherwise be emitted to the atmosphere regardless.	1
Climate mitigation effectiveness	The net emission of LFG-CCS systems is approximately 0.59 CO_2, e.q. in global models per kg of wet MSW supplied.[156] The UK Government BEIS factors state 0.06gCO_2e/MJ of energy. Lee et al (2017) note that landfilled food waste under poor LFG collection currently generates a lot of LFG emissions, and therefore has a large potential for GHG benefits when collected and used in WTE technologies.[157] The emissions from landfill gas could range from 8-12gCO_2e/MJ (BEIS Bioenergy model)	2
Risk score		5
Risk rating		Very low

[156] A sustainability framework for bioenergy with carbon capture and storage (BECCS) technologies – N, Pour et al (2016)
[157] Evaluation of landfill gas emissions from municipal solid waste landfills for the life-cycle analysis of waste-to-energy pathways – U, Lee et al (2017)

Availability commentary and trend	Ricardo (2017) reported the biogenic fraction sent to landfill as 15 Mt in 2015 and 9.4 Mt in 2050. However, forecasts do not take into account long-term availability of actual landfill capacity (Anthesis, 2017). Data published by the Environment Agency for England show a steady reduction in landfill input and capacity and suggest that if available landfill volumes continue to reduce by the rate of input seen in 2015, the available landfill capacity would be exhausted by 2025.	

10.11 Biogas from sewage sludge

Feedstock description and uses	Sewage sludge (sludge) is a semi-solid residual, or by-product, arising from the treatment of municipal wastewater. The activities associated with the treatment, transport and recycling/disposal of sludge are predominantly carried out by the ten water and sewerage companies (WaSCs) in England and Wales. -Technology: Conversion of organic matter into methane by bacteria then biogas is used as the energy source.	
Sustainability Criteria	**Details**	**Score**
Land competition	None	1
Resource competition	Currently around 80% of sewage sludge is disposed of through agricultural spreading in replacement of fertiliser.[158] However, the limits on use might therefore push more towards use in incineration / AD for energy production.	2
Wider sustainable development goal alignment	Some concerns are apparent with microplastics contained with waste water and subsequently sewage sludge. Iyare et al note that large numbers of plastic particles enter the terrestrial environment where sludge is reused for agriculture.[159] More research is needed on the environmental fate and impact of plastics in sludge-amended soils, in particular where agricultural reuse of sewage sludge is common practice. This negative impact is not a result of using this feedstock for energy generation but microplastics in digestate post biogas production would form a wide negative impact and could be in higher concentration when used on agricultural land post use. As with other biogas production feedstocks it should be noted that although it can significantly contribute to abate greenhouse gas emissions, attention must be paid towards undesired emissions of methane and nitrous oxide (N2O) Bakkalogu et al (2021) suggest that biogas methane emissions (methane losses from biogas plants to the atmosphere) may account for between 0.4 and 3.8%, with an average being 1.9% of the total methane emissions in the UK excluding the sewage sludge biogas plants.[160]	2
Climate mitigation effectiveness	The emissions from biogas from sludge could range from 12.4-22.7gCO_2e/MJ (BEIS Bioenergy model)	2

158 Waste water treatment in the United Kingdom 2012 - Implementation of the European Union Urban Waste Water Treatment Directive – 91/271/EEC - DEFRA (2012)
159 Microplastics removal in wastewater treatment plants: a critical review – P, Iyare et al (2020)
160 Quantification of methane emissions from UK biogas plants – S, Bakkaloglu et al (2021)

Risk score		7
Risk rating		Moderate
Availability commentary and trend	While the biosolids market would seem to be relatively modest at present, there are a number of factors that would indicate that there is potential for it to expand. In particular: population growth will further increase demand for food production; over the long run the cost of manufactured fertiliser is likely to continue to rise in line with its main input prices; and continued technological change is likely to further improve the cost effectiveness of biosolids to end users AeA (2011) used data from NNFCC and from Defra's Waste Strategy 2007 to develop baseline tonnages for sewage sludge generation. It estimated the baseline volume available for bioenergy to be 32.5 Mt (wet), forecasting bioenergy equivalents of 2.5–3.5 TWh in 2020, 2.9–3.6 TWh in 2030, and 3.5–4.0 TWh in 2050 (Anthesis, 2017)	

10.12 Biogas from livestock manures

Feedstock description and uses	Organic matter, mostly derived from animal faeces and urine, but normally also containing plant material (often straw), which has been used as bedding for animals and has absorbed the faeces and urine. Can be in a solid or liquid form -Technology: Conversion of organic matter into methane by bacteria then biogas is used as the energy source.	
Sustainability Criteria	**Details**	**Score**
Land competition	Land uses other than livestock rearing may become more prevalent in future as diets potentially transition to more sustainable lower meat/dairy options. Land could return to other types of food production and return to forestry. Generally, manures are readily available and disposal can be a challenge for farmers. Limit here is that it is likely crops (such as maize) must be added, so scored 2.	2
Resource competition	The potential of wet manure for bioenergy is dependent on the competing uses. A portion of manure is currently used in AD and, whilst there is further potential, land spreading could grow (Anthesis 2017),[161] with the additional benefit of replacing chemical fertilisers while prices are at abnormal highs.	2
Wider sustainable development goal alignment	Methane can be released during biogas incomplete combustion; however a strong contribution to this contaminant comes from diffusive emission related to biomass storage and digestate management. Biomass management strategies must be taken into account to abate emissions related to biogenic methane. Considering cattle manure, important reductions in methane emission are related to digestate processing and handling, since this kind of biomass is characterised by high methane emission rate when spread in the field without any pre-treatment.[162] Bakkalogu et al (2021) suggest that biogas methane emissions (methane losses from biogas plants to the atmosphere) may account for between 0.4 and 3.8%, with an average being 1.9% of the total methane emissions in the UK excluding the sewage sludge biogas plants.[163] Biogas can significantly contribute to abate greenhouse gas emissions. However, attention must be paid towards undesired emissions of methane and nitrous oxide (N_2O)	2
Climate mitigation	The emissions from biogas from manure could range from 12.4-22.7gCO_2e/MJ (BEIS Bioenergy model)	2

[161] Waste water treatment in the United Kingdom – 2012: Implementation of the European Union Urban Waste Water Treatment Directive – 91/271/EEC – DEFRA (2012)
[162] Environmental impact of biogas: A short review of current knowledge – V, Paolini et al (2018)
[163] Quantification of methane emissions from UK biogas plants – S, Bakkaloglu et al (2021)

effectiveness		
Risk score		8
Risk rating		High
Availability commentary and trend	The production of manure is regional, due to most cattle, pig and poultry farming occurring in the West. This geographic breakdown indicates that some areas of the UK which are more suitable to develop wet manure AD supply chains – particularly those where land spreading is limited due to nitrogen constraints. Effective supply chains are also necessary to collect the highly dispersed and very wet manures (Anthesis 2017).	

10.13 UK perennial energy crops

Feedstock description and uses	Crops which are grown for combustion. Short rotation coppice of species such as willow and poplar to 'grassy' energy crops such as Miscanthus.	
Sustainability Criteria	**Details**	**Score**
Land competition	The feedstock is grown specifically for use in different value chains, primarily for the bioenergy sector so has a direct impact on land use.	3
Resource competition	SRC is suited to a range of heat and power generation systems down to domestic level. There are other outlets for using SRC including high value horse and livestock bedding, sustainable composite materials for markets such as the production of biodegradable plastics and fibres for car parts and for domestic uses such as wood burners and open fires. Unfortunately, quantitative information on these end uses is difficult to find. Roughly speaking, less than half of all SRC and Miscanthus was used for power generation in 2020. Miscanthus is being given much interest to develop promising bio-products and bio-based value chains.[164]	2
Wider sustainable development goal alignment	In comparison with agricultural monocultures SRC provides a higher biodiversity, but it remains lower than that of mixed deciduous forests.[165] Well-managed SRCs can enrich biodiversity in an agriculture-dominated landscape, but that SRCs most probably have a negative effect on biodiversity when introduced into a highly forested landscape. Holder et al suggest that with reduced profitability of grassland agriculture, there is likely to be an increased interest in diversification of grassland and especially more marginal grassland.[166] The use of these lands for the growth of bioenergy crops may be one option for this diversification.	2

[164] Miscanthus in the European bio-economy: A network analysis – N, Fradj et al (2020)
[165] Biodiversity in short-rotation coppice – Vanbeveren & Ceulemans (2019)
[166] Soil N2O emissions with different reduced tillage methods during the establishment of Miscanthus in temperate grassland – A, Holder et al (2019)

Climate mitigation effectiveness	Former arable land converted to Miscanthus is most likely to lead to no change or an accumulation of soil organic carbon (SOC), becoming comparable to an agricultural grassland within the lifetime of the crop. Converting semi-permanent grassland to Miscanthus by traditional establishment (spraying, ploughing, tilling, and planting) results in an initial short-term soil carbon loss which is recovered as the crop matures.[167] The emissions from UK perennial energy crops could range from 7.7-28.9gCO_2e/MJ depending if it's in chips/bale form or pellets (BEIS Bioenergy model)	2
Risk score		9
Risk rating		High
Availability commentary and trend	121,000 hectares (ha) of agricultural land was used for bioenergy crops in the UK in 2020 (just under 2.1% of the arable land in the UK) comprising: **8,000 ha of miscanthus and 2,000 ha of short rotation coppice used in biomass.[168]** By planting in appropriate locations, government targets of 0.35 Mha of dedicated energy crops could be sustainably met by Miscanthus production without impacting essential food production. In the United Kingdom, future yield projections show temperature effects enabling miscanthus production further north than possible in the 20th century.[169]	

[167] Environmental costs and benefits of growing Miscanthus for bioenergy in the UK – J, McCalmont et al (2015)
[168] Area of crops grown for bioenergy in England and the UK: 2008-2020 - Defra (Dec 2021) (https://www.gov.uk/government/statistics/area-of-crops-grown-for-bioenergy-in-england-and-the-uk-2008-2020/summary)
[169] Projections of global and UK bioenergy potential from Miscanthus × giganteus—Feedstock yield, carbon cycling and electricity generation in the 21st century – Shepard et al (2019)

10.14 Biogas from energy crops

Feedstock description and uses	A plant grown for use in the generation of energy or the production of fuels such as bioethanol. Could be combined with CCS to deliver Bioenergy Carbon Capture and Storage	
Sustainability Criteria	**Details**	**Score**
Land competition	The feedstock is grown specifically for use in different value chains, including the bioenergy sector so has a direct impact on land use. Some researchers argue that growing bioenergy feedstocks on degraded lands would avoid competition for land. The term “degraded lands” has many meanings, but no matter how it is defined, it is hard to find lands that are doing little today for people, climate, or biodiversity and that could produce bioenergy crops abundantly.[170]	3
Resource competition	Use for biofuels - not included as end use for this report but for reference in 2020 just under 36 thousand hectares of UK crops were used for biofuels supplied to the UK road transport market which equates to 0.6% of the total arable area of the UK. (Department for Transport RTFO data, Agriculture in the UK) In June 2020 the area of maize being grown for AD was 75 thousand hectares. This is an increase of 12% compared to 2019 and equates to 34% of the total maize area in 2020 and 1.3% of the total arable area.[171] This demonstrates that most maize is used as silage for animal feed, especially for dairy cattle but an increasing amount is being directed to the energy sector.	3
Wider sustainable development goal alignment	A study over almost 10 years in SW England highlighted that late-harvested crops such as maize had the most damaged soil where 75% of sites were found to have degraded structure generating enhanced surface-water runoff.[172] Subsidies for the biogas industry have led to increased interest and production of crops specifically for biogas. This is very evident in Germany where entire regions of the country have been covered by the crop. In 2012 Der Spiegel	2

[170] Avoiding bioenergy competition for food crops and land – WRI (2015)
[171] Area of crops grown for bioenergy in England and the UK: 2008-2020 – DEFRA (2021)
[172] Soil structural degradation in SW England and its impact on surface-water runoff generation – Palmer & Smith (2013)

	reported that for the first time in 25 years Germany couldn't produce enough grain to meet its own needs.[173]	
Climate mitigation effectiveness	Bakkalogu et al (2021) suggest that biogas methane emissions (methane losses from biogas plants to the atmosphere) may account for between 0.4 and 3.8%, with an average being 1.9% of the total methane emissions in the UK excluding the sewage sludge biogas plants.[174] The emissions from biogas from energy crops could range from 26.4-35.3gCO_2e/MJ depending if it's in chips/bale form or pellets (BEIS Bioenergy model)	3
Risk score		11
Risk rating		High
Availability commentary and trend	The number of AD projects under development has dropped from 331 in April 2020 to 269 in 2021. This is directly linked to the closure of long-term government support schemes. These closures will likely be reflected in the size and scale of new projects as smaller scale systems are unlikely to stack up financially without the support. The support will be shifting towards Green Gas. The Green Gas Support Scheme (GGSS) is likely to result in an upturn in larger Biomethane to Grid plants and therefore demand for a reliable and stable yielding feedstock. The ability of farmers/producers to 'make a profit' - would be the most significant driver for the development of bioenergy, although uncertainty still surrounds the possible return available from biomass crops in the UK.[175]	

[173] Biogas Boom in Germany Leads to Modern-Day Land Grab – Der Spiegel (2012) (https://www.spiegel.de/international/germany/biogas-subsidies-in-germany-lead-to-modern-day-land-grab-a-852575.html)
[174] uantification of methane emissions from UK biogas plants – S, Bakkaloglu et al (2021)
[175] Barriers to and drivers for UK bioenergy development – P, Adams et al (2011)

10.15 Biogas from marine resources

Feedstock description and uses	Seaweed can be used to produce ethanol, which can be mixed with petrol, or methane, to produce heat. - Macro-algae like seaweed can be farmed, attached to lines or other floating structures, in ocean environments. - Macro-algae can be used in anaerobic digestion (AD) plants to produce biogas for combustion or production of biomethane for injection into the gas grid (HM Government 2010). - AD is a promising technology to convert organic compounds of seaweed biomass into biogas (Thakur et al, 2022).	
Sustainability Criteria	**Details**	**Score**
Land competition	Algae is a 3rd generation bioresource and doesn't compete with food and feed plants, nor is using resources for their growth.[176]	1
Resource competition	Balina et al (2017) state that only leftovers which can't be utilised in further production processes with a low-quality biomass is used for energy production; thus it is a nearly zero waste system; and it is assumed there is little competition for this waste.[177]	2
Wider sustainable development goal alignment	- The removal of beach cast macroalgae leads to cleaner beaches, with positive impacts for the local communities, and it can also lead to nutrient reduction in the sea.[178] - Seaweed farming has been shown to clean up the pollution from fish farms and kelp grows more quickly than land plants, turning sunlight into chemical energy more efficiently (Sanderson et al, 2012). - Some phytoplankton may be outcompeted for nutrients, but the swathes of kelp may provide hatcheries for fish.[179]	2

[176] Seaweed biorefinery concept for sustainable use of marine resources – K, Balina et al (2017)
[177] Seaweed biorefinery concept for sustainable use of marine resources – K, Balina et al (2017)
[178] A marine resource with many applications – EU Submariner Project (http://www.submariner-project.eu/index.php?option=com_content&view=article&id=90&Itemid=227)
[179] Seaweed biofuels: a green alternative that might just save the planet – The Guardian (2012) (https://www.theguardian.com/environment/2013/jul/01/seaweed-biofuel-alternative-energy-kelp-scotland)

Climate mitigation effectiveness	- The compounds seaweed gives off in summer could sink and trap climate-warming carbon on the seabed.[180] - Emissions data for commercial scale production are lacking, and calculations of carbon footprints rely on estimates and vary considerably, depending on the production process used. - For macroalgae, estimates suggest that emissions could be between 40 and almost 90% lower than natural gas.[181] - The impact could be as low as 10gCO_2e/MJ, dependent on the production process used. The impact would be higher for systems requiring fertiliser use in farming.[182] – The emissions from biogas from marine sources is not addressed in the BEIS Bioenergy model	2
Risk score		7
Risk rating		Moderate
Availability commentary and trend	- UK sites: Areas around the north-west coast of Scotland are considered highly suitable areas for macro-algal production, as evidenced by the extent of natural standing stocks. The total area of the natural standing stock of macro-algae in Scottish waters is 1,125 km2 (112,509 hectares).[183] - Global: FAO reported that the annual global cultivation of seaweeds is 32 million tons (Mt) of fresh weight.[184] - According to a 2010 government report, the yield of macro-algae begins at 15 dry tonnes per hectare per year and rises to 20 dry tonnes per hectare per year by 2025.[185]	

[180] Seaweed biofuels: a green alternative that might just save the planet – The Guardian (2012) (https://www.theguardian.com/environment/2013/jul/01/seaweed-biofuel-alternative-energy-kelp-scotland)
[181] Biofuels from Algae: Post Note – Houses of Parliament, Parlimentary Office of Science & Technology (2011)
[182] Worldwide Potential of Aquatic Biomass – Ecofys (2008)
[183] 2050 Pathways Analysis – HM Government (2010)
[184] Efficient utilization and management of seaweed biomass for biogas production – N, Thakur et al (2022)
[185] 2050 Pathways Analysis – HM Government (2010)

11 Annex 2 – Climate mitigation data for feedstocks

This table summarises the overall climate mitigation score used in our framework. It draws upon gCO_2e/MJ values reported in BEIS energy model to establish the emissions pathway alignment. The 'carbon cycle' length was applied based on time to sequester biogenic CO_2 emissions from combustion.

Biomass feedstock type	Name	Source	gCO_2e/MJ	Emissions pathway alignment (2050)	Carbon cycle length	Overall mitigation score
Short rotation forestry	Short rotation forestry (Chips/Bales, High)	BEIS Bioenergy Model	3.40	1.5C	Medium	2
Short rotation forestry	Short rotation forestry (Chips/Bales, Low)	BEIS Bioenergy Model	2.30	1.5C	Medium	2
Short rotation forestry	Short rotation forestry (Pellets, High)	BEIS Bioenergy Model	12.60	Below 2C	Medium	2
Short rotation forestry	Short rotation forestry (Pellets, Low)	BEIS Bioenergy Model	6.80	Below 2C	Medium	2
Stemwood	Stemwood (Chips/Bales, High)	BEIS Bioenergy Model	2.20	1.5C	Long	3
Stemwood	Stemwood (Chips/Bales, Low)	BEIS Bioenergy Model	1.70	1.5C	Long	3
Stemwood	Stemwood (Pellets, High)	BEIS Bioenergy Model	23.80	Not aligned	Long	3
Stemwood	Stemwood (Pellets, Low)	BEIS Bioenergy Model	7.70	Below 2C	Long	3
UK perennial energy crops	UK perennial energy crops (Chips/Bales, High)	BEIS Bioenergy Model	15.40	Below 2C	Short	2
UK perennial energy crops	UK perennial energy crops (Chips/Bales, Low)	BEIS Bioenergy Model	7.70	Below 2C	Short	2
UK perennial energy crops	UK perennial energy crops (Pellets, High)	BEIS Bioenergy Model	28.90	Not aligned	Short	3
UK perennial energy crops	UK perennial energy crops (Pellets, Low)	BEIS Bioenergy Model	19.30	Below 2C	Not applicable	2

Biogas from crops	Biogas from crops (Chips/Bales, High)	BEIS Bioenergy Model	35.30	Not aligned	Short	3
Biogas from crops	Biogas from crops (Chips/Bales, Low)	BEIS Bioenergy Model	26.40	Not aligned	Short	3
Biogas from food waste	Biogas from food waste (Chips/Bales, High)	BEIS Bioenergy Model	15.00	Below 2C	Not applicable	2
Biogas from food waste	Biogas from food waste (Chips/Bales, Low)	BEIS Bioenergy Model	5.00	1.5C	Not applicable	1
Biogas from livestock manures	Biogas from livestock manures (Chips/Bales, High)	BEIS Bioenergy Model	22.70	Not aligned	Not applicable	3
Biogas from livestock manures	Biogas from livestock manures (Chips/Bales, Low)	BEIS Bioenergy Model	12.40	Below 2C	Not applicable	2
Biogas from sewage sludge	Biogas from sewage sludge (Chips/Bales, High)	BEIS Bioenergy Model	22.70	Not aligned	Not applicable	3
Biogas from sewage sludge	Biogas from sewage sludge (Chips/Bales, Low)	BEIS Bioenergy Model	12.40	Below 2C	Not applicable	2
Landfill gas	Landfill gas (Chips/Bales, High)	BEIS Bioenergy Model	12.00	Below 2C	Not applicable	2
Landfill gas	Landfill gas (Chips/Bales, Low)	BEIS Bioenergy Model	8.00	Below 2C	Not applicable	2
Other	International woody biomass (Chips/Bales, High)	BEIS Bioenergy Model	25.00	Not aligned	Medium	3
Other	International woody biomass (Chips/Bales, Low)	BEIS Bioenergy Model	2.60	1.5C	Medium	2
Other	International woody biomass (Pellets, High)	BEIS Bioenergy Model	32.00	Not aligned	Medium	3
Other	International woody biomass (Pellets, Low)	BEIS Bioenergy Model	4.60	1.5C	Medium	2
Arboricultural arisings	Arboricultural arisings (Chips/Bales, High)	BEIS Bioenergy Model	5.30	1.5C	Not applicable	1
Arboricultural arisings	Arboricultural arisings (Chips/Bales, Low)	BEIS Bioenergy Model	2.10	1.5C	Not applicable	1
Arboricultural arisings	Arboricultural arisings (Pellets, High)	BEIS Bioenergy Model	15.40	Below 2C	Not applicable	2
Arboricultural arisings	Arboricultural arisings (Pellets, Low)	BEIS Bioenergy Model	7.70	Below 2C	Not applicable	2
Dry agricultural residue	Dry agricultural residues (Chips/Bales, High)	BEIS Bioenergy Model	6.90	Below 2C	Not applicable	2

Dry agricultural residue	Dry agricultural residues (Chips/Bales, Low)	BEIS Bioenergy Model	6.00	Below 2C	Not applicable	2
Dry agricultural residue	Dry agricultural residues (Pellets, High)	BEIS Bioenergy Model	17.50	Below 2C	Not applicable	2
Dry agricultural residue	Dry agricultural residues (Pellets, Low)	BEIS Bioenergy Model	10.00	Below 2C	Not applicable	2
Forestry residues	Forestry residues (Chips/Bales, High)	BEIS Bioenergy Model	5.30	1.5C	Not applicable	1
Forestry residues	Forestry residues (Chips/Bales, Low)	BEIS Bioenergy Model	2.10	1.5C	Not applicable	1
Forestry residues	Forestry residues (Pellets, High)	BEIS Bioenergy Model	15.40	Below 2C	Not applicable	2
Forestry residues	Forestry residues (Pellets, Low)	BEIS Bioenergy Model	7.70	Below 2C	Not applicable	2
Dry agricultural residue	International agricultural residues (Chips/Bales, High)	BEIS Bioenergy Model	19.60	Below 2C	Not applicable	2
Dry agricultural residue	International agricultural residues (Chips/Bales, Low)	BEIS Bioenergy Model	3.10	1.5C	Not applicable	1
Renewable fraction of wastes	Renewable fraction of wastes (Chips/Bales, High)	BEIS Bioenergy Model	11.10	Below 2C	Not applicable	2
Renewable fraction of wastes	Renewable fraction of wastes (Chips/Bales, Low)	BEIS Bioenergy Model	7.70	Below 2C	Not applicable	2
Sawmill co-products	Sawmill co-products (Pellets, High)	BEIS Bioenergy Model	11.60	Below 2C	Not applicable	2
Sawmill co-products	Sawmill co-products (Pellets, Low)	BEIS Bioenergy Model	4.50	1.5C	Not applicable	1
Waste wood	Waste wood (Chips/Bales, High)	BEIS Bioenergy Model	1.00	1.5C	Not applicable	1
Waste wood	Waste wood (Chips/Bales, Low)	BEIS Bioenergy Model	0.70	1.5C	Not applicable	1
Waste wood	Waste wood (Pellets, High)	BEIS Bioenergy Model	11.20	Below 2C	Not applicable	2
Waste wood	Waste wood (Pellets, Low)	BEIS Bioenergy Model	6.90	Below 2C	Not applicable	2