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Comparing Scottish bioenergy supply and demand in the context of Net-Zero targets

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Executive summary

As set out in the Climate Change Plan update (CCPu), biomass has an important role in achieving Scotland's net-zero targets – notably, through the potential for negative emissions when deployed as Bioenergy with Carbon Capture and Storage (BECCS). These negative emissions can offset residual greenhouse gas (GHG) emissions from hard-to-decarbonise sectors such as aviation and construction.

This report provides:

1. an update of previous estimates of Scotland's domestic biomass **supply;**
2. analysis of the **demand** for biomass within published decarbonisation pathways; and
3. an assessment of the scale of **BECCS** required to achieve negative emissions in the pathway set out in the CCPu.

Supply

Our estimate of the total current (c. 2020) bioresources produced in Scotland and used for bioenergy annually is 8.9 TWh (previously estimated as 6.7 TWh based on 2016 data). Of this, around 8 TWh/year are 'dry bioresources' (e.g. wood) suitable for combustion to generate power and/or heat, and 0.9 TWh/year are 'wetter' resources (e.g. wastes) more suited for anaerobic digestion to produce biogas, biomethane or more complex biofuels.

An additional 3.6 TWh/year is currently available for bioenergy but is not used. We estimate that 1.3 TWh/year of additional bioresources could be available by 2030, and a further 2.5 TWh/year by 2045.

These estimates include a contribution from perennial energy crops (Short Rotation Coppice (SRC) or Miscanthus). However, these crops are currently expected to have minimal contributions to the energy mix in 2030, representing ~7% of the total supplied bioenergy resource. This is due to the lack of development of the resource in Scotland and our estimated growth projections. If perennial energy crops are developed in Scotland then from 2040 they could represent an estimated 20% of the supplied bioenergy.

Demand

The outputs from two sources of future demand pathways for bioenergy were analysed as part of this study: the Scottish TIMES model which supported the CCPu, and the Committee on Climate Change (CCC) model used in its 6th Carbon Budget (6CB) report published in December 2020. Both of these models see a moderate to large increase in bioenergy demand in Scotland due, in part, to the deployment of BECCS in the electricity generation sector in order to provide negative emissions.

In the Scottish TIMES model the shift to BECCS electricity occurs at a faster rate than predicted in all of the CCC's pathways. This may be due, in part, to the more ambitious 2030 carbon emission reduction target included in the Scottish TIMES model. The Scottish TIMES *total annual demand for bioenergy* increases from 8.4 TWh in 2020 to 27 TWh in 2030, and 26 TWh in 2045. The *demand for bioenergy in the electricity generation* sector rises from 0.5 TWh in 2020 to 25.1 TWh in 2045 in the Scottish TIMES model. The simulated bioenergy demand in Scotland in the 6CB ranges from 7.6 TWh in 2020 to 10.3 - 23.5 TWh in 2045. In all 6CB pathways, 51-76% of this final bioenergy demand is estimated to be in the electricity sector.

Our analysis shows that bioenergy demand in 2030 and 2045 in the Scottish TIMES pathway is higher than our estimates for available domestic bioenergy resources (estimated as 14 TWh/year in 2030 and 16 TWh/year in 2045). Therefore, either substantial changes in the perennial energy crop outlook or imported biomass would be needed to meet bioenergy demands simulated in the Scottish TIMES pathway.

Compared to the 6CB pathways, domestic bioenergy supply is projected to meet the bioenergy demands to 2030 but not in all pathways to 2045.

BECCS

If the negative emission envelope for 2032 in the Climate Change Plan update (CCPu) pathway was met by BECCS power, then a total estimated generation capacity of around 0.5 - 1.0 GW electrical (GWe) would be required. This assumes that alternative negative emissions technologies, in particular Direct Air Carbon Capture (DACC), account for 0.5 Mt CO_2 removal equivalent.

Currently the largest BECCS power plant in full operation, located in Japan, operates at 50 MWe, capturing 180 kt CO_2/year. Meanwhile, Drax in Yorkshire is currently still in the development stage, and has been demonstrated to capture around 100 t CO_2/year. The proposals by Drax are to scale this up to capture all of the CO_2 emissions from one of their 660 MWe biomass boilers by 2027.

Our analysis concludes that in order for Scotland to achieve both the 2030 and 2032 BECCS component of emission removal envelopes via BECCS power, the equivalent of two 500 MWe power plants will be needed. Alternative BECCS technologies such as BECCS hydrogen or BECCS energy from waste (EfW) can contribute to the emission removal envelopes, which would reduce the required generation capacity of future BECCS power plants.

The new BECCS power capacity required can also be less if existing biomass plants are converted to BECCS, thus contributing to the 2030 and 2032 NETs envelope. The BECCS contribution under the CCPu (assuming 90% of the total NETs removal) is 5.2 Mt CO_2 removal per year by 2032. Retrofitting Scotland's three largest biomass plants (in Lockerbie, Glenrothes and Lochgelly) with CCS (i.e. converting them to BECCS) can potentially make up 15% of that BECCS contribution.

In order to deploy two 500 MWe BECCS power plants, our analysis finds that 9 -14 TWh/year of bioenergy resources, depending on feedstock, are required. The type of feedstock used in a BECCS plant is not constrained by the CO_2 capture technology, though if there is a need for flue gas pre-treatment prior to CO_2 capture then challenges can arise. Varying types of feedstock can be used for BECCS power, including forestry by-products and wastes, bioenergy crops or a combination.

If there was no shift from existing uses of domestic biomass supply, then in 2030 there would be an estimated 2.9 TWh per year (0.6 Mt/year) available of unused 'dry' domestic bioresources (i.e. those suitable for combusting in a BECCS power plant). This includes forestry by-products and foreseeable levels of energy crops.

To supplement the 2.9 TWh from existing unused 'dry' bioenergy supplies, the remaining bioenergy supplies required to meet the BECCS contribution under the CCPu are 6.0 – 10.8 TWh/year (1.2 – 2.3 Mt/year depending on feedstock). If this was supplied by energy crops it represents approximately 159,000 – 286,000 hectares of land dedicated for energy crops in 2030 - 2032, significantly higher than estimated in this project. Projected planting rates for energy crops represent less than 20% of this requirement; indicating that bioenergy imports would be needed to supplement domestic supplies.

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1 Introduction

1.1 The need for this research

The Scottish Government has adopted targets to reduce greenhouse gas emissions by 75% by 2030 and to reach net-zero by 2045. Key considerations to achieve these targets include: the adoption of low carbon technologies and energy efficiency measures; societal and behavioural change; and policy measures that promote the shift towards a reduction in emissions.

This report considers the potential role of Bioenergy with Carbon Capture and Storage (BECCS) technologies, with the resulting negative emissions to support the Scottish Government's net zero and interim targets, are included in this report. This report provides:

1. an update of previous estimates of Scotland’s domestic biomass **supply;**
2. analysis of the **demand** for biomass within published decarbonisation pathways; and
3. an assessment of the scale of **BECCS** required to achieve negative emissions in the pathway set out in the CCPu.

The UK and Scottish Government plan to support an increase in BECCS over the next 10-15 years. The implications that this has on the demand for bioresources both domestically and as imports has been reviewed as part of this project.

1.2 Policy background

The Update to the Climate Change Plan (CCPu)[1], produced by the Scottish Government, outlined a potential pathway to deliver Scotland’s climate change targets and the role that bioenergy could play in the transition to net zero. This was followed by a bioenergy update[2] in March 2021, which highlighted the key areas of policy and roles for bioenergy in the future in line with the net-zero target.

In November 2021 the Department for Business, Energy & Industrial Strategy (BEIS) released a Biomass Policy Statement[3] which highlights the UK's position on the sustainable use of biomass. The UK government plan to prioritise biomass use in areas such as sustainable aviation fuel and hydrogen production, helping to decarbonise greenhouse gas (GHG) intensive sectors such as aviation and industry. In addition, the they also plan for biomass to be used in combination with carbon capture, utilisation and storage (CCUS) where feasible. The BEIS statement highlights the need for research and innovation required for BECCS.

Market support and its subsequent criteria for different forms of power generation, and the regulation of the gas and electricity grids, are reserved to the UK Government and Ofgem, respectively. As such, the decisions taken by the UK Government on how it will support bioenergy technologies such as BECCS, future access to biomass imports through trade agreements, as well as incentives for green gas production (such as

[1] https://www.gov.scot/publications/securing-green-recovery-path-net-zero-update-climate-change-plan-20182032/
[2] https://www.gov.scot/publications/bioenergy-update-march-2021/
[3] https://www.gov.uk/government/publications/biomass-policy-statement-a-strategic-view-on-the-role-of-sustainable-biomass-for-net-zero

biomethane from anaerobic digestion), will be critical to maximising bioenergy potential in Scotland.

1.3 Bioresource uses & regulations

Bioresources are used throughout the economy in Scotland as part of a wider energy system. They are used in all sectors of the economy including for the generation of heat (and power in a combined heat and power (CHP) system) when combusted in suitable equipment, within manufacturing & construction as building products, as feedstocks in anaerobic digestion plants (to produce biogas or biomethane) and in the transport industry as sustainable fuels. There is a finite amount of bioresources that can be produced domestically and there is also worldwide competition for imported bioresources.

All of these uses compete with one another and must be compatible with a sustainable land use policy, regulations and obligations to ensure a sustainable global transition. The projected growth in one area, e.g., BECCS, will have an impact on the bioresources that are available for other uses.

1.4 Bioenergy with carbon capture & storage (BECCS)

The potential of BECCS and other Negative Emission Technologies (NETs) to aid Scotland in its journey to the 2030 emissions reduction target was introduced in the 2020 Climate Change Plan Update (CCPu). This is an approach which has also been endorsed by the UK's independent Climate Change Committee (CCC) in its 6th Carbon Budget (6CB)[4].The CCC highlight the importance of introducing NETs to the UK to help contribute towards reaching climate change targets by 2050. A GHG emissions removal analysis was undertaken by the CCC, covering pathways, methods and policy advice for GHG removals. However, this analysis was not conducted on a level specifically for Scotland.

This research aims to examine the bioresource, feedstocks and BECCS plants required to meet the GHG emission envelopes as laid out in the CCPu and in the 6CB.

[4] https://www.theccc.org.uk/publication/sixth-carbon-budget/

2 Bioenergy feedstock production & supply

2.1 Previous bioenergy feedstock estimates

A study by Ricardo Energy & Environment for ClimateXChange (CXC) in 2019[5] (herein referred to as the "R19" report) estimated quantities of existing biomass resources in Scotland, the quantities then used for bioenergy, and additional quantities which are likely to be available after taking account of competing uses. It also considered how policy, or changes in the underlying activities that generate wastes and residues could change the quantities of bioresources available in 2030.

For the present study, the estimates presented in R19 report have been reviewed and, where applicable, revised in light of latest developments and published literature as well as discussions with key stakeholders. Estimates of future availability have also been extended to 2045. Brief descriptions of the bioresources included in the analysis of this report are included in Annex A.

2.2 Updates to the R19 Analysis

The points below highlight the key assumptions for the analysis. Full details and reasoning are available in Annex B.

Where marked with a (↑), this indicates the resource estimate for 2030 has increased from the R19 report, a (↓) indicates a reduction in the estimate and a (-) indicates the estimate has remained the same.

2.2.1 Forestry

The availability of forestry products for bioenergy is primarily driven by the harvesting and processing of sawlogs, and demand for small round wood (SRW) and sawmill residues in other markets. Due to maturation time of conventional forests (typically 45-90 years), current afforestation will not increase levels of forestry products available for bioenergy use (apart from possibly a small amount of thinnings) until after 2045. The assumed expansion of Short Rotation Forestry (SRF) may, as for expansion of conventional forestry, impact the land available for other agricultural uses.

Small round wood (SRW) (↓)

- The updated forestry bioresource forecast provides a slightly lower estimated resource in 2030 compared to the R19 report.

Forestry residues (brash) (-)

- Estimates of residues available at harvesting have been updated to take account of the new wood availability forecast.
- The residue resource available for bioenergy has been assumed to be half of the operationally available resource, as recovery may not be possible from all sites.

Sawmill residues (↓)

- Going forward, half of the increase in sawmill residues by 2030 has been assumed to be available for bioenergy, so that bioenergy accounts for 34% of the total resource. By 2045, large diameter roundwood availability has declined, so the amount available for bioenergy decreases.

[5] The potential contribution of bioenergy to Scotland's energy system (climatexchange.org.uk)

Short rotation forestry (SRF) (↑)

- SRF resource availability was estimated assuming 1,000 ha per year is planted from 2025 onwards (about 10% of current afforestation targets, and 6% of the 2025 afforestation target).
- The assumed yield is 95 oven-dried tonnes (odt) per hectare per harvest. It is assumed that all harvested biomass is available for bioenergy.

Arboricultural arisings (-)

- No change in total arboricultural arisings resource is assumed by 2030 or 2045.

2.2.2 Agriculture

Bioenergy resources from agriculture include perennial energy crops – grown specifically for energy harvesting; straw, crop residues and harvested wastes from traditional agricultural harvesting and livestock farming by-products. Agricultural harvesting is expected to fluctuate in the future, but no trend for growth or decline is assumed. The assumed expansion of perennial energy crops will impact the land available for other agricultural uses.

Perennial energy crops (↑)

- Perennial crop estimates for this report are based predominantly around expanding short rotation coppice (SRC) areas due to lack of commercialisation of Miscanthus in Scotland.
- SRC planting is assumed to start at 1,000 ha per year in 2023, with uptake then accelerating. The assumed acceleration is a 20% per year, i.e. in 2024 it is assumed that 1,200 ha can be planted.

Straws (-)

- The availability of straw for bioenergy is assumed to be stable out to 2045.

Livestock Farming (-)

- Resources arising from livestock farming (slurries, farmyard manure (FYM) and poultry litter) have not changed since the R19 report.

2.2.3 Food & Drink Industry

This includes bioenergy resources produced as by-products, these are typically used in anaerobic digestion (AD) plants but some can also be dried and used as fuels for conventional combustion.

Whisky & Beer production (↑)

- By-products from whisky and beer production suitable for anaerobic digestion include draff, pot ale, spent lees/wash and Distillers dark grains (DDG) from whisky; and spent grain, hops and yeast from beer production.
- We have assumed that production in both industries, and hence volumes of waste products, increase by 7.5% by 2030 and 20% by 2045.

Other industries (-)

- No changes have been made to the R19 report estimates for total resource and available resource from fish, shellfish or animal processing by-products, or whey. Available quantities are assumed to remain at the same level to 2045.

2.2.4 Waste

This includes residual domestic and commercial waste streams that could be used for bioenergy.

Wood waste (-)

- No changes have been made to the R19 report estimate for waste wood total resource.

Food waste (↑)

- Estimates for 2030 have been updated to reflect Scotland's target to reduce food waste by 33% by 2025.
- It is assumed that 70% of food waste generated can be separated from the general waste stream.
- This leads to an overall increase in the resource available for bioenergy in 2030 of about 30%.

Sewage sludge and used cooking oil (UCO) (↑)

- The current resource for sewage sludge has been updated according to the latest annual return for Scottish Water, this has been projected to increase in proportion to the expected increase in the population of Scotland by 2030 and 2045.

2.2.5 Other

We reviewed current and projected bioenergy resource that may be available from macroalgae.

Macroalgae (-)

- The available resource of macroalgae for bioenergy has been set at nil for current, 2030 and 2045 estimates.

2.3 Bioresource estimates from 2020 to 2030 and 2045

Figure 1 shows current (based on the latest available data[6]) and projected solid feedstocks that are suitable for bioenergy. Solid bioenergy feedstock is predominantly used for combustion. Quantities are stated in TWh. Projections of available bioenergy resource to 2030 have been updated from the R19 estimates using the Scottish Bioresource Mapping Tool[7], as well as being extended to 2045.

The chart shows the additional resource that is expected to be available in 2030. Some resources reduce over time. Notably, the residual waste resource is expected to decrease by 470 k t[8] by 2030. Between 2030 and 2045, a decrease is also expected in the availability of forestry harvesting residues (brash) and sawmill residues. No resource from SRF is expected in 2030, but by 2045 0.5 TWh /year (190 k t/year) could become available. Figure 1 also shows that little additional availability of SRW is to be expected in 2030 or 2045.

[6] Current availability from 2020 is estimated where possible but in some cases only data for earlier years is available.

[7] https://www.ibioic.com/scottish-bioresource-mapping-tool

[8] Mass of all resources is given in green or wet tonnes. Where mass has been converted from odt, assumed moisture content is given in Annex B.

Figure 1 Availability of solid feedstocks suitable for combustion

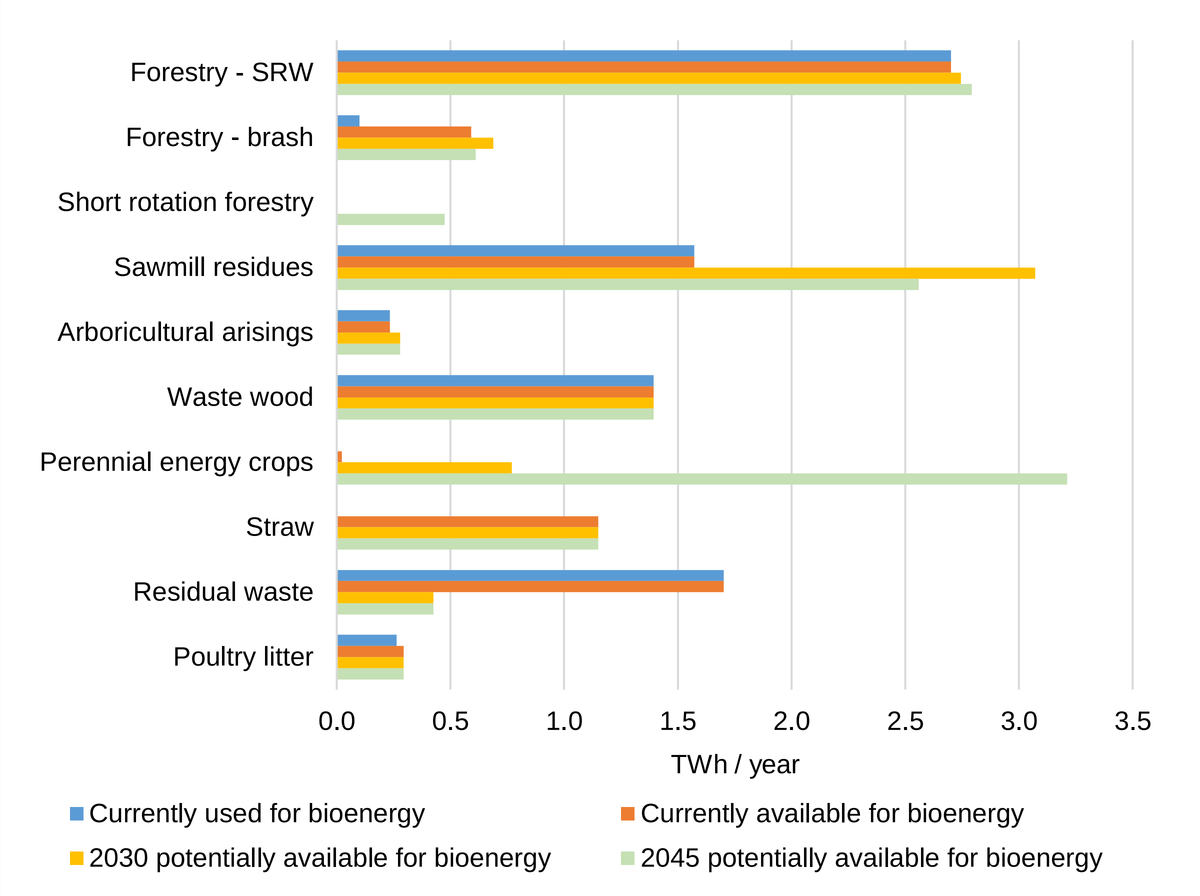

Figure 2 shows the availability of wetter feedstocks, more suitable for processes such as anaerobic digestion, quantities are stated in TWh. There is no expected increase in available resource for many of the feedstock types. However, many of the currently available resources are underutilised. In terms of energy potential, dairy and beef farmyard manures (FYM), followed by slurries, provide the largest potential for bioenergy. Tallow, despite its low tonnage, is the third largest resource by energy content. However, unlike FYM and slurries, the majority of the Tallow resource (assumed 2/3rds of the total resource) is already used for bioenergy.

By weight, significant increases in total resource are only seen in the whisky and beer industries. In terms of energy potential, the greatest increase between the current and 2030 estimate is provided by increasing availability of food waste (despite a decreasing total resource). From 2030 to 2045, only by-products from whisky production provide any notable increase in bioenergy potential.

Figure 2 Availability of wetter feedstocks more suitable for processes such as anaerobic digestion

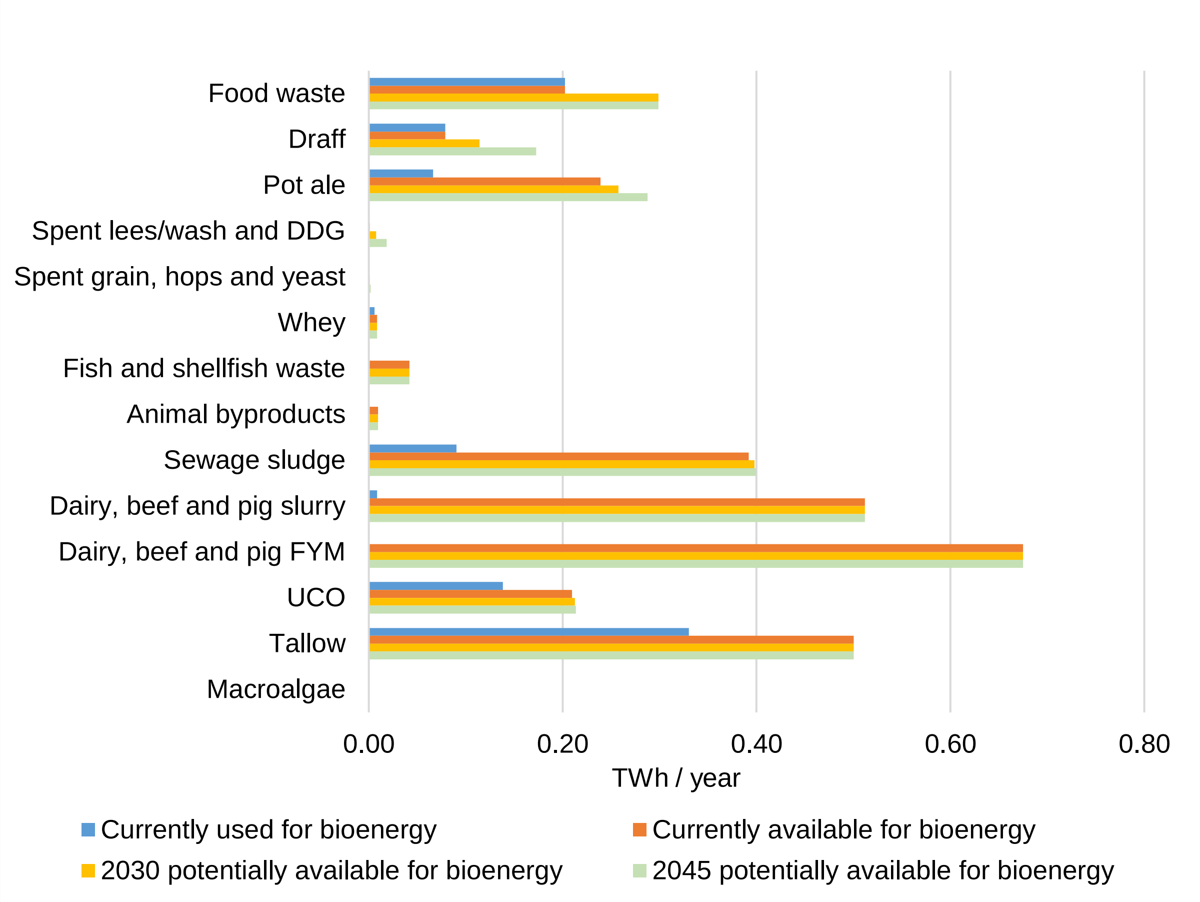

Figure 3 summarises the current availability of domestic bioresources currently, and projections for 2030 and 2045. In total, the currently used bioresource for bioenergy is 8.9 TWh/year (8 TWh/year of dry biomass and 0.9 TWh of wet biomass). The current potential is ~12.5 TWh, rising to ~13.9 TWh in 2030 and ~16.3 TWh in 2045.

To 2030, the greatest portion of the increased potential is provided by sawmill residues (an increase of 1.5 TWh). Between 2030 and 2045, almost the entire increase in bioenergy resource is provided by perennial energy crops (assumed to be SRC), increasing by ~2.4 TWh, followed by SRF providing ~0.5 TWh per year from 2040. Any increase in the other existing resources is counter-balanced by similar decreases.

Figure 3 Availability of bioresources for bioenergy use (TWh/year)

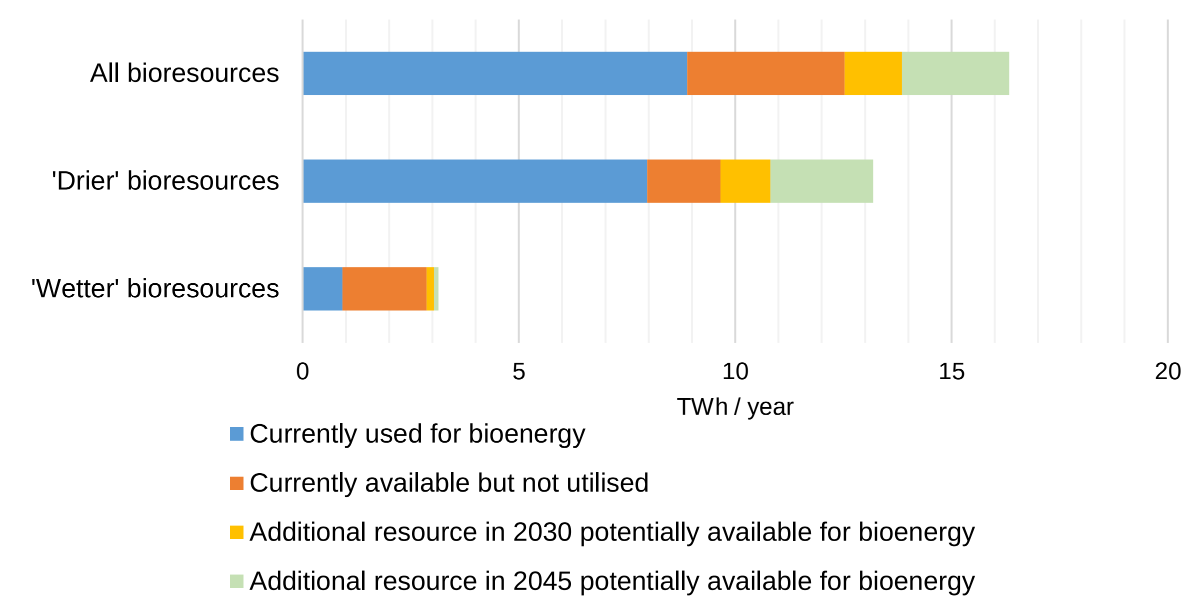

Table 1 provides an overview of the information contained within Figure 3.

Table 1 - Current, 2030 and 2045 bioenergy estimates

	Currently used for bioenergy	Currently available but not utilised for bioenergy	Current total available for bioenergy*	Additional resource in 2030 potentially available for bioenergy	2030 potentially available for bioenergy*	Additional resource in 2045 potentially available for bioenergy	2045 potentially available for bioenergy*
	TWh	TWh	TWh	TWh	TWh	TWh	TWh
All bioresources*	8.9	3.6	12.5	1.3	13.9	2.5	16.3
'Drier' bioresources	8.0	1.7	9.7	1.2	10.8	2.4	13.2
'Wetter' bioresources	0.9	1.9	2.9	0.2	3.0	0.1	3.1

*Totals may not sum due to rounding

Table 2 provides an overview of the updated bioenergy resource estimates. See appendix C for full resource update tables in TWh and typically presented figures. The impact on land-use has been included where required.

Table 2 - Updated bioresource estimates

Feedstock	Previous estimate (2030)	Has this estimate been updated since R19?	New estimates	
			2030	2045
	(TWh / year)	(Y/N)	(TWh / year)	(TWh / year)
'Dry' bioresources				
Forestry – small round wood (SRW)	2.8	Y	2.7	2.8
Forestry residues	0.7	Y	0.7	0.6
Short rotation forestry	0.0	N	0.0	0.5
Sawmill residues	2.3	Y	3.1	2.6
Aboricultural arisings	0.6	Y	0.3	0.3
Waste wood	1.4	N	1.4	1.4
Perennial energy crops	0.7	Y	0.8	3.2
Straws	1.2	Y	1.2	1.2
Residual MSW and commercial waste	0.6	Y	0.4	0.4
Poultry litter	0.3	N	0.3	0.3
TOTAL 'dry' bioresources*	**10.5**	**Y**	**10.8**	**13.2**
'wetter' bioresources				
Domestic and commercial food waste	0.5	Y	0.3	0.3
Draff	0.3	Y	0.1	0.2
Pot Ale	0.2	Y	0.3	0.3
Spent wash/lees	0.0	Y	0.0	0.0
DDGS	0.0	Y	0.0	0.0
Spent grain	0.0	Y	0.0	0.0
Spent hops	0.0	Y	0.0	0.0
Spent yeast	0.0	Y	0.0	0.0
Whey	0.1	N	0.0	0.0
Fish process waste	0.0	N	0.0	0.0
Shellfish waste	0.0	N	0.0	0.0
Animal by-products	0.0	Y	0.0	0.0
Animal by-products (fat)	0.0	N	0.0	0.0
Sewage sludge	0.4	Y	0.4	0.4
Dairy and beef slurry	0.5	N	0.5	0.5

Feedstock	Previous estimate (2030)	Has this estimate been updated since R19?	New estimates	
			2030	2045
	(TWh / year)	(Y/N)	(TWh / year)	(TWh / year)
Dairy and beef FYM	0.7	N	0.7	0.7
Pig slurry	0.0	N	0.0	0.0
Pig FYM	0.0	N	0.0	0.0
Used cooking oil	0.2	Y	0.2	0.2
Tallow	0.5	N	0.5	0.5
Macroalgae	0.0	Y	0.0	0.0
Total 'wetter' bioresources*	**3.5**	**Y**	**3.0**	**3.1**

*Totals may not sum due to rounding

3 Bioenergy demand analysis

In parallel to the supply of bioenergy resource analysis, a review of bioenergy demand within net-zero pathways was undertaken. This involved reviewing the current bioenergy demand pathways as laid out in the Scottish TIMES model simulation used to inform the CCPu and the CCC UK pathway simulations, used to inform the 6th Carbon Budget (6CB).

3.1 Projection modelling approach in published pathways

The current projection models which were analysed for the UK and Scotland are based on the 2018 Digest of UK Energy Statistics (DUKES)[9] energy statistics.

From this baseline data, the future demand (energy & bioenergy) estimates and profiles have been generated in the projection models and analysed using a variety of known sources and estimates of the future UK and Scotland energy-balances.

The two publications are based on different simulation models and with different net-zero targets. The CCC is based on their internal model and the UK-wide net-zero 2050 target, and the CCPu (based on the Scottish TIMES[10] model) has targets for Scotland of a 75% emissions reduction by 2030 and a 2045 net-zero target. As such, the projections for bioenergy supply and demand vary between the two simulation models.

The CCPu is a Scottish Government document which combined policy and strategy with Scottish TIMES modelling to determine a pathway to achieve emission reduction targets. In this report the TIMES model data that was used to inform the CCPu report is analysed on a total and sectoral bioenergy demand basis.

The CCPu sectors of *waste & the circular economy* and *LULUCF*[11] are not included as end-use/distributions in this analysis because these sectors do not represent end-uses that deplete the use of bioenergy resources. Note that "waste" bioresources e.g. gas from a landfill site, are included in the electricity sector (for electricity generation) and buildings (for heat from combustion); likewise for an EfW plant. See Annex D for terminology used in Scottish TIMES & CCC's 6CB.

3.2 Projections of bioenergy demand 2020-2045

The Scottish TIMES and CCC (balanced net-zero pathway) show 2020 final Scottish bioenergy demand at 8.4 and 7.8 TWh/year (Higher Heating Value (HHV) or Gross Calorific Value (GCV)), respectively. This is similar to our new estimate of Scottish supply of 8.9 TWh/yr.

Figure 4 shows projections of the final bioenergy demand in Scotland to 2045 for the five CCC pathways and the TIMES simulation model. All simulated pathways show an increase in bioenergy demand between 2020 and 2045. The scale of bioenergy demand simulated, in particular between 2020-2030, is significantly different between the TIMES simulation and each of the CCC pathways.

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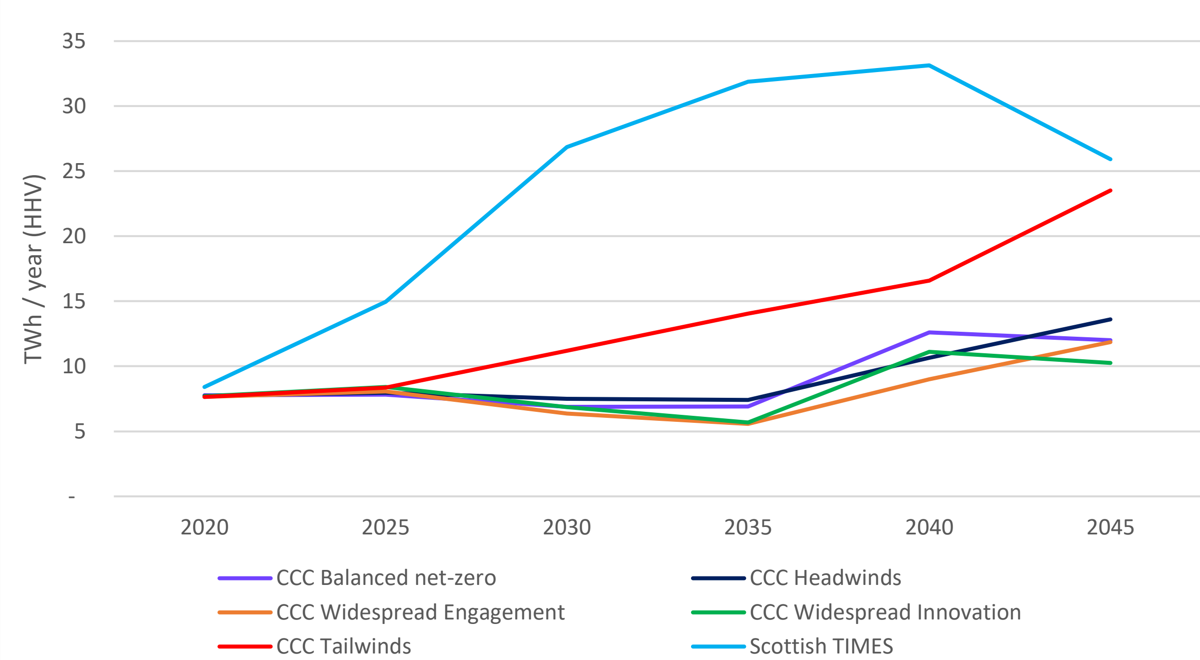
[9] https://www.gov.uk/government/collections/digest-of-uk-energy-statistics-dukes
[10] https://www.climatexchange.org.uk/research/projects/using-the-times-model-in-developing-energy-policy/
[11] Land Use, Land-Use Change & Forestry

By 2045, the final bioenergy demand in the TIMES simulation is far higher than four of the CCC pathways, with the CCC Tailwinds pathway being at a similar scale and with an opposite trajectory to the TIMES pathway.

Figure 4 - Final Bioenergy Demand (TWh / year)



3.3 Scottish TIMES bioenergy demand projections by sector

The Scottish TIMES model is the simulation tool that the Scottish Government used to inform the CCPu sector envelopes (including the NETs envelope). This section analyses the sectoral demand for bioenergy within TIMES.

3.3.1 **Overview of TIMES pathway**

1. Bioenergy demand is simulated to increase significantly from 2025 onwards – this corresponds to an increased electricity demand.

2. The increased electricity demand is linked directly to the electrification of heat with NETs being a favoured option to meet demand as it supports the target of 75% emission reduction by 2030.

3. The TIMES model simulates predominantly BECCS for electricity generation as the NET of choice, and this in turn uses biomass pellets as the fuel.

4. This increase in BECCS results in a significant increase in the quantity of simulated **imported biomass**. The increase in imports is simulated as an increase in biomass pellets (for combustion).

In the 2020 bioenergy distribution, there is currently no solid biomass consumption simulated. There are several sites in Scotland that use solid biomass as the fuel in large scale power/CHP sites (see section 4.2.2), but these do not appear in the TIMES electricity distribution.

3.3.2 2020 to 2045 bioenergy demand distributions

The bioenergy distribution simulated in the TIMES model is shown in Figure 5. The numerical values for 2030 and 2045 are contained within Table 3.

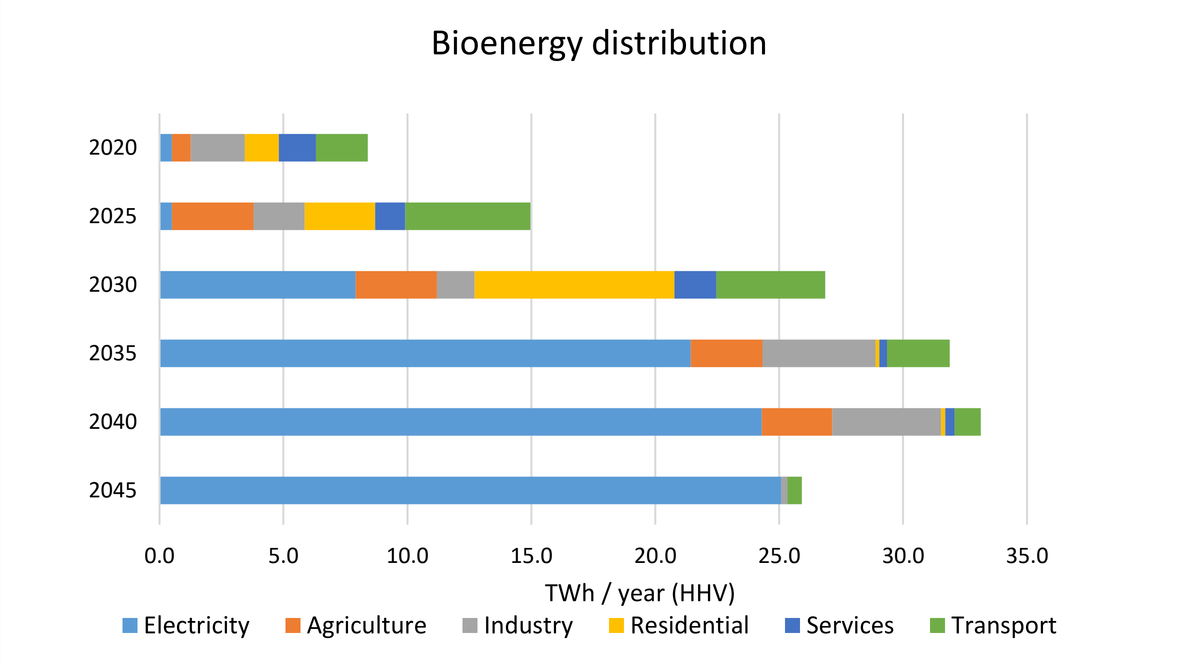


Figure 5 – TIMES model simulations of bioenergy demand distribution

From 2020-2025, there are increases in bioenergy for Agriculture (almost entirely from an increase in biomethane demand from AD) and Transport (from a combination of biodiesel and sustainable aviation fuel).

From 2025-2030, there is an overall increase in bioenergy demand of c.79% on total bioresource demand between 2025 and 2030. This is led by the residential sector (continued growth in biomethane demand delivered by a greener national grid) and the electricity sector. The electricity sector increases rapidly between 2025 and 2030 representing an increase of over 1,500% compared to 2025.

From 2030-2035, There is continued simulated growth in demand for BECCS electricity. Virtually all bioenergy simulated for use in the residential sector is removed, this is in line with the electrification of heat for buildings. This in turn is a driver of the simulated increase in BECCS electricity. The simulated increase in industrial demand predominantly arises in line with an increase in biowaste resources.

From 2035-2040, increases in BECCS electricity are the major difference to the preceding 5-year period.

From 2040-2045, there is a reduction in overall bioenergy demand due to reduction in agriculture and industrial bioenergy demands, though there is a slight increase in demand for electricity. A residual bioenergy demand in the transport sector remains.

Table 3 shows that the overall simulated demand for bioresources increases by over 3 times between 2020 and 2030 – with no simulated increase between 2030 and 2045. All sectors, with the exception of the electricity sector have lower demand in 2045 compared to 2020.

Table 3 – Scottish TIMES – bioenergy demands by sector

Sector	2020	2030	2045
	TWh / year		
Agriculture	0.8	3.3	0.0
Electricity	0.5	7.9	25.1
Industry	2.2	1.5	0.2
Residential	1.4	8.1	0.0
Services	1.5	1.7	0.0
Transport	2.1	4.4	0.6
Total*	**8.4**	**26.9**	**25.9**

*Totals may not sum due to rounding

3.3.3 Imported biomass in the Scottish TIMES model

The projected bioenergy electricity demand is met by a combination of domestically produced or imported biomass. In the TIMES model this is simulated predominantly as imports of high-grade pellets (other imports include biodiesel, bioethanol and straw biomass waste (for future pellet production). However, other feedstocks can be used in various industries (including BECCS power) to reduce the demand for pelletised imports. **Error! Reference source not found.** shows the biomass imports for primary bioenergy as simulated in the TIMES model. The shape of this time-series is similar to the final bioenergy demand shown in Figure 4, page 16.

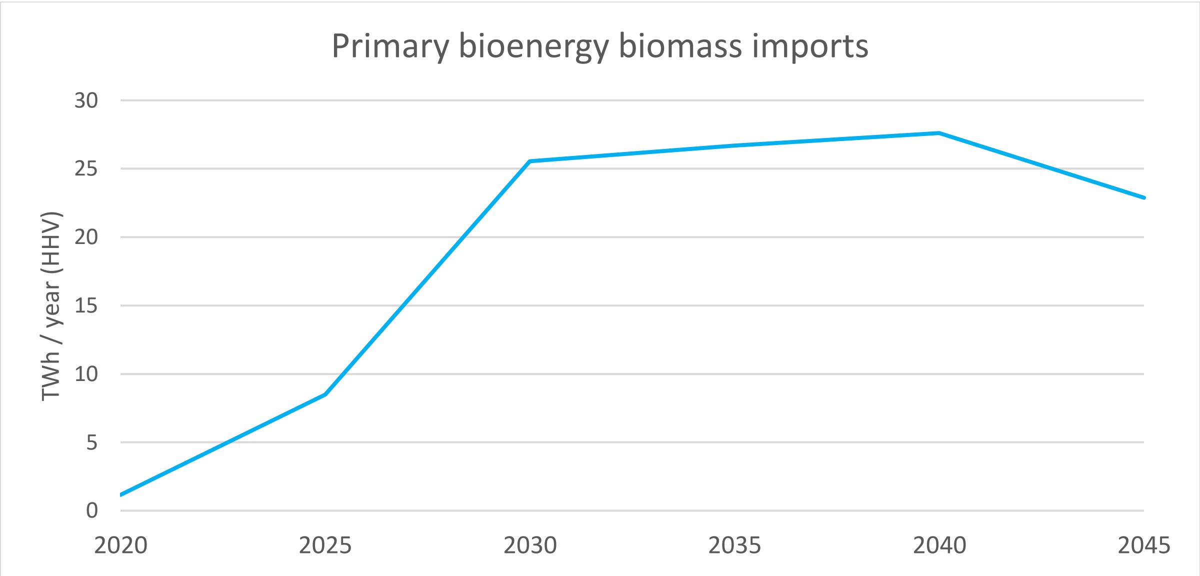


Figure 6 – Scottish TIMES simulation biomass imports for bioenergy

The TIMES simulation meets the emission reduction targets by increasing BECCS power, which requires fuel to be imported. **Error! Reference source not found.** shows the comparison of the domestic production of bioresources and imported bioresources used in the current TIMES simulation model.

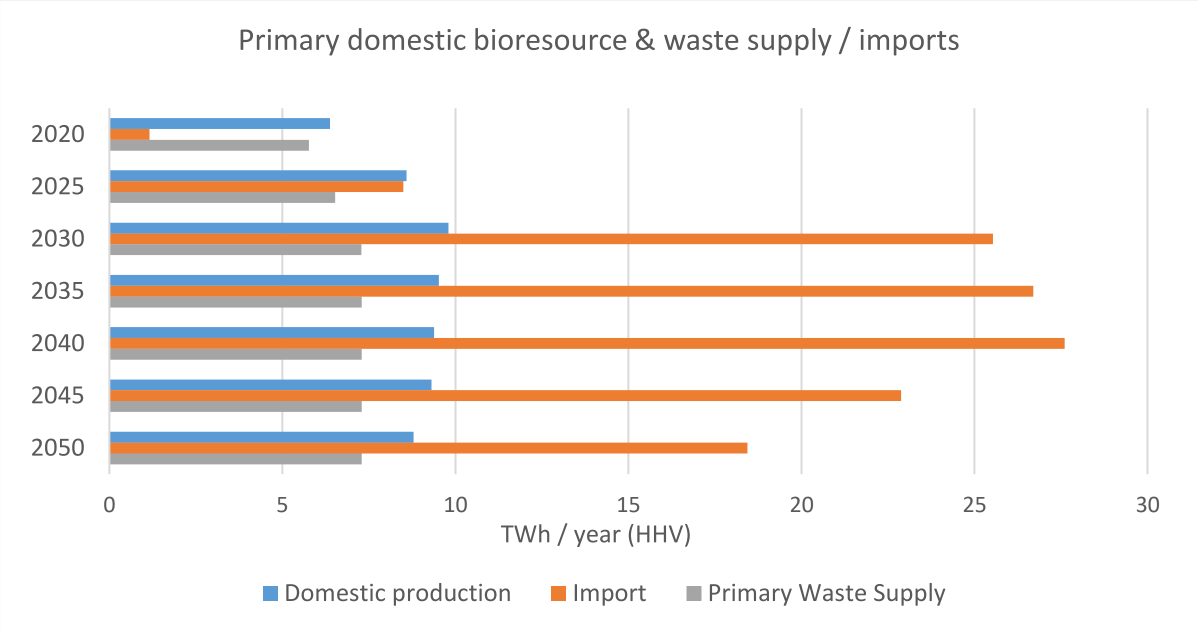


Figure 7 - Primary domestic bioresource & waste supply vs. biomass imports, Scottish TIMES model

This shows the magnitude of what is projected in the model. The biomass required far surpasses the primary biomass production in Scotland, which stays relatively constant from 2030 onwards in the current version of the TIMES model. The updated supply analysis presented in section 2 was not available at the time of the simulation.

This study was not tasked with life cycle analysis or evaluation of the supply chain for biomass pellets. However, these are important aspects that must be addressed if Scotland is to have a biofueled electricity sector that uses imported biomass pellets as the input fuel.

3.4 CCC balanced net-zero pathway bioenergy demand projections by sector

All CCC pathways show lower demand for bioenergy than the Scottish TIMES simulation, though the CCC pathways do not include the ambitious 2030 emission reduction target. Nevertheless, we show here the sector disaggregation of demand in the balanced net-zero pathway which is similar in the majority of the CCC pathways.

3.4.1 **Overview of the CCC pathway**

1. There is no demand for bioenergy electricity included until after 2030. This is not in-line with current bioenergy electricity production in Scotland, with several sites of moderate generation capacity already installed.

2. The increase in demand for bioenergy electricity occurs much later than in the TIMES simulation, and does not reach the same magnitude nor proportion of total bioenergy demand.

3. Bioenergy demand across other sectors remains from 2020 to 2045 with similar proportions to one another throughout the time period.

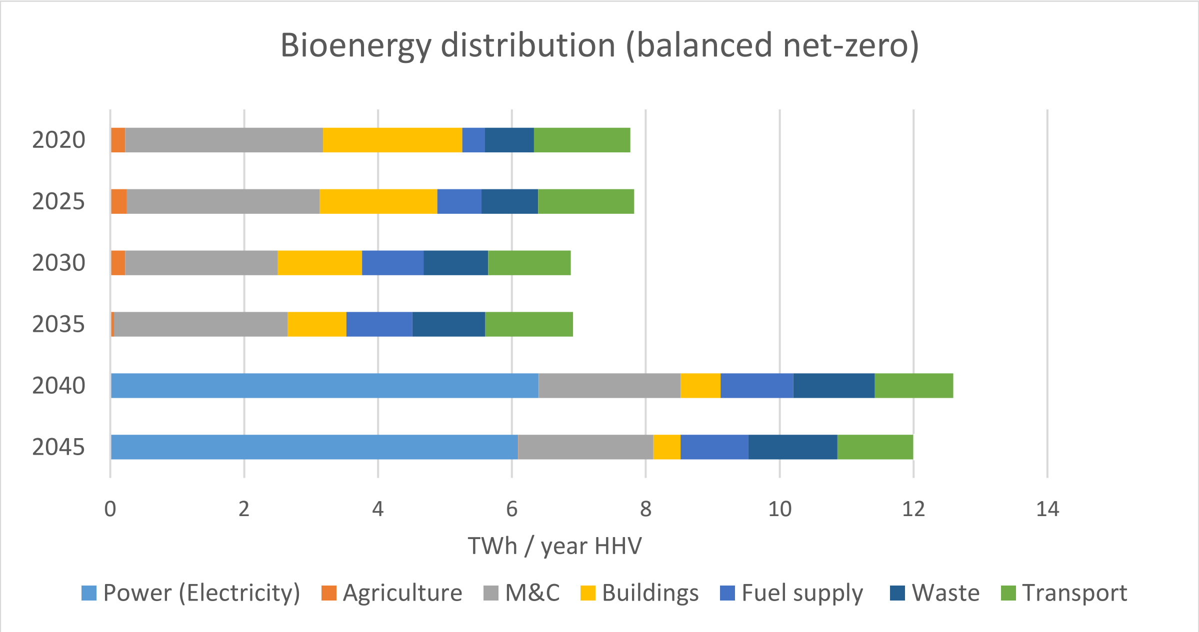
4. Total biomass imports (for all biomass uses, not only bioenergy) are projected to increase in the mid to late 2030s. It is likely, given the timing and discussion of CCS by the CCC, that this bioenergy for power is in the form of BECCS.

3.4.2 CCC Scotland sector level analysis

Other CCC pathway sector level graphs and figures are included in Annex E.

Annex D shows the end-use of bioenergy delivered (feedstock) to the specific sectors for the UK, provided by the CCC. This cannot be readily transferred to use for Scotland due to the methodologies used to generate the GHG emission inventories. However, the bioresource end-use/sector split is a useful comparator to the data presented in the TIMES simulation model as trends can be identified. Figure 8 shows how the bioenergy demand distribution changes within the CCC balanced net-zero simulation model. Note M&C stands for Manufacturing & Construction.

Figure 8 - bioenergy distribution (balanced net-zero pathway)[12]



For 2020-2035, there is a slight decrease in overall bioenergy demand, though no simulated bioenergy electricity demand. The fuel supply sector (i.e. various oil & gas processes as well as biomethane and hydrogen production) increases its bioenergy demand. Meanwhile, bioenergy demand for the Agricultural sector reduces almost entirely.

For 2035-2045, there is a large increase in bioenergy electricity demand. While it is not explicit in the data, it can be inferred from the CCC narrative that this increase is due to BECCS power. Other sector bioenergy demands remain relatively constant, with reductions in "Buildings and Manufacturing & Construction (M&C) but increases in the Fuel Supply and Waste sectors.

[12] Note that "Fuel Supply" or "Waste" are not simulated bioenergy demands in the CCPu. In the CCC "Fuel Supply" relates to "a combination of refining, oil and gas platforms, oil and gas processing terminals, gas distribution, coal mines (open and closed), and other fossil fuel production. It also includes biomethane and hydrogen production. Waste refers to "a combination of energy from waste, landfill, incineration, composting, Anaerobic Digestion (AD), Mechanical Biological Treatment (MBT)".

Table 4 shows the comparison between 2020, 2030 and 2045 bioenergy demand for Scotland.

Table 4 - CCC 2020 to 2045 end-use projections (balanced net-zero pathway)

Sector	**2020**	**2030**	**2045**
	TWh / year		
M&C	3.0	2.3	2.0
Agriculture	0.2	0.2	0.0
Transport	1.4	1.2	1.2
Buildings	2.1	1.3	0.4
Fuel supply	0.3	0.9	1.0
Power	0.0	0.0	6.1
Waste	0.7	1.0	1.3
Total*	**7.8**	**6.9**	**12.0**

*Totals may not sum due to rounding

The CCC simulation modelling for the balanced net-zero pathway shows overall stability in terms of the end-use bioenergy demand across the UK from 2020 to 2045, but an increase of over 50% in bioenergy demand in Scotland. This is driven by an increase in the Power industry, with BECCS Power being installed as was shown for the TIMES simulation. The timing of the BECCS electricity demand growth varies between the CCC simulations and the TIMES simulation.

The CCC simulations provide total biomass imported (not only for bioenergy purposes) – as such the import analysis is not directly comparative to the TIMES simulation model. See Annex F for the CCC pathway import analysis.

3.5 Comparison of bioenergy supply and demand

Figure 9 shows the simulated final bioenergy demands in the TIMES model and CCC balanced net-zero model against the updated estimates of domestic resources available for bioenergy (the analysis in chapter 2 of this report).

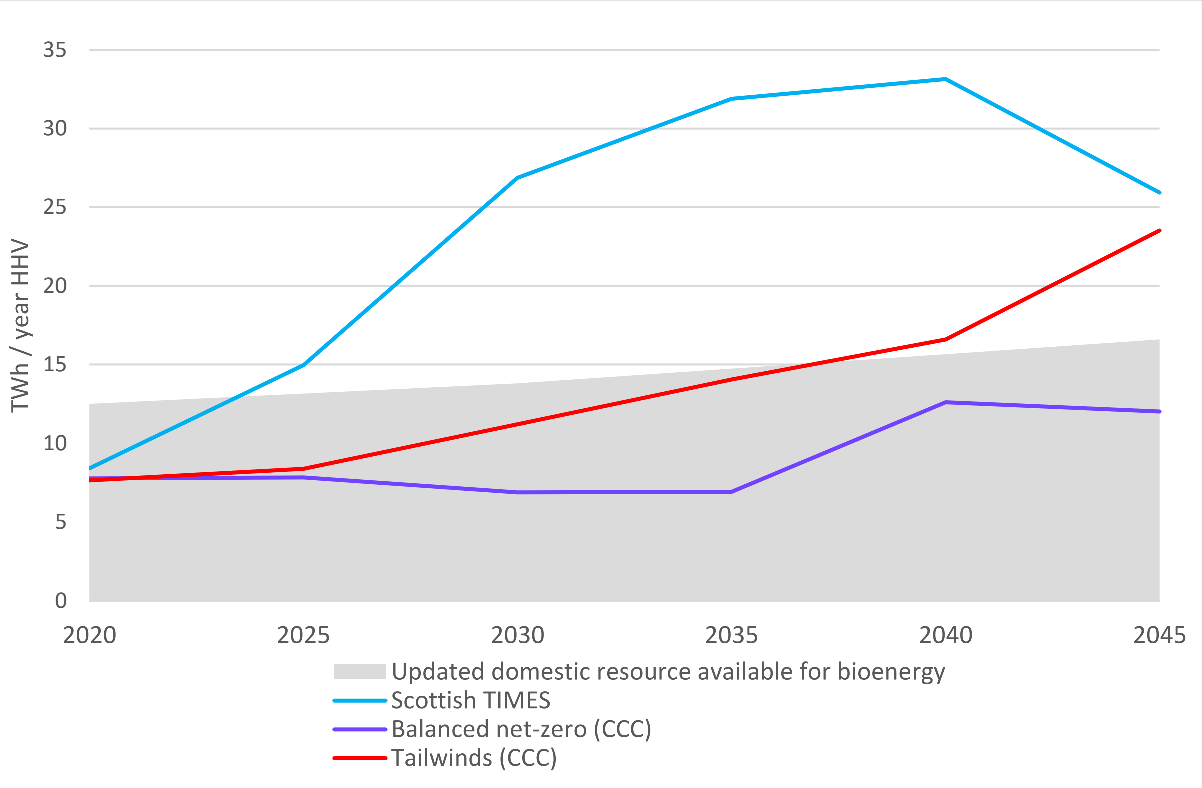


Figure 9 - Final bioenergy demands, imports and updated bioenergy supplies for Scotland; Scottish TIMES, CCC balanced net-zero & tailwinds pathways

Our analysis shows that the estimates for bioenergy demand outstrips domestic availability of bioresources in the TIMES model before 2025 due to the increased bioenergy demand for electricity simulated in the model.

The analysis shows that the CCC net-zero pathway simulation could be supplied with all domestic bioenergy supplies without the need for imports, assuming that the available bioresources could all be utilised in appropriate technologies. That is not the case for all CCC pathways – most notably, the tailwinds pathway.

The specific GHG reduction targets that the TIMES and CCC models are designed to simulate have different magnitudes and different timescales and so variance in the two final bioenergy demand series is to be expected.

4 Bioenergy with Carbon Capture & Storage (BECCS)

4.1 Introduction

The supply and demand figures presented in this report in Sections 2 and 3 account for the additional demand needed by BECCS. The CCC's 6th Carbon Budget (6CB) does not provide details on the NETs envelope specific to Scotland to achieve net zero so the discussion below is focussed on the CCPu negative emissions envelope.

The GHG removal envelopes within the energy sector in the CCPu are all predominantly linked to potential future use of BECCS. There are many types of BECCS applications and conversion paths through which a bioenergy feedstock can be processed. There is a range of bioenergy conversion systems which can be categorised as BECCS. Figure 10 provides an outline of various potential routes for BECCS.

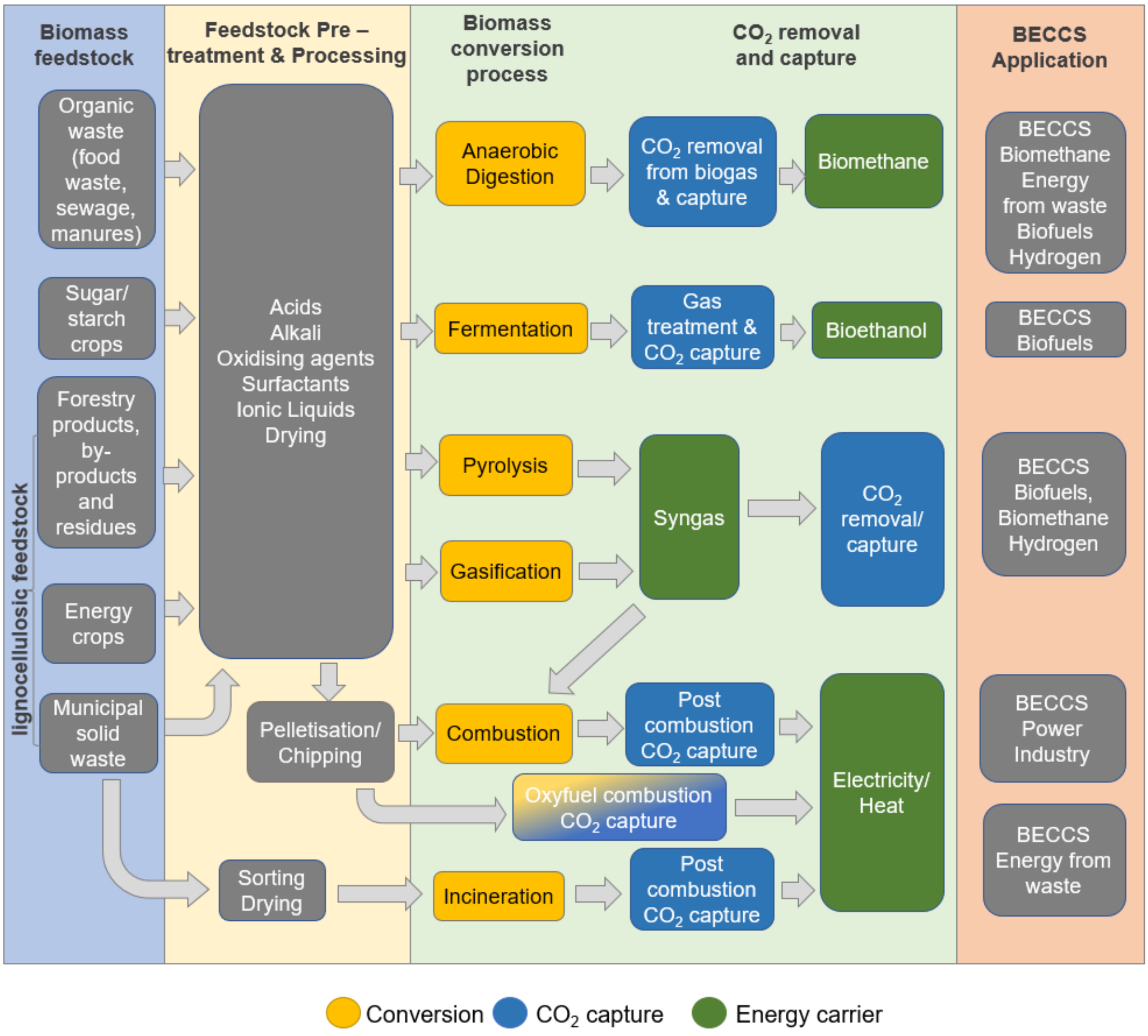
These include:

- **Biomass combustion and / or gasification with CCS** to produce electricity, utilising forestry products, energy crops, solid waste, wood chip and wood pellets,
- **Energy from Waste (EfW) plants equipped with CCS**, to produce electricity and heat, utilising solid and organic waste,
- **Industrial applications in the cement, distillery or pulp and paper sector**, utilising wood products and waste, industrial by-products and waste,
- **Biomethane-to-grid plants** where CO_2 is removed and captured from biogas, utilising a wide range of agriculture, industrial and municipal solid waste as well as sewage sludge and energy crops in anaerobic digesters,
- **Applications where CCS is combined with biomass gasification** to produce hydrogen, utilising a wide range of woody biomass and waste,
- **Applications where CCS is combined with biomass conversion** to produce biorefinery products such as bioethanol or other high value products such as bioplastics or speciality chemicals.

A wide range of biomass feedstocks can be used for the applications above. The Scottish TIMES model suggests extensive use of BECCS power as the predominant technology for NETS, therefore the discussion for the remainder of this section is focussed on requirements for BECCS Power.

The following sub-sections provide a summary of the estimated BECCS power requirements needed to satisfy the GHG removal envelopes associated with BECCS. This includes estimates of the size of BECCS power plant infrastructure required, the associated feedstocks and land area requirements needed to satisfy these envelopes. It also includes estimates of the capital and operating costs needed to demonstrate BECCS.

Figure 10 – Typical BECCS conversion routes & applications (adapted from several sources[13],[14])



4.2 GHG removals via NETS & BECCS

4.2.1 CCPu envelope

The CCPu NETs envelopes are 3.8 Mt CO_2e / year in 2030 and 5.7 Mt CO_2e / year in 2032. Despite substantial uncertainty, for the purposes of this study we have assumed that 0.5 Mt CO_2e reduction will come from direct air carbon capture and storage (DACCS) in 2030 and 2032. This leaves 3.3 Mt CO_2e and 5.2 MtCO_2e removals in 2030 and 2032 via BECCS.

4.2.2 Current estimates of biogenic CO_2 emitted in Scotland

It is possible to retrofit existing bioenergy plants with CCS, so we first briefly describe the opportunity for this within Scotland, before considering the new build approach.

The Scottish Carbon Capture & Storage (SCCS) centre at the University of Edinburgh produced a report in 2018 on NETs and estimated **biogenic CO_2 emissions in**

[13] European Biofuels Technology Platform, Biomass with CO_2 Capture and Storage (Bio-CCS)

[14] IEAGHG, Biomass with carbon capture and storage (BECCS/Bio-CCS), 2017

Scotland (from biogas and biomethane, biomass combustion, and fermentation) are of the order of 3.6 $MtCO_2$[15]. Discussions with SCCS indicated that they are currently updating their 2018 report with new estimates due in 2022.

Previous studies show that existing large scale biomass plants in Scotland provide an opportunity for retrofitting CCS thus helping achieve GHG removals and contributing to negative emission targets. Three large biomass plants that are primarily electricity generating facilities include:

- Markinch CHP plant in Glenrothes (55 MWe),
- Steven's Croft power station in Lockerbie (44 MWe),
- Westfield Biomass Plant in Cardenden (10 MWe).

If retrofitted with CCS, the total biogenic CO_2 which can potentially be captured from these three Scottish sites can add up to approximately 0.8 Mt/year which corresponds to 24% of the BECCS contribution under the CCPu in 2030 and 15% in 2032. There may be technical, economic or geographical reasons that these sites are deemed not suitable for CCS.

4.3 Scale of BECCS power required for CCPu envelopes

The total stated negative emission envelope within the CCPu by 2032 is 5.7 $MtCO_2e$/year with 90% of this total attributed to BECCS, with the remainder being based on DACCS, or other engineered removals such as biochar. The BECCS route with highest potential for NETs is electricity generation via biomass combustion with CCS as highlighted above.

The size of the BECCS power plant that can be demonstrated in Scotland by the end of the decade will depend on how fast the technology is scaled up. The most advanced plans for BECCS power plant in the UK are those for Drax which has successfully demonstrated the capture of 300kg CO_2 / day. The aim is to have one of the Drax biomass boilers (660 MWe, gross output) fully equipped with CO_2 capture and operational by 2027[16]. It can thus be expected that a BECCS power plant at this large scale can be operational in the UK by the end of the 2020s.

Our estimates show that in order to achieve BECCS targets in Scotland by 2032, approximately two large scale 500 MWe power plants (gross output) will need to be equipped with CCS. This estimate is based on wood pellets as typical feedstock and on a CO_2 capture efficiency of 90% which is the most prevalent assumption in the literature (IPCC Special Report on Carbon Dioxide Capture and Storage, 2005)[17].

The demonstration of a BECCS plant at this scale involves a wide range of activities including planning and permitting (including stakeholder consultation), engineering design (including feasibility, pre-FEED and FEED[18]), procurement, construction and commissioning and could span over a period of 4-5 years. This also requires advancing the development of the CO_2 transport and storage infrastructure (e.g. the Acorn project). Achieving the BECCS target in Scotland in the next decade thus requires planning to

[15] Negative Emission Technology in Scotland: carbon capture and storage for biogenic CO_2 emissions – Scottish Carbon Capture & Storage, available from https://www.sccs.org.uk/publications/. Note that this report looked at the following sectors and the total biogenic CO_2 as stated is based on these sectors only (biogas and biomethane, biomass combustion, fermentation)

[16] https://www.drax.com/press_release/drax-kickstarts-application-process-to-build-vital-negative-emissions-technology

[17] https://archive.ipcc.ch/pdf/special-reports/srccs/srccs_wholereport.pdf

[18] Front End Engineering Design (FEED)

start by 2025 at the latest to facilitate deployment of two 500 MWe BECCS plants by 2032.

4.4 Feedstock uses, conversions and suitability for BECCS

The deployment of BECCS in Scotland at the end of the 2020s will increase demand for biomass resources. The feedstock analysis has been updated to assess the availability and suitability of additional domestic bioresources in Scotland for use in BECCS power plants.

The feedstocks for bioenergy use outlined in section 2.3 have a number of different uses within the economy. On a dry weight basis, approximately 12% of the bioresources produced in Scotland are used for bioenergy purposes (see Annex A for other uses of bioresources).

The type of biomass which can be used in a BECCS power plant is not technically limited by the CO_2 capture technology, although various challenges will arise from different types of feedstocks (e.g. purity of CO_2). A wide range of biomass resources can be used in biomass combustion or gasification plant for power generation. The Drax BECCS demonstration is based on wood pellets while the Stockholm Exergi BECCS demonstration at the Värtan KVV8 biomass CHP plant in Stockholm is based on wood chip. In order to achieve NETs envelope by 2032 using BECCS, it is estimated that 1.9-3.0 M t/year of biomass feedstocks are needed depending on type[19]. This is discussed further in Section 4.4.1.

4.4.1 Feedstocks and land requirement to meet the CCPu envelopes

The land required to meet the GHG reduction envelope is intrinsically linked to the type of BECCS system installed (i.e., the specifics around the combustion, generation, and capture systems) and the fuel type (or types) that the plant is designed to combust. The analysis presented here is based on [20] previous work undertaken by Ricardo for BEIS in 2020. Note that the land requirement has been estimated based on 8 odt / ha for SRC.

Table 5 - Land use to achieve GHG reduction targets via BECCS power plant, allowing for upstream emissions

	CCPu envelope	Fuel required*	Pellets required	SRC required	
	Mt CO_2	TWh / year	Mt / year	M odt / year	hectares
2030 BECCS contribution to NET envelope	-3.3	8.9	1.9	1.9	235,000
2032 BECCS contribution to NET envelope	-5.2	14.0	2.9	3.0	371,000

*In the calculation of fuel/ BECCs required we have considered the upstream emissions associated with the BECCS plant as well as captured emissions from the CCS and have assumed that these emissions occur in Scotland. In that sense the values are a worst

[19] Fuel requirements are based on potential CO_2 captured in a post-combustion capture system and include an account for upstream emissions due to the production of the fuel
[20] https://www.gov.uk/government/publications/the-potential-of-bioenergy-with-carbon-capture

case (as it is likely that some of the fuel would need to be imported, with these emissions occurring outside of Scotland).

The calculations used to generate the supply estimates in section 0 use a constant base planting rate of 1,000 ha / year for Miscanthus and a base planting rate of 1,000 ha for SRC with a 20% expansion rate (i.e. the area planted increases by a margin each year).

Using these planting rates, an estimated total of approximately 27,000 ha would be planted by 2030 and 38,000 by 2032. That equates to **approximately 10 - 11% of the total land area that would be required** if energy crops were the only feedstock used in a BECCS power plant.

4.4.2 Available dry bioresources that could be used in a BECCS power system

Section 2 estimated the current available but unused dry bioresources in Scotland as 1.7 TWh/year. In 2030 and 2045, the available but unused resources (at current utilisation rates) are estimated to increase to 2.9 and 5.2 TWh / year respectively and we have interpolated that this represents approximately 3.2 TWh / year in 2032. This available but unused resource represents approximately 30-40% of the fuel required for BECCS power in the GHG NET envelopes (Table 5).

If all available bioresources were used for bioenergy, this would reduce the additional fuel required from ~1.9 - 3.0 M t /year to ~1.2 - 2.3 M t/year.

The availability of sustainable forestry by-products (i.e. small round wood & brash) are estimated to only provide a small additional resource in 2030 and 2045 which will need to be supplemented by other bioresources to support any large scale BECCS plant required to meet the CCPu NET envelopes.

Perennial energy crops, and, to an extent short rotation forestry both have the greatest potential to exceed the estimated planting rates suggested in this report (to 2030 and 2045). This would likely require policy intervention to incentivise the growth of these crops.

Perennial energy crops currently show the greatest difference between currently grown and future availability (Figure 1 & Table 2). However, the estimate of bioenergy availability in 2030 has been downgraded from the R19 estimate due to no uptake since that report. If the lack of uptake was to continue then it would further reduce the new 2030 and 2045 estimates of bioenergy availability.

Fluidised bed combustion (FBC) is the most common conversion technology for biomass. **FBC technology can accommodate a wide range of feedstocks and mixtures of feedstocks.** Such feedstocks can range from energy crops, to forestry products/by-products and wastes and miscanthus, to industrial and municipal solid waste. **The feedstock to be used for BECCS power has to be considered at the planning stage of a power plant. Considerations around mixed feedstocks are discussed in Annex G.**

The main challenge for the CCUS & BECCS industry is in the capture and eventual storage of CO_2 and not specifically with the types of feedstocks that could be used in a BECCS system.

4.5 Estimated costs associated with BECCS

The capital and operating costs reported here are for a single 500 MWe BECCS plant with post-combustion CO_2 capture. The costs will vary depending on the feedstock, biomass conversion technology and CCS system being used. The Wood report[21] analysed different BECCS systems for use in power generation. Various BECCS technologies were considered to provide an estimated range of costs

The outputs from the Wood report, which is the most comprehensive benchmarking study in the past five years, show that for a 500 MWe power plant the capital costs are estimated to be between £2.5 - 2.95 M/MWe depending on the exact technology used. It is assumed that feedstock choice does not affect the capital cost. The lower estimate is based on the system of biomass fluidised bed with post combustion. The higher estimate is for a system of Biomass Integrated Gasification Combined Cycle (BIGCC) with pre-combustion capture.

According to estimates in the Wood benchmarking study, the operating costs (including fuel costs) from a 500 MWe BECCS plant are in the range £390-450 million/year depending on feedstock used. The lowest estimate is for BIGCC with pre-combustion capture with wood chip as a feedstock. The highest estimate is for biomass oxy-combustion capture and wood pellets as a feedstock. For details on assumptions as well as a more detailed breakdown of costs, see Annex G. For a typical 500 MWe plant typical revenue will be in the range of £160-190 £M/y, based on a wholesale electricity price of 60 £/MWh.

4.6 Comparison of BECCS against other NETs

Table 6 below provides details on other NETs which can be deployed alongside BECCS to contribute towards reaching targets for net-zero. Of the technologies below, it is particularly important to understand the potential use of biochar, as this may be a competing technology for allocation of biomass resources. The table below is based on a review by The Royal Society on different types of NETs[22]. Further detail on the costs of NETs can be found in the Greenhouse Gas Removals call for evidence[23]. This gathers information from stakeholders on their reported Greenhouse Gas Removal (GGR) capture costs and compares them against the costs in the Royal Society review, as referenced in a report by Vivid Economics[24].

[21] Assessing the Cost Reduction Potential and Competitiveness of Novel (Next Generation) UK Carbon Capture Technology, BEIS. 2018

[22] The Royal Society, Greenhouse gas removal, 2018

23 BEIS, Greenhouse Gas Removals call for evidence, October 2021

[24] Vivid Economics, Greenhouse Gas Removal (GGR) policy options, 2019

Table 6 - Estimated costs and land requirements of NETs technologies[25]

NETs	Description	Cost of CO_2 captured, £/tCO_2	Land requirements (including land required to grow biomass) ha/tCO_2
BECCS	Use of biomass for energy combined with CO_2 capture	100 - 200	0.07(Value as calculated in this study) 0.03 – 0.06[26] (Literature values)
DACCS	Capture of CO_2 directly from the air	145 - 435	0.0004-0.0025[27]
Biochar	Addition of burnt/torrefied biomass to soil for long term storage	13 - 120	<1
Afforestation/ reforestation	Planting trees	10 - 20[28]	0.1[29]
Enhanced weathering	Spreading pulverized rock to take up CO_2 and form bicarbonate	37 - 350[30]	0[31]
Ocean alkalinity	Increasing ocean concentration of ions to increase uptake of CO_2 into the ocean	53 - 119	N/A

Carbon sequestration can be classified into two categories

- Technological options (including BECCS, biomass pyrolysis to produce biochar and DACCS), and
- Nature based systems including afforestation/reforestation, enhanced weathering and ocean alkalinity.

Biomass pyrolysis to produce biochar is a key biomass conversion technology which is still at an early stage of development in comparison to combustion for power. While CO_2 capture and storage through biochar is a more cost-effective option in comparison to BECCS, it has a much lower negative emission potential due to the smaller scale and lower maturity of biomass pyrolysis technology in comparison to biomass combustion.

[25] The Royal Society, Greenhouse gas removal, 2018
[26] Depending on the feedstock used
[27] Katie Lebling et al, Direct Air Capture: Resource Considerations and Cost for Carbon Removal, 2021
[28] Note that this considers future cost estimates for the year 2100.
[29] Over 100 years
[30] Dominated by mineral processing and transport costs
[31] Enhanced weathering on cropland requires no additional land and can be co-deployed (e.g. with the feedstocks for BECCS/biochar to increase sequestration potential per unit of land area)

Biochar also has higher land requirements per tonne of CO_2 removed due to the lower efficiencies of the technology. The Royal Academy of Engineering estimates that the potential of biochar as a GGR technology in the UK is around 5 Mt CO_2/year in 2050. As pyrolysis technology develops further in the coming decades, biochar production as a GGR technology will be a competitor to BECCS for biomass resources.

Direct air capture is also at an early stage of development with small-scale DACCS systems installed by key players in the market such as Climeworks and Carbon Engineering. The development of DACCS in Scotland will depend on how the technology is scaled up worldwide and unlikely to be deployed at a large scale until early 2030s.

Afforestation is the most common nature-based GGR option, where CO_2 is absorbed through plant growth and though managing existing forests. This is a low-cost option but has large land requirements in comparison to BECCS. From earlier it is estimated that if land was used for SRC, with the fuel being combusted in a BECCS plant, the carbon sequestration achieved is between 14 to 15 tCO_2 per ha per year.

Over a 25 year period (the typical life of an SRC plantation) then the carbon sequestration achieved from 1 ha of land would be about 350 to 384 t CO_2). The carbon sequestration achieved through afforestation over the same 25-year period and for the same 1ha land area is likely to be less than this. In the longer term, as rates of carbon sequestration in the forest decline, and assuming that the SRC was replanted, it is possible that the SRC plantation could offer greater sequestration than the ageing forest. However a more detailed analysis would be required to fully evaluate these options, including potential co-benefits.

5 Conclusions

Bioenergy carbon capture and storage is a widely used approach within assessments of how to achieve net-zero targets. The future demand for bioenergy as projected in the CCPu and the CCC's 6th Carbon Budget (6CB) is large, with increasing demand from the electricity sector combined with CCS. The inclusion of BECCS in future energy scenario modelling places an emphasis on the importance of bioresources currently unused and potentially available in the future.

Estimates of total current bioresources produced in Scotland and used for bioenergy have changed from 6.7 TWh in the R19 report to 8.9 TWh, mainly due to increases in the estimates of the amount of small round wood, waste wood and residual waste used for energy production. It is estimated that an additional 3.6 TWh is currently available for bioenergy and is not currently used for any other purpose. Of the 8.9 TWh generated from bioresources, around 8 TWh are 'dry bioresources' (wood & residues, energy crops, straw, residual MSW & commercial waste & poultry litter) suitable for combusting to generate power and/or heat (e.g. for process heat or district heating), and 0.9 TWh are 'wetter' resources (wastes, distilling/fermentation by-products, slurries etc), more suited for anaerobic digestion to produce biogas and/or more complex biofuels or biomethane.

Estimates suggest that some 1.3 TWh of additional bioresources would be available in 2030, and a further 2.5 TWh would be available in 2045. The new projections to 2045 show that there could be additional resource available from perennial energy crops, but these require trials (for Miscanthus) and market intervention in order to come to fruition. Some other bioresources are projected to have a lower availability in 2045 compared to 2030 (e.g. sawmill residues).

Bioenergy demand increases to 2030 and 2045 in all pathways were analysed. In the Scottish TIMES and the CCC's 6CB this increase in bioenergy demand is focussed in the electricity sector, and it is inferred that this is due to an increase in BECCS power to provide negative emissions. The increase in demand will require imported biomass that will either be used as bioenergy fuel, or as biomass in other industries where the currently used resources could be diverted from their current use. Our analysis shows that equivalent to two 500 MWe BECCS power plants are needed to achieve the 2032 NETs envelopes. This relates to between 1.9 - 3.0 Mt/year of bioenergy resources (equivalent to 8.9 – 14.0 TWh/year, depending on feedstock) being needed for BECCS in 2030 & 2032.

While BECCS can be implemented via various routes (e.g. on bioethanol plants, in industry or on biomethane plants), the capture of CO_2 from a biomass power/CHP station represents the highest magnitude potential in the near-term. Other forms of potential BECCS include energy from waste, advanced biofuels or the capture and utilisation of CO_2 within the distilling and brewing industries.

The capital expenditure for a 500MWe BECCS (based on post-combustion capture technology) is around £1.25Bn (£2.5M/MWe) based on the latest benchmarking studies. The reported levelised cost of electricity (LCOE, £/MWhe) for this type of plant is in the range of £170/MWhe[32]. For a typical 500MWe plant typical revenue will be in the range of £160 -190 £M/y, based on a wholesale electricity price of 60 £/MWh.

[32] LCOE taken from Wood/BEIS report "Assessing the cost reduction potential and competitiveness of Novel (Next Generation) UK Carbon Capture Technology"; Table 2-1 Page 8, Case 8 (biomass with post-combustion capture) https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/864688/BEIS_Final_Benchmarks_Report_Rev_4A.pdf

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7 Annexes

Annex A – bioresource descriptions

Feedstock	Description
Forestry	
Forestry - small roundwood	Small roundwood (SRW) which is removed from the forest to thin plantations, to allow larger diameter trees to flourish (i.e. thinnings) and smaller size material which is produced when the forest is finally harvested and is unsuitable for use as saw logs. SRW has typically been considered as wood with a diameter <16cm.
Forestry - residues from harvest	Residues from final harvest operations comprise the tops and branches of felled trees (often termed brash). Residues can also include unmarketable wood, such as diseased wood.
Sawmill residues	When harvested, timber is processed to sawn timber in a sawmill. Wood chips, sawdust and bark are produced as co-products. These are collectively known as sawmill residues. Panel board mills may also produce bark and sawdust residues.
Arboricultural arisings	Arboricultural arisings come from the management of trees and shrubs from public and private (non-forest) land, such as gardens, park land, utility land, and roadsides.
Short rotation forestry (SRF)	SRF uses fast growing species of trees on rotations of 8 to 20 years, depending on species and site to produce wood specifically for bioenergy. SRF plantations can be established on marginal agricultural land, permanent grassland and rough grazing. There are currently only trial plots of SRF in Scotland
Agriculture	
Perennial energy crops:	These include willow (or poplar) grown using a short rotation coppice (SRC) technique, and Miscanthus. Once planted SRC takes up to four years to reach maturity, after which it is harvested at regular intervals - typically four years for willow SRC. After about 20 to 25 years the crop is removed. Miscanthus is a woody grass, which after it has matured, is harvested every year.
Straw	Straw is a by-product from the production of cereal crops such as wheat, barley and oats and of the oil crop, oil seed rape.
Crop residues	These include the parts of harvested vegetables that are not consumed and are typically left on the field, such as brassica tops, stalks and leaves, carrot stalks and leaves, and potatoes haulms.
Harvested wastes	This is crops which are harvested but do not enter the food chain (e.g. if they are damaged or misshapen). Estimates include waste at harvest of key crops: potatoes, apples, brassicas, carrots, fresh vegetables and salad, strawberries, raspberries

Slurry	Slurry (from dairy and beef cattle, pigs and sheep) is excreta produced by livestock while in a yard or building, including excreta mixed with bedding, rainwater and washings. It has a consistency that allows it to be pumped or discharged by gravity.
Farmyard manure	Farmyard manures (FYM) from dairy, beef, pig and sheep are livestock excreta mixed with bedding material (such as straw), and has a higher dry matter content (>10%) than slurries.
Poultry litter	Poultry litter is chicken manure from broilers hens raised for meat production, mixed with the soft wood shavings or straw used as bedding for the poultry.
Food and Drink Sector	
Draff	A by-product of the whisky industry. Draff is spent grain left in the mash-tun after the liquor has been drawn off and has a high moisture content.
Pot ale	A by-product of the whisky industry. The liquor left in the wash still after the first distillation in the pot still process. It's very low solids content (of about 4%) means it is a very dilute source of biogenic matter.
Spent lees/wash	A by-product of the whisky industry. The residue in the Spirit Still after the distillation of the foreshots, potable spirits, and feints. Similar in properties to pot ale, but more dilute.
Distillers dark grains (DDG)	Draff and condensed pot ale are combined to produce distiller dark grains, an animal feed that is drier, has a higher nutritional value and is easier to transport than draff.
Spent grain	A by-product from brewing. The composition of spent grain makes it suitable for use as an animal feed.
Spent hops	A by-product from brewing. Hops are mixed with the wort and boiled, after which the solids are removed as trub and spent hops. Spent hops can be used as a mulch or soil conditioner, with or without composting.
Spent yeast	A by-product from brewing. Some spent yeast is reused in the brewing process. The remainder yeast is produced in a liquid form and can be disposed of with other liquid wastes to the sewage system.
Fish processing waste	Waste produced during fish processing operations can be solid or liquid, and includes skin, trimmings, bones, viscera. These may be made into fish paste, fishmeal or sold as a product.
Shellfish waste	Discarded shellfish (under-utilised, undersized or non-quota species) and parts of the shellfish that are not usually used for human consumption.
Abattoir waste and fat	Blood and bones can be rendered into blood and bone meal for fertiliser or blood meal for animal feed. Some of the abattoir waste produced is a fat.
Tallow	Tallow is a by-product of meat processing, produced when offal and carcass/ butcher's wastes are processed at rendering plants. Depending on the production method, some can be used in products

	such as soaps and cosmetics but other can only be used for industrial applications or burnt.
Whey	Whey is the liquid remaining after milk has been curdled and strained. It is a by-product of the manufacture of cheese or casein.
Wastes	
Waste wood	Waste wood arises from several sources and varies in quality, depending on its source. 'Clean' waste wood comes from packaging, pallets, joinery residues etc. 'Dirtier' grades include wood waste from construction and demolition, wood extracted from waste steams (e.g. at Civic amenity sites). Wood classed as hazardous waste includes fencing, railway sleepers and transmission poles.
Food waste	Food waste from the domestic and commercial sector separated at source
Residual domestic and commercial waste	Residual waste is the waste left after recyclables and food waste have been removed. It will still contain some material of organic origin, regarded as a "biogenic fraction". In some cases, residual waste can be processed into a refuse derived fuel (RDF), or if it meets specifications outlined in guidance, as a solid recovered fuel (SRF).
Used cooking oil	UCO comes from catering premises, food factories and households. This can be collected, cleaned and processed into biodiesel.
Sewage sludge	Sewage sludge from wastewater treatment plants.

Feedstock categorisation: (percentages based on a dry weight basis)

Used for bioenergy (~12%):

- Includes combustion for heat and/or power in boilers, power plant, CHP plant, and energy from waste plant, anaerobic digestion to produce biogas which can then be used to generate power and/or heat, or can be converted to biomethane for injection into the grid, and conversion of used cooking oils to biodiesel.

Used as a material (~45%):

- Includes use as animal feed, animal bedding, for fencing, panel board production, landscaping, horticulture and composting to produce a soil improver.

Disposal; to landfill, and for liquids, disposal to sewer, rivers and sea (~44%):

- This category also includes residues such as straw which may be ploughed back into the land and the spreading of slurries and farmyard manure on the land, and forestry residues which are left in the forest after harvesting. In these cases there may be some transfer of nutrients to the soil, i.e. 'disposal' of the bioresource may have some economic or environmental benefits.

Annex B – Bioenergy resource updates

The key assumptions used in bioenergy resource analysis are outlined in this annex.

Forestry

Forests are typically managed to produce large diameter saw logs which can be processed into sawn timber. However, thinning of forests and final harvesting also produces smaller diameter wood and small round wood (SRW), which is less valuable and can be used for energy and as a raw material for the production of particle board. Final harvesting of the forest also produces harvesting residues or brash (the tops and branches of trees) which are not suitable for any other use but can be collected for use for energy. Finally, processing of the large diameter logs at sawmills produces sawmill residues, which can be used for energy, particle board production, in horticulture or as animal bedding.

The availability of forestry products for bioenergy is therefore primarily driven by the harvesting and processing of sawlogs, and demand for SRW and sawmill residues in other markets. Harvesting is done when forests mature, so harvesting levels are determined by the age profile of forests and demand for sawlogs**.** As the time for forests to mature (under conventional forestry practices) is typically 45 to 90 years, harvesting levels out to 2045 are already determined by past planting patterns. This means that **current afforestation will not increase levels of forestry products available from traditional forestry practices for bioenergy use (apart from possibly a small amount of thinnings) until after 2045.**

Resource estimates in the R19 report were based on a report examining wood availability and demand to 2035[33]. The underlying forecast by Forest Research of softwood availability on which this was based has been updated[34], and now provides estimates of wood availability out to 2041. This updated forecast was therefore used to update estimates of SRW availability. Harvesting levels for the period to 2041 were assumed to be representative of 2045 harvesting levels. **The updated forestry bioresource forecast provides a slightly lower estimated resource in 2030.** Harvesting levels decline from 2030 onwards, so overall availability of SRW declines. Assumptions about the proportion of SRW going to energy uses are taken from the report on wood availability and demand. This assumed that the fraction of SRW used for energy would rise over time, from 56% in 2030 to 65% in 2035; we further assumed that this fraction remains constant going out to 2045. The increasing fraction of SRW going to bioenergy counteracts the overall decline in SRW availability, so that overall, the SRW resource for energy changes little between 2030 and 2045.

Estimates of residues available at harvesting have also been updated to take account of the new wood availability forecast, and data from a study on wood fuel availability in Britain[35], which estimated that the mass of "operationally available" forestry residues (the resource that can be removed from site) is 5.1% of the mass of harvested stemwood. **The residue resource available for bioenergy has been assumed to be half of the operationally available resource, as recovery may not be possible from all sites.**

The estimate of sawmill residues generated has been updated to be consistent with volume of sawlogs harvested in the updated wood availability forecast. This is based on

[33] Wood Fibre Availability Demand in Britain 2013 – 2035. John Clegg Consulting, 2016.

[34] National Forest Inventory – 25 year forecast of softwood timber availability UK 2016

[35] Woodfuel Resource in Britain. H. McKay, 2003.

data from Forestry Research statistics[36], which gives quantities of residues generated as 56.4% of sawmill roundwood consumption. In 2020, 26% of this was used for bioenergy (sold or used internally). Going forward, **half of the increase in sawmill residues by 2030 has been assumed to be available for bioenergy**, so that bioenergy accounts for 34% of the total resource. By 2045, large diameter roundwood availability has declined, so the amount available for bioenergy decreases.

Unlike conventional forestry, short rotation forests (SRFs) are plantations grown specifically for bioenergy. Trees are felled sooner than traditional practice as the objective is not to produce larger diameter sawlogs. This allows advantage to be taken of the higher growth rate of younger trees. There are currently no commercial scale SRF plantations in Scotland. **SRF resource availability was estimated, assuming 1,000 ha per year is planted from 2025 onwards (about 10% of current afforestation targets, and 6% of the 2025 afforestation target)**. Previous work on perennial energy crops for CXC identified that 912,600 ha of land was **theoretically** suitable for SRF[37], so the 21,000 ha assumed to be planted by 2045 is well within this. Areas are harvested after 15 years, therefore, the earliest any resource becomes available is 2040. The assumed yield is 95 oven-dried tonnes (odt) per hectare per harvest, approximately 0.5 TWh per 1,000 ha. **It is assumed that all harvested biomass is available for bioenergy.** The assumed expansion of SRF may, as for expansion of conventional forestry, impact the land available for other agricultural uses.

Arboricultural arisings occur from trimming and felling on local authority and private land, rather than through forestry operations. Arisings will include material suitable for bioenergy but may also include a large amount of “green” material such as leaves and grass. Brash arising from arboriculture is more difficult to collect and may require more processing compared to brash from forestry. For this estimate, the total resource includes only stemwood. **No change in total arboricultural arisings resource is assumed by 2030 or 2045.** However, the available resource may increase if better management of materials is incentivised. Current competing uses for stemwood (totalling 24 k odt) are assumed to remain stable.

Agriculture

Perennial energy crops include short rotation coppice (SRC) and annually harvested energy crops such as miscanthus. If implemented, both types of crop would require access to farmland, primarily the land most suited to this would be land that is currently used as permanent grassland. SRC is currently grown on a small commercial scale in Scotland, with around 250 ha planted. **Miscanthus is not currently grown at a commercial scale in Scotland and requires further formal trials to verify its potential future contribution.**

As Miscanthus is not frost tolerant for planting over smaller areas of Scotland; previous work for CXC identified that while around 220,000 ha are agronomically suitable for SRC; only around 52,000 ha are deemed suitable for Miscanthus[38]. **Perennial crop estimates for this report are, therefore, predominantly based around expanding SRC areas**. In some areas agronomic and climatic conditions could favour Miscanthus over SRC, but as the yields achieved by the two crops are similar the assumption that SRC is planted has little impact on the overall estimate of bioenergy resource from perennial energy crops.

[36] https://www.forestresearch.gov.uk/tools-and-resources/statistics/forestry-statistics/forestry-statistics-2021/
[37] Land Use Impacts of Perennial Energy Crops in Scotland, Ricardo, 2019. For ClimateXChange. The report identified land which was agronomically suitable for planting of SRF but did not consider any other constraints or barriers to planting SRF.

SRC has been modelled in a similar way to SRF. **SRC planting is assumed to start at 1,000 ha per year in 2023, with uptake then accelerating, so that each year the area planted increases by 20%, i.e. in 2024 it is assumed that 1,200 ha can be planted.** An annualised yield of 8 odt per hectare per year is assumed. In total it is assumed that 50,000 ha (25% of potential land suitable for SRC as determined in previous work for CXC[38]) is planted. However, it must be noted that, current agricultural rules (Greening) prevent the conversion of more than 5% of national permanent grassland area, which equates to 57,113 ha. The current area of SRC is included and all SRC resource is assumed to be available for bioenergy.

Straw is a by-product of harvested crops, most commonly cereal crops (wheat, oats and barley) but also oilseed rape. The current resource was calculated using the 2020 harvested areas of cereal and oilseed rape, and the assumed yield of straw per hectare for each crop. Harvested areas are expected to fluctuate in the future, but no trend for growth or decline is assumed. To note, there is an existing market for straw within Scotland (animal feed and bedding, and horticulture), previous work identified the current requirement for these potentially competing uses is ~1.2 Mt per year. These uses, particularly for animal feed and bedding will be affected both by changes in the herd size and potential future changes in climate, but it is not possible to forecast these with certainty. **The availability of straw for bioenergy is assumed to be stable out to 2045**.

Resources arising from livestock farming (slurries, farmyard manure (FYM) and poultry litter) have not changed since the R19 report. Projections of livestock numbers in the UK to 2050 have been produced by the FAO[39]. Under the business-as-usual scenario, cattle numbers are expected to decline to 90% of current levels by 2045. Pigs and sheep are expected to increase by 7% and 6% respectively, and poultry numbers will remain relatively stable. As these figures are for the UK as a whole, and part of a global projection, it was decided not to adjust the expected resource based on these projections.

Food & Drink Industry

By-products from whisky and beer production suitable for anaerobic digestion include draff, pot ale, spent lees/wash and Distillers dark grains (DDG) from whisky; and spent grain, hops and yeast from beer production. Previous projections had simply assumed no growth in either industry, but these sectors have both been identified as ones where significant growth could be possible in the future. We have therefore assumed that production in both industries, and hence volumes of waste products increase by **7.5% by 2030 and 20% by 2045.**

Some whisky and beer by-products are used for animal feed, e.g. 50% of draff is currently estimated to be used as animal feed. Quantities used for animal feed are assumed to remain the same to 2045, therefore, all additional resource generated as the industry expands becomes available for bioenergy. The whisky industry is keen to maximise the value extracted from their by-products, and it is possible that there could be additional demand for by-products to allow extraction of proteins and nutrients contained in them. This is difficult to forecast with any certainty, particularly as in some cases there may still be components of the by-products after extraction of higher value components which could be used for bioenergy.

[38] Land Use Impacts of Perennial Energy Crops in Scotland, Ricardo, 2019. For ClimateXChange
[39] Food and Agriculture Organization of the United Nations

No changes have been made to the R19 report estimates for total resource and available resource from fish, shellfish or animal processing by-products, or whey. Available quantities are assumed to remain at the same level to 2045.

Waste

No changes have been made to the R19 report estimate for waste wood total resource.

In the case of **food waste, estimates for 2030 have been updated to reflect Scotland's target to reduce food waste by 33% by 2025**. It is assumed that food waste generated remains constant from this period onwards (i.e. future efforts to prevent food waste are enough to counteract any growth in the food waste generated due to population growth). Assumptions about the proportion of food waste generated which can be made available for bioenergy have also been updated. **It is assumed that 70% of food waste generated can be separated from the general waste stream** (e.g. through source separated collection) and made available for bioenergy. This leads to an overall increase in the resource available for bioenergy in 2030 of about 30%.[40]

The estimate for residual domestic and commercial waste, i.e. the organic fraction remaining after extraction of recyclables and food waste has been revised downwards to allow for the increase in the amount of food waste which is extracted. It is assumed that policies aimed at waste prevention and the circular economy are successful in decoupling residual waste quantities from population and economic growth, so that the resource is assumed to remain at 2030 levels in 2045.

Sewage sludge and used cooking oil (UCO) arise from the human population. The previous estimates assumed no change in resource quantity from the current level to 2030. **The current resource for sewage sludge has been updated according to the latest annual return for Scottish Water, this has been projected to increase in proportion to the expected increase in the population of Scotland by 2030 and 2045** (an increase of 1.5% by 2020 and 2% by 2045). No change has been made to the current resource of UCO, and the forward projection is also in proportion to the expect population increase. All sewage sludge is assumed to be available for bioenergy, 70% of UCO is assumed to be available for bioenergy.

Macroalgae

Macroalgae resource includes four kelp species of which one, Laminaria hyperborea, is the most abundant. From modelling, the total stock of these four species is 22 Mt. A sustainable removal rate of 3% of standing stock per year has been assumed, giving a total resource of 676 kt[41].

Harvesting of 5 kelp species (including Laminaria hyperborea) from Scottish Crown Estate (covering half of Scotland's foreshore and almost all seabed) can only be carried out under licence. Currently, licences will not be issued when:

- Removal of the kelp would inhibit the regrowth of the individual plant, and,
- The kelp removed is intended for commercial use[42].

[40] Unseparated food waste still has the potential to generate negative emissions as bioenergy if waste incineration facilities are fitted with CCS (i.e. BECCS EfW)

[41] Wild Seaweed Harvesting as a Diversification Opportunity for Fishermen. HIE, 2018

[42] https://www.gov.scot/publications/wild-kelp---restrictions-on-removal-questions-and-answers/

For this reason, **the available resource of macroalgae for bioenergy has been set at nil for current, 2030 and 2045 estimates**.

Annex C – bioresource updates

Energy units

		Unit	Total Resource					Available Resource					Currently Used	
			R19		Update			R19		Update			R19	Update
			Previous	2030	Current	2030	2045	Previous	2030	Current	2030	2045		
Combustion														
Wood	Forestry - small round wood	TWh	5.2	4.9	5.2	4.9	4.3	2.3	2.8	2.7	2.7	2.8	2.3	2.7
	Forestry - residues from harvest	TWh	1.4	1.4	1.2	1.4	1.2	0.7	0.7	0.6	0.7	0.6	0.1	0.1
	Short rotation forestry	TWh	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.5	0.0	0.0
	Sawmill residues	TWh	6.7	8.5	6.0	9.0	8.0	1.5	2.3	1.6	3.1	2.6	1.5	1.6
	Arboricultural arisings	TWh	0.8	0.8	0.4	0.4	0.4	0.6	0.6	0.2	0.3	0.3	0.5	0.2
	Waste wood	TWh	2.8	2.8	2.8	2.8	2.8	1.4	1.4	1.4	1.4	1.4	0.9	1.4

		Unit	Total Resource					Available Resource					Currently Used	
			R19		Update			R19		Update			R19	Update
			Previous	2030	Current	2030	2045	Previous	2030	Current	2030	2045		
Perennial energy crops	Short rotation coppice and Miscanthus	TWh	0.0	2.2	0.0	0.8	3.2	0.0	0.7	0.0	0.8	3.2	0.0	0.0
Straw	Cereal straws	TWh	6.3	6.3	5.8	5.8	5.8	1.2	1.2	1.2	1.2	1.2	0.0	0.0
Residual MSW and commercial waste	Biogenic component only	TWh	1.9	0.7	1.9	0.5	0.5	1.7	0.6	1.7	0.4	0.4	0.1	1.7
Poultry litter	Poultry litter	TWh	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
		'Dry' sub total*	**25.4**	**27.9**	**23.6**	**25.8**	**27.0**	**9.6**	**10.5**	**9.7**	**10.8**	**13.2**	**5.7**	**8.0**
'Wet' bioresources suitable for anaerobic digestion														
Food waste	Domestic and commercial food waste	TWh	0.6	0.6	0.6	0.4	0.4	0.5	0.5	0.2	0.3	0.3	0.3	0.2
	Draff	TWh	0.7	0.7	0.7	0.7	0.7	0.3	0.3	0.1	0.1	0.2	0.2	0.1

		Unit	Total Resource					Available Resource					Currently Used	
			R19		Update			R19		Update			R19	Update
			Previous	2030	Current	2030	2045	Previous	2030	Current	2030	2045		
By-products from whisky industry	Pot ale	TWh	0.2	0.2	0.2	0.3	0.3	0.2	0.2	0.2	0.3	0.3	0.0	0.1
	Spent lees/wash	TWh	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	DDGS	TWh	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
By-products from brewery industry	Spent grain (Beer)	TWh	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Spent hops (Beer)	TWh	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Spent yeast (Beer)	TWh	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
By-product from dairy industry	Whey	TWh	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0
Waste from fish processing	Fish process waste	TWh	0.2	0.2	0.2	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Shellfish waste	TWh	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

		Unit	Total Resource					Available Resource					Currently Used	
			R19		Update			R19		Update			R19	Update
			Previous	2030	Current	2030	2045	Previous	2030	Current	2030	2045		
Abattoir waste	Animal by-products	TWh	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Animal by-products	TWh	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sewage sludge	Sewage sludge	TWh	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.1	0.1
Slurries	Dairy and beef slurry	TWh	0.7	0.7	0.7	0.7	0.7	0.5	0.5	0.5	0.5	0.5	0.0	0.0
	Dairy and Beef FYM	TWh	0.9	0.9	0.9	0.9	0.9	0.7	0.7	0.7	0.7	0.7	0.0	0.0
	Pig Slurry	TWh	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Pig FYM	TWh	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Used cooking oil	Used cooking oil	TWh	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.1	0.1
Tallow	Tallow	TWh	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.3	0.3

		Unit	Total Resource					Available Resource					Currently Used	
			R19		Update			R19		Update			R19	Update
			Previous	2030	Current	2030	2045	Previous	2030	Current	2030	2045		
Algae	Macro-algae seaweed	TWh	0.0	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wet sub-total*			**4.8**	**4.8**	**5.0**	**4.8**	**4.9**	**3.5**	**3.5**	**2.9**	**3.0**	**3.1**	**1.1**	**0.9**
All resources total*			**30.2**	**32.7**	**28.6**	**30.7**	**31.9**	**13.1**	**14.0**	**12.5**	**13.9**	**16.3**	**6.7**	**8.9**

* Totals may not sum due to rounding

Typical units

Additional land requirement for SRF & PEC are included in the table to show the spatial impact of these estimates.

		Unit	Total Resource					Available Resource					Currently Used	
			R19		Update			R19		Update			R19	Update
			Previous	2030	Current	2030	2045	Previous	2030	Current	2030	2045		
Combustion														
Wood	Forestry - small round wood	M t (wet)	2.2	2.1	2.3	2.1	1.9	1.0	1.2	1.2	1.2	1.2	1.0	1.2
Wood	Forestry - residues from harvest	M odt	0.3	0.3	0.2	0.3	0.2	0.1	0.1	0.1	0.1	0.1	0.0	0.0
Wood	Short rotation forestry	M odt	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0
Wood	Short rotation forestry	Additional land requirement (hectares)	-	-	-	-	15,008	-	-	-	-	15,008	-	-

		Unit	Total Resource					Available Resource					Currently Used	
			R19		Update			R19		Update			R19	Update
			Previous	2030	Current	2030	2045	Previous	2030	Current	2030	2045		
	Sawmill residues	M t	1.9	2.4	1.7	2.6	2.3	0.4	0.7	0.4	0.9	0.7	0.4	0.4
	Arboricultural arisings	M odt	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.0
	Waste wood	M odt	0.6	0.6	0.6	0.6	0.6	0.3	0.3	0.3	0.3	0.3	0.2	0.3
Perennial energy crops	Short rotation coppice and Miscanthus	M odt	0.0	0.4	0.0	0.2	0.6	0.0	0.1	0.0	0.2	0.6	0.0	0.0
		Additional land requirement (hectares)	250	53,750	500	26,999	75,250	250	16,500	500	26,999	75,250	-	-
Straw	Cereal straws	M t	1.6	1.6	1.5	1.5	1.5	0.3	0.3	0.3	0.3	0.3	0.0	0.0

		Unit	Total Resource					Available Resource					Currently Used	
			R19		Update			R19		Update			R19	Update
			Previous	2030	Current	2030	2045	Previous	2030	Current	2030	2045		
Residual MSW and commercial waste	Biogenic component only	"Mt of bio-degradable waste"	0.6	0.2	0.6	0.2	0.2	0.6	0.2	0.6	0.1	0.1	0.0	0.6
Poultry litter	Poultry litter	M t (wet)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
		Dry sub total*	**7.6**	**8.0**	**7.1**	**7.6**	**7.6**	**3.0**	**3.2**	**3.1**	**3.3**	**3.7**	**1.9**	**2.7**
'Wet' bioresources suitable for anaerobic digestion														
Food waste	Domestic and commercial food waste	M t (wet)	0.6	0.6	0.6	0.4	0.4	0.2	0.5	0.2	0.3	0.3	0.3	0.2
By-products from whisky industry	Draff	M t (wet)	0.7	0.7	0.7	0.7	0.8	0.3	0.3	0.1	0.2	0.3	0.3	0.1
	Pot ale	M t (wet)	2.0	2.0	2.0	2.2	2.5	2.0	2.0	2.0	2.2	2.4	0.4	0.6

		Unit	Total Resource					Available Resource					Currently Used	
			R19		Update			R19		Update			R19	Update
			Previous	2030	Current	2030	2045	Previous	2030	Current	2030	2045		
	Spent lees/wash	M t (wet)	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.1	0.1
	DDGS	M t (wet)	0.3	0.3	0.3	0.3	0.3	0.0	0.0	0.0	0.0	0.1	0.0	0.0
By-products from brewery industry	Spent grain (Beer)	M t (wet)	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Spent hops (Beer)	M t (wet)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Spent yeast (Beer)	M t (wet)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
By-product from dairy industry	Whey	M t (wet)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0
	Fish process waste	M t (wet)	0.2	0.2	0.2	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0

		Unit	Total Resource					Available Resource					Currently Used	
			R19		Update			R19		Update			R19	Update
			Previous	2030	Current	2030	2045	Previous	2030	Current	2030	2045		
Waste from fish processing	Shellfish waste	M t (wet)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Abattoir waste	Animal by-products	M t (wet)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Animal by-products	M t (wet)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sewage sludge	Sewage sludge	M t (wet)	1.5	1.5	1.5	1.6	1.6	1.5	1.5	1.5	1.6	1.6	0.4	0.4
Slurries	Dairy and beef slurry	M t (wet)	5.6	5.6	5.6	5.6	5.6	4.2	4.2	4.2	4.2	4.2	0.1	0.1
	Dairy and Beef FYM	M t (wet)	7.4	7.4	7.4	7.4	7.4	5.5	5.5	5.5	5.5	5.5	0.0	0.0
	Pig Slurry	M t (wet)	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.0	0.0

		Unit	Total Resource					Available Resource					Currently Used	
			R19		Update			R19		Update			R19	Update
			Previous	2030	Current	2030	2045	Previous	2030	Current	2030	2045		
	Pig FYM	M t (wet)	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.0	0.0
Used cooking oil	Used cooking oil	M t	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Tallow	Tallow	M t	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0
Algae	Macro-algae seaweed	M t (wet)	0.0	0.2	0.7	0.7	0.7	0.0	0.2	0.0	0.0	0.0	0.0	0.0
		Wet sub-total*	**20.0**	**20.2**	**20.7**	**20.8**	**21.2**	**15.4**	**15.9**	**14.7**	**15.0**	**15.5**	**1.4**	**1.4**
		All resources total*	**27.6**	**28.2**	**27.8**	**28.4**	**28.8**	**18.4**	**19.1**	**17.7**	**18.3**	**19.2**	**3.3**	**4.1**

* Totals may not sum due to rounding

Resource masses in section 2.3 are given in green or wet tonnes. The following moisture contents were assumed when converting from oven dry tonnes:

- Forestry – Brash, 50%
- Short rotation forestry, 50%
- Arboricultural arisings, 50%
- Waste wood, 20%

- Perennial energy crops, 30%

Annex D – Terminology used in CCPu, TIMES & CCC

Table 7 - TIMES simulation, CCPu and CCC categories

TIMES model	CCPu	CCC
Agriculture ↔	Agriculture ↔	Agriculture
Electricity ↔	Electricity ↔	Power
Transport ↔	Transport ↔	Transport
Industry ↔	Industry	Manufacturing & Construction
Residential Services	Buildings	Buildings
	Waste & the circular economy	Fuel Supply
	LULUCF	Waste

For clarity between the TIMES model and CCPu document:

- Agriculture
- Electricity
    - Electricity generation, includes electricity generated in CHP (where the heat would then either be categorised in industry or buildings)
    - Includes electricity generated from energy from waste
- Industry
    - Relates to heavy industry
- Transport
- Residential
    - solely as heat in stationary combusting equipment in domestic properties
- Services
    - used as heat in non-domestic properties
        - refrigerants & AC equipment
        - appliances
            - not required as part of the bioresource mapping

Table 8 – CCC sectors, sub-sectors and bioresource feedstock (UK)

Sector/ end-use	Sub-sector	Bioresource feedstock
Manufacturing and Construction	Manufacturing	UK biomass Biogas Dry bio-waste Dry non-bio waste
	Off-road mobile machinery	Biodiesel FAME
Agriculture	Agriculture	UK biomass Biogas
	Agricultural off-road mobile machinery	Biodiesel FAME
Transport	Cars/vans/taxis/motorcycles	Biodiesel FT Biodiesel FAME Bioethanol
	HGVs/buses/coaches	Biodiesel FT Biodiesel FAME
	Aviation	Biojet
Buildings	Domestic buildings	UK biomass Biodiesel FAME BioLPG
	Non-domestic buildings	UK biomass
Fuel supply	Gas grid	Biomethane
	Hydrogen	BioH2
Power	Power without CCS	UK biomass Imported biomass Biogas Dry non-bio waste
	Power with CCS	UK biomass Imported biomass
Waste	Energy from waste	Dry bio-waste Dry non-bio waste
	Waste sector	Dry bio-waste Dry non-bio waste

Points to note:

Manufacturing & Construction

- This is similar to the "Industry" category as represented in the TIMES simulation

Transport

- Biodiesel FT (Fischer-Tropsch)
- Biodiesel FAME (Fatty Acid Methyl Esters)
- Bioethanol
- Biojet conversion from bioethanol or waste oils/fats

Buildings

- BioLPG conversion from biomass

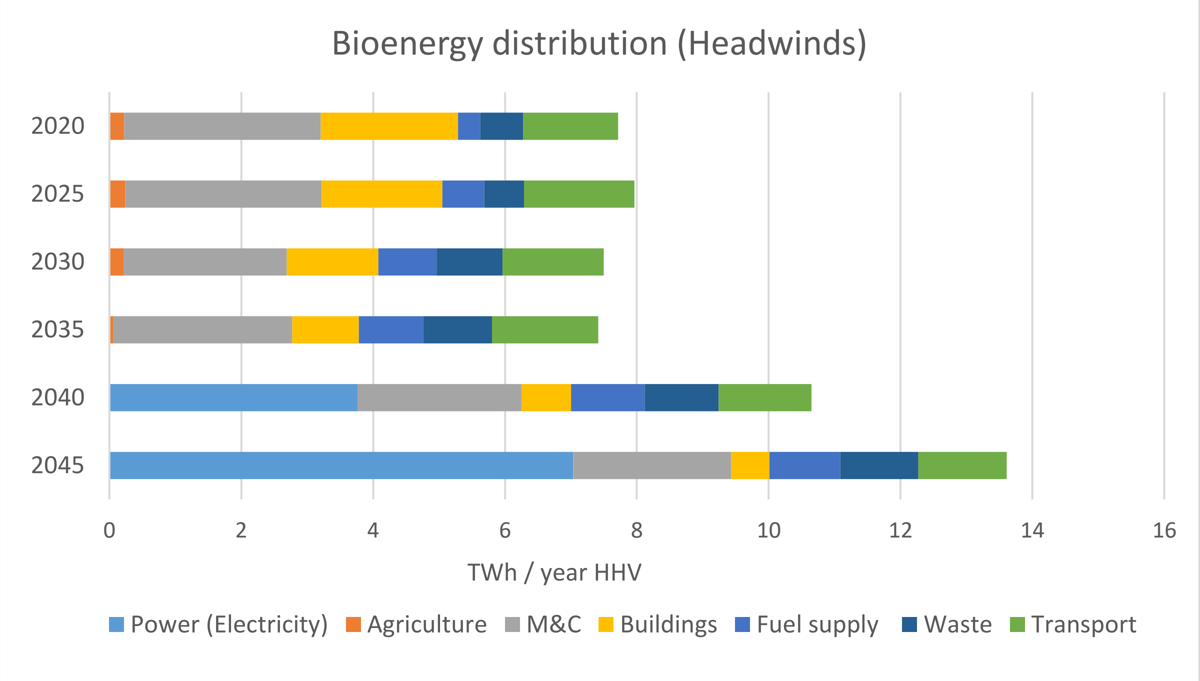
Fuel Supply

- Biomethane conversion from biogas
- Bio H2 conversion from biomass

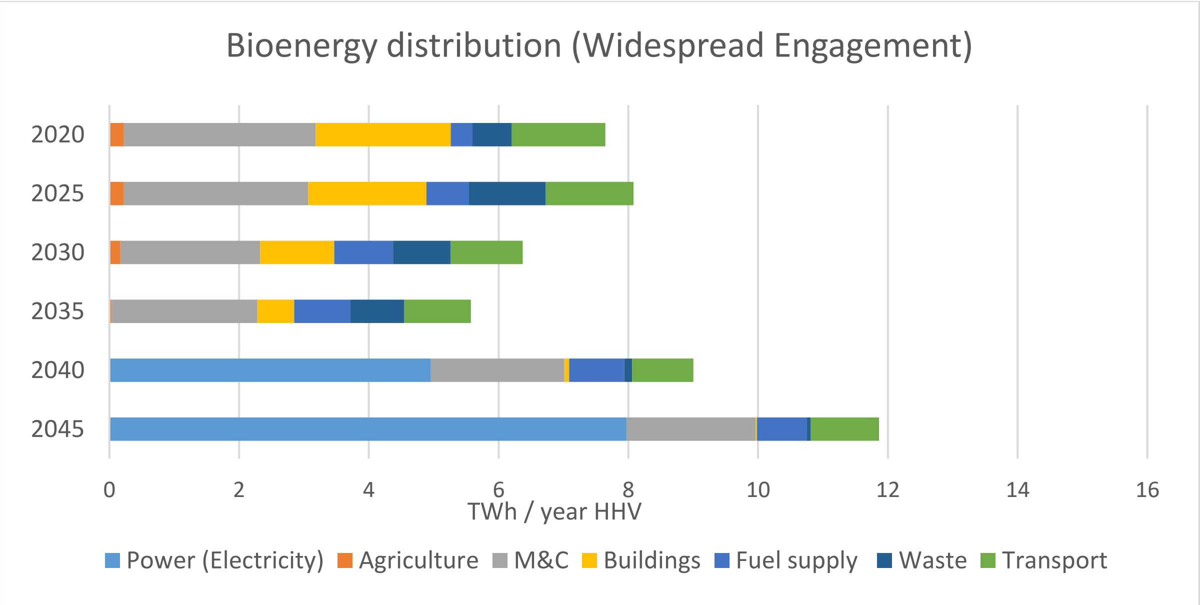
Annex E– CCC pathway demand distributions

The demand distribution graphs for the other CCC pathways are provided in this Annex.

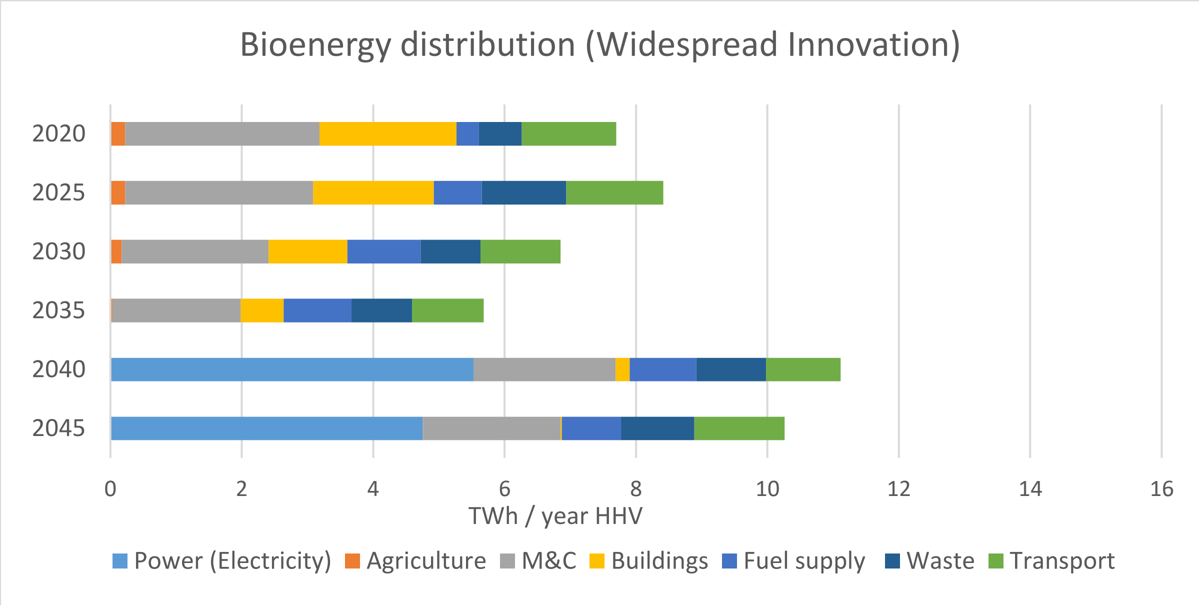
Headwinds



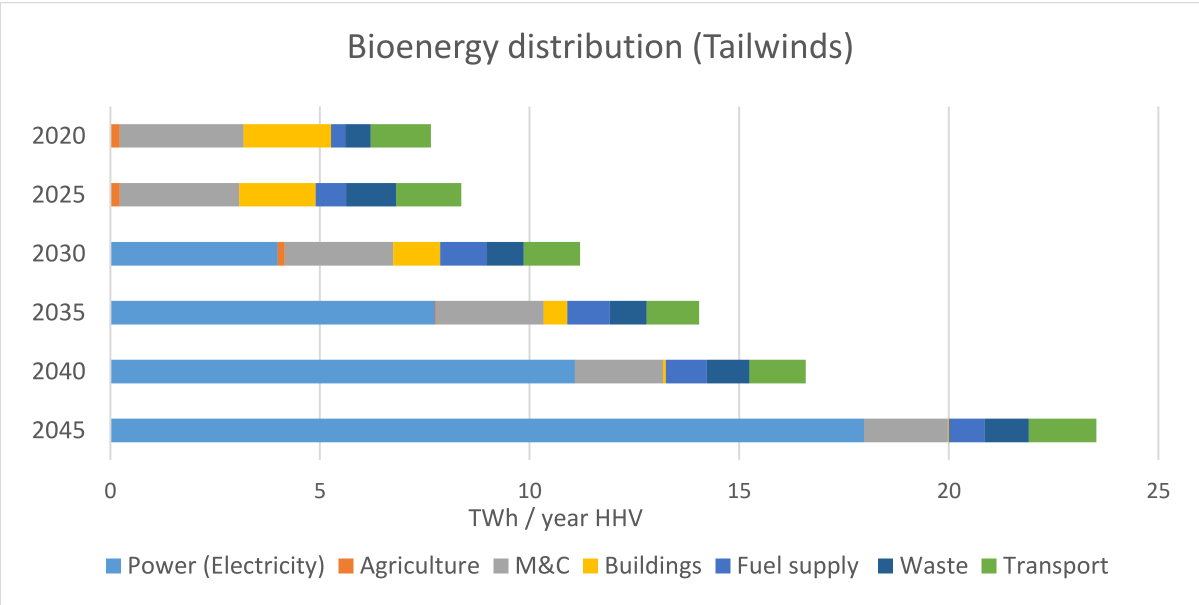
Widespread Engagement



Widespread Innovation



Tailwinds



Annex F – CCC biomass imports

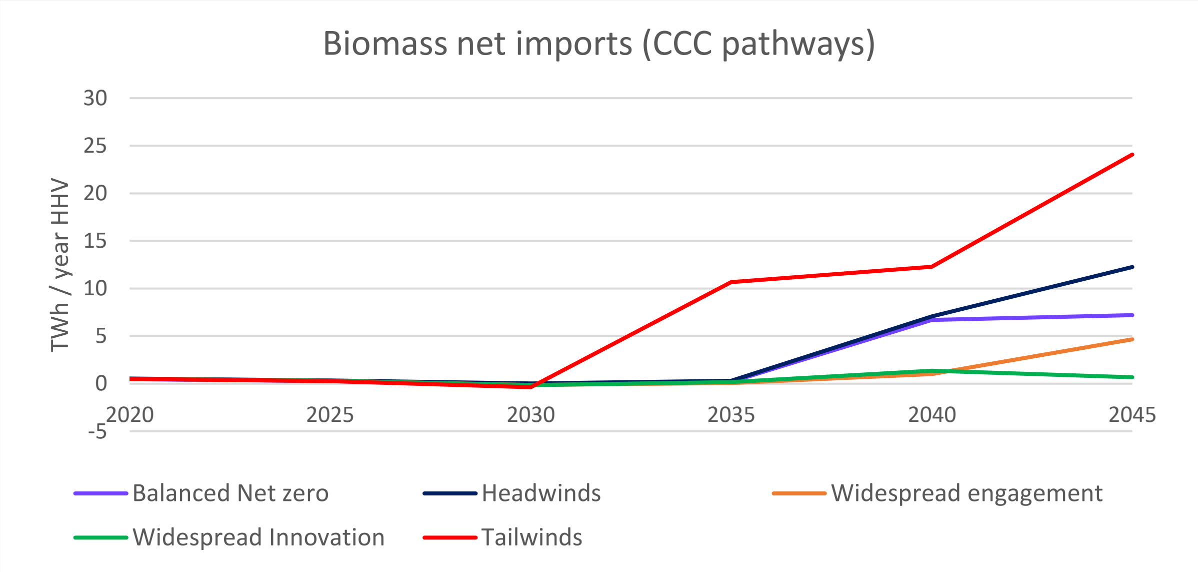


Figure 11 - All CCC pathways - biomass imports

The CCC's 6th Carbon Budget (6CB) shows biomass imports (and not bioenergy imports, as in Scottish TIMES). From the CCC's 6CB:

> *"Actual biomass imports in any year are determined by the balance of total UK biomass supply and total UK biomass demand, and so biomass imports in all years before 2050 are lower than the maximum scenario availability."*

Thus, the biomass imports are calculated based on the difference between supply and demand and show some negative figures in the calculation (i.e. they do not represent years where biomass is being exported).

In all CCC simulated pathways, biomass imports are predicted to increase from approximately 2030 -2035 onwards. The magnitude of imports varies depending on the simulation model, with the balanced net-zero simulation an "average" of the 5 (3rd highest/lowest of the 5 pathways). In 2045 magnitude of imports (biomass, not solely for bioenergy purposes) in the Tailwinds scenario is similar to that of the TIMES simulation.

The timing of these projected imports are due to **new** BECCS power stations coming on-line and are not due to converting any existing assets, although there are a number of existing biomass fuelled plants of medium capacity (see section 4.2.2) that could be candidates for retrofit of BECCS technology in the future (note that the upgrade of these to BECCS would not necessarily be predicted to increase biomass imports and could in theory be undertaken prior to any "new" BECCS.

Annex G – Supplementary information on BECCS

The role of BECCS in helping Scotland achieve net zero targets

Most global emissions pathways that meet the Paris temperature targets consider negative emission technologies, which are considered a critical component for reaching net-zero emissions in 2050. However, economic incentives supporting commercialisation and deployment of BECCS and DACC are still not developed. It is now recognised that BECCS is expected to play a key role in helping Scotland achieve net zero targets by 2045 and is expected to be a factor in the future demand for bioenergy in Scotland. The demand for biomass by BECCS depends on the split of technologies assumed and what feedstocks are applicable for what technologies.

Efforts are underway in the UK and other countries (for example Sweden and at the EU level) to include CO_2 removal credits under existing mechanisms such as the ETS or the Renewable Energy Directive (RED). For BECCS, the sustainability of biomass is expected to be a key consideration in determining the negative emission potential. For example, the life cycle emissions and impacts associated with wood pellet imports from overseas for use in BECCS for power should be considered when estimating the negative emission potential for Scotland.

A mechanism to support BECCS is essential for projects to develop. Possible mechanisms include:

- Governmental guarantees for purchasing BECCS output,
- Quota obligation on selected sectors to acquire BECCS output (e.g. electricity supply),
- Allowing BECCS credits to compensate for hard-to-abate emissions within the ETS,
- Private entities for voluntary compensation,
- Other states acting as buyers of BECCS outcomes to meet their mitigation targets under the Paris Agreement.

Including BECCS under the ETS links it to a large carbon-pricing regime with opportunities for cost-effectiveness and expanded financing. A BECCS policy should be part of an integrated climate policy framework, considering the mitigation of GHG emissions and the creation of a circular economy. A well-designed policy package should guarantee that BECCS is not used to postpone the reduction of fossil fuel-based emissions.

The main elements of a BECCS system consist of a feedstock, biomass conversion system and CCUS system, which can be achieved through various combinations of feedstocks, biomass conversion systems and CCUS systems.

Mixed feedstocks in BECCS plants

Biomass feedstocks can be blended together in order to take advantage of lower-cost feedstocks and reduce reliance on a single feedstock, though there are also challenges associated with mixed feedstocks such as boiler combustion design and flue abatement technologies required.

Blending biomass feedstocks can also be used to reduce the variability in chemical and physical properties of biomass, resulting in more consistent feedstocks[43]. Low-density feedstocks also require more resources for transportation and shipping[44], therefore blending biomass feedstocks can also result in reduced transportation costs. There are many different feedstocks which can be blended; however, research here focuses on the potential to combine forestry by-products and energy crops together within a BECCS plant.

[43] Charles W.Edmunds et al, Blended Feedstocks for Thermochemical Conversion: Biomass Characterisation and Bio-oil production from switchgrass-pine residues blends, 2018
[44] Allison E. Ray et al, Biomass Blending and Densification: impacts on feedstock supply and biochemical conversion performance

Mixing of feedstocks is a common practice. While woody biomass is the most widely used feedstock for pellet production, where pellets are then combusted, other sources for pellet production such as agricultural residues and energy crops have also been considered. Some of these have low bulk density, high ash content and low calorific value. In practice, woody and non-woody biomass can be combined to increase pellet quality.

Several combinations have been considered in ethanol BECCS plants, including mixes of forestry by-products and energy crops. Studies have demonstrated that mixed feedstocks can result in comparable ethanol yields[45] but further studies are still underway to optimise feedstock mixing and improve process performance.

Cost estimates of BECCS power plants

Table 9 - Cost estimates of BECCS power plants

Technology	Plant capacity MWe	CAPEX £M/MWe	OPEX £M/y (wood pellets feedstock)	OPEX £M/y (wood chips feedstock)
Biomass oxy-combustion with ccs	500	2.60	433	373
Biomass with post combustion ccs	500	2.50	453	393
Biomass IGCC with pre combustion CCS	500	2.95	424	369

Feedstock costs

Table 10 - Feedstock costs

Feedstock	Cost £/MWh
Wood pellets	23.7
Wood chips	19.0

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[45] Mushafau Adebayo Oke et al, Mixed feedstock approach to lignocellulosic ethanol productions – prospects and limitations, 2016