UK & Global Bioenergy Resource Model (2024)

Methodology

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Glossary

ALC	Agricultural land class
BECCS	Bioenergy carbon capture and storage
BEAC	Biomass Emissions and Counterfactual Model
CCS	Carbon capture and storage
CCUS	Carbon capture, utilisation and storage
CO_2	Carbon dioxide
CCC	Climate Change Committee
CHP	Combined heat and power
C&I	Commercial and industrial
C&D	Construction and demolition
DAERA	Department for Agriculture, Environment and Rural Affairs
DESNZ	Department for Energy Security and Net Zero
Defra	Department for Environment, Food and Rural Affairs
DfT	Department for Transport
DUKES	Digest of UK Energy Statistics
EfW	Energy from waste
FT	Fischer–Tropsch
FAO	Food and Agriculture Organisation
FABRA	Foodchain and Biomass Renewables Association
GJ	Gigajoule
gCO2eq	Grams of CO2 equivalent
GHG	Greenhouse gas
GDP	Gross domestic product
ha	Hectares
HTL	Hydrothermal liquefaction
ILUC	Indirect land use change
IPCC	Intergovernmental Panel on Climate Change
IEA	International Energy Agency
ITL	International territorial level
kha	Kilohectare
kt	Kilotonne
LULUCF	Land Use, Land-Use Change and Forestry
MJ	Megajoule
MELMod	Methane Emissions from Landfills Model
Mha	Million hectares
MSW	Municipal solid waste
NAEI	National Atmospheric Emissions Inventory
odt	Oven dried tonne
PJ	Petajoules
RTFO	Renewable Transport Fuel Obligation
SSP	Shared socioeconomic pathway
SRC	Short rotation coppice

SRF	Short rotation forestry
SRW	Small roundwood
SAF	Sustainable aviation fuel
t	Tonne
UKGBRM	UK and Global Bioenergy Resource Model
UKGHGI	UK GHG Inventory
UCO	Used cooking oil
WEO	World Energy Outlook

1. INTRODUCTION

In 2011, Ricardo developed the UK and Global Bioenergy Resource Model (UKGBRM). The purpose of the UKGBRM was to estimate the potential availability of bioenergy feedstocks to the UK. The insights from the model were used to support the 2012 Bioenergy Strategy. In 2017, an updated version of the UKGBRM was published which better captured feedstock sustainability as well as expanding the range of feedstocks modelled to reflect developments in the market.

In 2021, Ricardo were contracted by the Department for Business Energy and Industrial Strategy, now the Department for Energy Security and Net Zero (DESNZ) to rebuild the UKGBRM. This rebuilt model has been used to support the 2023 Biomass Strategy (DESNZ, 2023). This report details the methodology that underpins the new model, the **UK and Global Bioenergy Resource Model (2024)** (“the model”).

2. MODEL OVERVIEW

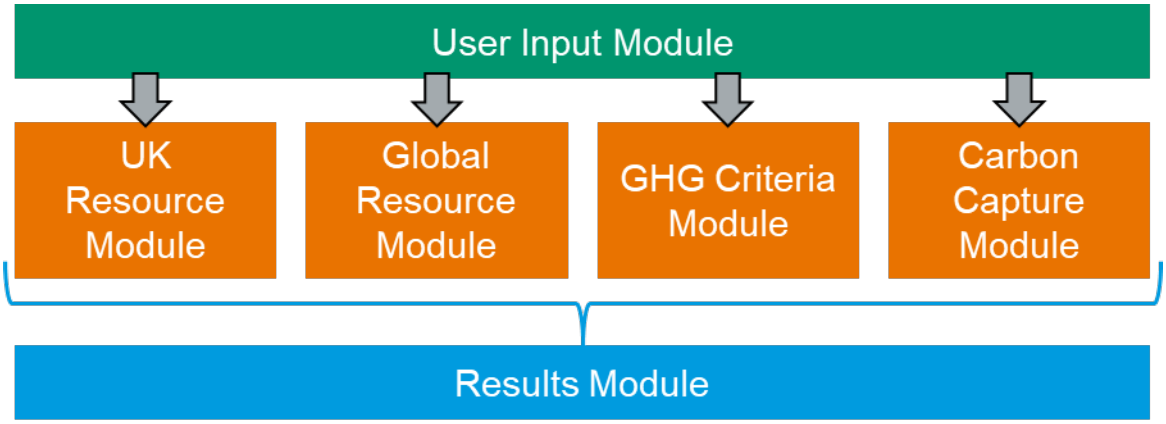
The model is designed as a scenario-based tool that allows the user to develop estimates of the energy content of the **potential** biomass availability to the UK from 2025 until 2050. It is configured to allow the user to explore the impact of key assumptions, about both UK biomass resources and the global supply and demand for biomass, on the availability of biomass to the UK. Given uncertainty in the development of societies, it can be used to explore scenarios of the future rather than to provide a single forecast of the availability of biomass, particularly when looking out to 2050,

This methodology document summarises the reference data, default inputs and assumptions that are contained within the model, as well as providing an overview of the logic that underpins the model calculations. While the model contains a range of potential inputs the user can select from, it has also been configured so that key assumptions can be conveniently updated, or additional UK feedstocks/feedstock scenarios can be added. Further details can be found in the accompanying user guide.

2.1 HIGH-LEVEL STRUCTURE

Figure 2-1 shows the high-level structure of the model, which is comprised of six modules. All calculations in the model are performed in the UK, Global, Greenhouse Gas (GHG) Criteria and Carbon Capture modules. These calculations are based on a series of user inputs, which are defined in the User Input Module. The outputs of the calculations are aggregated in the Results Module.

Figure 2-1 High-level structure of the model.



2.2 MODEL INPUTS AND REFERENCE DATA

All key inputs and reference data for the model are contained within the model itself, i.e. the model does not require any external files to run. The data sources, assumptions and supporting calculations for the derivation of the model reference data are contained in a series of **supporting workbooks**. A description of key model inputs is provided in this document.

3. UK MODULE

The UK Module estimates the availability of resources produced domestically in the UK. This data is aggregated at both the national and regional level (International Territorial Level 1). The outputs of the UK Module are either fed directly to the Results Module or to the Sustainability Module, depending on whether the user elects to apply the sustainability criteria or not.

3.1 UK RESOURCES

The model contains 24 discrete resources (‘feedstocks’) for the UK. The feedstocks included in the model can be broadly split into three categories: **wastes/residues, forestry products** and **crops** specifically grown for bioenergy purposes**.**

Where appropriate, more than one feedstock availability scenario has been included in the model. The user may select which scenario they would like to apply for each feedstock in the User Input Module. More details on the scenarios available are provided below.

Resource estimates have two components: **unconstrained resource potential** and **non-bioenergy competing uses**. The unconstrained resource potential is the total amount of the resource that is available while non-bioenergy competing uses are the common uses for the resource, other than bioenergy. Non-bioenergy competing uses are subtracted from the unconstrained resource potential to determine the resource available for bioenergy.

Table 3-1 ITL1 regions used for spatial disaggregation of resources.

ITL1 code	ITL1 Region
TLD	North West (England)
TLE	Yorkshire and The Humber
TLF	East Midlands (England)
TLG	West Midlands (England)
TLH	East (England)
TLI	London
TLJ	South East (England)
TLK	South West (England)
TLL	Wales
TLM	Scotland
TLN	Northern Ireland

Each resource estimate is also spatially disaggregated into the International Territorial Level (ITL) 1 regions (as used by the Office for National Statistics) shown in Table 3-1. Where data on the spatial distribution of resources is available, this is used to disaggregate the resource estimate. When such data is not available, a suitable ‘proxy indicator’ considered to be linked to the key driver determining resource availability is used. Where data is available, we allow the relative spatial disaggregation of a resource between regions to vary over time (e.g., where the proxy indicator is population, regional estimates are available for the whole time series so the distribution of resources deemed to be driven by population will vary over time, following trends in the distribution of population). However, in some cases forecasts are only available at the national level and in these cases, the relative spatial disaggregation is assumed to remain constant. For perennial energy crops and SRF, where there is no significant resource at present, spatial disaggregation of the forecast resource has been done based on assumptions made for the development of the biomass stagy about how planting might be distributed within England, combined with data on agricultural land class (ALC) as a proxy for areas available for cultivation of these crops. This means that there is no change in the spatial disaggregation of these resources over time. This methodology also implicitly assumes that the average regional yield for the crops is the same in all regions. In practice yields are likely to vary across the country and this is a refinement which could usefully be incorporated into the model in the future if the necessary data on regional yields for perennial energy crops was available.

It is assumed that competing uses follow the same spatial distribution as the unconstrained resource, i.e., resources are primarily used for non-bioenergy purposes within the ITL1 region they arise.

The following sections describe the methodology, key assumptions and references used to derive references. Further information including source data, a comprehensive list of values used for assumptions and the final resource estimates can be found in the background workbooks.

3.1.1 UK forestry products

Three feedstocks resulting from the existing UK forestry sector are included in the model: small roundwood, forestry harvesting residues and sawmill co-products. Other forestry related feedstocks included in the model are short rotation forestry (SRF), where trees are grown with a short rotation to specifically provide biomass for energy, and arboricultural arisings. Ricardo were supported in the development of these feedstock estimates by Forest Research.

3.1.1.1 Small roundwood, forestry harvesting residues and sawmill co-products

Small roundwood (SRW) is trunk or branchwood with a top diameter of 7-14 cm. This material is produced and collected as part of the sustainable management of forests. It may be available from thinning operations or at the final harvest of a forest for saw logs.

Forestry harvesting residues refer to small stem wood that is not suitable for other purposes, small branches and brash usually left on the forest floor. These could be obtained as part of current forestry operations. However, to do this there is a need for additional investment to enable their collection, either as part of the first pass forestry operations or for collection from the forest in a second pass operation. Retention of some of this resource is important to maintain biodiversity, soil structure and carbon and so it is assumed that not all can be collected, and some must be left in the forest.

Sawmill co-products are clean wood residues from processing of harvested timber in sawmills. They include slabs, chips, sawdust and bark.

Unconstrained resource potential

Estimates of the unconstrained resource potential of these three forestry products are derived from the CARBINE model (Forest Research, 2023). CARBINE is a model of the UK forestry stock that is used to provide forecasts to DESNZ for emissions associated with forestry for the greenhouse gas inventory and projections of emissions from the Land Use Land Use Change and Forestry (LULUCF) sector emission projections.

Two scenarios were used for these resources that represent the central and low emissions scenarios in the most recent set of LULUCF GHG projections. The central emissions scenario includes the effect of existing policies (until 2050) and firmly planned ones. It uses forest planting rates according to funding secured for grants within each devolved administration. From 2024 (in England & Northern Ireland) and after 2021 (in Scotland & Wales), planting rates drop to 620 ha/year (10% of the average planting achieved between 2008-2009). This reflects the lack of secured funding beyond that time horizon (as of June 2020).

The low emissions scenario assumes that an afforestation ambition at UK level of approximately 30,000 ha/year from 2025 onward is achieved, and that current afforestation rates gradually rise to meet this. In the early 2020s afforestation rates in Scotland and Northern Ireland (NI) match the targets set in Scotland’s 2018-32 Climate Change Plan’s annual planting targets (Scottish Government, 2020) and NI Forests for our Future programme (DAERA, 2020).

In both scenarios, the assumed split between broadleaf and conifer is consistent with current policy aspirations and grant availability/targeting/scoring:

- Scotland: 60% conifer
- England: 30% conifer
- Wales: 16% conifer
- Northern Ireland: 2% conifer.

The CARBINE model provides estimates of saw logs, small roundwood and forestry harvesting residues generated each year from harvesting in each of the devolved administrations. The quantity of sawmill residues is calculated assuming that 46.4% of coniferous sawlogs end up as sawmill residues and 48.5% for broadleaf sawlogs.

Further regional disaggregation of the English forestry estimates is made using the National Forest Inventory 2011 woodland map (Forestry Commission, 2013) which gives areas of coniferous and broadleaf forest. A simplifying assumption is made that the regional England split continues to apply in 2050, while afforestation rates in English regions may vary depending on regional differences in landowner appetite.

Competing use

Small roundwood and sawmill co-products are assumed to have competing uses including pulp mills, panel board production and fencing. Data on the estimated percentages of the coniferous and broadleaf resources going to these non-fuel uses was provided by Forest Research. This percentage is assumed to remain constant until 2050.

Forest harvesting residues are often left in the forest for environmental reasons, therefore this is counted as a competing use. Two scenarios are included for forest harvesting residues competing use: maximum extraction and minimum extraction. Minimum extraction assumes that 100% of residues are left in the forest, while maximum extraction assumes that 30% are extracted. These are combined with the two unconstrained potential scenarios, to give four scenarios overall[1].

3.1.1.2 Short Rotation Forestry (SRF)

Short rotation forestry (SRF) refers to the planting of trees that are felled when they have reached a size of 10-20 cm diameter at breast height. Depending on the tree species this usually takes between **eight and 20 years**. This is an intermediate timescale between SRC and conventional forestry. This has the effect of retaining the high productivity of a young plantation while increasing the wood to bark ratio.

Unconstrained Potential

As there is currently no significant SRF crop in the UK, other than several trial sites, and so there is no current resource. Furthermore, there can be no harvest until the end of the first rotation of the first year's planting. Consequently, the year of first harvest depends on when planting starts and the rotation length.

Two potential scenarios for SRF planting in England were developed by a key stakeholder for use in the biomass strategy. No information was available from stakeholders in the devolved administrations. One scenario reflects an ‘ambitious supply’ scenario, and the other models a ‘restricted supply’ scenario. Both scenarios include a mix of Sitka spruce, native broadleaf and exotic species. Table 3-2 shows key assumptions for SRF planting in England.

The supporting workbook also contains a methodology for developing additional scenarios. In this methodology the planting rate is assumed to increase by 50% each year until a maximum rate is achieved. The yield is dependent on the choice of species planted as well as the site and growing conditions. Once a steady state is achieved, the planting rate will equal the area harvested each year and the total area planted, and the annual harvest will remain constant. In addition to the planting rate and yield, available land area is also a significant factor in determining SRF availability.

Table 3-2 Key assumptions for SRF planting in England.

Species	Biomass strategy: ambitious supply scenario Area planted by 2050 (ha)	Biomass strategy: restricted supply scenario Area planted by 2050 (ha)	Rotation length (years)	Biomass at harvest (odt/ha)
Sitka spruce	6,825	13,650	20	301.5
Native broadleaf	46,200	92,400	20	134.4
Exotics	16,100	16,100	15	301.5
Total	69,125	122,150		

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[1] The minimum extraction scenarios result in zero bioenergy availability for forestry harvesting residues, as they are all assumed to be retained in the forest.

It is assumed that SRF is planted on poorer quality land, graded as 4 or 5 in the Agricultural Land Classification (ALC) system. The stakeholder provided assumptions on the broad split of planting by species spatially, and these were combined with data on the area of ALC grade 4 and 5 land in each ITL region to spatially disaggregate the England resource estimate.

Competing Use

SRF is assumed to be produced exclusively for bioenergy purposes, therefore there are no competing uses.

3.1.1.3 Arboricultural arisings

Arboricultural arisings are the cut wood left after tree surgery or tree felling where the trees are outside woodlands, e.g., in urban spaces or along the side of transport corridors (road or rail). The arisings contain both thicker trunk and branch wood, as well as small diameter twiggy material and (depending on the season) green material.

Unconstrained Potential

The unconstrained potential for arboricultural arisings is based on a detailed study for the Forestry Commission Scotland (Forestry Commission Scotland, 2010). The report assumes that the resource is proportional to the total area of trees outside woodlands. Furthermore, the report assumes that only material classified as roundwood (>2 inch diameter) is potentially suitable for bioenergy uses. The green portion and brash are considered unsuitable because the high proportion of bark, the likelihood of contamination by soil and the very low bulk density make it uneconomic to collect and dry these materials. The high proportion of bark and contamination also mean that utilising these resources would require purpose-designed combustors that would not be justified unless there was a large, very low-cost resource available. Given that arboricultural arisings tend to be dispersed in nature, e.g., along transport corridors, private estates, private gardens etc., aggregation of the resource is difficult and therefore these conditions are unlikely to be met.

These assumptions are applied to the *Tree Cover Outside of Woodland* dataset, which contains regionalised estimates of tree cover outside of woodland (Forest Research, 2017) to estimate the current unconstrained potential of arboricultural arisings. It was assumed that the areas of trees outside woodland would change significantly between 2020 and 2050, therefore estimates of future resource are the same as of the current resource.

Competing Use

Based on the assumptions made in calculating the unconstrained resource potential, arboricultural arisings do not have any competing uses aside from bioenergy.

3.1.2 UK wastes and residues

3.1.2.1 Used cooking oil

Used cooking oil (UCO) is virgin cooking oil that has been used for cooking food and is no longer fit for purpose.

Unconstrained potential

Estimates of current and future UCO availability in the UK are based on a report by Greenea (Greenea, 2016). We note that two prevalent and more recent reports covering UCO availability are available, namely *Used Cooking Oil (UCO) as biofuel feedstock in the EU* (CE Delft, 2020) and *Sustainable biomass availability in the EU, to 2050* (Concawe, 2021). However, the Greenea data set is the primary data set used for the UK in these reports. Therefore, we have used the primary (Greenea) data source in our analysis.

Table 3-3 Data available from Greenea on UCO availability in the UK.

Sector	Total Resource Potential / tonnes		Collection Rate		Collected Resource / tonnes	
	2015	2030	2015	2030	2015	2030
Household	42,000	51,000	12%	20%	5,000	10,200
Professional	n/a	n/a	n/a	n/a	100,000	115,000

Table 3-4 UK household UCO scenario summary.

Scenario	Scenario Name in Model	Maximum Resource Potential Reached	20% Collection Rate Reached
Low	Little increase in availability	No change	No change
Medium	Maximum availability reached by 2040	2040	2040
High	Maximum availability reached by 2030	2030	2030

The data contained in the Greenea report is summarised in Table 3-3. This data is used to produce low, medium and high scenarios for UCO availability in the UK.

The data reported by Greenea is for 2015. Analysis of available Renewable Transport Fuel Obligation (RTFO) statistics from 2015-2020 (DfT, 2023a) shows that the quantity of UCO from the UK used to produce biofuels for the UK has not changed significantly in this period. Therefore, in the absence of better data, we assume that UCO availability and collection rates in 2020 are the same as reported in 2015 by Greenea.

For household UCO, the total resource potential is provided for 2015 and 2030 (Table 3-3). The total resource potential reflects the maximum quantity of the resource that **could** be collected. Greenea also provide collection rates for 2015 and 2030, i.e., the percentage of the total resource that **is** collected. Greenea note that the 2030 figure (20%) is highly ambitious. Therefore, we include low, medium and high scenarios that differ by both the rate at which the total resource grows and the year in which a 20% collection rate is achieved. These scenarios are summarised in Table 3-4.

For the professional sector, Greenea only provide data on the total collected resource. Furthermore, Greenea state that an additional 15,000 tonnes of UCO could be collected from the professional sector compared to 2015. However, no specific timeline is given for this growth. Therefore, low, medium and high scenarios are included that differ by the point in time by which this growth is reached – which is 2025, 2030 and 2035, respectively.

The respective scenarios from the household and professional sectors were combined to give an overall UK UCO resource potential.

The UK level UCO resource was disaggregated to a regional level based on population data and forecasts from the Office of National Statistics (ONS, 2022) and (ONS, 2020).

Competing use

All UCO collected in the UK is assumed to be available for bioenergy use. Therefore, there are no competing uses.

3.1.2.2 Tallow

Tallow is rendered animal fat and is produced as a waste product of the animal by-product processing industry.

Unconstrained potential

Data for the unconstrained potential of tallow in the UK in 2020 is provided by the Foodchain and Biomass Renewables Association (FABRA), who represent around 90% of tallow producers in the UK[2]. Only Category 1 tallow has been considered as available for bioenergy use because Category 3 tallow is used to produce animal feed, soap and cosmetics[3]. It is assumed that the total available resource does not increase from current levels on the basis that cattle and pig livestock numbers in the England have remained relatively constant from 2014-2020 and are predicted to do so to 2030 (Defra, 2020).

The tallow resource estimate is disaggregated to a regional level based on 2021 devolved administration livestock statistics for England (Defra, 2021b), Wales (Welsh Government, 2022), Scotland (Scottish Government, 2021) and Northern Ireland (Daera, 2021). Cattle, sheep, poultry and swine are considered as

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[2] Data was provided in a personal correspondence with FABRA UK.

[3] To the best of our knowledge, no facilities in the UK produce Category 2 tallow.

contributing to overall tallow production and the quantity of tallow generated is assumed to be proportional to carcass weight. The share of overall tallow produced in each region is calculated on this basis.

Tallow is produced through the rendering of animal carcasses at dedicated rendering facilities. However, rendering facilities are not present in all regions. Therefore, we have mapped the location of the major facilities throughout the UK, based on data provided by FABRA[2]. If a region does not have a rendering facility, we assume that livestock carcasses are shared equally between facilities in neighbouring regions.

Competing use

Only Category 1 tallow is considered as available for bioenergy use in the resource estimate, which does not have any competing uses.

3.1.2.3 Brown grease

Brown grease is a mixture of oils and fats retrieved from grease traps (Argus, 2021).

Unconstrained potential

Brown grease has emerged as a biofuel feedstock in the UK over recent years according to the RTFO (DfT, 2023a). This RTFO data is used to estimate the current availability of brown grease in the UK. We have been unable to identify any literature pertaining to the generation of brown grease in the UK. Therefore, we have used a figure of 6 kg of brown grease per year, per person in combination with UK population projections to estimate the future availability of brown grease. This brown grease generation figure is based on an estimate of annual brown grease generation per capita for the United States (NREL, 1998).

Like UCO, brown grease must be collected from the source, e.g., commercial kitchens. Therefore, we assume that the collection rate of brown grease could match that of UCO over time, given the similar logistics. The assumed overall maximum collection rate of commercial UCO is 60%. Therefore, we have developed a low ("*Maximum collection rate reached by 2050*"), medium ("*Maximum collection rate reached by 2040*") and high ("*Maximum collection rate reached by 2035*") scenario in which the maximum 60% collection rate is reached by 2050, 2040 and 2035, respectively. The current collection rate, based on the quantities of UK brown grease currently used to produce biofuels, is around 1%.

The brown grease resource estimate is disaggregated to a regional level using population as a proxy, following on from the assumption that brown grease is generated on a per capita basis. As for UCO this is based on ONS data (ONS, 2022) and (ONS, 2020)

Competing use

We assume that there are currently no competing uses for brown grease, as its collection is not well established. Therefore, we assume that all brown grease collected is available for bioenergy uses.

3.1.2.4 UK agricultural processing residues

Agricultural residues are inedible materials produced through the processing of crops. The agricultural residues considered in this study are selected because they are solids and have a relatively high energy density. Consequently, they are well suited to use as a feedstock for bioenergy production and can be transported efficiently.

Unconstrained Potential

The crops that produce agricultural residues that are grown in the UK are wheat, barley and oats. Current annual production figures for these crops are taken from Defra statistics (Defra, 2022). The five-year average production figure is used to account for any seasonal variations in yield. We assume that the yield of wheat, barley and oats does not change between 2020 and 2050. This is based on input from Ricardo's agricultural experts. A processing residue ratio is used to calculate the quantity of agricultural residues produced to process the crop (ICCT, 2013).

Competing use

Agricultural residues can be incorporated into animal feed or used as animal bedding (Feedipedia, 2022). Therefore, we have assumed that a proportion of the total resource must be used to meet this demand. Primary data is not available that quantifies the demand for agricultural residues for these uses. Therefore, our estimates are based on cautious expert judgment. Competing demand is applied as a percentage of the total resource and this percentage is kept constant from 2020-2050 in each scenario.

On this basis, the availability of agricultural residues for bioenergy uses is dependent on the demand for these feedstocks in the production of animal feed/bedding.

3.1.2.5 UK agricultural field residue

Straw is the stems of cereal crops and is an agricultural residue that occurs in the field during harvesting rather than during processing.

Unconstrained resource

Straw availability in the UK is estimated based on straw and cereal crop production published by Defra (Defra, 2021a; Defra, 2023b). As no forecasts are available for future cereals production, this is assumed to remain constant. Straw production therefore remains at current levels. The resource is spatially disaggregated using data on cereal farm areas within England and each of the devolved administrations.

Competing use

Defra statistics (Defra, 2021a) identify several non-bioenergy competing uses for straw, the most significant (~80%) being animal bedding. We have assumed that competing uses for straw remain constant over time.

3.1.2.6 UK residual waste

Residual waste is the part of Municipal Solid Waste (MSW) and Commercial and Industrial (C&I) waste remaining after all recycling and material recovery has occurred. It is typically either incinerated for energy recovery or landfilled. It has both a biogenic and a fossil component and the exact fraction of each varies depending on the waste composition.

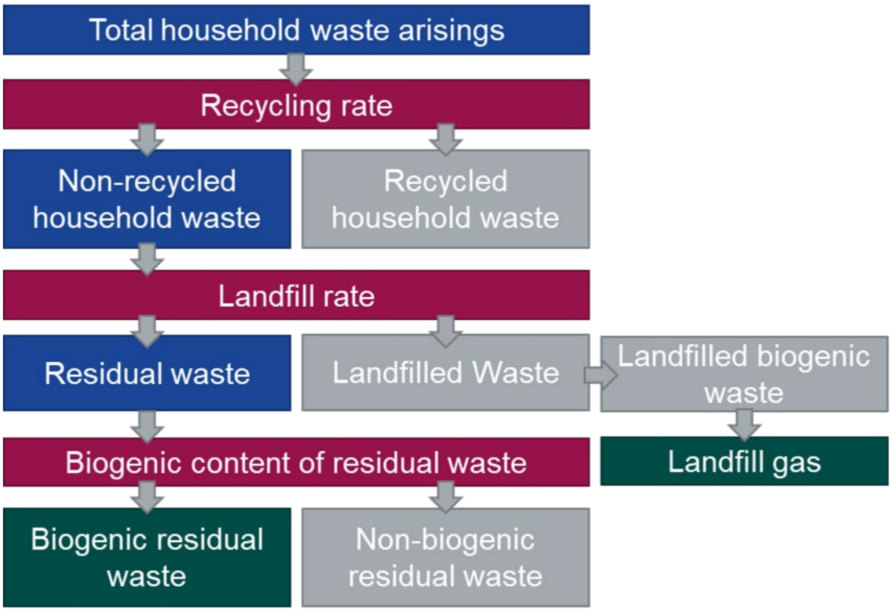
Unconstrained resource

Residual waste is classed as either originating from households, or the commercial and industrial sectors. Data for current resource availability for both is available from Defra (Defra, 2023d).

A summary of the methodology applied to determine the biogenic residual waste availability from households is shown in Figure 3-1. A recycling rate is applied to the total household waste arisings to estimate the quantity of household waste that is not recycled. Following this, the quantity of non-recycled waste that is landfilled is estimated. The availability of biogenic residual waste is calculated using the estimated biogenic content of the residual waste stream.

England, Scotland, Wales and Northern Ireland are all modelled separately as each nation has its own policies and targets on waste minimisation, recycling and landfilling. The scenario for England was developed in close co-operation with Defra in 2022 and updated in 2024 to reflect the waste policies and targets in place at that time. For England, several scenario variants were developed.

Figure 3-1 Summary of the methodology used to estimate residual waste availability from households.



3.1.2.7 Landfill gas

Landfill gas is a by-product generated following the decomposition of biogenic material in landfills.

Unconstrained potential

The current resource estimate is based on data from the UK GHG Inventory (UKGHGI) on landfill gas generated and data from the Digest of UK Energy Statistics on landfill gas utilised for electricity generation.

The Methane Emissions from Landfills Model (MELMod) is used to estimate the future generation of landfill gas. MELMod is used in the UK Greenhouse Gas Inventory to estimate quantities of landfill gas generated based on the quantity and composition of waste landfilled. Projections of future waste arisings and policy targets for recycling rates and landfilling of waste described in Section 3.1.2.6 were combined to generate trends in the future quantities of biodegradable waste landfilled. This data was input into MELMod to estimate the corresponding production of landfill gas. Thus, each residual waste scenario has a corresponding landfill gas scenario. The percentage of landfill gas which can be recovered and is thus available for use for energy is based on data for 2020 as used in the UKGHGI and is assumed to remain constant until 2050. Although as landfill gas generation rates decline once landfill sites are closed, so that the collection and utilisation factor may drop, it is assumed that this trend will be counteracted by the move to a small number of active landfill sites.

MELMod produces results separately for the four nations. Results for England were disaggregated using population as a proxy, i.e., it is assumed that residual waste is proportional to population and that residual waste generated within an ITL1 region will be landfilled within that region, though some denser regions export to neighbouring ones e.g., London to East Anglia and the South East.

Competing use

There are currently no competing uses for landfill gas.

3.1.2.8 Food waste

Food waste is waste food material generated in households, as well as the hospitality and food service sector, retail and wholesale and food manufacturing industries.

Unconstrained potential

Food waste generated in households is estimated by combining data from WRAP on current household food waste arisings (WRAP, 2020) with ONS population forecasts for each nation (ONS, 2022). Food waste generated per capita is reduced to 2030 in line with the reduction assessed by WRAP (WRAP, 2022) as necessary to meet the UN Sustainable Development Goal (SDG) 12.3 to halve per capita global food waste. It is assumed that 70% of food waste in households can be separated at source and thus made available for collection.

The Environment Act 2021 requires all local authorities to implement weekly source separate food collection (although authorities may be exempt if it is not technically possible). The Government's 'Simpler Recycling' announcement[4] has confirmed that this will be required in England by 31 March 2026 for households, 31 March 2025 for businesses and non-domestic premises, and 31 March 2027 for micro-firms. It is assumed that by 2027 the percentage of local authorities will have risen to 100%, from 35% in 2020. It is assumed that the effectiveness of this collection (i.e., from exempt areas and areas such as flats) where collection rates may be lower rises from 62% in 2020 to 85% in 2030. This means that the overall effectiveness of collection is 85% by 2030, and it is assumed to remain at this level until 2050. Similar assumptions to those imposed by the Environment Act for England were assumed for the devolved administrations.

The availability of C&I food waste is based on a report from WRAP (WRAP, 2021), which provides statistics on food waste generation in the food retail, food manufacturing and hospitality, and food services sector in 2018 and 2030 – assuming UN 12.3 SDG is met. C&I food waste is disaggregated using ONS population forecasts for each nation (ONS, 2022).

Competing use

There are no non-bioenergy competing uses for food waste.

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[4] https://www.gov.uk/government/consultations/consistency-in-household-and-business-recycling-in-england/outcome/government-response

3.1.2.9 Waste wood

Waste (or recycled) wood is any wood that is not virgin timber or a product of the processing of virgin woods (i.e., the timber/forestry industry).

Unconstrained potential

Estimates on the current availability of waste wood in the UK are taken from a report by Tolvik (Tolvik, 2019), which is split into household, commercial and industrial, and construction and demolition streams. For household and commercial and industrial sourced waste wood, we assume that the fraction of waste wood extracted from the respective waste streams remains constant at 2020 levels to 2050. This is applied to the residual waste estimates discussed in Section 3.1.2.6 to estimate the quantity of waste wood from these sources.

For construction and demolition waste wood, we adopt the approach reported by BioReg (BioReg, 2018) and calculate the generation of waste wood as a function of population (i.e., tonnes per capita) and project this to 2050 using population projections.

The waste wood resource estimate is disaggregated to a regional level using population as a proxy, following on from the assumption that waste wood is generated on a per capita basis. The population change in regions is based on ONS data (ONS, 2022) and (ONS, 2020).

Competing use

Three categories of competing uses were identified for waste wood: panel board, other recycling uses and export. Extending the BioReg approach, we assume that the demand for waste wood for use in panel board increases as a function of population. Other recycling uses are assumed to remain constant at 2020 quantities and exports are assumed to decline to zero by 2025.

3.1.2.10 Manure

Unconstrained potential

Overall, the total constrained resource is projected based on forecasts of animal population numbers[5] and excretion rates. Estimates are made for the availability of cattle and pig manures/slurry. Manure availability is disaggregated to a regional level based on 2021 devolved administration livestock statistics for England (Defra, 2021b), Wales (Welsh Government, 2022), Scotland (Scottish Government, 2021) and Northern Ireland (Daera, 2021).

Competing use

A set of eight scenarios has been constructed to reflect uncertainty on the amount of this resource which could be practically collected and used for bioenergy via anaerobic digestion. It is likely that collection and utilisation on smaller farms might not be viable, therefore this is explored through the scenarios. Similarly, a scenario exploring the impact of assuming that resource is only available from farms already using a liquid system for waste management is explored.

3.1.2.11 Sewage Sludge

Sewage sludge is a by-product of the wastewater treatment industry.

Unconstrained potential

The current quantity of sewage sludge available is based on the estimates used in the UKGHGI (1990 to 2021). The future resource estimate is determined using the 2017-2021[6] average of sewage sludge generated per capita combined with population forecasts.

The sewage sludge resource estimate is disaggregated to a regional level using population as a proxy, following on from the assumption that sewage sludge is generated on a per capita basis. This is based on ONS data (ONS, 2022) and (ONS, 2020).

Competing use

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[5] Forecasts are those used for projecting air pollutants and are taken from ANNEX IV B-WM: Template for reporting national projection Activity Data(a) - With Measures. Projections of air pollutants for reporting under CLRTAP. https://naei.beis.gov.uk/data/ as accessed on 1/12/2021

[6] Excluding 2020 when generation dipped due to the impact of Covid.

Competing uses for sewage sludge are assumed to be all options which do not involve anaerobic digestion, which allows for production of biogas. Competing uses are therefore composting, landfill, incineration and spreading on land without treatment. There has been a distinct step towards greater use of digestion in the last few years and competing uses have declined. The current competing uses for sewage sludge are therefore calculated based on data for 2020 and 2021 from the GHG inventory data. In the "*No change in current treatment routes*" scenario, the fraction going to competing uses is kept as the average of the 2021/2022 fraction. In the "*Digestion replaces land spreading, landfill and composting*" scenario it is assumed that spreading of undigested sewage sludge to land is phased out by 2030.

3.1.2.12 Waste Tyres

Waste tyres are tyres that can no longer be used on vehicles. Around 45% (by mass) of a tyre is rubber. Of this rubber, between a third to two-thirds (i.e., 15-30% of the total mass of the tyre) is natural rubber with the remaining rubber being synthetic (Afrin, et al., 2021). Therefore, waste tyres are part biogenic (natural rubber) and part fossil (synthetic rubber).

Unconstrained potential

UK end of life tyre generation figures for 2019 were obtained from ERTMA (ETRMA, 2019). It is assumed that generation of waste tyres will remain constant to 2050 as the car/truck fleet is not expected to grow significantly in this period. Collection of waste tyres is already very high in the UK (97%) but is assumed to increase to 100% by 2050 in the high scenario.

Regional estimates of waste tyres are derived using the number of vehicles licensed in each region, based on data available from DfT (DfT, 2022b). This assumes that waste tyre arisings remain in the region in which the vehicle is licensed.

Competing use

The main competing use for waste tyres is in construction and civil engineering. Estimates for this are also available from ERTMA and they are assumed to remain constant to 2050. Therefore, the availability of waste tyres for energy recovery is not anticipated to change significantly in the UK.

3.1.3 UK crop feedstocks

A distinguishing feature of crop feedstocks is that their potential is primarily dependent on the land area that is available for their production. Consequently, they are treated differently in the model to the other feedstocks. Five UK energy crop feedstocks are included in the model: wheat, sugar beet, maize, miscanthus and short rotation coppice (SRC) willow. Crop feedstocks have two inputs into the model: yield (tonnes produced per hectare) and land availability (kha). The user may independently select from a yield scenario (where available, on a crop-by-crop basis) and a land availability scenario.

3.1.3.1 Land availability

The model includes three scenarios of land availability. Each individual land availability scenario contains an estimation of the land available for **all five crops**. The land area refers explicitly to land available for **bioenergy purposes only**. Therefore, within the model, crops produced for this purpose do not have any non-bioenergy competing uses.

For wheat and sugar beet the land area is assumed to be the same in all scenarios. We have assumed that the UK harvested area remains at the five-year average (2016-2020) according to Defra data (Defra, 2021a). This is because we do not anticipate any increased demand for crop-based bioethanol in the UK from current levels due to the RTFO crop cap (DfT, 2023c). In the case of sugar beet, it is assumed that all sugar beet production for bioethanol occurs in the vicinity of the existing sugar beet bioethanol plant in the East of England, as sugar beet is typically processed close to where it is grown. In the case of wheat, spatial disaggregation is based on the distribution of all wheat production within the UK.

The land availability scenarios for the remaining crops (maize, SRC willow and miscanthus) are summarised in Table 3-5. The first two scenarios were developed by Government for the Biomass Strategy. The third was developed by Ricardo based on the estimates of land availability for energy crops in the UK in 2050 from the Climate Change Committee's (CCC) Sixth Carbon Budget report (CCC, 2020). This estimate is combined with assumptions about the rate at which planting might expand to derive a time series for land areas which potentially maybe harvested in each year to 2050.

Table 3-5 Summary of the assumptions made regarding land availability for perennial energy crops and maize.

Scenario Name	SRC willow & Miscanthus	Maize
Biomass Strategy: restricted supply scenario	Restricted supply scenario developed for the biomass strategy. SRC area increases to 51.7 kha by 2050 and miscanthus to 65.9 kha.	Area of maize for bioenergy doubles by 2030 and then remains constant.
Biomass Strategy: ambitious supply scenario	Ambitious supply scenario developed for the biomass strategy. SRC area increases to 101.4 kha by 2050 and miscanthus to 109.8 kha.	Area of maize for bioenergy doubles by 2030 and then remains constant.
CCC 6th Carbon Budget scenario	**Maximum** area predicted by CCC for SRC and Miscanthus assumed available (900 kha). **Rapid growth** driven by policy interventions. Area planted in 2023 taken as **maximum** of new plantings over last 10 years. Area planted each year increases by 30% each year. Land area split 50% SRC/50% miscanthus	Area of maize for bioenergy increases by 50% by 2030 and then remains constant.

In the scenarios developed for the biomass strategy, an indicative split for planting of SRC and miscanthus between broad areas of England is assumed. There was also an assumption about the ALC that the crops could be grown on. Data on the distribution of the relevant ALCs in each ITL region was used to split the provided regional split for planting into the area planted within each ITL region. The split is assumed to remain constant over time, i.e., planting in each region grows at the same rate. This simplifying assumption is required because of the lack of any more detailed modelling of how energy crop planting might develop over time. Modelling of regional development is complex as it is likely to be affected by a number of factors, including the availability of suitable land, profitability of energy crop cultivation compared to other uses for that land, soil and climatic conditions (which may affect yield and hence profitability), and proximity to end users.

3.1.3.2 UK crop yields

The UK crop yields used in the model are summarised in Table 3-6. The user must select one yield scenario per crop, which is then combined with the selected land availability scenario. Crop yields are assumed not to vary regionally when performing spatial disaggregation.

Wheat

The model has two scenarios for wheat yields (Table 3-6**Error! Reference source not found.**). The first assumes that the current five-year average (2016-2020) (as derived from Defra statistics (Defra, 2021a)) is maintained. The second scenario assumes that the yield decreases due to a 20% reduction in fertiliser use by 2030, as targeted by the Farm to Fork strategy (European Commission, 2020). The reduction in crop yield is estimated by combining the reduction in fertiliser application with yield response data.

Sugar beet

The model has two scenarios for sugar beet yields (Table 3-6). The first assumes that the current five-year average (2016-2020) (as derived from Defra statistics (Defra, 2021a)) is maintained. The second assumes that the yield is reduced due to restrictions on the use of pesticides to control yellow virus. Note, as of February 2023, relevant pesticides have been given emergency authorisation by Defra (Defra, 2023a).

Table 3-6 Summary of the UK crop yields used in the model.

Crop	Scenario Description	Yield (t/ha/year)		
		2020	2030	2050
Wheat	Yields maintained at current level	8.0	8.0	8.0
	20% reduction in N fertiliser use by 2030	8.0	7.7	7.7
Sugar beet	Yields maintained at current level	71.8	71.8	71.8
	Pesticides for control of yellow virus no longer approved so infection levels rise (to 25%) and yield for infected crop drops by 50%	71.8	67.4	67.4
Maize	Yields maintained at current level. Assumes cultivation without plastic film.	40.0	40.0	40.0
SRC willow	Biomass strategy	8.0	9.9	9.9
	15 odt/ha by 2050	8.0	10.3	15.0
	20 odt/ha by 2050	8.0	12.0	20.0
Miscanthus	Biomass strategy	10.0	10.3	10.3
	15 odt/ha by 2050	10.0	11.7	15.0
	20 odt/ha by 2050	10.0	13.3	20.0

Maize

Maize yields (Table 3-6) are assumed to remain constant, at the current five-year average according to Defra statistics (Defra, 2021a).

SRC willow & miscanthus

Current (2020) yield data for SRC willow and miscanthus (8 and 10 odt/ha/year) is based on the most recent production year provided in Defra's statistics (Defra, 2021a). Three scenarios for future yield growth are included. In the first, future yields are as assumed in the scenarios modelled for the Biomass Strategy i.e., they remain constant at slightly above current yields from 2025 to 2050. In the second scenario, the yield of both crops increases linearly to 15 odt/ha/year by 2050. This is the assumption made by the CCC in their Sixth Carbon Budget report and is assumed to be achieved by better agronomic practices and innovations (CCC, 2020). It is also the upper end of the range of yield suggested in Nix (Redman, 2021) and by NNFCC (NNFCC, 2011) for current average yield. The second scenario assumes a yield of 20 odt/ha/year by 2050, driven by investment and innovation in both breeding and cultivation techniques. The 20 odt/ha/year reflects an optimistic 'stretch' scenario and is based on suggested yield improvements in the CCC's Land-use-Reducing scenario (CCC, 2020).

Yields in the stakeholder scenario were provided by the stakeholder and assume yields slightly above current yields for new planting (9.9 odt/ha/year for SRC and 10.25 odt/ha/year for miscanthus). These are assumed to remain constant to 2050.

3.1.4 Other Feedstocks

3.1.4.1 Micro Algae

Microalgae are single celled organisms that have a characteristically high lipid content. Technology for the commercial scale production of microalgae, or corresponding biofuels is yet to be proven commercially. This is primarily a result of several technical barriers that exist, which mean that production of microalgae for use in biofuel production is not currently economically feasible (E4tech, 2016).

The resource estimates for microalgae are highly uncertain. Based on our literature survey and historical trends, it is our assessment that microalgae production is not likely to increase without a strong pull from the market due to the unfavourable economics of production.

Unconstrained potential

The production of microalgae requires available non-arable land for the construction of the relevant infrastructure. A 2012 report by Skara estimated the potential for microalgae production in the UK based on the availability of suitable marginal land (Skarka, 2012). These figures are used to estimate the maximum production potential in the UK. However, the Sakra report does not consider competition for the marginal land from other sectors e.g., perennial energy crop production. Therefore, we assume that only 10% of the maximum potential reported by Skara can be achieved[7]. Regional estimates of microalgae availability are produced based on relative land area of each of the ITL1 regions.

In the low scenario, we assume that microalgae production does not change from current levels. In the high scenario, we assume that microalgae production reaches 10% of the practical maximum in 2030 and 100% of the practical maximum in 2050. The medium scenario is the midpoint of the low and high.

We assume that the lipid content of microalgae is 30% on a dry weight basis, according to literature values (Morris, 2021).

Competing use

Food supplements, cosmetics and animal feed are identified as the main competing uses for microalgae. Currently, 95% of the microalgae produced is used in these applications (Araújo, et al., 2021). We assume that the absolute value of this demand, based on 2020 production, does not change to 2050. This assumption is made because there is no data to suggest otherwise.

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[7] This is based on Ricardo's judgement, rather than primary data.

3.1.5 Feedstock prices

The model includes indicative prices for all of the UK feedstocks. Prices are defined in tranches that refer to the percentage of the overall resource that is available at the respective price point. Sources for price data are provided in the supporting workbook for each resource.

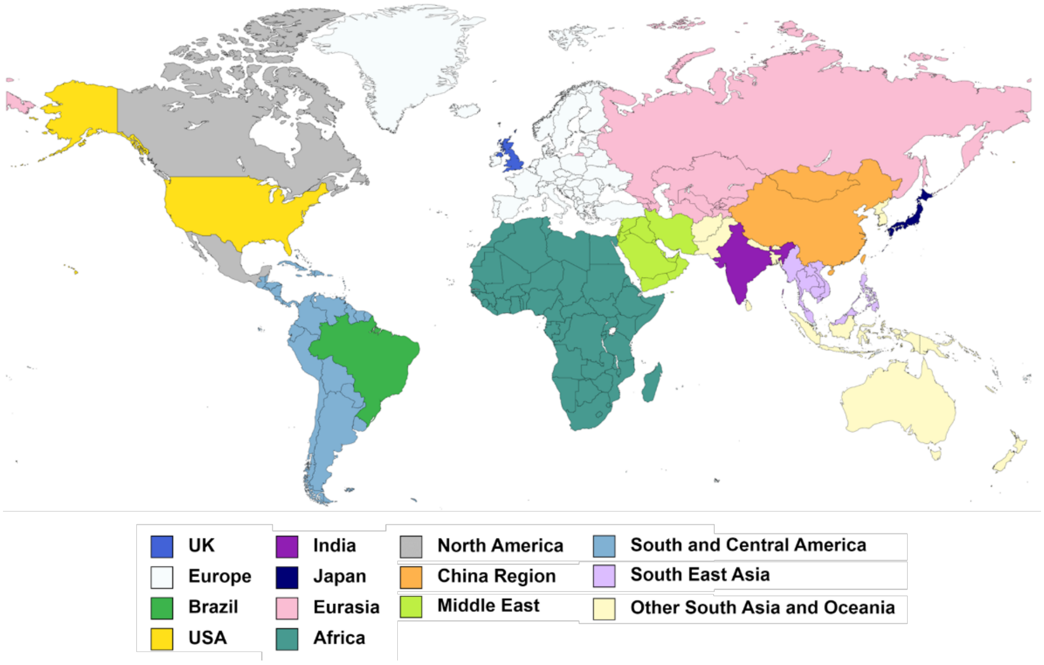
4. GLOBAL MODULE

The global module calculates the availability of biomass to the UK from elsewhere in the world.

4.1 MODEL REGIONS

The model is split into **13 global regions**, excluding the UK (Figure 4-1). These regions are dictated by the two regionalised data sets that underpin the global calculations in the model: the **IMAGE** integrated assessment model (IMAGE, 2022) and the International Energy Agency (IEA) **World Energy Outlook** (WEO) (IEA, 2021). The IMAGE dataset is used to assess the availability of land for crop production (see Section 4.3.1.1) and is split into **26 regions**. The IEA dataset is used to assess global demand for biomass (see Section 4.2) and is split into **13 regions**. To reconcile these two datasets, we determined the **highest level of common resolution** between the sets of regions (Figure 4-1). All final calculations in the global module are performed at this regional level.

Figure 4-1 Regions used in the global module of the model.



4.2 GLOBAL RESOURCE DEMAND

Demand scenarios are modelled for the *Stated Policy*, *Announced Pledges* and *Sustainable Development Scenarios* from the WEO dataset. These scenarios were selected because both regional and global data is provided in the WEO dataset. Only global data is provided for the *Net Zero Emissions by 2050* scenario, therefore it could not be included in the model.

4.2.1 Liquid biofuels

4.2.1.1 Total demand for liquid biofuels

Total demand for liquid biofuels (in petajoules, PJ), in each model region and for each of the three demand scenarios is input into the model.

We have estimated the total demand for liquid biofuels (i.e., total demand for bioethanol, biodiesel, renewable diesel and biojet) in each of the model regions from 2020 to 2050 using the WEO 2021 (IEA, 2021)[8].

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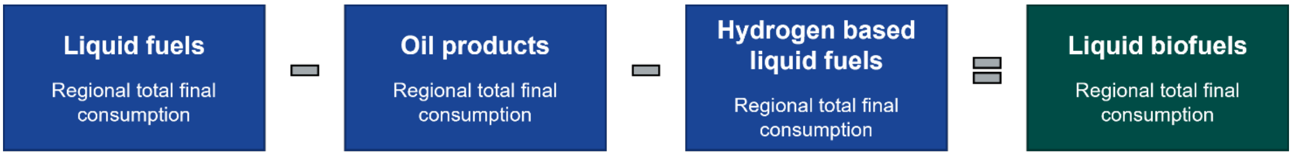
[8] The WEO dataset was purchased as part of the study and its direct reproduction in the model is not permitted. The purchased data has been manipulated as described and has not been used directly as an input to the model.

Figure 4-2 Approach to estimating the regional total final consumption of liquid biofuels.



The approach used to estimate the regional total final consumption of liquid biofuels is summarised in Figure 4-2. The WEO dataset contains data on the regional total final consumption of liquid fuels, oil products and hydrogen based liquid fuels. We have assumed that liquid biofuels are the share of total liquid fuels that are **not** oil products or hydrogen based liquid fuels. To validate this assumption, we compared the sum of the **regional** total final consumption of liquid biofuels across all regions with another dataset provided in the WEO – the **global** demand for "*modern biomass liquid – total final consumption*".

In all scenarios, from 2020 to 2050, the global demand for modern biomass liquid is slightly higher than the sum of the regional total final consumption. This is because the global total accounts for biofuels supplied via international bunkers for maritime and aviation, whereas the regional total does not. Therefore, we have adjusted the regional figures to include the biofuels provided by international bunkers. This adjustment is made by calculating the total quantity of liquid biofuels stored in bunkers and partitioning this total between each region based on its share of the overall regional demand. These calculations are carried out for each IEA region and transposed to the model regions.

4.2.1.2 Current demand for bioethanol and biodiesel

The total demand for liquid biofuels calculated as described in Section 4.2.1.1 covers both bioethanol and biodiesel (which, in the context of this model, also includes renewable diesel and biojet). As bioethanol and biodiesel are separate resources in the model, we need to estimate the share of the total demand attributed to each fuel type. This is achieved using the *IEA Renewables - Biofuels 2021* dataset (IEA, 2021).

The *IEA Renewables – Biofuels 2021* dataset contains historical biofuel production and consumption data by region/country and biofuel type. Using the consumption data, we calculated the share of total biofuel consumption that was bioethanol in 2020 for each region and applied this to the share to the total liquid biofuel share calculated in Section 4.2.1.1. The remainder is assumed to be biodiesel. The results of this analysis are shown in Table 4-1 and give the demand for bioethanol and biodiesel by model region in 2020. The demand for liquid biofuels in 2020 is the same in all three demand scenarios modelled.

4.2.1.3 Future demand for bioethanol and biodiesel

In the model, the relative share of total liquid biofuel demand between bioethanol and biodiesel **varies with time, region and demand scenario**. This variation is based on data from the WEO 2021 (IEA, 2021), which estimates **global** demand for conventional and advanced bioethanol and biodiesel in 2020, 2030 and 2050 for the *Stated Policies*, *Announced Pledges* and *Net Zero Emissions Scenarios.* No data are available for the *Sustainable Development Scenario* needed for the model; therefore, we assume that the demand in the *Sustainable Development Scenario* is the average of the *Announced Pledges* and *Net Zero Emissions Scenarios*.

The calculations described in Section 4.2.1.2 estimate the share of bioethanol at a regional level. However, the data for the future demand is only available at a global level. Therefore, we calculate the change in the percentage share in 2030 and 2050 **relative to the percentage share in 2020** at a global level (Table 4-2) and apply this to the regional share of bioethanol in 2020. The percentage share in the intervening years is calculated by linear interpolation. It is assumed that the demand for biodiesel is equivalent to the share of demand that is not bioethanol.

Application of the assumptions discussed above result in a **decline** in the share of bioethanol of the total liquid biofuel demand between 2020 and 2030/2050, for all scenarios in all regions. This is to be expected and can be rationalised assuming a general decline in the relative proportion of gasoline-powered vehicles due to increased electrification resulting in a lower demand for bioethanol.

Table 4-1 Demand for bioethanol and biodiesel in 2020.

Region	Demand for liquid biofuels in 2020 (PJ)	
	Bioethanol	Biodiesel*
USA	1,068	367
Other North America	68	23
Brazil	640	237
Other South and Central Americas	48	53
Africa	1	1
Europe	110	629
Eurasia	-	-
Middle East	-	-
India	34	5
China	101	32
Japan	-	17
Southeast Asia	37	287
Other South Asia and Oceania	18	23
Total	2,125	1,675

*Note: biodiesel includes renewable diesel and biojet.

A secondary implication of these assumptions is that regions that do not consume any bioethanol in 2020 according to the IEA Renewables data (IEA, 2021) i.e., Eurasia, Middle East and Japan, never do so in the future. This cannot be easily avoided without regionalised projections of future demand for bioethanol or biodiesel. The impact of this is likely to be minimal as total liquid biofuel demand in these regions is a maximum of 3% of total global demand in 2050.

4.2.1.4 Demand for bioethanol and biodiesel summary

The demand for bioethanol and biodiesel is input into the model as a percentage, which reflects the percentage of the total demand for liquid biofuels that is comprised of bioethanol. The remainder is assumed to be biodiesel. A high-level schematic overview of this logic is presented in Figure 4-3.

Table 4-2 Reduction in the percentage share of bioethanol relative to the percentage share in 2020.

Scenario	Reduction in percentage share of bioethanol relative to the percentage share in 2020	
	2030	2050
Stated Policies	91%	78%
Announced Pledges	81%	33%
Sustainable Development	73%	26%

4.2.1.5 Demand for crop based bioethanol

In the model, bioethanol is defined based on the type of feedstocks from which it is produced. There are two categories of bioethanol – crop based bioethanol and non-crop based bioethanol (Figure 4-4). Crop based bioethanol refers to bioethanol produced from annual crops such as wheat, corn, sugar beet, etc. Non-crop based bioethanol refers to bioethanol produced from feedstocks other than annual crops, for example lignocellulosic biomass, food waste, starch slurry, etc.

Figure 4-3 Schematic overview of the high-level logic used to estimate the global demand for liquid biofuels

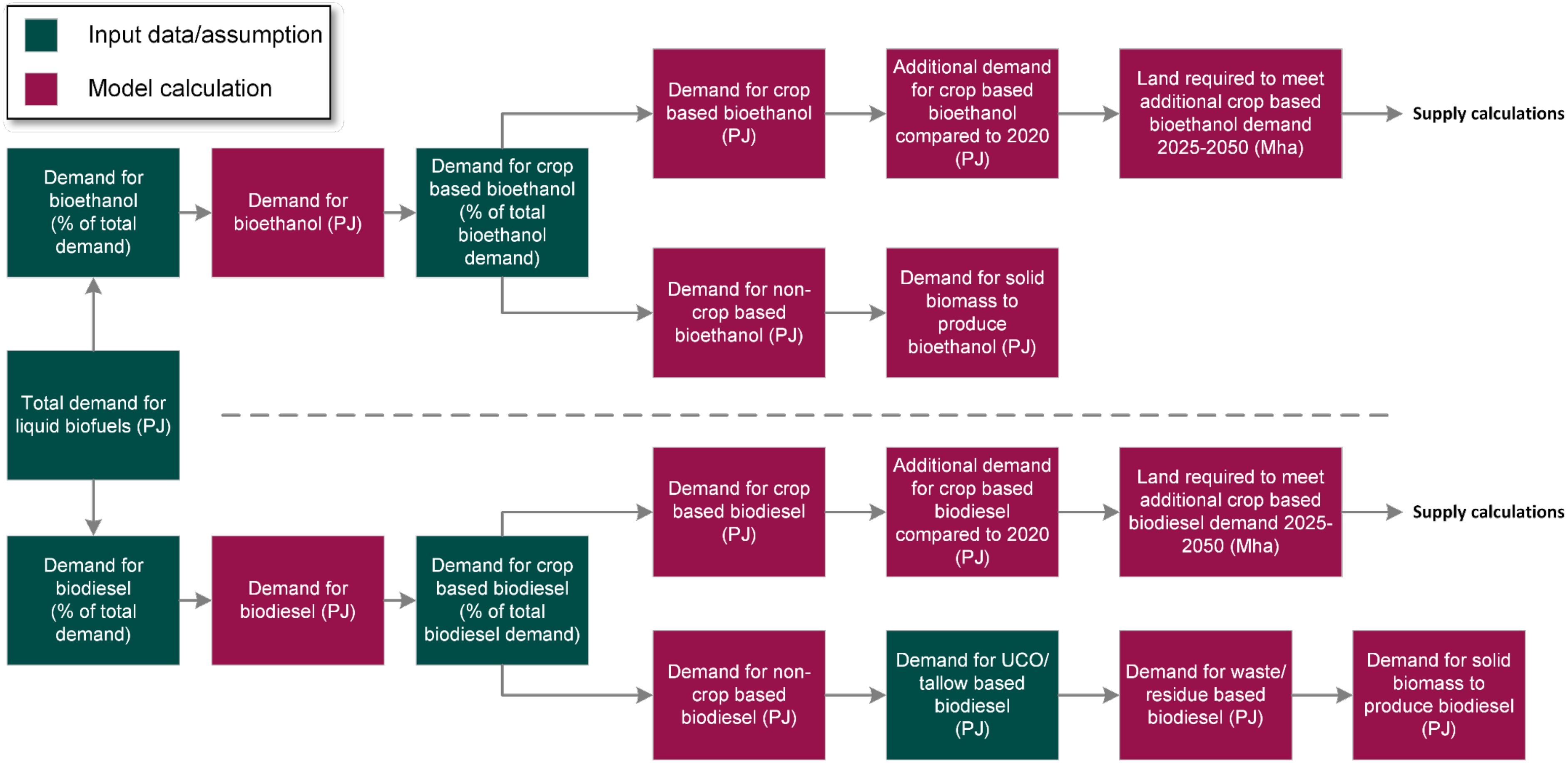
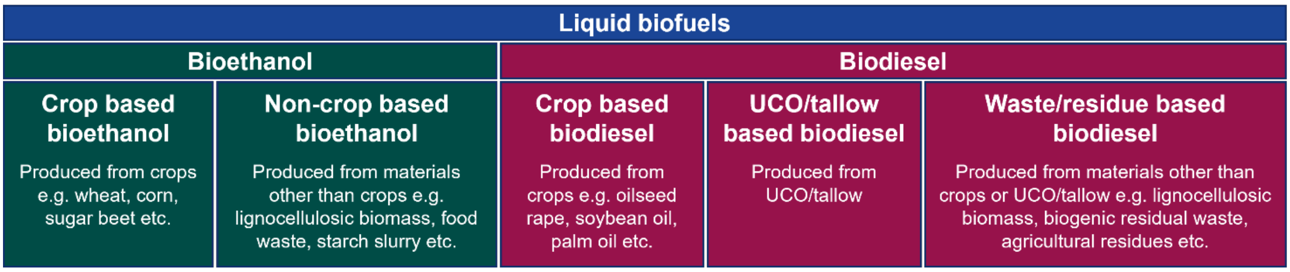


Figure 4-4 Definition of the liquid biofuel types considered in the model.



Liquid biofuels				
Bioethanol		Biodiesel		
Crop based bioethanol	**Non-crop based bioethanol**	**Crop based biodiesel**	**UCO/tallow based biodiesel**	**Waste/residue based biodiesel**
Produced from crops e.g. wheat, corn, sugar beet etc.	Produced from materials other than crops e.g. lignocellulosic biomass, food waste, starch slurry etc.	Produced from crops e.g. oilseed rape, soybean oil, palm oil etc.	Produced from UCO/tallow	Produced from materials other than crops or UCO/tallow e.g. lignocellulosic biomass, biogenic residual waste, agricultural residues etc.

The share of bioethanol that is crop based is calculated based on WEO 2021 data (IEA, 2021). Data is available that forecasts the demand for conventional (i.e., crop based) and advanced (i.e., non-crop based) bioethanol in 2020, 2030 and 2050 at a **global** level for the *Stated Policies*, *Announced Pledges* and *Net Zero Emissions Scenarios.* There are no data available that forecasts the demand under the *Sustainable Development Scenario,* therefore this is assumed to be the average of the *Announced Pledges* and *Net Zero Emissions Scenarios.* The demand for crop based bioethanol, in absolute terms (i.e., PJ), is converted to a percentage and applied to the regionalised estimates for total bioethanol demand. The percentage of total demand met by crop based ethanol in each demand scenario is given in Table 4-3. The percentage of overall demand for crop based bioethanol is assumed to be the same across all regions in the model as regionalised data is unavailable.

Demand for crop based bioethanol is input into the model as a percentage (of the overall demand for bioethanol) in *I4_Global_Demand* section *I4.3 Crop based demand.* The absolute demand (in PJ) for crop based bioethanol is calculated in the model (Figure 4-3).

The demand for crop based bioethanol is converted to the equivalent land area required for its production. This is calculated on the basis of the **additional** land required compared to 2020 production. The calculated land area is necessary for the supply calculations. This is therefore discussed in more detail in Section 4.3.1.3.

Table 4-3 Percentage of bioethanol demand met by crop based bioethanol.

Scenario	Percentage of the demand for bioethanol that is crop based		
	2020	2030	2050
Stated Policies	100%	95%	73%
Announced Pledges	100%	91%	62%
Sustainable Development	100%	85%	53%

4.2.1.6 Demand for non-crop based bioethanol

The remaining demand for bioethanol after the crop based share is accounted for is assumed to be non-crop based bioethanol. Within the model, this is converted to an equivalent demand for solid biomass using an assumed conversion efficiency of 28%, which is representative of lignocellulosic ethanol production (JRC, 2017). This demand is then added to the demand for solid biomass calculated in Section 4.2.2.

The default assumption is that 100% of the demand for solid biomass for bioethanol production is met by **feedstocks in the model**. Analysis of the RTFO statistics (DfT, 2023a) suggests that currently, in the UK, ~94% of non-crop bioethanol is produced from feedstocks **not** in the model – predominantly food waste and waste starch slurry. However, this picture is likely to change over time as lignocellulosic ethanol production facilities come online. To allow for this uncertainty, the user can adjust the proportion of the demand for solid biomass for bioethanol that is likely to be met by feedstocks not included in the model. In the absence of sufficient data aside from the RTFO (which is UK based and a single time point) to proceed otherwise, we selected the default position that 100% of the demand for solid biomass for bioethanol production is met by feedstocks in the model because it is inherently the most conservative.

4.2.1.7 *Demand for crop based biodiesel*

An analogous approach to that described for bioethanol is adopted to estimate the proportion of biodiesel that is crop based. The WEO 2021 data (IEA, 2021) is used to estimate the share of crop based biodiesel (Table 4-4), and implicitly the remainder is assumed to be non-crop based.

As with crop based bioethanol, the demand for crop based biodiesel is converted to additional demand for land compared to 2020 production and is discussed in more detail in Section 4.3.1.3.

Table 4-4 Percentage of biodiesel demand that is met by crop based biodiesel.

Scenario	Percentage of the demand for biodiesel that is crop based		
	2020	2030	2050
Stated Policies	99%	76%	40%
Announced Pledges	99%	72%	51%
Sustainable Development	99%	50%	26%

4.2.1.8 *Demand for non-crop based biodiesel*

Non-crop based biodiesel is split into two sub-categories within the model: UCO/tallow based biodiesel and waste/residue based biodiesel (Figure 4-4). The assignment to each category is made using expert judgment as follows. In 2020 and 2025, we assume that 100% of non-crop based biodiesel is produced from UCO/tallow in all regions. For higher income regions[9] we assume that the UCO/tallow share declines to 95% by 2030. Then, from 2035-2050, the share of UCO/tallow is maintained at the absolute (i.e., PJ) value from 2030. For other regions (except Eurasia) we assume the UCO/tallow share reaches 95% by 2035. From 2040-2050, the share of UCO/tallow is maintained at the absolute value from 2035. For Eurasia, demand in 2030 is fixed at the absolute 2030 level, as according to the WEO dataset, demand for biodiesel drops to zero in 2035, before recovering in 2040, which we have interpreted as an anomaly. Overall, these assumptions mean that the absolute production capacity for biodiesel from UCO/tallow is maintained at 2030/2035 levels in all regions.

Demand for biodiesel produced from UCO/tallow is input to the model as an absolute value, in PJ, for each region and each demand scenario.

The demand for waste/residue based biodiesel is calculated by subtracting the demand for UCO/tallow based biodiesel from the total demand for non-crop based biodiesel. This demand is then converted to an equivalent demand for solid biomass using a conversion efficiency of 45%, which is representative of a gasification Fischer-Tropsch biodiesel production route (JRC, 2020).

As with bioethanol, the default assumption is that 100% of the demand for solid biomass for biodiesel production is met by **feedstocks in the model**. Again, the user may alter this percentage as a user input for the reasons discussed above.

4.2.2 Demand for solid biomass

The demand for solid biomass is calculated based on the IEA WEO 2021 (IEA, 2021), which provides a global estimate of the demand for solid, liquid and gaseous biomass. Using this dataset, we calculated the share of solid biomass over time for each demand scenario. The WEO also provides regionalised estimates of *Modern Biomass* demand for each of the demand scenarios. The regionalised demand for solid biomass is calculated by applying the share of solid biomass estimated at a global level, to the regional demand for modern biomass. Following this analysis, the demand for solid biomass is reorganised from the IEA regions to the model regions.

The WEO data reports the energy content of the feedstock in the energy balance corresponding to its final use[10]. This means that the demand for solid biomass for liquid fuels (bioethanol and biodiesel) **is not** included in the demand for solid biomass as previously described. Therefore, the demand for solid biomass for

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[9] Higher income regions are assumed to be USA, Other North America, Brazil, Other South and Central Americas, Europe and Japan.

[10] This was confirmed through personal correspondence with the WEO team at the IEA.

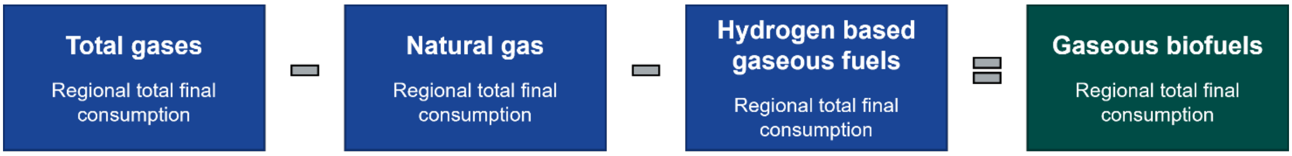
bioethanol/biodiesel production is added to the demand for solid biomass to give the total demand for solid biomass.

Demand for solid biomass is input into the model for each region/demand scenario as absolute values.

4.2.3 Demand for gaseous biomass

Demand for gaseous biomass is also estimated using the IEA WEO 2021 (IEA, 2021). The WEO dataset contains estimates of regional total final consumption of natural gas and hydrogen based gaseous fuels, which are subtracted from the demand for total gases to give the demand for gaseous biofuels (Figure 4-5).

Figure 4-5 Approach to estimating the regional total final consumption of gaseous biomass.



However, this estimate of total final consumption of gaseous biofuels does not include biogas that is converted directly to electricity. Therefore, a correction factor was applied to account for this. The correction factor is equal to the total demand for gaseous biofuels, as calculated in Figure 4-5, divided by the total global demand in the IEA data for *Modern Biomass Gas.* The correction factor is applied to the total demand for gaseous biofuels, to give a total demand for gaseous biofuels which **includes** those that are used to generate electricity. The total demand for gaseous biomass is input to the for each region/demand scenario as absolute values.

Within the model, manure is the only global feedstock commonly used to produce gaseous biofuels. Therefore, we also calculate the share of the total demand for gaseous biofuels that is anticipated to be produced from manure. This calculation is based on the *IEA Outlook for Biogas and Biomethane* (IEA, 2020), which suggests that in 2018 an average of 18% of biogas/biomethane was produced from manures[11], and this is likely to rise to 35% by 2040. We assume that the share of biogas/biomethane produced from manure increases from current levels to 35% in 2040 for all regions. The proportion of gaseous biofuel demand met by manure is input into the model in as a percentage for each demand scenario/region. The absolute share (in PJ) of the gaseous biofuel demand that is met by manure is calculated directly in the model.

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[11] Regionalised estimates for Asia Pacific, North America, Central and South America, Europe, Africa and the Rest of World are provided in the report, which are used in the calculations rather than the average.

4.3 GLOBAL RESOURCE SUPPLY

The global resources included in the model can be spilt into three general categories: crops, forestry products and wastes and residues. The estimation of the supply, or production, of each of these categories of resources is handled differently in the model. The varying approaches are summarised in Table 4-5.

Table 4-5 Approaches adopted to modelling global feedstock supply.

Resource Category	Resources	Supply modelling approach
Global crops	Bioethanol/biodiesel from crops, perennial energy crops	Supply is dynamically calculated in the model based on the selected supply and demand scenario, as well as several other advanced user inputs.
Global forestry products	Small roundwood, sawmill residues, bark, branchwood	Supply is calculated exogenously to the model using an international forestry model configured with 3 pre-agreed scenarios.
Global wastes & residues	Agricultural processing residues, agricultural field resides, used cooking oil, tallow, residual biogenic waste, waste wood, manure	Supply is estimated exogenously to the model. Details of specific resource estimates can be found in the corresponding background workbooks.

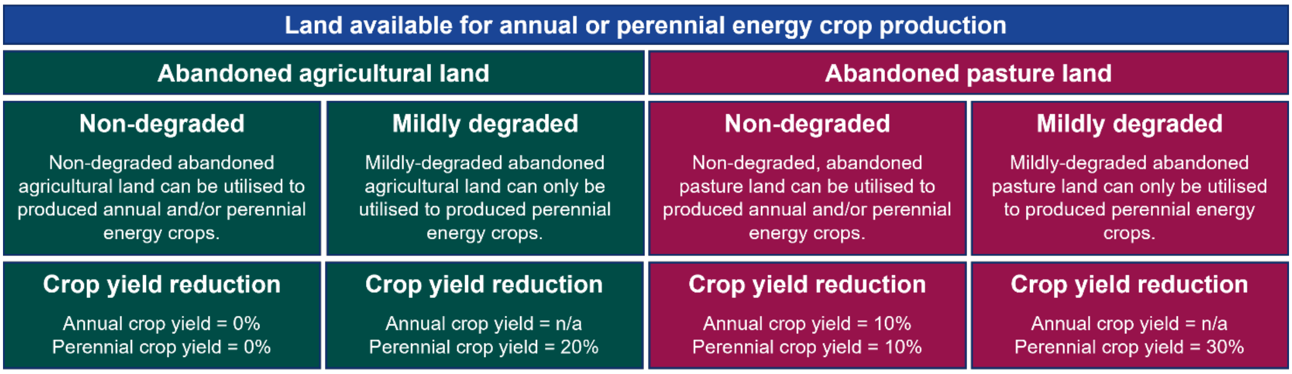
4.3.1 Global crops

The availability of global annual and perennial energy crops is calculated dynamically in the model. At the simplest level, the availability of these resources is dependent on the availability of land to grow them. The following section describes the methodology implemented in the model to allocate available land to crop production.

4.3.1.1 Total land availability and classification

We have used data from IMAGE 3.2 (Integrated Model to Assess the Global Environment) to estimate the availability of land for annual and perennial energy crop production (IMAGE, 2022). The data was provided through direct correspondence with the IMAGE team and is comprised of estimates of the area of abandoned agricultural and pasture land (Table 4-6) available in the 26 IMAGE regions (IMAGE, 2022) for three Shared Socioeconomic Pathways (SSPs): SSP1, SSP2 and SSP3 (Van Vuuren, 2021). Descriptions of these SSPs are provided in Table 4-6. Further details of the assumptions underlying the SSPs can be found in the IMAGE supporting documentation (Van Vuuren, 2021). The data was aggregated to the 13 regions used in this model and the areas of available abandoned agricultural land and pasture land are input directly to the model.

Figure 4-6 Overview of the land type classifications used in the model and their impact on crop yields.



Land available for annual or perennial energy crop production			
Abandoned agricultural land		**Abandoned pasture land**	
Non-degraded Non-degraded abandoned agricultural land can be utilised to produced annual and/or perennial energy crops.	**Mildly degraded** Mildly-degraded abandoned agricultural land can only be utilised to produced perennial energy crops.	**Non-degraded** Non-degraded, abandoned pasture land can be utilised to produced annual and/or perennial energy crops.	**Mildly degraded** Mildly-degraded abandoned pasture land can only be utilised to produced perennial energy crops.
Crop yield reduction Annual crop yield = 0% Perennial crop yield = 0%	**Crop yield reduction** Annual crop yield = n/a Perennial crop yield = 20%	**Crop yield reduction** Annual crop yield = 10% Perennial crop yield = 10%	**Crop yield reduction** Annual crop yield = n/a Perennial crop yield = 30%

Table 4-6 Descriptions of the SSP scenarios available in the model from Van Vuuren, 2021.

Supply scenario	Scenario name	Scenario description
SSP1	Sustainable development	Represents a world that aims for green growth. Assumes rapid technology development. Concerns about environmental impacts lead to high energy efficiency and high shares of renewable energy. The investments into education and development at the same time are assumed to lead to low population levels and, as a result, **lower pressure on land**.
SSP2	Middle of the road	Represents a world under median assumptions compared to SSP1 and SSP3.
SSP3	Regional rivalries	Represents a world of fragmentation. Economic growth and technology development are assumed to be slow.

In the SSP1 and SSP2 scenarios the Aichi biodiversity targets for 17% of global land area to be protected are met. This is not in the case in SSP3. Therefore, because the UK is signatory to the Convention on Biological Diversity, areas of abandoned grassland in SSP3 are set to the areas in SSP2 to ensure Aichi targets are considered in all scenarios.

The proportion of abandoned pasture land available for growing bioenergy crops is set as a user input in the model. By default, only abandoned agricultural land is considered available to grow energy crops in the future. This is because growing annual energy crops on pasture land which has been permanent pasture can cause significant loss of carbon. Carbon losses may be less if perennial energy crops are grown as carbon in the root system helps to sequester carbon in the soil. However, this carbon may be lost again when the crop is 'grubbed up' i.e., removed at the end of the plantation's lifetime.

The available agricultural and pasture land is further divided into **non-degraded** and **mildly degraded** subcategories (Table 4-6). This is to reflect the likelihood that within each SSP a proportion of the theoretically available land is likely to be unavailable due to concerns around factors, such as land degradation, water scarcity and biodiversity. Of the theoretically available land, we assume that a proportion that is either severely degraded, had severe water shortages or is required to form new protected areas for biodiversity is unavailable. The remaining land is split into **non-degraded** land and **mildly degraded** land, which also includes land that has mild water shortages. This division is applied as a percentage in the model and is based on work by Van Vuuren et al (Van Vuuren, 2009) which was used to calculate the percentage of land falling into each category. These percentages are assumed to be valid for the updated IMAGE SSP scenarios used in the model.

The categorisation of available land into non-degraded and mildly degraded land has two main implications in the model. Firstly, it is assumed that only non-degraded land can be used to produce annual energy crops because mildly degraded land is not of sufficient quality. Secondly, the yield of annual and perennial energy crops is assumed to be reduced on mildly degraded land (Table 4-6). In addition, yields are assumed to be lower on pasture land as historically, higher quality land is more likely to have been brought into agricultural production rather than used as pasture land.

4.3.1.2 Representative bioethanol and biodiesel crops

Estimation of the supply and demand of bioethanol or biodiesel from crops requires assumptions on the crops produced in each region. Therefore, we assign representative bioethanol and biodiesel crops, and corresponding yields, to each region in the model.

Representative crops and yields were determined by analysing available Food and Agriculture Organisation (FAO) data (FAO, 2022). Average crop production (2016-2020), and the relevant yield of the crop and the efficiency with which it can be converted to biodiesel or bioethanol[12], were combined to estimate the bioethanol

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[12] Representative conversion efficiencies were obtained from Biograce version 4d. For cassava, the conversion efficiency is taken from Pabon-Pereira, 2019.

production potential (from maize, sugar beet, sugar cane, wheat and cassava) and biodiesel production potential (from groundnut oil, palm oil, soybean oil, rapeseed oil) in each region.

For bioethanol, the representative crop was selected as the crop with the highest bioethanol potential in each region with the following exception. In cases where sugar cane was not the crop with the highest bioethanol potential, but was within 5% of the crop that was, sugar cane was selected as the representative crop. This reflects the fact that sugar cane has more desirable sustainability credentials than the other crops under consideration. For biodiesel, in all cases the representative crop was selected as the crop that produces the highest quantity of oil in each region.

Crop yields were obtained from FAO on a country basis (FAO, 2022). The representative crop yield for each crop/region was calculated as the weighted average yield, based on total production, for each country in the region. Crop yields are input to the model for each representative crop in tonnes/ha. Crop yields are discussed in more detail in Section 4.3.1.6.

4.3.1.3 Land required to meet bioethanol and biodiesel demand

As referenced in Sections 4.2.1.5 and 4.2.1.7, which discuss the demand for crop based bioethanol and biodiesel respectively, we have used the forecast demand for these fuels to estimate the corresponding land area that is needed to enable the production to meet demand. The demand for bioethanol/biodiesel is calculated in terms of PJ of finished fuel. To convert this quantity into an equivalent land area, we utilise the representative crop yield (tonnes/ha) and conversion efficiencies (GJ/t) to determine a biofuel production yield (PJ/Mha). The land area (Mha) required to be in use for biofuel production to meet the bioethanol/biodiesel demand is then calculated from the demand for the respective demands.

For 2020, we assume that the land used to meet production is calculated as above. Furthermore, we assume that this area of land is maintained, possibly through crop rotations, for biofuel crop production until 2050. From 2025-2050, we calculate the area of **additional** land that is required, compared to 2020, which must be drawn from the available abandoned land pool.

4.3.1.4 Land available for bioethanol and biodiesel production

Section 4.3.1.1 describes how the total amount of land available for annual **and** perennial energy crop production is calculated. While Section 4.3.1.3 describes how the land **required** for bioethanol and biodiesel production is calculated, in the following section, we describe how the land **available** for bioethanol and biodiesel production is calculated.

The demand for land for biofuel production calculated in Section 4.3.1.3 is based on the demand for crop based biofuels as calculated from the IEA's WEO energy projections. Therefore, as a first step, we compare this estimate of the land area **required** for biofuel production with the land area **available** for biofuel production (which is based on IMAGE date) to ensure that sufficient land is available. The **minimum** of the land area available and the land area required is assumed to be available for bioethanol/biodiesel production.

The implication of the assumption above is that using land for lignocellulosic energy crop production is not permitted in the model until production of crops for bioethanol/biodiesel to meet the specified demand for crop based biofuels is met. Once this demand has been met, however, any available land is assumed to preferentially be used for lignocellulosic energy crop production. As the model is not an optimisation model, it is necessary to exogenously decide how land should be allocated between crops for biofuels and energy crops. This approach of ensuring that demand for crop based biofuels is met, but then favouring energy crop production, ensures internal consistency of the model with the energy demand forecasts used to determine regional biomass demand, while recognising that production of energy crops that can be used in plants with carbon capture and storage is desirable.

Only non-degraded land is considered available for bioethanol/biodiesel crop production and the model preferentially utilises abandoned agricultural land over abandoned pasture land for annual crop production, for the reasons discussed in Section 4.3.1.1.

The total land area available for bioethanol/biodiesel production is assigned to each fuel type based on the relative demand in each region (see 4.2.1 for details of demand calculations) and the corresponding quantity of bioethanol/biodiesel produced is determined.

It is possible that the land available in a given region is insufficient to meet bioethanol/biodiesel demand. Therefore, the model calculates how much of this demand can be met from bioethanol/biodiesel produced outside of the region. To do this, any land eligible for bioethanol/biodiesel production that is **not utilised** to meet **demand in the region**[13] is assumed to be used to meet this demand remaining **globally**. Land is allocated to bioethanol or biodiesel crop production based on the relative share of global bioethanol/biodiesel production that is not met by in-region production. It should be noted that this methodology does not guarantee that the demand for bioethanol/biodiesel is met. Rather, it maximises the supply of bioethanol/biodiesel using all available land. The bioethanol and biodiesel produced in excess of the regional demand is added to the bioethanol/biodiesel produced to meet regional demand.

The approach described above ensures that production of annual energy crops to meet forecast bioethanol/biodiesel demand on non-degraded abandoned agricultural and pastoral land is prioritised over the utilisation of the same land to produce perennial energy crops to satisfy the demand profile in the IEA scenarios.

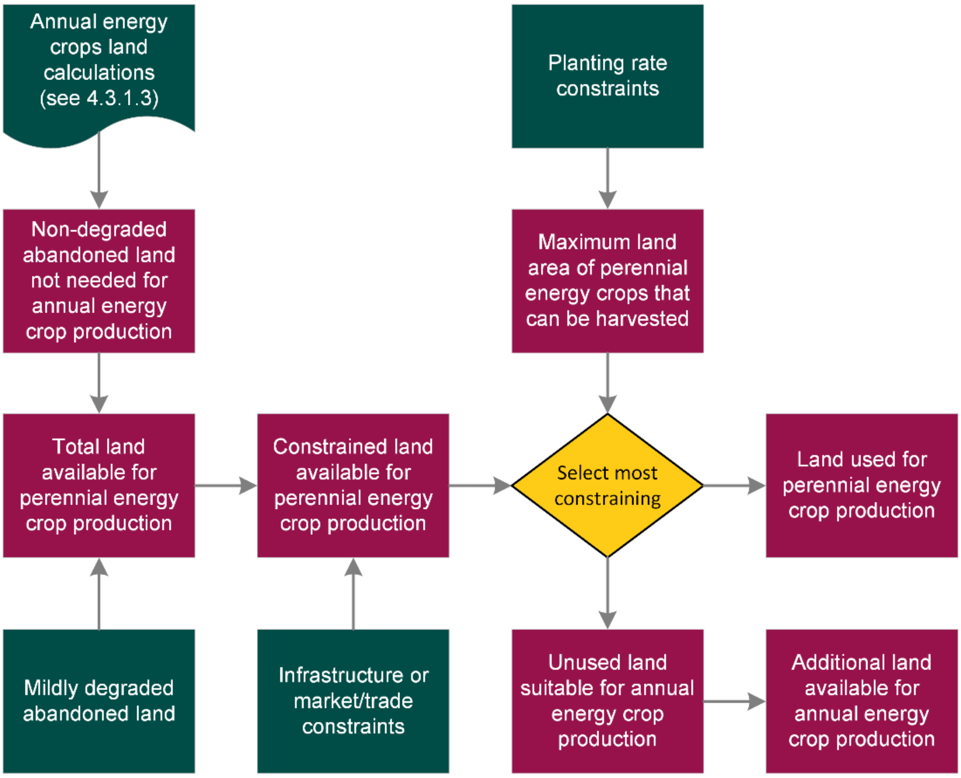
4.3.1.5 Land available for perennial energy crop production

Once available land has been allocated to maximise the proportion of the demand for crop based bioethanol and biodiesel that is met, land is next allocated to the production of perennial energy crops. Any non-degraded abandoned agricultural/pasture land not required to produce annual energy crops is assumed to be available to produce perennial energy crops. Furthermore, mildly degraded land can also be used to produced perennial energy crops. The pool of land available to produce perennial energy crops is comprised of surplus non-degraded abandoned agricultural/pasture land **and** all available mildly degraded abandoned agricultural/pasture land (Figure 4-7).

Unlike annual energy crops, land availability is not the only constraint to the production of perennial energy crops. Firstly, the overall land available for perennial energy crop production is reduced to account for market/trade and infrastructure constraints. Secondly, the production of perennial energy crops is limited by planting rate constraints.

We assume that in all regions, perennial energy crop production is zero in 2020 and that harvesting of perennial energy crops does not commence until 2025. Following this, the rate at which the area used to produce perennial energy crops increases is dependent on the initial area planted in 2025 and the annual expansion rate, which varies depending on the supply scenario.

Figure 4-7 Overview of the approach used to allocate land to perennial energy crop production.



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[13] This situation arises when the area of land required to meet the in-region demand is less than the area of land available.

We have used expert judgement to develop input parameters for both the harvested land area and the annual rate of expansion. This is unavoidable as there is an absence of data that can be used to forecast perennial energy crop production. The area harvested in each country was derived by considering afforestation rates in each of the regions, while the annual growth in harvested area was developed to represent the differing views of society in each of the SSPs used in the supply scenarios.

The model is configured to determine the most constraining factor out of available land and planting rate (i.e., select the minimum land area) and to use this in the calculation of perennial energy crop production (Figure 4-7). Similarly, the model is configured to prioritise the use of mildly degraded land over non-degraded land for perennial energy crops. This is so that any land that is/cannot be used to produce perennial energy crops, can be reallocated to produce annual energy crops – which it is assumed cannot be grown on mildly degraded land.

4.3.1.6 Crop yields

Sections 4.3.1.1 to 4.3.1.5 above describe how we determine the land area available to produce annual and perennial energy crops. These land areas are used in conjunction with crop yields to calculate the overall crop availability. Furthermore, we allow for crop yields to change over time, to reflect potential impacts of a changing climate.

For annual energy crops, the yield in 2020 was determined based on analysis of available FAOSTAT data as described in 4.3.1.2. In the model, baseline 2020 yield is allowed to vary between 2025 and 2050, depending on the supply scenario selected. This variation is implemented as an annual percentage change in yield and is based on a report by FAO (FAO, 2018) that defines the impact on crop yields of three potential scenarios: *towards sustainability*, *business as usual* and *stratified society.* These FAO scenarios are broadly consistent with the world views represented in the supply scenarios and are therefore paired with SSP1, SSP2 and SSP3, respectively, to vary the crop yield in each scenario, in a time dependant, region specific manner. The FAO scenarios provide yield changes over two periods, 2020-2030 and 2030-2050, and therefore we also implement this approach in the model for consistency. Finally, as indicated in Figure 4-6 above, a 10% reduction in yield is applied to annual energy crops grown on non-degraded pasture land.

Table 4-7 Perennial energy crop yields on non-degraded, abandoned agricultural land used in the model.

Model region	Perennial energy crop yield (GJ/ha)
USA	189
Other North America	190
Brazil	170
Other South and Central Americas	170
Africa	139
Europe	145
Eurasia	205
Middle East	57
India	185
China	134
Japan	168
South East Asia	185
Other South Asia and Oceania	182

Perennial energy crop yields are input for each region in the model. The 2015 version of the model used data on crop yields derived from Hoogwick for key regions (Hoogwijk, et al., 2005). This was then extrapolated to provide values for other regions. In this update, the Hoogwick data has been supplemented from the database produced by Li which catalogues regional yields reported for a range of crops (Li, et al., 2020). These two data sets were combined to produce typical values for each of the 26 regions modelled in IMAGE. These yields were then combined with data from on the areas of land available to produce a weighted average value for the aggregated regions in the model. These yields (Table 4-7) represent a generic 'perennial energy crop' as opposed to a specific species and are expressed in terms of primary energy content. The yields specified in Table 4-7 refer to the yield on non-degraded agricultural land and are reduced according to the values in Figure 4-6 (above) for pasture land and mildly-degraded land types.

We have also allowed for a yield change in perennial energy crops, expressed as an annual percentage change, for each supply scenario, based on expert judgement which can be modified by the user.

4.3.1.7 Bioethanol and biodiesel fuel production yields

To simplify the calculations in the model, we determine a bioethanol/biodiesel yield in PJ/Mha. This allows the available land to be converted directly to available fuel. The bioethanol/biodiesel yield is calculated from the crop yield (t/ha) described above and a production yield (GJ/t), where the production yield reflects the efficiency with which feedstock is converted to finished fuel.

Production yields are input to the model for bioethanol and biodiesel production in each region and are consistent with the selected representative crop (see Section 4.3.1.2). Furthermore, production yields are allowed to vary with time, so that potential increases in process efficiency are accounted for as with crop yields, production yield changes are implemented as an annual percentage change over two phases: 2020-2030 and 2035-2050. Production yield changes are specified for each of the supply scenarios and the default values are based on expert judgement.

4.3.1.8 Summary

The calculations described in Section 4.3.1 result in the determination of the quantity of bioethanol, biodiesel and perennial energy crops produced, based on the selected user inputs (i.e., supply and demand scenarios) as well as other assumptions described above. The primary variable in these calculations is the availability of land.

Bioethanol and biodiesel are produced using non-degraded, abandoned agricultural and pasture land with the aim of maximising the proportion of the forecast demand that is met. Any land that is not required to meet the bioethanol or biodiesel demand is then used for perennial energy crop production.

Perennial energy crops are produced on all land types, however mildly degraded land is used preferentially. Production of perennial energy crops is constrained by either infrastructure, trade/market or planting rate constraints. Any non-degraded land available once the production of perennial energy crops is maximised, is reallocated to produce additional annual energy crops, in excess of demand.

4.3.2 Global forestry products

Resource estimates for small roundwood, bark and sawmill residues are all generated using a global forestry model developed by Forest Research with assistance from Ricardo.

The model contains data on areas of coniferous and non-coniferous primary, 'old' and 'young' regenerated forest and plantation forest on a country-by-country basis. Regenerated forest is split into 'old' regenerated forest and 'young' regenerated forest. Larger countries (e.g., China, USA, Brazil and Australia) are modelled on a regional basis. These forest areas are combined with estimates of the mean yield class[14] of each type of forest in each country, to estimate the annual potential harvest of forestry biomass wood in that country, subject to certain constraints[15].

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[14] Yield class is a measure of the potential for wood production from a stand of trees. It has units of cubic metres of stem volume per hectare per year. The basis of yield class and its interpretation are described in Matthews *et al*. (2016) and further relevant discussion can be found in Appendix 2 of Matthews ***et al***. (2014)

[15] The model does not allow for net afforestation, which would lead to an increase in forest area. However, over the timescale of the model (30 years), due to the time needed for a forest to mature in most regions, it is unlikely that significant quantities of forestry products for bioenergy would be available by 2050 from the newly forested areas.

Estimates are made of the amount of biomass available as stemwood, branchwood and stumps and roots, and allowances are made for supply chain losses. The model then allocates fractions of stemwood and branchwood that are likely to be used for energy rather than as materials to produce an estimate of biomass available for energy. As part of this allocation, the model also estimates the fraction of stemwood likely to be suitable for conversion to sawnwood products. This is then used to generate an estimate of sawmill residues. An assumption is then applied about the fraction of sawmill residues available for bioenergy rather than material use.

The global forestry model includes a number of mechanisms to allow the user to represent the implementation of sustainability criteria. The first is the ability to specify the proportions of each of the forest types represented in the model (primary, old naturally regenerated, young naturally regenerated and plantation) which should be included in the analysis. For example, primary forests, which may have high biodiversity and high carbon stocks, can be excluded from the analysis.

A second mechanism is to allow the user to select a threshold yield class below which harvesting is assumed to be avoided or partially restricted. The carbon stock of a forest stand is depleted when wood is harvested from it, but if it is sustainably managed and is replanted to replace wood which has been removed, the carbon stock of the stand can recover, and the carbon stock of the forest is maintained by the growth of the remaining stands. The speed of recovery is very sensitive to the potential growth rate of the regenerating or on-growing trees. In slow growing forests, i.e. those with a low yield class, this may take many years, whereas in fast growing forests with a high yield class, this will happen much more rapidly. The ability to set a yield class threshold in the model therefore allows the user to reflect desires to avoid situations where harvesting will lead to excessively slow subsequent recovery of individual stand carbon stocks.

The yield classes used in the model represent a mean value for a whole country or region. Therefore, there will be proportions of the growing stock within the country where the yield class will be higher and others where it will be lower. In recognition of this, the model allows for a certain proportion of the forest area that has a mean yield class below the threshold yield class to be included as available for wood production, rather than excluding the entire area. This is done by setting a lower threshold and an upper cut-off for each forest type and evaluating where the mean yield class sits in relation to this.

Ideally, the modelling would allow for the distribution of yield classes observed in coniferous and non-coniferous forest areas in each country. However, this level of detail is not represented in the primary data or estimates of yield class reported for many countries and regions. For some countries, there are no formally reported estimates of yield class and the modelling relies on ‘best available information’ or assumptions about likely yield classes in some countries and regions. The model also allows the user to decide whether harvesting of stumps and roots is allowed.

The forestry model allows for an annual increase in total wood production. Countries and regions where harvesting is below the annual sustainable harvesting level are allowed to increase their harvest until the annual sustainable harvesting level is met, after which, harvest is kept constant. The model identifies countries where current harvesting appears to be above the annual sustainable limit – using wood production data from Forestry Production and Trade statistics held within FAOSTAT. Where countries within this grouping are also identified as having significant deforestation, the model only allows harvest levels to be the annual sustainable level from 2025 onwards. For countries within this grouping without significant deforestation, the harvest level is assumed to gradually decline towards the sustainable harvest level. This is because there are a number of legitimate reasons why the harvest level may temporarily exceed the calculated sustainable level (e.g., age structure or unmanaged forests being brought back into active production). However, over the longer term for the resource to be sustainable, annual harvesting levels must not exceed this sustainable harvest level.

A low, central and high run were created for each SSP scenario using the global forestry model and the outputs transferred to the main resource model. Within the biomass model the user may choose between a low, central and high estimate for global forestry product availability. Values for key parameters are as shown in Table 4-8.

The main difference between SSP scenarios is the year by which countries currently harvesting above the sustainable limit but having no deforestation, must return to their annual sustainable harvest This is 2040 in SSP1, 2045 in SSP2 and 2050 in SSP3.

Table 4-8 Key parameters in global forestry model (all SSP scenarios).

Parameter	Unit	Low	Central	High
Fraction of primary forest areas included	%	0%	0%	0%
Fraction of old regenerated forest areas included	%	10%	35%	50%
Fraction of young, regenerated forest areas included	%	40%	75%	85%
Fraction of plantation forest areas included	%	100%	100%	100%
Lower threshold for growth rate (boreal)	Yield class[a]	3.5	2.5	2
Lower threshold for growth rate (temperate)	Yield class[a]	3.5	2.5	2
Lower threshold for growth rate (tropical)	Yield class[a]	3.5	2.5	2
Full production growth rate (boreal)	Yield class[a]	11.5	9	7.5
Full production growth rate (temperate)	Yield class[a]	11.5	9	7.5
Full production growth rate (tropical)	Yield class[a]	11.5	9	7.5
Fraction of stumps and roots for energy use	%	0%	0%	15%
Fraction of branch wood for energy use	%	10%	30%	50%
Fraction of bark for energy use	%	50%	80%	90%
Fraction of small roundwood for energy use	%	20%	40%	90%
Fraction of industrial residues for energy use	%	60%	80%	90%
Fraction of sawnwood for energy use	%	0%	0%	10%
Annual increase in total wood production (linear growth)	% per year	0.7%	0.8%	1.0%

[a] Yield class in m3/ha/year

4.3.3 Global wastes and residues

Resource estimates for global wastes and residues for bioenergy use are calculated in the respective supporting workbooks and copied directly into the model.

4.3.3.1 Global used cooking oil

Primary data on the availability of UCO outside of the UK and EU is sparse. Separate approaches are adopted to estimate UCO availability in the EU, Asia and the rest of the world, based on the availability of data. Overall, low, medium and high scenarios for total global UCO availability are developed in the supporting workbook. However, **only the medium scenario is hard coded into the model**.

UCO availability in the EU

The Greenea report is used as the basis for the EU UCO estimates for both household and commercial UCO sources (Greenea, 2016). Potential changes in household and commercial UCO are given for each Member State. These are implemented in our scenarios on a Member State basis in the same manner as for the UK, and then aggregated to give the total UCO availability in the EU.

We note that two prevalent, and more recent reports covering UCO availability are available, namely *Used Cooking Oil (UCO) as biofuel feedstock in the EU* (CE Delft, 2020) and *Sustainable biomass availability in the EU, to 2050* (Concawe, 2021). However, the Greenea data set is the primary data set used in these reports. Therefore, we have used the primary (Greenea) data source in our analysis.

UCO Availability in Asia

The ICCT have recently published estimates of UCO availability in key UCO exporting countries in Asia - China, India, Indonesia, Japan, Malaysia and the Republic of Korea (ICCT, 2022). These estimates give upper and lower bounds for current collection estimates, as well as an estimate of the maximum collection potential. The estimates are not broken down into household and commercial sources.

For 2020 UCO availability, we have used the lower bound of the current UCO collection estimates across all scenarios, as a consistent and conservative baseline. To forecast UCO availability, the lower, upper and maximum estimates for current collection are converted to UCO per capita figures and extrapolated to 2050 using population projections.

This approach assumes that UCO generation is a function of population, i.e., demand for food. It is adopted due to the absence of any additional data on the forecast availability of UCO in these regions.

UCO availability in these countries increases in all scenarios. However, the forecasts suggest that there is a significant uncertainty in the extent of growth potential of UCO in most cases. With the exception of China and South Korea, these countries collect less than half of the maximum collectable UCO at present. Therefore, there is significant but undefined potential for change. The result of this is a large range between the maximum quantities of UCO available between each scenario.

UCO availability in the remainder of the world

No consistent datasets are available that report UCO availability globally. Therefore, we have adopted the approach reported by Teixeira *et al* (Teixeira, et al., 2018) to estimate the quantity of UCO available in countries not discussed above. Teixeira derived a statistical relationship that estimates 32% of the vegetable oil consumed within a country is ultimately available to be collected as UCO. Therefore, we used vegetable oil consumption per capita data from FAOSTAT (FAO, 2022) in conjunction with this relationship to estimate the quantity of UCO that is available to be collected. This relationship was validated by comparison with the data available for the UK, EU and Asia discussed above[16]. The total available UCO is forecast to 2050 according to the per capita vegetable oil consumption and population estimates.

Teixeira suggests that collection potential for UCO ranges from 23% in low performing countries to 75% in high performing countries. This is generally consistent with the data discussed above for the UK, EU and Asia. We applied these collection rates to the total quantity of available UCO. In all scenarios, we assume that the current collection rate is 12% which is 50% of the low collection rate described by Teixeira and reflect the fact that most of the countries included in this estimate do not have established UCO collection industries. In the low scenario, a 23% collection rate is achieved by 2030 and a 50% collection rate by 2050. In the medium scenario, a 23% collection rate is achieved by 2025, 50% by 2030 and 75% by 2050. The high scenario follows the same trajectory as the medium, except that the 75% collection rate is achieved by 2040.

As a general trend, UCO availability increases overall. However, the total quantity of UCO available is highly sensitive to collection rates. No primary data is available that indicates current collection rates, or how these are likely to change in the future. This is a significant source of uncertainty within this UCO estimate.

4.3.3.2 Global tallow

Current estimates of tallow production are based on data from FAOSTAT (FAO, 2022). This data is available at a country level and is aggregated to a regional level in the supporting workbook. Only Category 1 and 2 tallow is assumed to be available for bioenergy. However, we have been unable to find any literature estimates on the split of global tallow by category. Therefore, we have used the values for the UK, and assume that 60% of tallow produced is Category 3 and the remainder is available for bioenergy.

Future estimates of global tallow availability are projected on a tallow per capita basis. This assumes that the production of tallow is directly correlated to the production of livestock for food and that this is driven by population size. The forecasts are made at a country level, using UN population projections, and aggregated to the regional level in the supporting workbook.

4.3.3.3 Global agricultural processing residues

The global agricultural processing residues considered are maize cob, olive stones, sunflower husks, walnut shells, oat husks, soybean husks, groundnut shells, cocoa bean husks, bagasse, palm kernel expeller and sheanut shells. While some of these residues are unlikely to be imported to the UK under current conditions, their inclusion in the model is necessary to allow for a more accurate evaluation of the likely competition for the global biomass surplus, i.e., these resources can be used to meet in-region demand, reducing competition for the surplus resource. Furthermore, there is a possibility that the market may develop in the future such that importing these resources becomes more economically viable.

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[16] This validation gave an R^2 of 0.85, which indicates a good correlation.

As with the UK agricultural processing residues, we use estimates of crop production combined with a residue ratio to estimate production.

Data on crop production is based on FAOSTAT (FAO, 2022). The five-year average production figure is used to account for any seasonal variations in yield. We have applied estimated yield variations for these crops based on scenarios from FAO (FAO, 2018). We have used the business-as-usual scenario, which gives the highest crop yields overall.

Competing demand is assessed by expert judgment, based on literature reports of competing use for each residue. We did not identify any competing uses for olive stones, groundnut shells or sheanut shells, therefore competing demand for these feedstocks is set to zero.

4.3.3.4 Global agricultural field residues

Agricultural residues are inedible materials produced through the processing of crops. The agricultural residues considered in this study are selected because they are solids and have a relatively high energy density. Consequently, they are well suited to use as a feedstock for fuel production and can be transported efficiently.

Unconstrained resource

Data on the current availability of cereal crops was obtained from FAOSTAT (FAO, 2022). The cereal crops considered are barley, maize, oats, rice, rye, triticale and wheat. Cereal crop production is projected to 2050 using yield forecasts from FAO, as described for agricultural processing residues in Section 4.3.3.3.

A crop specific straw-to-grain ratio is applied to the projected cereal production to estimate residue availability and it is assumed that 66% of straw produced can be collected. The remaining 33% is assumed to be unavailable due to limiting technical factors, such as combine type, cutting height and dry matter content (Weiser, et al., 2014).

Constrained resource

It is assumed that only 50% of the unconstrained resource is available for bioenergy, based on literature estimates (ICCT, 2013). The remainder is assumed to be required for animal bedding and fodder, as well as other horticultural uses.

4.3.3.5 Global manure

Unconstrained resource

Livestock numbers for dairy cattle, non-dairy cattle, breeding swine and market swine in 191 countries was obtained from FAOSTAT (FAO, 2022)[17]. Estimates of the volatile solids generated per day by each livestock type was obtained from Chapter 10 of the Intergovernmental Panel on Climate Change (IPCC) Report, Volume 4 (Dong, et al., 2006) and was used to calculate the dry matter generation of each livestock type.

Constrained resource

The IPCC report (Dong, et al., 2006) outlines data for the proportion of excreta going to nine types of waste management systems, and of these nine systems, the use of pasture, range and paddock is identified as the competing use for this resource. The proportion of excreta used for pasture, range and paddock is excluded from the accessible dry matter.

The size of holding is also identified as a limiting factor for manure availability. Where holdings are small, it is unfeasible for the manure to be collected. The same thresholds are implemented to the global model as were found in the UK. These thresholds, in combination with data from FAOSTAT on the number of livestock per agricultural area, are used to generate a minimum holding size per region, which is used to derive the minimum collection threshold. FAOSTAT data on the number of holding sizes per size for all countries is aggregated into the model regions to calculate the percentage of holdings per size range. The minimum holding area is used to allocate the holding size percentages to the manure generated, which results in the available and accessible dry matter for each region and globally.

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[17] Consideration of poultry manure was outside of the scope of this model update. However, it is potentially a significant resource and could be considered for addition to the model in any future updates.

4.3.3.6 Global residual waste

As discussed in Section 3.1.2.6, residual waste is the remnant of Municipal Solid Waste (MSW) and C&I (Commercial and Industrial) waste after recycling and material recovery. It is composed of both biogenic and fossil components with the exact fraction varying depending on the composition. However, for the purpose of this section, the data sources used classify MSW as 'residential, commercial and institutional waste” (Kaza, et al., 2019).

Unconstrained resource

The global residual waste resource has been calculated using the World Bank’s ‘What a Waste’ dataset and report (Kaza, et al., 2019) combined with the World Bank’s follow up report, ‘More Growth, Less Garbage’ (Kaza, et al., 2021). The data set contains information on MSW arisings for each country, together with information on Gross Domestic Product (GDP) and population. Data is for the latest year available, thus varies from country to country. The World Bank report analysed this data and found a correlation between MSW per capita and GDP per capita: initially MSW per capita rises as GDP rises, but as income levels become higher there is a plateauing off, and growth in MSW per capita slows and eventually begins to decline. This relationship was used to project MSW per capita from the latest base year data, using actual changes in GDP to create a full data set for 2020 and then GDP forecasts from the IMAGE model for 26 global regions to forecast forward to 2050. These MSW per capita forecasts were then multiplied by population forecasts from the UN to calculate total MSW generated.

Waste composition data is also available from the ‘What a Waste’ dataset and this was used to estimate the biogenic fraction of MSW in each country. A simplifying assumption is made that the composition of the waste does not change over time. The categories, food, paper and carboard, wood and yard/garden/green waste, are assumed to be 100% biogenic, and the categories, rubber/leather and ‘other’, are assumed to be 50% biogenic.

Constrained resource

The World Bank’s ‘What a Waste’ dataset also provides information on treatment routes for MSW for the year of data collection. The treatment methods were combined into three categories:

- Materials’ recovery (recycling, anaerobic digestion and composting)
- Incineration and managed landfills
- Unmanaged waste.

Over time, it is assumed that countries move towards higher levels of recycling and that for countries where some waste is currently unmanaged, all wastes become managed. The levels which are assumed to be achieved in 2030 and 2050 for each category of country are shown in Table 4-9. It is assumed that waste, which is in the incineration and managed landfill category, is available for bioenergy.

Table 4-9 Assumptions for waste management routes in 2030 and 2050.

	Assumed level in 2030			**Assumed level in 2050**		
	Materials' recovery (%)	Incineration and landfill (%)	Unmanaged (%)	Materials' recovery (%)	Incineration and landfill (%)	Unmanaged (%)
Lower income	25%	50%	25%	60%	30%	10%
Lower middle income	35%	50%	15%	65%	30%	5%
Upper middle income	50%	50%	0%	70%	30%	0%
Higher income	70%	30%	0%	75%	25%	0%

4.3.3.7 Global waste wood

Waste (or recycled) wood is any wood that is not virgin timber or a product of the processing of virgin woods (i.e., the timber/forestry industry). Waste wood can be collected from three waste streams, MSW, construction and demolition (C&D) waste, and commercial and industrial waste.

Unconstrained resource

Data for C&D waste and industrial waste was obtained from the World Bank's 'What a Waste' 2.0 report and dataset. Data is only available for a limited number of countries, hence gap filling of the data set was necessary. This was done by calculating the ratio of C&D and industrial waste to MSW. The average ratio for countries in an income group was then applied to countries MSW arisings to estimate their C&D and industrial waste arisings. As no data at all was available for Low Income countries, ratios were set to 70% of the ratio for Lower Middle-Income countries. Wood in MSW was calculated based on composition data from the 'What a Waste' data set for MSW. It is assumed that 2% of C&D waste is wood based on data from Eurostat (DG GROW, 2018). The fraction of wood in industrial waste is estimated at 4.9% based on data from the UK on the quantity of waste wood generated per NACE economic activity classification[18] (Defra, 2023c). The fraction of wood which can be recovered from each waste stream is assumed to be the same as the recovery percentage set out in in Table 4-9.

Constrained resource

The principal non-energy use of waste wood is for panel board, although this is limited to 'clean' waste wood. Specific data on the use of waste wood for this purpose globally could not be found, as statistics do not generally distinguish between post-consumer waste wood, and other sources of non-virgin wood, such as sawmill residues. From the limited data available it was assumed that in most regions, 10% of waste wood goes into non-bioenergy use, and for regions known to have a significant panel board industry (Europe, USA and Other North America), a slightly higher value of 15% is assumed.

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[18] Mining and quarrying, water-related services and construction have been excluded due to their exclusion within the 'What a Waste' figures.

4.4 GLOBAL RESOURCE BALANCE

The model is configured to operate in one of two operating modes:

1. Global resource **production** mode
2. Global resource **surplus** mode.

The operating mode of the model dictates the maximum resource that is potentially available to trade on the global market. The model mode is selected as a user input.

4.4.1 Global resource production

Global resource production refers to the total regional supply of individual resources for **bioenergy** uses. The global production of a given resource is equivalent to the supply described in Section 4.3. Operating the model in *Global resource production mode* **does not** account for any domestic demand for the resource. All of the resource produced within a region is assumed to be available for export. This is the theoretical maximum resource that the UK could access. It should be noted that in production mode, all solid biomass resources considered non-exportable (see Section 4.4.2.3) are converted to biofuels before being deemed available to the UK (see Section 4.4.2.5).

4.4.2 Global resource surplus

Figure 4-8 The relationship between resource production and surplus.

Global resource surplus refers to the quantity of regional resources that are available to trade once regional demand has been met. The surplus is equal to the total regional production minus the regional demand (Figure 4-8). The methodology used to determine the surplus is dependent on the resource, as described below.

4.4.2.1 Surplus crop based bioethanol and biodiesel

The surplus of crop based bioethanol and biodiesel is calculated by subtracting the demand (see Sections 4.2.1.5 and 4.2.1.7) from the supply (see Section 4.3.1) in each region. If demand exceeds supply, the 'surplus' is set to zero.

4.4.2.2 Biodiesel from UCO/tallow

The surplus of biodiesel from UCO/tallow is calculated by subtracting the demand (see 4.2.1) from the supply (see Section 4.3.3.1 and 4.3.3.2) in each region. To enable this calculation, the supply of UCO/tallow is converted to the equivalent quantity of biodiesel, using a conversion efficiency of 97% (JRC, 2020). If demand exceeds supply, the 'surplus' is set to zero.

4.4.2.3 Solid biomass

Solid biomass resources are split into two categories, exportable and non-exportable (Table 4-10) Non-exportable resources are designated on the basis that either they have low energy densities that render long distance transport economically unviable, or they are wastes and therefore not likely to be traded.

Non-exportable resources are used preferentially over exportable resources to meet the in-region demand for solid biomass as this approach maximises the availability of solid biomass to the UK. All non-exportable resources are assumed to be used in equal percentages to meet the overall demand, i.e., use of any one resource is not given a preference. Any non-exportable resources not required to meet the solid biomass demand are converted to biofuels (see Section 4.4.2.5), which is regarded as surplus (rather than the resource itself).

Table 4-10 Categorisation of exportable and non-exportable solid biomass resources.

Exportable global solid biomass resources	Non-exportable global solid biomass resources
Small roundwood	Agricultural field residues
Sawmill residues	Waste wood
Agricultural processing residues	Residual biogenic waste
Perennial energy crops	Bark
	Branchwood

The demand for solid biomass that is outstanding once all non-exportable resources have been used is met using exportable resources. As with non-exportable resources, the use of any one resource is not given a preference. Any remaining exportable resources not required to meet regional demand are considered surplus, and available to the UK.

4.4.2.4 Gaseous biomass

Manure is the only global resource that is used to meet the demand for gaseous biomass. The demand for manure to meet the gaseous biomass demand (see Section 4.2.3 is subtracted from the supply of manure (see Section 4.3.3.5) for each region. Any manure not required to meet the demand is converted to a biofuel before it is considered as being surplus and available to the UK.

4.4.2.5 Resource conversion

Non-exportable solid biomass and manure are converted into biofuels before they are considered as available to the UK. These resources can either be converted to road transport fuel or sustainable aviation fuel (SAF). This choice does not have an impact on the overall energy delivered as finished fuel, as the conversion efficiencies are assumed to be the same. However, different sustainability criteria are applied to road transport fuel and SAF (see Section 5). For this reason, UCO and tallow are also allocated as either road transport or SAF. Allocation of these resources as road transport fuel or SAF are user inputs.

5. GHG CRITERIA

To be eligible for support or to count towards obligations and targets, biomass used in the UK must meet sustainability criteria, including a minimum GHG emissions' criterion. These criteria apply to biomass used for heat, power and transport.

Under the GHG criteria, emissions associated with the cultivation, processing and transport of the feedstock must be estimated. These are then combined with the efficiency of the end use conversion technology (in the case of heat and power) to generate a GHG emissions' factor in grams of CO_2 equivalent (gCO_2eq) per MJ of delivered electricity/heat/transport fuel. The model includes estimates of typical GHG emissions associated with production of all UK and global feedstocks in model.

When the user chooses to apply GHG criteria, these emissions are compared to the GHG criteria set in UK legislation to assess what proportion of the feedstock would meet the criteria (referred to below as 'the pass rate'). This is then applied to the feedstock resource estimate to calculate the quantity of **sustainable** resource available. In using the model for the biomass strategy the GHG criteria were applied along with using other model parameters to approximate to the land criteria.

As the GHG criteria are based on the final form of energy delivered, which varies between end use, it is also necessary to specify whether the biomass will be used for heat, power or transport as well as the specific technology used – as this determines the conversion efficiency. This 'end use' of the biomass is specified by the user (see Section 5.1.4).

UK legislation also contains other sustainability criteria that biomass must meet, e.g., ensuring that it has not been grown on land with high biodiversity value or soils with a high carbon stock. It is not possible to explicitly evaluate these in the model, but these factors have been considered in deriving feedstock estimates. For example, estimates of land available for growing energy crops are based on estimates of abandoned agricultural land, and the global forestry estimates exclude harvesting from protected areas and primary forests, and extraction of forestry harvesting residues, whose retention can be important for soil quality, are limited to 30%.

In assessing GHG emissions associated with use of the resources, the model uses the methodology specified in UK legislation around use of biomass for energy, which focuses on emissions associated with use of the resource. The methodology does not consider counterfactuals for the use of the feedstock[19], e.g., alternative disposal routes for wastes and residues that may have high GHG impacts, which are then avoided by utilising the feedstock for bioenergy. This has however been explored in previous work by DESNZ, see for example the Biomass Emissions and Counterfactual (BEAC) report which assesses the GHG impacts, including impacts on the carbon stock of the forestry resources in North America[20].

5.1 ESTIMATING GHG EMISSIONS FOR FEEDSTOCKS

5.1.1 Typical emissions

The model contains estimations of:

- Direct emissions associated with producing and transporting biomass
- Emissions associated with Indirect Land Use Change (ILUC)
- Negative emissions associated with carbon capture and storage (if applicable).

The **direct emissions** associated with cultivating and transporting biomass have been estimated as shown in Table 5-1. The values have been estimated using typical transport distances for feedstocks to any preprocessing point, and then onwards to the final end user. For global resources, distance within the country of origin and for shipping to the UK are based on typical distances for a major producing country within the region and are calculated for each region. Where pelleting is required, it is assumed that emissions are minimised by using the biomass being pelleted to fuel a combined heat and power (CHP) plant to provide heat

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[19] Apart from the very specific case of using manure in anaerobic digestion, in which case a credit is given for the avoided emissions from not having to store the manure in some cases.

[20] The model and report are available at https://www.gov.uk/government/publications/life-cycle-impacts-of-biomass-electricity-in-2020

and power for the pelleting process. The models and data sources used to develop the emissions' estimates are briefly described in Table 3-1.

The central value provided in the model is a best estimate of emissions assuming good practice in the supply chain. It is recognised that there will be a spread of values and this is allowed for by modelling a distribution of emissions around this central value. This is explained further below.

The model contains tables for emissions associated with **ILUC** for each feedstock and the user can choose whether to include these in the estimation of overall GHG emissions using the user inputs. At present, UK legislation does not require the inclusion of ILUC emissions when assessing whether biomass meets the GHG criteria. Consequently, values for ILUC emissions within the model are set to **zero as a default**.

Negative emissions are calculated based on the carbon content of the biomass feedstock, the carbon capture rate for the technology the biomass is utilised in and the overall efficiency of the carbon transport and storage network (see Section 6). The user can choose whether these negative emissions are accounted for when calculating total emissions associated with the biomass to compare with the GHG criteria.

Table 5-1 Methodology and sources for GHG emissions' estimates.

	Feedstock category	Source for emissions estimates
UK	Solid feedstocks	Emissions are based on values from the Solid and Gaseous Biomass Carbon Calculator 2.0 (build 36) (B2C2). Two values are provided, one for material provided as bales, or chips, and one for feedstocks provided as pellets. This is because the pelletisation process, while improving the energy density of materials for transport, is a source of additional emissions due to the heat and electricity required for the process. It is assumed biomass is used to provide the heat required for the process.
UK	Feedstocks for liquid biofuels (UCO, tallow, wheat, sugar beet)	Data on reported emissions from UK RTFO (5th provisional RTFO report for 2021) combined with assumptions about conversion efficiency of technologies used in the model.
UK	Feedstocks used to produce biogas/biomethane *food waste, sewage sludge, manures)	Data on reported emissions from UK RTFO (5th provisional RTFO report for 2021) combined with assumptions about conversion efficiency of technologies used in the model.
Global	Crop based bioethanol and biodiesel	It is assumed these are predominantly imported as finished biofuels. Emissions calculated using UK & Ireland Carbon Calculator (v 13.0)[21] together with typical activity data specified in v12. For each region in the model, a key producer country is identified and country specific values for yield of the crop in that country (from FAO) is used. Distances for shipping biofuel to the UK were based on shipping distances from ports typically used to export biofuels in these countries to the UK. Emissions from processing are estimated without including the conservativeness factor of 1.4.
Global	Road and aviation fuel from UCO and tallow	UCO and the category of tallow considered within the model are classified as wastes/residues under UK sustainability legislation and therefore emissions association with their generation do not need to be considered. Emissions are therefore estimated using data from the UK & Ireland Carbon Calculator (v 13.0), which reflect emissions from transport of the wastes to a central point, refining and processing into a transport fuel and transport of the finished fuel to the UK.
Global	Road and aviation fuel from other wastes and residues	Emissions are estimated using data from the UK & Ireland Carbon Calculator (v 13.0), which reflect emissions from transport of the wastes to a central point, refining and processing into a transport fuel and transport of the finished fuel to the UK.
Global	Agricultural residues	For residues, current sustainability legislation only requires estimation of emissions from the point at which they are collected. Emissions associated with collection and onward transport to the UK were estimated using the Solid and Gaseous Biomass Carbon Calculator 2.0 (build 36) designed to help with reporting of GHG emissions to Ofgem.

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[21] As v13 of the calculator no longer contains typical values for 'activity' data, e.g., quantity of fertiliser used, values from modelling biofuels production in v12 of the calculator were used. V13 was used to generate results as it contains updates to many of the emissions factors, e.g., kg CO_2/kg fertiliser.

	Feedstock category	Source for emissions estimates
Global	Forestry products: small roundwood (SRW) and sawmill residues	SRW is based on data in the Solid and Gaseous Biomass Carbon Calculator 2.0 (build 36) designed help with reporting of GHG emissions to Ofgem. Estimates allow for pelletising before transport to the UK. Heat needed for drying pre-pelletisation is assumed to come from biomass. For sawmill residues, sustainability legislation means that emissions associated with the production of the residue do not need to be considered, hence these are excluded. Emissions are based on those associated with pelletisation and onward transport to the UK. As sawmill residues typically have low moisture content, no drying pre-pelletisation is assumed.
Global	Energy Crops	The Solid and Gaseous Biomass Carbon Calculator 2.0 does not contain entries for cultivation and harvesting of energy crops outside the UK. Emissions for these aspects were therefore estimated using data within the tool on UK energy crop production to derive a relationship between emissions and yield. This was combined with the typical energy crop yield estimated for each country to give emissions for these stages. The energy crops are then assumed to be dried and pelleted and emissions from these stages are estimated in the B2C2 tool, which is also used to estimate transport distances.

Table 5-2 Description of sources for GHG emissions estimates

Solid and Gaseous Biomass Carbon Calculator 2.0 (build 36) (B2C2)	This calculator (was developed by E4Tech (now part of ERM) for Ofgem (https://www.ofgem.gov.uk/publications/uk-solid-and-gaseous-biomass-carbon-calculator) to help UK operators calculate emissions associated with the use of biomass to produce heat and power, and demonstrate compliance with UK GHG sustainability requirements. The calculator is no longer available for download, although the user manual can be accessed here: https://www.biomass-suppliers-list.service.gov.uk/wp-content/uploads/2022/11/b2c2rhiusermanualv7.3_3.pdf. It should be noted that it uses many of the same assumptions and emissions' factors as those used in European biomass lifecycle tools, such as Biograce (https://www.biograce.net/), and as in the UK & Ireland Carbon Calculator (v 13.0), it is an equivalent calculator for the production of biofuels for the transport sector.
UK & Ireland Carbon Calculator (v 13.0)	This biofuels carbon calculator is supplied by DfT for fuel suppliers to calculate the carbon saved on a batch of fuels as required under the Renewable Transport Fuel Obligation. It allows the calculation of the carbon intensity of biofuels according to the methodology specified in RTFO legislation, and includes all the biofuels, feedstocks and biofuel production processes and emissions from regional cultivation of biofuel feedstocks. It is available at https://www.gov.uk/government/publications/biofuels-carbon-calculator-rtfo.
5th provisional RTFO report for 2021 (DfT, 2023b)	Obligated parties under the RTFO must report the GHG emissions associated with the biofuels they supply to meet their obligation. These must be calculated in accordance with the methodology specified in RTFO legislation. These are reported by DfT in annual RTFO reports and provide an overview of emissions associated with production of biofuels used in the UK, split by feedstock and country of origin.

5.1.2 Time dependency

Emissions associated with the production and transport of biomass are likely to decrease over time – as the whole economy decarbonises and, for example, the carbon intensity of fuels used in cultivation and harvesting equipment or for transporting biomass, fall. The model accounts for this by allowing a time trend to be entered for emissions, which specifies the typical emissions for each five-year period as a percentage of emissions in 2020. The default value is set to 100% in each time period, but this can be edited by the user based on projections of regional decarbonisation.

5.1.3 Distribution of emissions

All of the parameters used to estimate emissions will naturally vary depending on producers, locations and years, etc. This means that in the real world, there will inevitably be a range around the typical values estimated. The model allows for this by assigning a range to the typical emission. From examination of typical reported variances and some sensitivity modelling, this is set to +/- 20% as a default. This range can be amended by the user. The upper and lower range can be varied for each five-year period, but in the default setting, the range is assumed to be constant over time.

Each feedstock is then considered to have five levels of emissions: a central value, based on the typical value of emission, a higher and lower value, based on the upper and lower range set, and mid-level ranges set as the average of the upper and lower value and typical value.

Depending on the emissions distribution chosen in the user inputs (low/central/high), a proportion of the feedstock is assumed to have emissions at each emissions level. Default values used for each distribution are shown in Table 5-3. Once again, the distributions can be edited by the user.

Table 5-3 Emissions' distributions used in the model, reflecting the fraction of feedstock at each emissions level.

Distribution	Description	Low emissions	Central emissions	High emissions
Emissions level 1	Lower end of range, e.g., 80% of typical value	30%	20%	10%
Emissions level 2	Average of lower and typical value (i.e., levels 1 and 3) e.g., 90% of typical value	30%	20%	10%
Emissions level 3	Typical value	20%	20%	20%
Emissions level 4	Average of upper and typical value (i.e., levels 5 and 3) e.g., 110% of typical value	10%	20%	30%
Emissions level 5	Upper end of range e.g., 120% of typical value	10%	20%	30%

5.1.4 Conversion technologies and efficiencies

A range of conversion technologies that biomass feedstocks can be used in are listed in the model. For each five-year period the user must specify the proportion of each feedstock which will go into each conversion route. This is so that the impact of GHG sustainability criteria on the resource estimate can be determined. It is necessary because the GHG criteria are specified per MJ of finished fuel or heat or electricity rather than per MJ of feedstock. Therefore, it is necessary to specify both the final form of the energy produced from the biomass and the efficiency of that conversion to estimate the emissions associated with the biomass feedstock when it is utilised.

The conversion efficiencies are drawn from a number of established sources, as shown in Table 5-4. For CHP, the methodology specified in UK legislation allows for emissions to be allocated between heat and power outputs based on exergy. The electricity generating efficiency assigned to CHP in the model has been adjusted to include the equivalent of the heat generated to allow for this and ensure that when dividing biomass feedstock emissions by the conversion efficiency the correct value per MJ electricity is obtained. It is therefore higher than the actual generating efficiency would be in practice. For conversion technologies using UK solid feedstocks, two variants are given in the model, one for using chips or baled materials, and one for using pellets. This is because the emissions associated with provision of feedstock in those two forms are different, so an assumption must be made about which is used. Where the conversion process produces biomethane that can be used in transport or injected into the gas grid to be used, e.g., to produce heat, two variants are given in the model as the end use criteria, which must be applied, are different. In both cases the conversion efficiency for the conversion technology is assumed to be the same.

Table 5-4 Conversion efficiencies and technologies for solid feedstocks.

Conversion technology	Efficiency	Notes and source
Power generation	29%	(DESNZ, 2020)
Power generation with CCS	31%	(Wood, 2018)
CHP	39%	(DESNZ, 2020) Adjusted to allow for allocation of some emissions to heat production. Assumes heat to power ratio of 2 and that heat is below 200°C
CHP with CCS	31%	Based on efficiency without CCS but assuming 50% of heat produced is required for operation of CCS and adjusted to allow allocation of some emissions to remaining heat
Boiler	85%	Typical value
Energy from Waste (EfW) (residual MSW)	28%	(DESNZ, 2020)
EfW with CCS (residual MSW)	18%	Based on value for EfW without CCS but with reduced electricity output based on data from (Energy Systems Catapult, 2020)
Waste gasification to produce power (RDF from MSW)	25%	(DESNZ, 2020)
Waste gasification with CCS (RDF from MSW)	16%	Based on value for waste gasification without CCS but with reduced electricity output based on data from (Energy Systems Catapult, 2020)
EfW with CHP (residual MSW)	38%	EfW with CHP (residual MSW)
EfW with CHP with CCS (residual MSW)	30%	Based on value for EfW without CCS but with reduced electricity output based on data from (Energy Systems Catapult, 2020)
Biomethane via gasification with CCS (for injection to gas grid and for transport) (biomass)	66%	Based on data supplied by DESNZ on values used in TIMES modelling which is itself based on data compiled for the Biomass Heat Pathways tool produced by Ecofys for BEIS
Biomethane via gasification with CCS (for injection to gas grid and for transport) (waste)	63%	Based on data supplied by DESNZ on values used in TIMES modelling which is itself based on data compiled for the Biomass Heat Pathways tool produced by Ecofys for BEIS
Hydrogen from gasification with CCS (biomass)	67%	(DESNZ, 2021)
Hydrogen from gasification with CCS (waste)	72%	Based on data supplied by DESNZ on values used in TIMES modelling which is itself based

Conversion technology	Efficiency	Notes and source
		on data compiled for the Biomass Heat Pathways tool produced by Ecofys for BEIS
Transport fuel (road or aviation) from solid biomass (FT gasification process)	45%	Wood to Syndiesel Plant (JRC, 2020)
Transport fuel (road or aviation) from solid biomass with CCS (FT gasification process)	45%	Wood to Syndiesel Plant: No efficiency penalty for CCS as process strongly exothermic (JRC, 2020)
Transport fuel (road or aviation) from high moisture content biomass (Hydrothermal liquefaction (HTL) process)	84%	(JRC, 2020)
Transport fuel (road or aviation) from high moisture content biomass (Hydrothermal liquefaction (HTL) process) with CCS	65%	Impact of CCS on conversion efficiency estimated from data in (Lozano E, 2020)
Road fuel from wate tyres (pyrolysis process)	62%	Wood to Pyrolysis diesel (JRC, 2020) No data available for waste tyres so assumed to be same as for wood
Transport fuel (road or aviation) from fates and lipids (UCO, tallow, algal oil) (hydrotreatment)	97%	(JRC, 2020)
Bioethanol from wheat **UK** only (with and without CCS)	54%	Biograce 1, ver 4d[22]
Bioethanol from sugar beet **UK** only (with and without CCS)	54%	Biograce 1, ver 4d[22]
Transport fuel (road or aviation) from crops UCO/tallow and other waste and residues – **global feedstocks only**	100%	Assumed to be converted to fuel in country of origin so conversion efficiency is accounted for already in estimating direct GHG emissions
Biomethane from anaerobic digestion of manures and slurries	50%	Based on typical biogas yield per tonne, NCV of feedstock and ratio of gross to net biogas yield to allow for own use of biogas on plant and additional 1% loss of biogas upgrading to biomethane (JRC, 2020)
Biomethane from anaerobic digestion of food waste	54%	As above
Biomethane from anaerobic digestion of landfill gas	90%	As above
Biomethane from anaerobic digestion of maize	59%	As above
Biomethane from anaerobic digestion of sewage sludge	26%	As above
Biomethane from anaerobic digestion of manures and slurries with CCUS	46%	Calculated from value without CCS based on additional electricity consumption from biogas

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[22] BIOGRACE

Conversion technology	Efficiency	Notes and source
		powered CHP for CO_2 compression. Electricity consumption estimated from (Jackson S, 2018)
Biomethane from anaerobic digestion of food waste with CCUS	51%	As above
Biomethane from anaerobic digestion of landfill gas with CCUS	89%	As above
Biomethane from anaerobic digestion of maize with CCUS	56%	As above
Biomethane from anaerobic digestion of sewage sludge with CCUS	22%	As above
Electricity from biogas from anaerobic digestion of manures and slurries	20%	Based on values for efficiency of biogas production as above and value for electricity generation efficiency of 40% from (DESNZ, 2020)
Electricity from biogas from anaerobic digestion of food waste	22%	As above
Electricity from biogas from anaerobic digestion of landfill gas	40%	As above
Electricity from biogas from anaerobic digestion of maize	24%	As above
Electricity from biogas from anaerobic digestion of sewage sludge	10%	As above

5.2 GHG CRITERIA

The GHG criteria set in UK legislation, which are used in the model, are shown in Table 5-5. In some legislation, the criteria that must be met varies over time, e.g., for biofuels for transport it depends on the age of the installation that production comes from. This is not taken into account in the values below, which assume that all production comes from newer installations for which more stringent limits will apply. At present there are no criteria differences for bioenergy power plant equipped with CCS (bioenergy carbon capture and storage, BECCS) and no allowance is made for the negative emissions that BECCS can generate. The values to 2025 for electricity are taken from the Renewables Obligation requirements, The values from 2030 onwards are based on the EU's 2018 Renewable Energy Directive. However, this could potentially change in the future so criteria for BECCs plants are specified separately in the model to allow this to be updated if necessary. All values can be re-defined by the user.

Table 5-5 Values assumed for GHG sustainability criteria.

	2020 (gCO2 eq/MJ)	2025 (gCO2 eq/MJ)	2030 (gCO2 eq/MJ)	2035 (gCO2 eq/MJ)	2040 (gCO2 eq/MJ)	2045 (gCO2 eq/MJ)	2050 (gCO2 eq/MJ)
Electricity (without CCS)	55.6	50.0	36.6	36.6	36.6	36.6	36.6
Electricity (with CCS)	55.6	50.0	36.6	36.6	36.6	36.6	36.6
Heat	34.8	34.8	31.2	27.6	24.0	24.0	24.0
Biomethane to grid	34.8	34.8	31.2	27.6	24.0	24.0	24.0
Road transport fuel	42.3	39.2	36.0	32.9	32.9	32.9	32.9
Sustainable aviation fuel	44.5	44.5	44.5	44.5	44.5	44.5	44.5
Hydrogen	20.0	20.0	20.0	20.0	20.0	20.0	20.0

6. CARBON CAPTURE AND STORAGE

Carbon capture is represented in the model in two ways:

1. As negative emissions that are used when assessing if the feedstock/technology combination meets the relevant GHG sustainability (if the user selects to do so)
2. As the total quantity of carbon captured under the set of conditions specified in the model.

6.1 NEGATIVE EMISSIONS

As discussed in Section 5.1.1 negative emissions from the use of carbon capture and storage (CCS) can be included in the GHG calculations when determining the typical emissions associated with each feedstock[23]. The model contains two levels of control over the inclusion of negative emissions in these calculations. The first is that the user can opt to switch on or off the inclusion of negative emissions when assessing whether resources meet the GHG criteria calculations for **all feedstocks**. The second is that the user can define the technologies for which negative emissions are included in the sustainability calculations.

As a default, negative emissions are included in the GHG criteria calculations for all technologies with CCS (when the user selects to include negative emissions). However, as the inclusion of negative emissions in GHG calculations is specified on an individual conversion technology basis, it is possible to have a differentiated approach by energy vector, e.g., excluding negative emissions from the sustainability calculation for all power generation technologies while allowing it to be included for all transport fuel conversion technologies. These individual technology settings are however overridden by the generic on/off setting, i.e., even in cases where this advanced user setting specified to include negative emissions for some conversion technologies, they will not be included if the user selected the general option not to allow for negative emissions in the sustainability calculations.

Negative emissions are calculated in the model as gCO_2 per MJ of feedstock to allow for their inclusion in the GHG sustainability assessments. For solid and liquid biomass feedstocks used in combustion based technologies (for heat and power or via gasification for production of liquid or gaseous fuels), this is calculated in the model using the **CO_2 emissions** from combustion of the fuel multiplied by the **CO_2 capture rate** of each technology and the overall **system efficiency** for CO_2 transport and storage. That is,

CO_2 captured (kt) = *quantity of resource assigned to technology (PJ)* **X** *CO_2 emission factor for resource (kt CO_2/PJ)* **X** *carbon capture efficiency for technology (%)* **X** *carbon transport and storage system efficiency (%).*

Other technologies where the capture of CO_2 can occur are when CO_2 is released from the fermentation of crops to produce bioethanol and when CO_2 is removed when upgrading biogas produced from anaerobic digestion to biomethane. In these cases the CO_2, which is produced, is related to the quantity of fuel produced, hence a proxy carbon content is calculated for feedstocks going into these technologies, which gives the correct amount of CO_2 that can potentially be captured. Therefore, for these fuels,

CO_2 captured (kt) = *CO_2 released in production final fuel (bioethanol or biogas) (kt)* **X** *carbon capture efficiency for technology (%)* **X** *carbon transport and storage system efficiency (%)*

Where:

CO_2 released in production of final fuel (bioethanol or biogas) (kt) = *quantity of resource assigned to technology (PJ)* X *proxy CO_2 emission factor for resource (kt CO_2/PJ).*

6.1.1 Carbon content of feedstocks.

For solid biomass feedstocks, the carbon emission factors used to estimate carbon emissions when combusted or gasified are shown in Table 6-1. Values are taken from the National Atmospheric Emissions Inventory (NAEI) and are used to calculate emissions of biogenic CO_2 in the UK's GHG inventory (NAEI, 2021). These values are also used for solid biomass resources which are imported to the UK **unprocessed** (i.e., agricultural processing residues, energy crops, sawmill residues and small roundwood).

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[23] The model assesses GHG emissions arising directly from use, processing, transport and conversion of the resources into heat power and fuels, and the CO_2, which may be captured though the use of CCS technologies. It is outside the scope of the model to make a fuller assessment of carbon fluxes, e,g., carbon sequestered in the biomass while it is growing, any changes in soil carbon, and also any GHG emissions or removals associated with a counterfactual use of the feedstock.

Table 6-1 Carbon emissions available for capture from combustion of feedstocks.

Biomass Type	Feedstock	Carbon emission (ktCO$_2$/PJ input)
Solid Biomass	Agricultural processing residues	100
	Agricultural field residues	100
	Arboricultural arisings	100
	Energy crops	100
	Forestry harvesting residues	100
	Miscanthus	100
	Residual biogenic waste	100
	Sawmill residues	100
	Short rotation forestry	100
	Small roundwood	100
	SRC willow	100
	Waste tyres biogenic fraction	100
	Waste wood	100
Liquid Biomass	Brown Grease	72
	Microalgal oil	70
	Tallow	70
	UCO	70
Gaseous Biomass	Landfill gas	55

Table 6-2 Proxy carbon emission factor assigned to feedstocks used for AD and bioethanol production.

	UK feedstock	Proxy carbon emission factor (ktCO$_2$/PJ)
Feedstocks for anaerobic digestion	Cattle manure and slurry	16
	Pig manure and slurry	16
	Food waste	28
	Maize	28
	Sewage sludge	25
Feedstocks for bioethanol production	Sugar beet	19
	Wheat	19

6.1.2 Carbon capture efficiency

Carbon capture efficiency is defined in the model for each technology with CCS. Carbon capture efficiencies are mainly based on factors provided by DESNZ, from assumptions in UKTIMES, and are therefore consistent with values used in other DESNZ energy modelling. Carbon capture efficiency reflects the amount of carbon that can be captured at the point the feedstock is initially converted into an energy vector, i.e., heat, power, a liquid biofuel or biomethane, and therefore varies between different technologies. For combustion for heat and power, it reflects the fraction of CO_2 in the flue gas that can be captured. Where feedstocks are processed into liquid or gaseous fuels via gasification, it allows for the fact that much of the CO_2 released from the feedstock will be retained in the fuel, hence CO_2 in the flue gas is lower than for heat and power. For bioethanol production based on fermentation (e.g., from starch and sugar crops), it reflects the proportion of CO_2 released during fermentation that can be captured, and for biomethane production via anaerobic digestion the fraction of the CO_2 extracted from the biogas in the upgrading process that can be captured. As discussed above, the carbon capture efficiencies for these last two processes are applied to an estimate of the CO_2 produced during the production process (fermentation and anaerobic digestion, respectively). Values assumed for carbon capture efficiency are given in Table 6-3.

Table 6-3 Carbon capture efficiencies.

Technology	Carbon capture efficiency
Biomethane production via anaerobic digestion and upgrading of biogas	99%
Bioethanol production via fermentation of crops	95%
Power generation, energy from waste and CHP	90%
Hydrogen production via gasification	90%
Biomethane production via gasification	38%
Liquid fuel production via gasification and FT process	46%
Liquid fuel production via hydrothermal liquefaction	23%

6.1.3 System Efficiency

A ‘system efficiency’ for carbon capture is defined in the model, which is included to allow the user to explore the impact of the possibility that less than 100% of carbon captured is being stored. This could be due to losses during the transport of CO_2 to the storage facility, for example. However, the default setting is 100% system efficiency.

6.2 UK CARBON CAPTURE AND STORAGE POTENTIAL

In addition to allowing for the consideration of negative emissions, an approximate estimate is made of the total carbon that would be captured **in the UK**, given the allocation of feedstocks to each conversion technology made by the user. This calculation is therefore only made where conversion of the feedstock to the final energy vector happens in the UK.

The total carbon captured is calculated by multiplying the quantity of feedstock (in PJ) assigned to each conversion technology by the carbon emission factor for the feedstock. This carbon emission factor represents the carbon content of the feedstock. This gives the mass of CO_2 generated for each feedstock/conversion technology pairing. The total mass of CO_2 generated is then multiplied by the relevant carbon capture efficiency (see Section 6.1.2) and the system efficiency to give the mass of carbon captured. The above calculations are applied separately to domestically produced resources and imported resources so that the results can be presented at the same level of resolution.

7. AVAILABILITY OF GLOBAL RESOURCES TO THE UK

Section 4.4 describes the two operating modes of the model, global resource **production** and global resource **surplus**. These operating modes dictate the **total** amount of resource that is calculated to be available on the **global market**. In this section of the report, we describe the model inputs that determine the **share** of this resource that the **UK can potentially access** (i.e., import). The UK is only able to access feedstocks considered 'exportable' (see Table 4-10 above) as well as finished fuels. Finished fuels are split between road fuels and aviation fuels because the sustainability criteria, specifically the GHG threshold, are different for road and aviation fuel.

7.1 UK FEEDSTOCK IMPORTS: 2020

The quantity of feedstocks imported to the UK in 2020 is shown in Table 7-1 and is calculated based on literature data as described below and reflect the actual quantity of each resource used by the UK in 2020.

7.1.1 Imports of sawmill residues and small roundwood

Imports of sawmill residues and small roundwood are based on the Digest of UK Energy Statistics (DUKES) (DESNZ, 2022) and Drax power station feedstock sources data (Drax, 2021; Drax, 2022). According to DUKES, the UK imported 154.8 PJ of wood pellets in 2020. Given that the majority of this is consumed by the large Drax power station, supplemental data from the 2021 and 2022 Drax ESG reports, which detail the source of wood used to produce the wood pellets it consumes, was used to categorise the pellets as either sawmill residues or small roundwood. On average, 65% of the imported feedstocks used by Drax are categorised as small roundwood, with the remaining 35% being sawmill (or other wood industry) residues.

Table 7-1 Quantities of feedstocks imported to the UK in 2020.

Resource	Imported to the UK in 2020 (PJ)	2020 Imports as a Share of Global Surplus		2020 Imports as a Share of Global Production	
		GHG Criteria Off	GHG Criteria On	GHG Criteria Off	GHG Criteria On
Sawmill residues	55	0.92%	2.11%	0.88%	1.93%
Small roundwood	100	2.14%	6.87%	0.80%	1.56%
Perennial energy crops	0.00	0.00%	0.00%	0.00%	0.00%
Agricultural processing residues	1.24	0.02%	0.03%	0.02%	0.03%
Biodiesel (from crops)	2.80	1.52%	13.37%	0.17%	0.44%
Bioethanol (from crops)	6.29	8.90%	9.01%	0.30%	0.30%
Road fuel from UCO/tallow	45.5	15.71%	15.71%	15.40%	15.40%
Road fuel from waste/residues	0.00	0.00%	0.00%	0.00%	0.00%
Aviation fuel from UCO/tallow	0.00	0.00%	0.00%	0.00%	0.00%
Aviation fuel from waste/residues	0.00	0.00%	0.00%	0.00%	0.00%

7.1.2 Imports of energy crops and agricultural processing residues

The *Ofgem Biomass Sustainability Dataset 2020-21,* which gives types and origin of biomass used for electricity generation under subsidy schemes, is used to determine the 2020 imports of perennial energy crops and agricultural processing residues *(Ofgem, 2022)*. No evidence could be found of imports of these crops for use for heat production only. According to the Ofgem dataset, 428 tonnes of miscanthus and 71,078 tonnes of agricultural processing residues were imported to the UK for use in electricity generation in 2020. This was converted to primary energy content using NCVs of 13.3 GJ/t and 17.4 GJ/t for energy crops and agricultural processing residues, respectively.

7.1.3 Imports of liquid biofuels

Liquid biofuels produced outside of the UK can be imported to the UK in the model. In the case of UCO and tallow, the model does not differentiate between UCO and tallow imported to the UK as finished fuels and UCO and tallow imported as feedstocks for processing in the UK. Similar assumptions are applied for biodiesel and bioethanol from crops, where all imports are assumed to be finished fuels. Quantities are estimated based on analysis of ComTrade import statistics (UN, 2022), and RTFO statistics (DfT, 2022a). RTFO statistics show no imports of aviation fuel, or road fuels from wastes and residues in 2020, so these are set to zero.

7.1.4 2020 UK share of global resources

For 2020, the absolute quantities of resources imported to the UK are known. However, the UK share of global resources in 2020 (as a percentage) will differ depending on the operating mode of the model (production vs surplus) and whether the GHG criteria are applied. Consequently, the UK percentage share of resources is calculated for all model operating modes, as shown in Table 7-1.

7.2 UK SHARE OF GLOBAL RESOURCES: 2025-2050

The share of available global resources that the UK can access between 2025 and 2050 is estimated in the model. The overarching assumption in this estimation is that the UKs ‘fair’ share of a resource is proportional to its share of global GDP. However, within this, two options are available:

a) To calculate the ‘fair’ share as UK GDP/total global GDP
b) To calculate the ‘fair’ share as UK GDP/sum of GDP in regions with insufficient domestic biomass resource to meet the regional demand for biomass, i.e., other biomass importers.

The second approach is intended to reflect a viewpoint that the UK will only be competing for biomass resources with other countries that wish to import biomass and therefore it is correct to calculate the ‘fair’ share just based on their GDP. This second approach can only be applied when the user has chosen to operate the model in global surplus mode.

7.2.1 Estimation of GDP for UK and other model regions

The GDP for the model regions are taken from the underlying data for the SSP scenarios modelled in IMAGE. This data is only provided at the regional level, so to forecast UK GDP additional data from OECD GDP forecasts (OECD, 2018) (for the UK and Western Europe) was used to estimate the fraction of Western Europe GDP within the IMAGE forecasts that should be allocated to the UK. The user may also create scenarios with other assumptions than GDP share as driving the UK share of either production or surplus biomass.

7.2.2 Calculation of UK Share

As indicated above the UK share of a global feedstock resource in 2020 is based on actual quantities imported, divided by either the total quantity of that resource produced globally (production mode) or the quantity of resource available globally after in-region demands for biomass have been met (surplus mode). For each mode, the user may choose one of three scenarios for extrapolating the 2020 share to that achieved in 2050.

In surplus mode the three scenarios are:

1) Surplus scenario 1: 2050 imports are set as the UK's share of global GDP in 2050. For 2030-2045, imports are set depending on 2020 imports in relation to the 2020 share of global GDP. If the 2020 import share is less than the 2020 UK share of global GDP, then the 2030-2050 import share is equal to the UK share of Global GDP. However, if the 2020 import share is greater than the 2020 UK share

of global GDP, then the UK import share declines linearly to the share of global GDP in 2050. Values in 2025 are linear interpolations between 2020 and 2030 for both cases.

2) Surplus scenario 2: as in Surplus scenario 1 but instead of global GDP the calculations use the GDP of all regions that are net importers of the feedstock.
3) Surplus scenario 3: is available for the user to input values from 2025-2050. 2020 values are fixed as in scenarios 1 and 2.

In production mode the three scenarios are:

1) Production scenario 1: from 2030 the share is equal to the UK's share of global GDP. 2025 is an average of the (actual) 2020 value and the forecast 2030 value.
2) Production scenario 2: from 2030 the share is equal to 20% of the UK's share of global GDP. 2025 is an average of the (actual) 2020 value and the forecast 2030 value. This was a scenario examined in the Biomass Strategy (DESNZ, 2023).
3) Production scenario 3: is available for the user to input values from 2025-2050. 2020 values are fixed as in scenarios 1 and 2.

7.2.3 Application of GHG criteria

If the user has chosen to apply sustainability criteria, then the 'pass rate' rate that the model has calculated for each feedstock (see Section 5) may be applied to imported feedstocks in one of two ways, depending on the methodology chosen by the user. The options are:

A. **Combine import and GHG compliance fractions:** The model combines the import fraction with the GHG compliance fraction and applies the product to the fraction of the global resource.

   This operating mode assumes that all countries wishing to import biomass have similar GHG saving criteria to the UK and that the fraction of the resource that meets these criteria is the same for all of them. This assumption may be conservative, as long transport distances increase GHG emissions for resources substantially. Consequently, more of the global resource could meet the GHG saving criteria locally than modelled, e.g., the GHG compliance fraction for the UK could be higher if it was only drawing its share of global biomass from regions closer to it.

B. **Take minimum of import and GHG compliance fractions:** The model applies the minimum of the import fraction and the GHG compliance fraction. This operating mode assumes that the UK draws its imports from those regions where exported resources can meet the UK's GHG saving criteria – typically those closer geographically to the UK.

   It is assumed that other regions, which have GHG saving criteria and need to import resources, are also able to import from neighbouring regions.

Worked examples of the two approaches are given in Table 7-2.

Table 7-2 Worked examples of approaches to applying sustainability pass rate to determine imports.

Approach	Feedstock available globally (PJ)	Import share	GHG criteria pass rate	Imports available
A	260	5%	60%	=260 x 5% x 60% = 7.8 PJ
B	260	5%	60%	=260 x 5% = 13 PJ
A	320	25%	20%	=320 x 25% x 20% = 16 PJ
B	320	25%	20%	=260 x 20% = 64 PJ

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