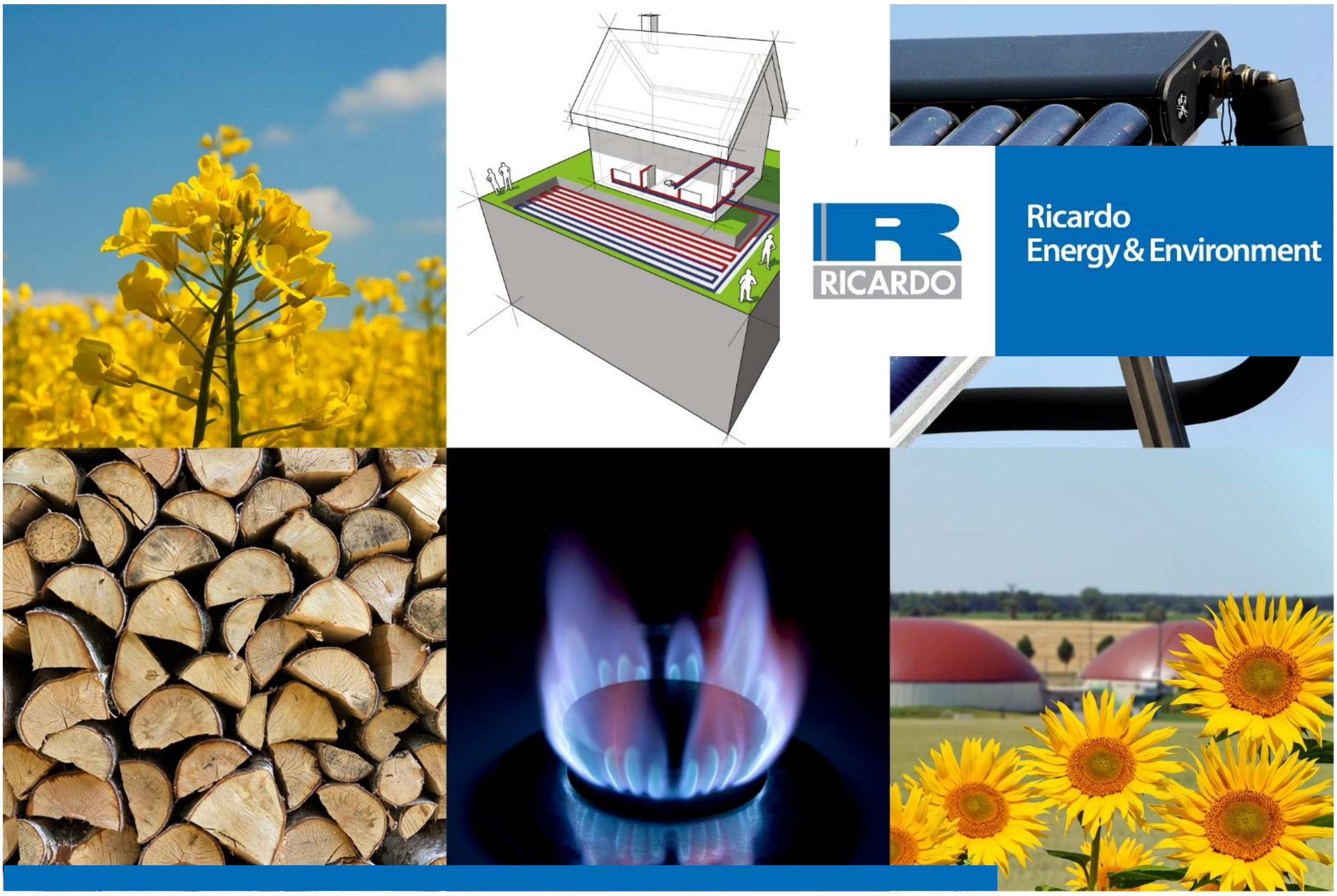

User Guide: UK and Global Bioenergy Resource Model v8.09

Report for BEISt

Forest Research

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1 Introduction

This model, developed by Ricardo Energy & Environment for BEIS, estimates the potential UK and global bioenergy resource available to the UK from 2015 to 2050 under scenarios which can be constructed by the user. This user guide gives instructions as to how to run the model. Key principles behind the model were described fully in the report supporting the original version of the model in 2011 (AEA, 2011); changes and improvements which were made to the model in developing the current version (v8.08) are summarised in Ricardo Energy & Environment (2017).

The model is accompanied by a set of background workbooks which give more background to the estimates of individual resources contained in the model, and to assumptions made about the global biofuels and energy crop resources. All key assumptions and sources for input data in the model are recorded in the assumptions log. An overview of the model structure and flows of data in the model is given in the 'Model flowchart' worksheet in the model.

Throughout the model, input data worksheets and calculation worksheets have cells that are colour coded to indicate which cells contain input data and can be modified by the user, and which cells contain formulae and should not be edited.

Key:	
	Data input value
	Interpolated or extrapolated value
	Calculated value

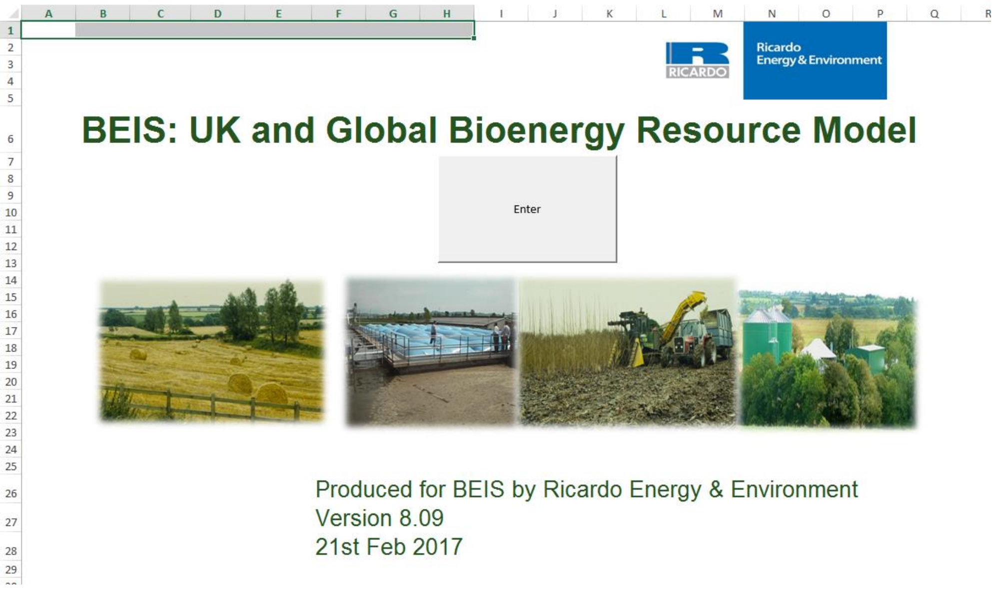
Please note that Ricardo Energy & Environment and BEIS accept no liability whatsoever to any third party for any loss or damage arising from any interpretation or use of the information contained in the model, or reliance on any views expressed therein.

1.1 Launching the model

This model is designed to run in MS Excel 2010.

It is recommended that before using the model you make a copy of the file to keep as a master version. This ensures that a version with default values for all input data is always available. To use the model

1) Open the file.
2) Enable macros. To do this click the options button by the security warning in the ribbon and then click 'enable content'.
3) Click the 'Enter' box. This will open all worksheets and take you to the 'Set Scenarios' worksheet



2 Setting the scenarios

The 'Set Scenarios' worksheet allows the main parameters defining the supply of the biomass resource to be set. Other key parameters which influence supply can be set in the other input data sheets as described in Section 3. Note that the default assumption is that all liquid biofuels and solid and gaseous biomass must meet the relevant sustainability criteria, i.e. only biofuels and biomass which meet the sustainability criteria are considered to be available for use within the UK. This assumption can be altered in the 'Sustainability data' input worksheet.

2.1 Set assumptions for UK Supply

The 'Set Scenario worksheet' is where assumptions which influence the supply of biomass resources within the UK are selected.

Three parameters can be set:

- **Price level:** this defines the price (for supply of the resource in bulk at the point of use e.g. wood chips provided in bulk), for which the resource will be estimated. Click on the yellow cell to show a drop down menu allowing a choice of **£4/GJ, £6/GJ**, or **£10/GJ.**

- **Level of barriers overcome**: there may be several barriers restraining the availability of the resource. This parameter allows a choice about the level of barriers which are overcome. Click on the yellow cell to show a drop down menu allowing a choice of:

  - No barriers overcome
  - Easy barriers only overcome
  - Easy and medium barriers overcome
  - All barriers overcome
  - Set for feedstocks individually

  If any of the first four options are chosen then these will be applied to all feedstocks. If the final option 'set for feedstocks individually' is chosen, then the grey boxes against each individual feedstock will turn yellow, and a choice of level of barriers overcome should be made for each feedstock. If the option 'set for feedstocks individually' is chosen than the level of barriers overcome must be set for all feedstocks or it will cause a #REF error in the scenario results. If the option 'set for feedstocks individually' is not chosen, but entries are made against individual feedstocks, then these will be ignored.

- **Land based crops:** in order to avoid land use change, biofuels crops and 'woody' energy crops are assumed to only be grown on 'spare' agricultural land. While some 'spare land' that could be used for bioenergy crops is only suitable for growing woody energy crops, some could be used for either woody energy crops, or crops suitable for use in 'first generation' biofuels (wheat and sugar beet to produce bioethanol, or oil seed rape to produce biodiesel), or crops e.g. maize which can be anaerobically digested to produce biogas. The model allows the user to choose whether to maximise production of perennial woody energy crops (such as Miscanthus or Willow grown as Short Rotation Coppice) or of annual crops for either liquid biofuels or anaerobic digestion (AD).

1	Set assumptions for UK supply of biomass

Price level	£6/GJ
Level of barriers overcome	Easy barriers only overcome
Perennial vs annual energy crops	Maximise production annual energy crops
When annual crops maximised	Maximise production annual energy crops Maximise production perennial energy crops

If 'Maximise production of annual energy crops' is chosen, then the user is required to make a further choice as to whether to maximise production of crops for biogas or crops for liquid biofuels.

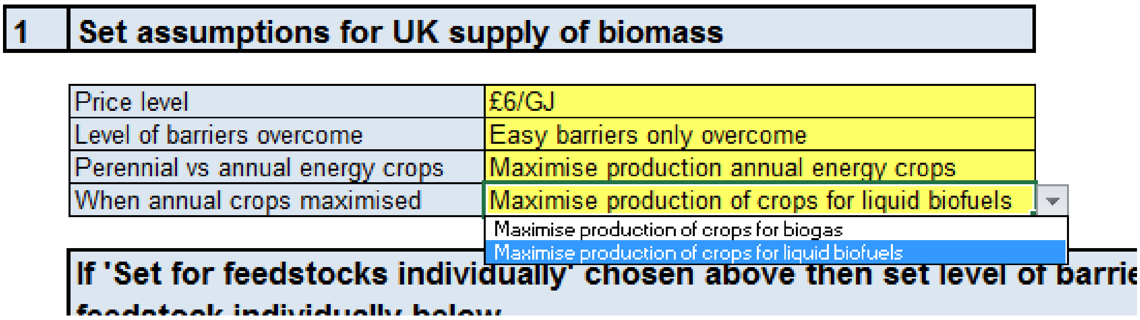


Table 1 summarises the underlying data sets contained in the model which these choices activate. More information on the assumptions about land availability for the crop in each of these cases is given in the accompanying background workbooks.

Table 1 UK Feedstock estimates used for different set scenarios choices

Perennial vs annual energy crops	Which annual crops maximised	Energy Crops	Bioethanol Crops	Biodiesel Crops	Biomethane Crops
Maximise production perennial energy crops	n/a	Energy_Crops_Max	Bioethanol_Crops_Min	Biodisesel_Crops_Min	Biomethane_Crops_Min
Maximise production annual energy crops	Maximise production of crops for liquid biofuels	Energy_Crops_Min	Bioethanol_Crops_Max	Biodisesel_Crops_Max	Biomethane_Crops_Min
Maximise production annual energy crops	Maximise production of crops for biogas	Energy_Crops_Min	Bioethanol_Crops_Min	Biodisesel_Crops_Min	Biomethane_Crops_Max

2.2 Set assumptions for Global Supply

Three parameters may be set to define the global supply.

2	Set assumptions for global supply of biomass

Global scenario	BAU/continuing trends
Global bioenergy demand	BAU (including new policies)
Land based crops	Maximise production annual energy crops

- **Global scenario:** In order to examine the potential impact of global economic, agricultural and technical development, three scenarios of global supply were developed:

    - Business as usual (BAU)/continuing trends
    - High investment/globalisation
    - Low investment/regionalisation

  The choice of global scenario will affect the increases in yields assumed for biofuels and energy crops, the rate at which energy crop plantations could expand and the constraints placed on estimates of the total resources. In summary;

    - **BAU/ continuing trends:** In this scenario constraints on investment and trade are based are on current experience, and lead to modest yield increases and planting rates
    - **High investment/ globalisation:** In this scenario trade and investment are maximised, leading to higher energy crop yield increases and higher possible planting rates.
    - **Low investment/ regionalisation:** In this scenario there is little investment and trade in energy crops, which leads to low yield increases and planting rates.

- **Global bioenergy demand:** In order to understand what proportion of the feedstock resource in other countries might be traded it is necessary to take demand in the country of production and other countries into account. The two bioenergy demand scenarios which can be used are:

    - **BAU (including new policies) -** as predicted in the IEA World Energy Outlook 2016 (IEA, 2016)
    - **High bioenergy demand** - based on the '450 scenario' included in the IEA World Energy Outlook. This illustrates how the international goal to limit the rise in long-term average global temperature to the 2 degrees Celsius by stabilising the atmospheric concentration of greenhouse gases at 450 parts per million (ppm) of CO_2 –equivalent might be achieved. In this scenario, use of bioenergy is much higher than under the 'New Policies' scenario,

- **Land based crops:** Land available globally for biomass is split into land suitable for both energy crops and first generation (1G) biofuels feedstocks. Choosing **'Maximise production annual energy crops'** produces resource estimates which assume that all suitable spare land is used for first generation biofuels crops and that only land unsuitable for these crops is used for woody energy crops. Choosing **'Maximise production perennial energy crops'** keeps production of first generation biofuels at the level required to meet the demand for first generation biofuels globally and allows spare land to be used for energy crops (subject to constraints on the rate at which energy crops can be planted). Further details are given in Section 4

In total, there are 12 combinations of the main scenario parameters for global supply. These are shown in Table 2 below.

Table 2 Main scenario parameters for global supply

Choice of global scenario	Choice of global biomass demand	Choice of crops to maximise	Number of Combinations
BAU / continuing trends High investment / globalisation Low investment / regionalisation	BAU Global Biomass Demand High Global Biomass Demand	Maximise perennial energy crops Maximise annual energy crops	
3 ×	2 ×	2 =	12

2.3 Set assumptions for fraction of global surplus UK can acquire

The model estimates the bioenergy resource by calculating the potential resource in 13 regions of the world, and then subtracting the forecast demand for bioenergy in that region. This establishes which regions of the world have a 'surplus' of bioenergy resources which could be exported. The UK is then assumed to have access to a percentage of this surplus, i.e. it is competing for the surplus resource with other countries which also need to import resources to meet their forecast demand.

Default values are set for the percentage of the surplus which the UK is assumed to acquire. These are 10% in 2015 and 2020, followed by a linear decline from 10% in 2020 to 2% in 2050. These values are the assumptions used for the medium supply scenario in DECC's Bioenergy strategy (2012).

As these values are applied directly to the portion of the global surplus which is deemed sustainable, they have a significant impact on the resource available. For example, an assumption that the UK could acquire 3% of the global surplus in 2050 rather than 2%, would increase the resource available in 2050 by 50%. The user should therefore give careful consideration to the values entered here.

It is possible to enter different values for each of the four global bioenergy resources entered. In the default data set, these are all set to the same value, however the user may wish to differentiate between the resources to reflect particular situations. For example the sustainability criteria for liquid biofuels, mean that in the future only a fraction of the potential liquid biofuels which could be produced meet the sustainability criteria and could therefore be used in the UK. However a much smaller number of countries (i.e. only those which also have sustainability criteria for biofuels) would be competing strongly for this pool of sustainable biofuels, and therefore the UK might have access to a higher percentage.

3 Set assumptions for fraction of global 'surplus' of bioenergy UK can acquire

Fraction of global bioenergy 'surplus' which the UK can acquire

	2015	2020	2025	2030	2035	2040	2045	2050
Agricultural Residues	10%	10%	9%	7%	6%	5%	3%	2%
Woody Biomass	10%	10%	9%	7%	6%	5%	3%	2%
1G - Bioethanol	10%	10%	9%	7%	6%	5%	3%	2%
1G - Biodiesel	10%	10%	9%	7%	6%	5%	3%	2%

4 Go to scenario results to see estimated supply of biomass to UK under above conditions

Note

1) Other data sets and assumptions may be altered by the user on the appropriate input data pages

2) The sustainability criteria applied to solid and gaseous biofuels depend on the assumed end use of the feedstocks. This can be set on the 'Assumed end use' sheet

2.4 Set other key assumptions

There are a number of other key assumptions that will influence the scenario results that the user can set in the ‘set other key assumptions’ sheet. These are listed below. A full description of how the assumptions are used in the model is given in Section 4 of the user guide, and this may be helpful to the user in deciding how to vary these values.

Assumptions	Explanation
Sustainability criteria	The user can choose whether to apply greenhouse gas (GHG) emissions sustainability criteria to biofuels, bioliquids and heat and electricity produced from bioenergy, and the level of emissions savings that these criteria should be based on. The user can also specify a distribution range (optimistic/ pessimistic or central) for the greenhouse gas emissions associated with the cultivation, processing and transport of feedstocks
Assumptions about end use of feedstocks	The greenhouse gas (GHG) emissions per unit of useful energy from bioenergy depend on the efficiency of the technology used to convert it to heat, electricity or a biofuel. It is therefore necessary to specify both which technology the feedstocks will be used in and the conversion efficiency of the technology. This then allows GHG emissions per unit of energy to be calculated and compared with the GHG emissions sustainability criteria defined in the sustainability criteria section. This section contains a check table to the right to make sure that the allocation of feedstocks between end uses does not exceed 100%.
Assumptions for international production of perennial energy crops	In many of the scenarios, perennial energy crops form a significant part of the resource in later years. Assumptions about increases in the yield of crops and the rate at which the area of energy crops planted can expand, can significantly influence results. By default the model assumes that no abandoned pasture land is used for growing either perennial energy crops or annual energy crops (for biofuels). This assumption can be changed here.

The values for these parameters in the ‘set other key assumptions’ sheet reflect the default assumptions in the model.

It is recommended that if the user changes any of these values then the model is saved with a different name so that a version of the model which contains the default values is retained.

3 Scenario results

Two 'Scenario Results' worksheets (in PJ and TWh respectively) display a summary of the bioenergy available to the UK in the scenario. An example is shown in Figure 1. The top table and graph on these results sheets summarise the total biomass resource available to the UK under the scenario. The three tables in the detailed results section show:

- The potential UK resource by feedstock type
- The potential international resource available to the UK
- The potential international resource available in regions with a surplus of bioenergy resource. The quantities in this table are multiplied by the fraction of the surplus the UK is assumed to be able to access to give the potential international resource available to the UK.

A third results worksheet - Scenario Results (land use).summarises the land area required in the UK to produce the domestic resource available in the scenario, and an estimate of the land required outside the UK to produce the bioenergy assumed to be available for import to the UK. Tables included (Figure 2) are:

- UK land area required by crop
- International land area by type of feedstock (bioethanol crops, biodiesel crops and perennial energy crops)
- Breakdown by regions for international supply of bioethanol, biodiesel and perennial energy crops, plus a summary table by region.

A number of graphs (Table 3) are also available which display the scenario results (as well as the main graph on the scenario results page). These can be found to the far right of the list of tabs (after the tab Graphs).

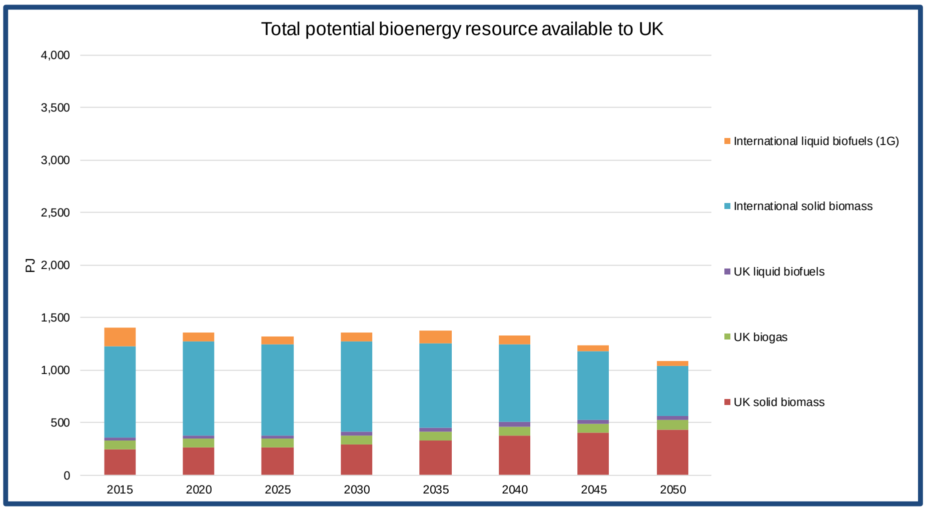
Table 3: List of graph tabs at far right of workbook

Sheet	Contents
All bioenergy	Total bioenergy (domestic and imported) available to the UK
All international	International supply of imported bioenergy to the UK (broken down by feedstock category)
All domestic	Total domestic supply of both biomass and biofuels by feedstock category
UK wood	Domestic supply of wood fuels (broken down by feedstock category)
UK crops	Domestic supply of agricultural feedstocks (dry agricultural residues and perennial energy crops)
UK biogas	Domestic supply of biogas from landfill and anaerobic digestion of crops, manures, sewage sludge and waste
UK wastes	Domestic supply of solid wastes (renewable fraction of wastes and waste wood)
UK biofuels	Domestic supply of liquid biofuels (broken down by feedstock category)

Figure 1 Scenario Results (Bioenergy)

Summary Results

Total potential bioenergy resource available to UK	2015	2020	2025	2030	2035	2040	2045	2050
	PJ	PJ	PJ	PJ	PJ	PJ	PJ	PJ
UK solid biomass	242	263	261	290	326	374	403	435
UK biogas	86	83	82	84	86	88	85	87
UK liquid biofuels	28	25	30	35	38	39	35	35
International solid biomass	865	905	875	864	801	738	653	484
International liquid biofuels (1G)	179	79	72	85	122	91	58	44
Total	**1,400**	**1,355**	**1,319**	**1,357**	**1,373**	**1,331**	**1,234**	**1,085**



Detailed Results

Potential UK Resource	2015	2020	2025	2030	2035	2040	2045	2050
	PJ	PJ	PJ	PJ	PJ	PJ	PJ	PJ
UK perennial energy crops	2	2	11	33	51	74	96	123
Dry agricultural residues	71	71	71	71	84	97	97	97
Forestry residues	7	8	9	9	9	9	9	7
Stemwood	5	6	6	7	7	7	7	6
Short rotation forestry	0	0	0	0	1	9	10	13
Sawmill co-products	19	20	22	24	23	21	20	18
Arboricultural arisings	12	13	13	13	14	14	14	14
Waste wood	86	95	95	95	95	95	95	95
Renewable fraction of wastes	42	48	34	37	42	49	55	62
Total UK solid biomass	**242**	**263**	**261**	**290**	**326**	**374**	**403**	**435**
Biogas from food waste	21	23	25	28	30	32	34	36
Landfill gas	49	41	36	35	34	34	34	33
Biogas from sewage sludge	13	14	15	15	16	16	16	16
Biogas from livestock manures	1	1	1	1	1	1	1	1
Biogas from crops	2	4	4	4	5	5	0	0
Total UK biogas	**86**	**83**	**82**	**84**	**86**	**88**	**85**	**87**
Bioethanol from crops	10.8	12.2	17.2	22.2	25.6	28.8	24.0	24.2
Biodiesel from crops	6.5	2.1	2.2	2.2	2.2	0.0	0.0	0.0
Biodiesel from UCO	7	7	7	7	7	7	7	7
Biodiesel from tallow	4	4	4	4	4	4	4	4
Total UK liquid biofuels (1G)	**28**	**25**	**30**	**35**	**38**	**39**	**35**	**35**
Total UK	**356**	**371**	**372**	**408**	**450**	**502**	**522**	**558**

Potential International Resource Available to UK	2015	2020	2025	2030	2035	2040	2045	2050
	PJ	PJ	PJ	PJ	PJ	PJ	PJ	PJ
International agricultural residues	484	516	476	429	354	277	200	121
International woody biomass	381	389	399	435	447	461	454	363
Total international solid biomass	**865**	**905**	**875**	**864**	**801**	**738**	**653**	**484**
International bioethanol	147	52	47	62	100	74	45	34
International biodiesel	32	27	25	23	22	17	14	9
Total international liquid biofuels (1G)	**179**	**79**	**72**	**85**	**122**	**91**	**58**	**44**
Total international	**1,044**	**984**	**947**	**949**	**923**	**829**	**712**	**527**

International resource available to the UK is based on a total potential international resource available for trade as shown below

Potential International Resource Available for Trade	2015	2020	2025	2030	2035	2040	2045	2050
	PJ	PJ	PJ	PJ	PJ	PJ	PJ	PJ
International agricultural residues	4,838	5,157	5,494	5,850	5,896	5,942	5,988	6,034
International woody biomass	3,809	3,892	4,600	5,931	7,457	9,869	13,614	18,141
Total international solid biomass	**8,647**	**9,049**	**10,094**	**11,781**	**13,352**	**15,811**	**19,602**	**24,175**
Bioethanol - sustainable	1,471	521	546	845	1,667	1,586	1,337	1,723
Biodiesel - sustainable	323	269	287	316	370	369	409	469
Bioethanol - non sustainable	373	930	1,302	1,817	1,801	2,905	4,290	5,091
Biodiesel - non-sustainable	261	578	658	710	836	1,152	1,433	1,692
Total international liquid biofuels (1G)	**2,428**	**2,299**	**2,793**	**3,688**	**4,673**	**6,013**	**7,470**	**8,975**
Total international	**11,075**	**4,076**	**5,040**	**6,532**	**7,680**	**10,439**	**13,602**	**16,227**

Figure 2 Scenario Results (Land use)

UK

UK land area needed to meet projected bioenergy supply from UK	2015	2020	2025	2030	2035	2040	2045	2050
	kha	kha	kha	kha	kha	kha	kha	kha
Maize (for biomethane)	20	38	40	40	40	40	0	0
Wheat (for bioethanol)	151	143	138	133	128	124	77	74
Sugar beet (for bioethanol)	9	9	8	8	8	7	0	0
Oilseed rape (for biodiesel)	5	2	2	2	2	0	0	0
Total (annual crops)	***185***	***192***	***188***	***183***	***178***	***172***	***77***	***74***
Perennial energy crops	10	20	71	210	675	1,283	1,556	1,850
Short rotation forestry	0	2,537	34,497	84,497	137,437	192,337	247,237	302,137
Total (all crops, including SRF)	***195***	***2,749***	***34,756***	***84,890***	***138,290***	***193,791***	***248,870***	***304,061***

International

Land area needed outside the UK to meet projected bioenergy supply to UK from international sources	2015	2020	2025	2030	2035	2040	2045	2050
	kha	kha	kha	kha	kha	kha	kha	kha
Bioethanol crops	1,324	377	-22	390	640	467	216	176
Biodiesel crops	410	235	276	272	307	230	168	145
Perennial energy crops	0	54	558	1,078	1,682	2,250	1,821	1,534
Total (all crops)	***1,734***	***665***	***812***	***1,739***	***2,629***	***2,947***	***2,204***	***1,855***

International by region

Bioethanol

Land area needed outside the UK to meet projected bioethanol supply to UK from international sources

	2015	2020	2025	2030	2035	2040	2045	2050
	kha	kha	kha	kha	kha	kha	kha	kha
Canada & Mexico	63	7	36	36	57	30	14	15
US	890	152	147	142	301	153	0	0
Latin America	197	139	-278	144	214	218	176	148
Middle East	0	0	0	0	0	0	0	0
Africa	0	0	0	0	0	0	0	0
EU (Without UK)	0	0	0	0	0	0	0	0
Eurasia & non EU Europe	0	0	0	0	0	0	0	0
Russia	0	0	0	0	0	0	0	0
India	22	11	0	0	0	0	0	0
China	0	0	0	0	0	0	0	0
Rest of Asia	0	0	0	0	0	0	0	0
Japan	65	67	73	67	69	67	26	13
Australia, New Zealand & South Korea	87	0	0	0	0	0	0	0
World	1,324	377	-22	390	640	467	216	176

... | Set Scenarios | Scenario Results (PJ) | Scenario Results (TWh) | **Scenario Results (land use)** | Input data >>> | Sustainability data | Assumed end us ...

4 Other background assumptions worksheets

The model uses several other assumptions and background data sets. These are contained in the following background data and assumptions worksheets.

- Sustainability data
- Assumed end use
- Land availability data
- Perennial energy crop data
- Biofuels data
- UK crop yields
- Global constraints
- Global demand data
- Global demand – biomass type

The source of the default data which is included on each of these sheets is given in the assumptions log in the model. There are also background work books giving more information on the perennial energy crop data and biofuels data. Some of these background assumptions may be changed by the user and this is identified in the text below. In such cases the parameter is listed on the 'set other key assumptions' sheet and should be changed by the user there, rather than on these background assumptions worksheets.

4.1 Sustainability data

The percentage of a resource which would meet sustainability criteria is assessed by comparing typical greenhouse gas emissions associated with the feedstock against the relevant sustainability standard. This worksheet contains the necessary data to make this assessment:

Application of sustainability criteria. The user may choose to remove the application of sustainability criteria for bioliquids and solid and gaseous biomass in the 'set other key assumptions' worksheet.

Lifecycle GHG emissions associated with the production of solid biomass feedstocks and biogas (rows 37 to 53). Data on emissions associated with feedstock production for solid and gaseous feedstocks are taken from a variety of sources, but principally a spreadsheet used previously by DECC, and data from the UK Solid and Gaseous Biomass Carbon Calculator. For feedstocks which may be provided as chips or pellets, emissions estimates are given separately for the two forms, as depending on how pelleting is done, this can increase emissions substantially due to the need to dry the feedstock first.

Indirect land use change (ILUC) emissions (rows 55 to 71) associated with the production of solid biomass feedstocks and biogas. These are currently set to zero as robust estimates of these emissions have not yet been agreed. Values may be input by the model developer as they become available.

Lifecycle GHG emissions and ILUC emissions associated with liquid biofuels production (rows 133 to 205 for bioethanol, 207 to 278 for biodiesel from crops, and 280 to 350 for biodiesel from used cooking oil (UCO) and tallow. Emissions vary over time, to allow for improvements in crop yields, potential reductions in crop inputs and improvements in conversion efficiencies. Emissions may be set to vary according to the global scenario chosen, although in the default data set, values are the same in all scenarios. More information is given in the assumptions log. As for solid and gaseous biomass, ILUC emissions are currently set to zero.

Emissions associated with feedstock production are likely to vary. In order to allow for this, emissions are assumed to vary between a high and low value. Five points are defined, and the sets of data described above assume that emissions vary linearly between these high and low values. For biofuels, as the basis of the data set is typical values from the previous model, an estimate of the percentage variation between typical and high values and typical and low values is used to derive the high and low values used.

Distribution of emissions (rows 92 to 95**).** Three distributions for this variation in emissions are defined to allow for sensitivity analysis:

a) central - a 'square distribution'; an equal fraction of the feedstock (20%) is assumed to have emissions at each of the levels defined

b) low weighted - a pessimistic view; a skewed distribution in which a greater proportion of the feedstocks are assumed to have higher emissions

c) high weighted - an optimistic view: a skewed distribution in which a greater proportion of the feedstocks are assumed to have lower emissions

Choice of distribution. The 'distribution' used to calculate results is chosen by the user in in the 'set other key assumptions' worksheet. By default this is set to 'central'.

Sustainability criteria (rows 98 to 118). Sustainability criteria are typically set as a percentage saving of a fossil fuel comparator. For electricity and heat the comparison is made per MWh of electricity and heat produced respectively, whereas for biomethane and liquid biofuels it is per unit of energy in the biomethane and biofuel respectively. The default values in the table reflect those in current legislation. In the case of biofuels, savings of at least 50% must be achieved from 2017 onwards, but from 2018 the saving must be at least 60 % for biofuels produced in installations in which production started on or after 1 January 2017. The savings required is thus increased from 50% to 60% over time. The fossil fuel comparator values and the percentage saving required can be set by the user in the 'set other key assumptions' worksheet.

Conversion technology efficiencies (rows 121 to 130): as in the heat and power sector, the sustainability criteria are applied per unit of heat or electricity produced. The assumed end use of the feedstock (for heat or power production) and the efficiency with which the feedstock is converted to heat and/or power both affect whether the feedstock is considered sustainable or not. Typical conversion efficiencies must thus be defined. The typical conversion values may be set by the user in the 'set other key assumptions' worksheet.

4.2 Assumed end use

As discussed above, sustainability criteria for heat and power are set per MWh of delivered energy. It is therefore necessary to make an assumption about what technology the feedstock is used in to determine whether or not it will meet the sustainability criteria. The default is for biomass to be used for cofiring, but this can be changed by the user in the 'set other key assumptions' worksheet.

This information is not required for liquid biofuels as the same sustainability criteria (per MJ of fuel) applies whether they are used as a transport fuels or as fuel for heating or electricity production.

4.3 Land availability data

The production of biofuels crops and perennial energy crops internationally is assumed to only occur on abandoned agricultural land or pasture land. This worksheet contains:

- Estimates of the abandoned agricultural and rest land available in 17 regions of the world to 2050 (columns C to U). Note that the term rest land is used in the IMAGE model from which the data is derived to cover both abandoned pasture land and unused grasslands such as steppes and savannahs. The model allows for different estimates of land availability under the three global scenarios.
- Estimates of fraction of abandoned land suitable for use for annual or perennial energy crops and fraction of abandoned land which is mildly degraded and suitable for perennial energy crops only (columns W to AM).

In the set other key assumptions' worksheet 'the user may set the fraction of abandoned pasture (rest) land assumed to be used for cultivation of annual or perennial energy crops. The default value is that this is set to zero, as potentially use of some grasslands could contravene sustainability criteria (e.g. if the grassland has a high carbon stock).

4.4 Perennial energy crop data

This worksheet contains input data on perennial energy crops which are grown for combustion. These can range from short rotation coppice of species such as willow and poplar to 'grassy' energy crops such as Miscanthus. Species cultivated will vary by region and are not specified in the model, which instead uses generic descriptive data for each region as described below.

- **Perennial energy crop yield by region** (cells B25:C43). These are the expected current (2015) yields on abandoned agricultural land which is not degraded in any way.
- **Reduction in yield for different types of land** (cells E25:I31). These are the reduction in yield that could be expected if the crop is grown on other types of land (e.g. abandoned pasture land, or abandoned agricultural land which is mildly degraded)
- **Future yield increases** (cells E33:I38). These are per annum yield increases, which are applied in the model in a compound way i.e. if the value is 1.5% then each year the yield increases by 1.5% so that over a 10 year period the yield has increased by $1.015^{10,}$ i.e. by 16%. These values may be adjusted by the user in the set other key assumptions' worksheet.
- **Planting rate data (column K to Q).** Unlike annual crops grown for biofuels, which are usually traditional agricultural crops, perennial energy crops such as Miscanthus and short rotation coppice, can require specialist planting and harvesting equipment and the development of a supply of planting material. There is therefore likely to be a limit to how fast plantations of energy crops can be established. Furthermore, large areas of perennial energy crops have not been planted to date. This is represented in the model through three sets of data. Column M specifies the first year in which a harvest could be expected from the energy crops planted. This is set to 2020 as a default value to reflect the time taken for energy crops planted now to reach maturity and be available for harvest[1]. Column N specifies the maximum area it is considered could be available for harvest by this year. Columns O to Q specify the annual growth rate in the new area or energy crops planted each year. The annual growth rate may be adjusted by the user in the 'set other key assumptions' worksheet.

4.5 Biofuels data

This worksheet contains input data relevant to annual energy crops and the production of biofuels:

- Representative bioethanol and biodiesel crops for each region, and their current yield (in t/ha) on abandoned agricultural land which is not degraded (cells B22:F41)
- Annual increases in crop yields for each of the global scenarios (cells M22:S41)
- The reduction in yield for crops if planted on abandoned grass land (cell K29)
- Biofuels production per tonne of feedstock (cells B45:F64)
- Future improvements in the efficiency with which biofuels feedstocks are converted to biofuels (M46:S64)
- The assumed pattern of supply to meet global demand for biofuels (cells B68:J87 for bioethanol and M68:U87 for biodiesel. The potential production from all countries is calculated in the model, but in scenarios where energy crop production is maximised then the initial demand for biofuels (as forecast in the bioenergy demand projection chosen by the user) is assumed to be met according to this pattern of supply, with land still available after the biofuels demand has been met then available for cultivation of energy crops.
- Percentage of available land suitable for bioethanol (sugar/starch) crops and biodiesel (oil) crops (rows 90:108). Only the percentage of land suitable for bioethanol crops needs to be specified by the user as the remainder of the land area is assumed to be available for biodiesel crops.

[1] This will vary according to the type of energy crop planted.

4.6 UK crop yields

This worksheet contains input data relevant to yields of crops in the UK used for:

- Biofuels (wheat, sugar beet, oilseed rape),
- AD (maize)
- Combustion (UK perennial energy crops such as SRC and Miscanthus)

These are used in conjunction with information on the net calorific values of solid fuels, or the biogas or biofuels yield per t of feedstock to calculate the land areas associated with the resources the model forecasts are available. The default values provided in the model are consistent with the assumptions made in the UK resource estimates contained in the model and care should therefore be taken if the yield values are changed. Ideally the UK resource estimates (which use land availability as their starting point) should be recalculated to ensure they are consistent with the new yield values.

In the case of bioethanol, the energy output in the model represents bioethanol produced from both sugar beet and wheat. In deriving the estimates of bioethanol production, it was assumed the existing sugar beet bioethanol plant at Wissington would continue to operate at its current throughput (of 1.4351 PJ of bioethanol per year) until 2040 (the end of the plants lifetime), apart from scenarios where the user chooses to maximise production of liquid biofuels in the UK, in which case its lifetime is assumed to be extended to 2050. This data is recorded here as an input, as it later used in the calculation of land areas.

Finally, this sheet contains information used in estimating the land areas required for short rotation forestry (SRF), yield. NV and the maximum rate at which the planted area may expand prior to 2020

4.7 Global constraints

This worksheet contains input data relevant to constraints on the availability of the following global resources:

- Forestry products (small roundwood, forestry residues, sawmill coproduct)
- Woody (perennial) energy crops (as described in Section 4.5 this includes all perennial energy crops grown for combustion, including ‘grassy’ crops such as Miscanthus)
- 1G (crop based) bioethanol and biodiesel
- UCO and tallow

The following estimates are made for each of the three global scenarios

1) Estimate of the level of barriers/constraints due to availability of infrastructure. These relate to physical constraints on developing and exploiting the resource, such as:

- Distribution and accessibility of land for crop production
- Distribution and accessibility of forestry resource, and the nature of terrain
- Transport infrastructure to move crops to storage/ distribution centres

2) Estimate of the level of barriers/constraints due to market/trade constraints. These relate to the ability to operate a reliable supply chain to bring the resource to the market for trading, both to supply the domestic and international market, and to develop arrangements for trading. Aspects considered included:

- Political stability and ability to attract financial investment
- Development and implementation of standards to define quality of feedstocks
- Current market maturity for export of bulk goods including feedstocks.

3) **Percentage of available supply (after infrastructure and trade constraints) demanded by competing non-energy uses.** These are set to zero for woody energy crops which are assumed to be grown specifically to supply bioenergy demand, and biofuels.

The overall constraint which is considered to apply is the maximum of the infrastructure and market trade constraints, adjusted for competing feedstock uses.

Infrastructure and market constraints are specified as shown below. The appropriate abbreviation is selected by the user from a drop down menu in each cell. Constraints are specified for each region, for every 10 year period, for each scenario. The level of barrier is converted to a numeric value as shown below in Table 4.

Competing non-energy uses are specified directly as a percentage. Note that the supply regions for forestry products are different to those for other feedstocks[2].

Table 4 Conversion of qualitative assessment of level of barriers to percentage

Level of Barrier/constraint	Abbrev	Restriction on supply
Not available at all	NA	100%
Very high	VH	95%
High	H	75%
Medium	M	50%
Low	L	20%
No barriers or constraints	NONE	0%

4.8 Global demand data

As described in Section 2.2, bioenergy use under two global energy demand scenarios is modelled. Both scenarios are based on data contained in the IEA publication, World Energy Outlook 2016 (WEO 2016). Choice of the scenario is made in the 'Set Scenarios' worksheet. The two scenarios are

1) BAU (including new policies): this is the IEA's New Policies scenario, which is the central scenario of the WEO 2016. It incorporates existing energy policies as well as an assessment of the results likely to stem from the implementation of announced intentions, notably those in the climate pledges submitted for COP21.

2) High bioenergy demand: this is the IEAs 450 Scenario which illustrates how the international goal to limit the rise in log-term average global temperature to the 2 degrees Celsius might be achieved. In this scenario, use of bioenergy is much higher than under the New Policies scenario

The WEO data is provide for 2012, 2020, 2025, 2030, 2030, 2035 and 2040 for the New Policies scenario and 2020, 2030, and 2040 for the 450 scenario. This is included in the top table (in mtoe) for each region.

The bottom tables convert this data to PJ for each 5 year period required by the model.

Data for 2015 is estimated based on linear interpolation between 2012 and 2020. Data for 2045 and 2050 are estimated for the New Policies scenario by using the growth rate from 2035 to 2040, for each of the two new five year periods. Data for 2050 for the 450 scenario is estimated by using the growth rate from 2030 to 2040 and applying it to 2040 data to estimate 2050 data. 2045 is then interpolated linearly from 2040 and 2050.

4.9 Global demand – biomass type

The WEO data in the 'Global demand data' worksheet forecasts the quantity of biomass and waste used in each region. However the model requires an estimate of the demand for woody biomass (i.e.

[2] The supply regions for feedstocks vary depending on the regions used in the source data.

biomass of a form suitable for export as well as domestic use) only. This worksheet contains the additional assumptions (about the fraction of biomass and waste which comes from 'woody biomass' as opposed to wastes or residues) necessary to calculate this.

In the case of biofuels, the WEO data specifies the demand for biofuels, but the model requires an estimate of demand for first generation biofuels (produced from crops or UCO or tallow), and the demand for second generation biofuels for which the feedstock is woody biomass (as opposed to wastes or residues). This worksheet contains the additional assumptions (about the fraction of biofuels that are second generation (2G) and the fraction of 2G biofuels that are derived from woody biomass) to calculate this.

It also adjusts biomass demand figures for some countries to adjust for the use of traditional biomass (noted in comments in the relevant cells)

This worksheet also contains assumptions on the fraction of EU demand for bioenergy that is attributable to the UK.

5 UK resource estimates

These include source data on the resource available at different prices and the impact of constraints. A full set of workbooks (one per feedstock) are available separately which include background assumptions used to derive the estimates. There are two versions of worksheets for energy crops, biofuels and biogas from crops, to reflect the assumptions about whether production has been maximised (see Section 2.1).

Worksheet title	***Feedstock***
Energy_Crops_Max	Woody energy crops – maximum area planted
Energy_Crops_Min	Woody energy crops – area planted when 1G feedstocks maximised
Dry_Agr_Res	Dry agricultural residues i.e. straw
Forestry_Residue	Forestry residues – thinnings and wood too small for use as roundwood
SRW	Small round wood
SRF	Short rotation forestry
Sawmill	Waste wood produced at sawmill
Arbs	Arboricultural arisings
Waste_wood	Waste wood
MSW	Renewable fraction of municipal solid waste
Sewage_Sludge_AD	Biogas from anaerobic digestion of sewage sludge
Food_Waste_AD	Biogas from anaerobic digestion of source separated food waste
Landfill_Gas	Landfill gas
Wet_manures_AD	Biogas from anaerobic digestion of manures
Biomethane_Crops_Max	Biogas from anaerobic digestion of maize (production maximised)
Biomethane_Crops_Min	Biogas from anaerobic digestion of maize (production minimised)
Bioethanol_Crops_Max	Bioethanol production from wheat and sugar beet – production maximised
Bioethanol_Crops_Min	Bioethanol production from wheat and sugar beet – production minimised
Biodiesel_Crops_Max	Biodiesel production from oil seed rape – production maximised
Biodiesel_Crops_Min	Biodiesel production from oil seed rape – production minimised
Tallow	Biodiesel production from tallow
UCO	Biodiesel production from used cooking oil

6 Global resource estimates

Source data on global resources of agricultural residues, global forestry resources and global supplies of UCO and tallow are contained in the following worksheets. Background data for each of the worksheets is contained in accompanying workbooks.

Worksheet title	***Information contained***
Global residues data	This worksheet contains estimates of agricultural residues which might be available globally. Only residues which are of a physical form suitable for transport and export are considered. It contains two sets of data, The first set of data 'unconstrained resources' provides an estimate of the total resource available based on estimates of crop production leading to the residues. The second set of data 'constrained resource available for export' provides estimates of the resource which might be available for export (after considering competing non-energy uses for the resource, domestic use of the resource for energy, and infrastructure constraints).
Global forestry data	This sheet contains estimates of small roundwood, forestry residues and sawmill residues which are theoretically available in different regions of the world. They do not take into account competing uses, i.e. demand for non-bioenergy uses, or any barriers or constraints to bring this resource to market. These factors are set in the global constraints input data sheet.
Global UCO data	This worksheet contains estimates of UCO available globally. The resource estimate for the EU explicitly excludes the UK resource to avoid double counting. The estimates are of UCO which is theoretically available. They do not take into account any barriers or constraints to bring this resource to market. These factors are set in the global constraints input data sheet.
Global tallow data	This worksheet contains estimates of tallow available globally. The resource estimate for the EU explicitly excludes the UK resource to avoid double counting. The estimates are of tallow which is theoretically available. They do not take into account any barriers or constraints to bring this resource to market. These factors are set in the global constraints input data sheet.

7 Global calculation worksheets

These worksheets utilise the input data to calculate the potential biofuels and energy crops resource available globally. Details of the calculations are given in row 28 on each worksheet. These sheets should not be modified by the user.

Worksheet title	***Information contained***
Global crop calcs	This worksheet calculates intermediate data sets relevant to perennial and annual energy crops which are needed by the two sheets 'Global 1G Max' and 'Global Energy Crops Max' It uses as input data, data from 'Land availability data', 'Perennial energy crop data' and 'Biofuels data'.
Global 1G Max	This worksheet calculates production of biofuels from annual energy crops and of woody biomass from perennial energy crops for when the scenario setting 'maximise production annual energy crops' (i.e. for 1G biofuels crops) is chosen. It is assumed that all biofuels demand in 2015 is met using land that is not classified as abandoned agricultural land in 2015, but that all production above this level must be met from crops growing on abandoned agricultural or pasture land that is not degraded. Outputs from this worksheet are used in the global supply sheets for bioethanol, biodiesel and energy crops. Intermediate results are also used in Global Energy Crops Max
Global Energy Crops Max	This worksheet calculates production of biofuels from annual energy crops and of woody biomass from perennial energy crops for when the scenario setting 'Maximise production perennial energy crops' is chosen. Outputs from this worksheet are used in the global supply sheets for bioethanol, biodiesel and energy crops. Intermediate results are also used in Global 1G Max
Global UCO & Tallow	This worksheet contains information on the global UCO and tallow resources. These are expressed as the PJ of biofuels production they would give. The worksheets take the unconstrained resource, applies constraints, and then divides the constrained resource into that used for domestic biofuels production and that available for export. It uses input data from the global UCO and tallow data sheets, the global constraints sheet, and the biofuels data sheet. Results from the sheet are used in Global 1G Max and Global 1G Waste bioD.

Worksheet title	Information contained
Sust calcs solid	This worksheet calculates the 'pass rate' for solid and gaseous biomass, i.e. the fraction of the feedstock that would pass the sustainability criteria given a) the assumed end use of the feedstock (set in 'Assumed end use'). b) emissions associated with feedstock production (set in 'Sustainability data') c) the appropriate GHG criteria that emissions should be compared against. The appropriate criteria to use is determined by the assumed end use (e.g. heat or electricity). The actual GHG sustainability criteria are set in 'Sustainability data The top tables in this sheet show the overall 'pass rate for the feedstock' taking into account the assumed end use, and it is these pass rates which are applied to the overall feedstock considered to be available, to give the sustainable feedstock available. The overall 'pass rate' is calculated from the percentages assumed to be going to different 'end uses' and the pass rates for feedstocks in end use technologies, which are detailed in the series of tables labelled 'Pass rates for individual technologies'. These pass rates are calculated from the pattern of emissions from feedstock production (which include direct emissions and, where assumed, ILUC emissions), the assumed conversion efficiency for the technology and the GHG criteria the end use emissions should be compared to. All of this data is specified in 'Sustainability data'. Note that it is necessary to take into account the conversion technology efficiency as for heat and electricity the sustainability criteria are set per MJ or MWh of heat and electricity.
Sust calcs liquid	This worksheet calculates the 'pass rate' for biofuels, i.e. the fraction of the biofuels that would pass the sustainability criteria for liquid biofuels set in the input data worksheet 'Sustainability data'. It uses data on the emissions for biofuels produced in different regions, which is also set in the input data worksheet 'Sustainability data' The pass rates in the final block of data are then used in the intermediate results worksheets 'Global supply - crop bioethanol' and 'Global supply - crop biodiesel'.

8 Land Use calculations

These worksheets utilise the input data to calculate the land used for supply of the calculated quantity of feedstock. These sheets should not be modified by the user.

Worksheet title	***Information contained***
UK Biofuels Land Use	This worksheet separates bioethanol production between production from wheat and production from sugar beet. It then uses input data on crop yields and conversion to biofuels to calculate land areas required.
UK SRF Land Use	This worksheet assumes SRF planting begins in 2017 with a 15 year harvesting cycle. A planting pattern is generated for each year which is used to calculate the cumulative area planted. It is assumed that areas are replanted after harvesting.
Global Land Use	This worksheet uses yield data and potential energy data by supply region and converts it into land required to fulfil UK needs by demand region. This is completed for energy crops, bioethanol and biodiesel.

9 Intermediate results worksheets

9.1 UK Supply Summary

This worksheet collates the data from the individual UK feedstocks worksheets. It contains no new calculations. The named ranges on this sheet are then called on by the 'Scenario Results' worksheets

9.2 Global Supply Summaries

These worksheets combine the estimates of potential supply with the appropriate set of constraints (apart from energy crops and agricultural residues where constraints have already been taken into account) to produce an estimate of the supply to the market under the global scenario chosen. The worksheets also organise the regional supply data into a set of regions which can be matched with the regions for which demand is specified. Named ranges for these resources by demand region are then called on in the 'Global output scenario' worksheet.

Worksheet title	***Information contained***
Global Supply – Ag Res	Agricultural residues
Global Supply - Forestry	All forestry products: small round wood, forestry residues ad sawmill waste This worksheet takes the data from the global forestry data worksheet and then calculates the actual constrained resource which is available by applying the constraints data from the input data worksheet 'Global constraints'.
Global Supply – Energy Crops	This worksheet pulls forward the data on energy crops available from the 'Global 1G max' and 'Global Energy Crops Max' worksheet depending on the choice made in 'Set Scenarios' worksheet
Global Supply – crop bioethanol	Supply of bioethanol from sugar and starch crops. This worksheet takes the data from the 'Global 1G max' and 'Global Energy Crops Max' worksheet depending on the choice made in the 'Set Scenarios' worksheet. The actual 'constrained' resource which is available is then calculated by applying the constraints data from the input data worksheet 'Global Constraints'. This is then split into a sustainable 'RED compliant' supply and an unsustainable 'non-RED compliant' supply based on the pass rates calculated in the 'Sust calcs liquid' worksheet
Global Supply – crop biodiesel	Supply of biodiesel from oil crops Calculations as for bioethanol
Global Supply – 1G waste bioD	Supply of biodiesel from UCO and tallow Calculations as for bioethanol

9.3 Summary Global Demand

This worksheet simply organises the data from the global demand - biomass type worksheet, into a structure which can be used by the 'Global Output Scenario' worksheet.

9.4 Global Output - Scenario

This worksheet calculates the potential 'surplus' of bioenergy available in regions after demand in the region is met. The total amount of bioenergy available after constraints are taken into account is taken from the preceding ‘Global Supply’ worksheets. Global demand is pulled forward from the global demand worksheet. The net surplus or deficit in a region is calculated by subtracting demand from supply. The total amount of biomass and biofuels in regions with a surplus is then summed, and is considered to be the global surplus, which the UK can compete for. The total demand for this surplus (from regions which have a deficit of bioenergy resources to meet their demand) is given in rows 131 to 145.

Negative numbers in this worksheet indicate that there is a shortage of bioenergy resource within a region to meet the demand specified for that region in the global demand worksheet.

10 References

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