UK Government

Lifecycle Assessment of Anaerobic Digestion

Guidance for the Modelling Tool

Department for Energy Security and Net Zero (2026)

Acknowledgements

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Background

This document is part of a project (PS23029) commissioned by the Department for Energy Security & Net Zero (DESNZ) on the lifecycle assessment (LCA) of anaerobic digestion (AD) and provides guidance to users of a tool developed as part of the work.

A carbon accounting methodology for sustainability reporting for biomethane under the Renewable Heat Incentive (RHI) and the Green Gas Support Scheme (GGSS) is laid out clearly in national legislation and associated guidance, and aligned with EU legislation. However, this methodology is somewhat limited in scope, focussing on a well-to-tank approach as opposed to a broader lifecycle approach, and differing elements of the calculation are subject to potential development and evolution as new processes and new thinking emerges.

A bespoke tool has been developed to calculate the lifecycle emissions of biomethane and to examine the GHG impacts of parameters beyond the current scope, to better inform future policy and industry thinking on the potential of the AD sector.

The tool serves to demonstrate the impact of various LCA methodology choices on the calculated carbon intensity of biomethane. Furthermore, it serves to run various scenarios that can be used to shape future policy using actual or modelled data.

This document outlines the assumptions and calculations used in the tool.

Limitations of the tool

This tool only covers a common range of AD options. The tool is not suited to several feedstocks. For example, the tool is not suited to post-separated municipal solid waste (i.e. the organic fraction of ‘black bag waste’ obtained at a waste-processing facility) because these processes are very different in design (e.g. use ‘dry AD’), have different energy requirements and do not generate a useful digestate.

The tool is also not suited to many wastewater and sludge processes, partly because some wastewater AD processes are completely different in design (e.g. upflow anaerobic sludge blanket, UASB) and barely generate any digestate, and partly because the environmental impacts of biogas from wastewater sludge are best considered in the context of the energy supplied to the wastewater treatment plant with which they are associated, rather than in isolation.

This tool is not intended to be used for making claims about an AD site’s GHG emissions. Calculating GHG emissions associated with biogas or biomethane production should be carried out in compliance with a specific scheme, such as (in the UK) RHI, GGSS, FIT or RTFO, and (in other countries) ISCC-EU. This tool should not be used for this purpose.

Tool overview

The LCA tool can operate in two modes: ***model*** and ***actual***. These are selected from a drop-down menu on the *Welcome* page. This enables the user to run common scenarios (model mode), as well as running data from site surveys (actual mode).

The ***model*** mode allows scenarios to be selected from drop-down lists associated with a number of key variables in the calculator. Variables include size of plant, feedstock selection, source of energy supply, gas grid constraints, operational performance, energy needs, process efficiency, gas flare, and various considerations associated with accounting for fugitive methane emissions. Model scenarios are grounded in engineering principles and data from operational sites, as well as information from industry and literature – the user can select a scenario by choosing a combination of appropriate variables at the outset, and the tool will be populated with representative data throughout. The model mode scenarios can be found in the worksheet named *Models*.

The ***actual*** mode allows data to be entered and variables selected freely, rather than being pre-populated based on selected scenarios. However, it should be used with caution, as it is possible to generate unrealistic situations from scenarios. Data can be entered for actual mode in the worksheet named *Actuals*.

Throughout the tool, 'IF' equations are used to call up the appropriate value from either the *Models* worksheet or the *Actuals* worksheet, depending on whether the Model or Actual option has been selected in the *Welcome* worksheet.

Colour coding is used throughout the worksheets, shown in Table 1.

Table 1: Key

	Green	*Open – only enter data into these cells*
	Cream	*Locked – identifies key assumption values*
	Light Grey	*Locked – presents results of calculations*
	Dark Grey	*Cells not operational due to user selection*

User guide

The following section is a guide on how to use the **Model** functionality of the tool. To do this, 'Model' must be selected in the drop-down menu of the 'Welcome' worksheet.

It is also possible to operate the tool in Actual mode, but this is not recommended for most users and is therefore not described herein.

For information on how the tool works, rather than on how to use it, please see section 'Tool overview' (page 7).

Loading different models in the Models worksheet

The ***model*** part of the tool allows users to generate scenarios of individual AD plants based on a model of mass and energy balance.

To use the model, make a selection for each of the parameters in the drop-down menus on the left hand side of the sheet (column D).

Design - please select an option for each

Feedstocks	Custom feed
Useful products	Biomethane only
Size	Medium
Energy supply	Mainly biogas
Fugitive methane - design	Low

Constraints - please select an option for each

Grid-required GCV	Medium

Operation - please select an option for each

Outputs performance	Medium

Electricity needs	Medium
Digestion efficiency	Medium
Flared gas	Medium
Fugitive methane - operation	Medium - REDII
Fugitive methane - digestate	Medium

- **Feedstocks**
  - This drop-down menu allows the user to select from a list of pre-defined feedstocks or mixtures of pre-defined feedstocks.
  - For more information on the feedstock mix used in each scenario, see the 'Feedstocks' table in row 75 downwards.
  - The characteristics of each feedstock can be found in the 'Methane yields' section of the 'References' worksheet.

  - It is possible to customise the mix of feedstocks by inputting information into the bottom of the feedstocks table in row 84.
  - It is possible to use a feedstock outside of the pre-defined list using cell H84. More information on this below, in the section 'Using custom feedstocks'.

- **Useful products**
  - This drop-down menu allows the user to select from a list of pre-defined useful products or mixtures of useful products.
  - 'Useful products' refers to exported products only.
    - e.g. If an AD plant exports biomethane and also combusts biogas in a CHP to generate electricity and heat, but only uses this within the AD plant, then biomethane is the only product.
    - e.g. if an AD plant upgrades biogas to biomethane, CO_2 is not a useful product unless it is being captured and used or permanently stored.
  - Digestate is not mentioned in this list as it is considered a useful product from all AD plants.
  - N.B. Newer AD plants are less likely to generate excess exportable electricity and heat because there is no longer a government incentive (i.e. RHI and FIT) to do so. Such plants are likely to either export only biomethane, or biomethane and CO_2.

- **Size**
  - This drop-down menu allows the user to select from a list of pre-defined range of sizes.
  - As is the convention in the AD industry, plants are sized based on their installed biomethane, electrical or heat capacity.
  - Details on plant size can be found in the Size table in rows 102 to 109.
  - In this tool, the energy demand at each size is pre-defined. This can be found in rows 111 to 118.
  - A custom size may be used. If this is selected, custom energy demand must also be entered.

- **Energy supply**
  - This drop-down menu allows the user to select from a list of pre-defined energy sources.
  - Energy for AD can be supplied from a number of sources. The tool is designed to handle biogas to CHP, natural gas to CHP and only imported electricity. Alternatives like heat pumps are not included in the model.
  - Depending on the size of the site, the size of the CHP (if present) changes.

- **Fugitive methane – design**

- This drop-down menu allows the user to select from a list of pre-defined fugitive methane scenarios related to the site and equipment design.
- N.B. This tool contains 3 separate categories of fugitive methane emissions.
  - Fugitive methane emissions that are linked to the *design* of the plant are easier to predict than fugitive methane emissions from operations or digestate management, as they are typically linked to the type, model or age of the equipment.
- Fugitive methane emissions from the following pieces of equipment are included: boiler, CHP and biogas upgrading unit. Details can be found in the 'Fugitive methane design' table in row 127 and below.
- Boilers and CHPs using natural gas in place of natural gas (or biomethane) typically have lower fugitive methane emissions because there is a higher level of incomplete combustion of a dilute gaseous fuel. In this model, emissions from equipment using natural gas are half of the emissions from equipment using biogas. If equipment is using biomethane instead of biogas, values will be similar to natural gas.
- If the default fugitive methane scenarios are not suitable, it is possible to override them by selecting 'Custom' and entering custom values in row 134.
- If uncertain, select 'low'.

- **Grid-required GCV**
  - This drop-down menu allows the user to select from a list of pre-defined GCVs demanded by the grid.
    - Biomethane is typically injected into the gas distribution network (GDN) – the lower-pressure part of the gas grid.
    - Depending on the location of the GDN, the biomethane injector is typically required to meet different gross calorific values (GCV), which can be achieved by blending propane into the biomethane.
  - The values of low, medium and high can be found in the 'GCV needed' table in row 136 and below.
  - If biomethane is injected directly into the National Transmission System (NTS), it may not need to be blended with propane at all, in which case 'None' can be selected.
  - If none of the defaults are suitable, it is possible to override them by selecting 'Custom' and entering a custom value in row 142.
  - If uncertain, select 'medium'.
- **Outputs performance**
  - This drop-down menu allows the user to select from a list of pre-defined output performances.

        - This option describes the extent to which the AD plant reaches its nameplate capacity, in terms of injection capacity and/or CHP capacity.
    - The values of low, medium and high can be found in the 'Outputs performance' table in row 144 and below. These numbers are empirically derived from the case studies. The medium scenario represents the mean, and the low and high scenarios represent one standard deviation either side of the mean.
    - If none of the defaults are suitable, it is possible to override them by selecting 'Custom' and entering a custom value in row 149. A number above 100% should not be entered as is not technically possible.

- **Electricity needs**
    - This drop-down menu allows the user to select from a list of pre-defined electricity need levels.
        - This option describes how much electricity an AD plant needs, and is determined relative to its installed capacity.
    - The values for electricity needed consist of the electricity needed for digestion, plus electricity needed for biogas upgrading and electricity needed for CO_2 compression, where applicable.
    - These values can be found in the 'Energy demand' table in row 111 and below, and describe the 'medium' scenario.
    - For electricity for digestion, a multiplier is applied to this value for the 'low' and 'high' scenarios: 67% for the 'low' scenario and 133% for the 'high' scenario. These numbers are empirically derived from the case studies. The medium scenario represents the mean, and the low and high scenarios represent one standard deviation either side of the mean.
    - For electricity for biogas upgrading, a multiplier is applied to this value for the 'low' and 'high' scenarios: 60% for the 'low' scenario and 140% for the 'high' scenario. These numbers are empirically derived from the case studies. The medium scenario represents the mean, and the low and high scenarios represent one standard deviation either side of the mean.
    - For electricity for CO_2 compression, there is only one scenario as no real data was available (only manufacturers' rules of thumb).
    - If none of the defaults are suitable, it is possible to override them. As energy requirements are tied to plant size, this function will only work correctly if 'custom size' is also selected under 'Size' in D14. In order to add a custom electricity requirement, 'Medium' must be selected under 'Electricity needs' and the custom electricity demand must be entered in row 118.

- **Digestion efficiency**
    - This drop-down menu allows the user to select from a list of pre-defined digestion efficiencies, i.e. the extent to which the biomethane potential of feedstocks are reached.

  - Details on the high, medium and low scenarios can be found in the 'Digestion efficiency' table in row 151 and below.
  - These numbers are empirically derived from the case studies. The medium scenario represents the mean, and the low and high scenarios represent one standard deviation either side of the mean.
  - N.B. The medium scenario is 113% digestion efficiency. While it seems unlikely that digestion efficiency is over 100%, this was the result gathered in the case studies and presumably reflects that feedstocks - particularly mixed wastes - are variable, and that the biomethane potential provides only a snapshot of a feedstock.

- **Flared gas**
  - This drop-down menu allows the user to select from a list of pre-defined flare rates, which can be seen in rows 159 to 163.
  - In the tool, the amount of flared gas has little impact on the carbon intensity of the biomethane generated, as the emissions are calculated based on the biomethane generated (injected *and* flared gas), rather than based on biomethane injected.
  - Often, biomethane is flared because it has been rejected from the gas grid (typically because the GCV is too low). This is a market failing, and has a large impact on the profitability of biomethane generation, and the information is interesting for this reason. However, it has been argued that it is not fair that this should affect the carbon intensity of the biomethane generated.
  - The low medium and high scenarios are based on maximum permitted flaring under the Environment Agency (EA) in England, which is 10%, with the medium scenario being half of that (5%) and the low being 0%.
  - A 'custom' option is also available. This can be selected from the drop-down menu and the value should be entered in D163.
  - N.B. although flaring is capped at 10% by the EA, it is not impossible that more than 10% of biomethane is rejected by the gas grid.

- **Fugitive methane – operation**
  - This drop-down menu allows the user to select from a list of pre-defined fugitive methane emissions that are tied to the operation of the AD plant, rather than the design.
  - Fugitive methane emissions that are linked to the *operation* of the plant include those that arise during maintenance and sampling, those that arise due to aging or faulty parts, and those that arise due to human error.
  - These emissions may be long-term (e.g. faulty parts) or very temporary (e.g. digester opening for maintenance), and are very difficult to measure as a result.
  - Values can be seen in the 'Fugitive methane – operation' table in row 166 and below. These are derived from several literature sources (see below).

    - If none of the defaults are suitable, it is possible to override them by selecting 'Custom' and entering custom values in row 172.

- **Fugitive methane – digestate**
    - This drop-down menu allows the user to select from a list of pre-defined fugitive methane emissions that are tied to the digestate storage. The pre-defined values can be seen in rows 175 to 181.
    - If selecting the custom option, custom values should be entered in D181.

Notes on fugitive methane emissions

Overall, data on fugitive methane emissions was obtained from a number of literature sources including:

- Bakkaloglu *et al.* (2021) Quantification of methane emissions from UK biogas plants (https://doi.org/10.1016/j.wasman.2021.01.011
- Wechselberger *et al.* (2023) Methane losses from different biogas plant technologies. https://doi.org/10.1016/j.wasman.2022.12.012
- Reinelt & Liebetrau (2019) Monitoring and Mitigation of Methane Emissions from Pressure Relief Valves of a Biogas Plant. https://doi.org/10.1002/ceat.201900180
- Reinelt *et al.* (2016) Analysis of operational methane emissions from pressure relief valves from biogas storages of biogas plants. https://doi.org/10.1016/j.biortech.2016.02.073
- Scheutz & Fredenslund (2019) Total methane emission rates and losses from 23 biogas plants. https://doi.org/10.1016/j.wasman.2019.07.029

As well as a number of German-language publications, particularly around the EvEmBi project ("Evaluation and reduction of methane emissions from different European biogas plants"), including:

- Knoll *et al.* (2022) Schlussbericht zum Vorhaben… EvEmBi. https://www.fnr.de/ftp/pdf/berichte/22407917.pdf
- DBFZ & Universität Stuttgart (2020) Hintergrundpapier Methanemissionen an Biogasanlagen https://www.biogas.org/edcom/webfvb.nsf/id/DE-H-011/$file/20-10-06_H-011_Hintergrundpapier-Methanemissionsminderung-BGA.pdf

- Other options
    - In model mode, there is also an option to change digestate processing, although this is not recommended. This can be done in cell P47, where it is possible to select between digestate separation (e.g. with a screw press, into a more solid and a more liquid fraction) and no digestate separation. The tool automatically assumes that 25% of the digestate volume is recovered in the solid fraction and

75% of the volume in the liquid fraction. The dry matter content of the digestate can also be modified in cell R41, and the dry matter of the solid fraction (if separated) can be modified. The liquid fraction is calculated based on the dry matter content of the solid fraction.

Changing transport distance for feedstocks

For all feedstocks – whether default or custom – transport distance can be changed. This is possible under the relevant feedstock worksheet (i.e. 'Crop', 'Residue', 'Waste' and 'Manure'), in the green cell in the transport table, next to the cell labelled 'km'.

Transport		Default
Mode of transport		Truck for dry product (40 ton)
Transport	km	150
Fuel type		Diesel
Fuel needed	MJ/year	-

Using alternative modes of transport

- The tool is currently only set up to accommodate diesel transport.
- To understand the impact of transport on the overall emissions, it is possible to set feedstock transport distance to zero; this would be equivalent to a transport method with zero GHG emissions. By comparing the GHG emissions with zero feedstock transport and diesel-based feedstock transport, it is possible to draw high-level conclusions about other, lower-carbon forms of transport whose emissions lie somewhere between zero and those of diesel.
- The same is possible for tractors fuelled with alternative fuels, for the default crop (under the 'Crops' worksheet) or for a custom crop (under the 'Custom (model)' worksheet). By reducing the fuel used for ensiling (under the table 'Silage making') and tilling, sowing and harvesting (under the table 'Diesel for tilling, sowing & harvesting') to zero, it is possible to see the impact of diesel use in tractors and draw high-level conclusions about other, lower-carbon forms of powering tractors.

Changing some parameters for default crop cultivation

For the default crop, it is recommended not to change the cultivation parameters because they are all interlinked. For example, fertiliser use is typically linked to crop yield, and reducing fertiliser input without changing crop yield is not credible. If interested in using a different custom crop, the 'Custom' function should be used (see subsequent section, below).

Nonetheless, it may be interesting for a user to understand the impact of these parameters on GHG emissions, so there are some options to change these parameters.

To do this, select 'override' in cell D37. This will grey out the default values in column E and open up the fields in column F for override with other values.

Use default or override?	override

Transport		Default	Override
Mode of transport		Truck for dry product (40 ton)	Truck for dry product (40 ton)
Transport	km	20	20
Fuel type		Diesel	Diesel
Fuel needed	MJ/year	-	-

Silage making			
Losses from silage production		10%	10%
Diesel for silage making	kWh/t	3.88	3.88

Crop cultivation			
Crop yield	t/ha	39.67	40.76

Annualised increase in soil carbon			
Annualised increase in soil carbon stock	t/ha (per year)	-	1.50

Fertiliser use			
Nitrogen fertiliser	kg(N)/ha	71.0	63.2
Urea	kg(N)/ha	-	-
Digestate	kg(N)/ha	183.5	259.9
Untreated manure	kg(N)/ha	-	-
P2O5	kg(P2O5)/ha	61.7	38.5
K2O	kg(K2O)/ha	63.5	24.0
Lime (CaCO3)	kg(K2O)/ha	179.9	279.6

Summary of nitrogen use			
Total nitrogen application	kg(N)/ha	254.5	323.1
Inorganic nitrigen fertiliser	kg(N)/ha	71.0	63.2
Organic nitrogen fertiliser	kg(N)/ha	183.5	259.9

Pesticide	g(active ingredient)/Ha	5.5	6.7

Seed	kg/Ha	55.3	25.0

Diesel for tilling, sowing & harvesting			
Diesel for tilling, sowing & harvesting	litres/Ha	85.0	85.1

- Enter data on silage making (F48 and F49). If no other data is available, typical values are 10% dry matter losses and 3.881 kWh of diesel per tonne silage.
- Enter the crop yield, in field (F53).
- Enter the annualised increase in soil carbon stock (F56). If unknown, this should be left blank or entered as 0.
- Enter the nitrogen fertiliser, urea, digestate and/or untreated manure used in crop cultivation, as appropriate (F59–F62). Some default data can be copied from the ‘Model crop’ worksheet. The units are all kg of nitrogen per ha, and may need to be adapted from the units used in literature sources.
- Enter the amounts of other soil inputs used, in the requested units (F63–E65).
- Enter the pesticide used, in the requested units (F72).
- Enter the volume of seeds used, in the requested units (F74).
- Enter the diesel needed for all of tilling, sowing and harvesting (F77).

Using custom feedstocks

The tool is best suited to operating with the default feedstocks entered. However, it is possible to override this and use other feedstocks.

To run a scenario with a custom feedstock:

- In the 'Models' worksheet
  - Select 'Custom feed' under Feedstocks (D12).
  - Enter the relevant percentage that the custom feedstock should occupy (e.g. 100%) in H84.
- In the 'References' worksheet.
  - Enter the feedstock characteristics under row 39.
- In the 'Custom (model)' worksheet.
  - Select whether the custom feedstock is a product (for which pathway emissions are counted) or a residue/waste/manure (for which pathway emissions are not counted).
  - Select whether the use of this feedstock is associated with a credit (e.g. a manure credit).
    - If the use of the feedstock is associated with a credit, enter the value in gCO_2eq/t_{FM}. Please note that these units are different from the units typically used for the manure credit.
      - To calculate the credit in gCO_2eq/t_{FM} from the value in $gCO_2eq/MJ_{feedstock}$, multiply by the $MJ_{feedstock}/t_{DM}$ and then multiply by t_{DM}/t_{FM}. For manure, the typical $MJ_{feedstock}/t_{DM}$ is 12,000 (see also 'References' E29). This means that a poultry manure with a DM content of 40% would have a credit of −45 * 12,000 * 0.4 = −216,000 gCO_2eq/t_{FM}, based on a manure credit of −45 $gCO_2eq/MJ_{feedstock}$.
  - Check whether the correct feedstock parameters have loaded in row 16.
  - Select the appropriate transport mode in E31 (usually 40 ton truck, for dry or liquid products where appropriate) and enter the transport distance in E32.
  - Fuel is set to Diesel – the tool is not designed to handle alternative fuels at this stage. See also above, under 'Using alternative modes of transport'.
  - If the feedstock is a product, also enter values for feedstock cultivation.
  - Enter crop dry matter yield (E40), which is the dry matter content of the crop when harvested. This is usually closely tied to the data on crop yield (in weight) and cultivation inputs. Crop dry matter content is typically lower than the dry matter content of silage owing to in-field drying before ensiling.

- Enter data on silage making (E44 and E45). If no other data is available, typical values are 10% dry matter losses and 3.881 kWh of diesel per tonne silage.
- Enter the crop yield, in field (E49). This should tie in with the crop dry matter yield.
- Enter the annualised increase in soil carbon stock (F52). If unknown, this should be left blank or entered as 0.
- Enter the nitrogen fertiliser, urea, digestate and/or untreated manure used in crop cultivation, as appropriate (E55 – E58). Some default data can be copied from the 'Model crop' worksheet. The units are all kg of nitrogen per ha, and may need to be adapted from the units used in literature sources.
- Enter the amounts of other soil inputs used, in the requested units (E59 – E61).
- Enter the pesticide used, in the requested units (E68).
- Enter the volume of seeds used, in the requested units (E70).
- Enter the diesel needed for all of tilling, sowing and harvesting (E73).

Changing the LCA approach in the LCA worksheet

The LCA worksheet displays the overall outcomes of the GHG emissions calculations.

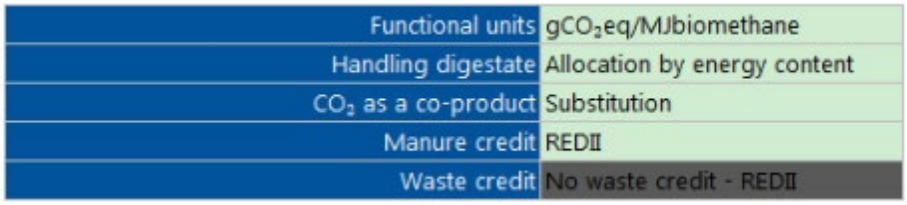
Results are displayed under the title EMISSIONS RESULTS, broken down into components like digestion, fugitive emissions and feedstocks.

EMISSIONS RESULTS

Total emissions from biogas production	$gCO_2eq/MJbiomethane$
Total	**- 9.9**
Digestion	2.6
Fugitve emissions	11.7
Crops	8.0
Residues	-
Waste	-
Manures	- 32.3
Custom (model)	-
Digestate credit	-
CO_2 credit	-

Fugitive methane	% of total biogas generated
Total	2.50%

In the top left hand corner, a selection must be made for each drop-down menu. These choices affect how the GHG emissions are calculated. Some menus may appear greyed out; this means they are not applicable based on selections elsewhere.



The drop down menus are described below in more detail.

- Functional units
  - $gCO_2eq/MJ_{biomethane}$
    - This is the units that biomethane producers typically report, for example under GGSS, RHI or ISCC-EU.
    - Emissions have been allocated to co-products including the solid fraction of digestate and, where applicable, exported heat, electricity and CO_2.
  - gCO_2eq/year (biomethane)
    - This is the value obtained above, multiplied by the amount of biomethane generated (which includes biomethane flared) per year.
    - Emissions have been allocated to co-products including the solid fraction of digestate and, where applicable, exported heat, electricity and CO_2.
  - $gCO_2eq/MJ_{electricity}$
    - This is the units that electricity producers typically report, for example under FIT.
    - Emissions have been allocated to co-products including the solid fraction of digestate and, where applicable, exported heat, biomethane and CO_2.
  - gCO_2eq/MJ_{biogas}
    - This is emissions before the use of biogas (for example, in a CHP or biogas upgrader) has been taken into account.
      - If the site's energy is mainly supplied by biogas, the difference between this per-biogas value and the per-biomethane value will be large, as some of the biogas is needed to supply energy to the site.
      - If the site's energy is mainly imported (e.g. from the grid or with natural gas), the difference between this per-biogas value and the per-biomethane value will be small.
    - Emissions have been allocated to co-products including the solid fraction of digestate.
  - gCO_2eq/year (all products)
    - This is all the emissions associated with an AD site in a year.
    - No emissions are allocated, all are captured here.

- Handling digestate (see section below titled ‘Allocation’ for a discussion of what these different LCA approaches mean)
    - Allocation by energy content
        - This approach is permitted by RED and REDII and therefore also by RHI, GGSS, RTFO and ISCC-EU.
    - Surplus (disregard digestate)
        - This approach may also be used under RED and REDII.
    - Allocation by economic value
        - This approach is common in LCA but is not permitted under RED/REDII/REDIII. It may be used under schemes not associated with biofuel reporting in the UK or EU, such as ISCC-PLUS.
        - In order for allocation by economic value to work, economic values for all co-products must be entered in the ‘Digestion’ worksheet under I51 to I55. These values are very sensitive to market fluctuations.
    - Substitution
        - This approach is common in LCA but is not permitted under RED or REDII. It may be used under schemes not associated with biofuel reporting in the UK or EU, such as ISCC-PLUS.
        - Substitution values must be entered in the ‘Digestion’ worksheet under P52.
- CO_2 as a co-product
    - Substitution
        - This approach is permitted by RED and REDII and therefore also by RHI, GGSS, RTFO and ISCC-EU.
    - Surplus (disregard)
        - This approach may also be used under RED and REDII, and should be used if the CO_2 saving is to be claimed elsewhere.
    - Allocation by economic value
        - This approach is common in LCA but is not permitted under RED or REDII.
        - In order for allocation by economic value to work, economic values for all co-products must be entered in the ‘Digestion’ worksheet under I51 to I55. These values are very sensitive to market fluctuations.
- Manure credit
    - REDII
        - This corresponds to a credit of 45 gCO_2eq/MJ_{manure}, where the MJ manure are based on the dry matter content and a value of 12 MJ/kg_{dry}.

    - No manure credit
        - This approach is used in RED (i.e. RHI and FIT) and RTFO.
    - Custom manure credit
        - This allows the user to play with a range of other possible manure credits, for example based on new evidence of emissions from manure storage.
        - Values must be entered in the 'References' worksheet under cell E62.
- Waste credit
    - No waste credit – REDII
        - This approach is used in RED and REDII.
    - Estimated waste credit
        - This approach was added based on user feedback and an estimated waste credit. Information on the value of the estimated waste credit can be found in section below titled 'Allocation'.
    - Custom waste credit
        - This allows a custom waste credit to be used, for example based on new evidence on emissions from current waste management practices.
        - Values must be entered in the waste credit table in the References worksheet (E68).

Changing global warming potential

The global warming potentials (GWPs) listed in REDII have been used, which are:

- 1 gCH_4 = 25 gCO_2eq
- 1 gN_2O = 298 gCO_2eq

It is possible to change the GWPs, for example to the newer values used in the EU since early 2024[1]. This can be done by changing the values in the 'References' worksheet under E55 and E56. However, this will only affect the impact of fugitive methane emissions. All other emissions factors are given only as CO_2 equivalents, based on the GWPs listed above, and will not change if other GWPs are entered.

[1] Commission Implementing Regulation (EU) 2022/996 of 14 June 2022 on rules to verify sustainability and greenhouse gas emissions saving criteria and low indirect land-use change-risk criteria (Text with EEA relevance) http://data.europa.eu/eli/reg_impl/2022/996/oj

Mass and energy balancing

The following section provides more context for the user to understand the functionality and outputs of the tool and explains the key mass and energy balancing equations used, as well as providing an overview of the AD process.

Overview of anaerobic digestion

Anaerobic digestion (AD) involves the conversion of biomass into biogas under anaerobic conditions (in the absence of oxygen). Every AD process involves biomass (waste, crop, sludge, etc) being fed into a digester (typically multiple digesters), where an anaerobic environment is obtained and then maintained. The biomass is transformed into biogas, made primarily of methane (CH_4) and carbon dioxide (CO_2). Not all carbon present in the biomass is transformed into these gases, most remains in the residual digestate. The digestate also contains virtually all the inorganic matter from the processed biomass, such as nitrogen, phosphorus and potassium compounds, as well as a high proportion of the water. Digestate is typically stored on site or in satellite storage facilities and can either be removed from site whole (unprocessed), or as separated solid and liquid fractions, having been subject to mechanical separation and potentially also further dewatering.

Biogas from AD can be used in different ways, including biogas upgrading (to produce biomethane for gas grid injection and CO_2 as a by-product), combustion in a CHP (to generate electricity and heat), and/or combustion in a boiler (to generate heat). Each of these processes is associated with conversion efficiencies and losses. Some methane or biogas also escapes into the environment, and some is flared on site where it cannot be effectively utilised or captured. It is essential to understand the flow of biogas and co-products in the process in order to correctly allocate emissions in an LCA.

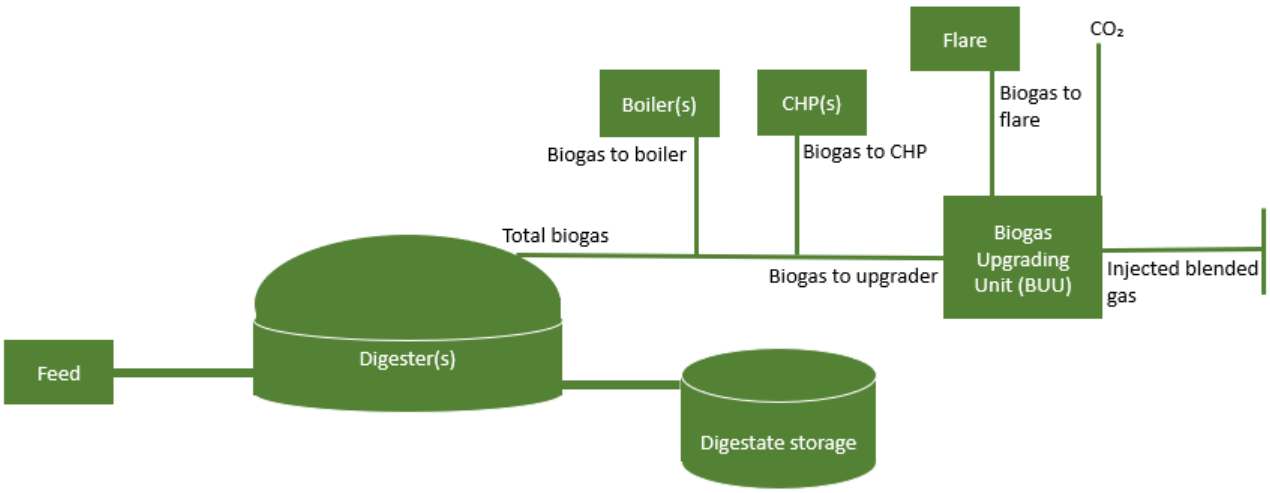


Figure 1: AD process flow diagram.

Equations for mass and energy balance

Both modes of the tool require the use of mass and energy balancing. Mass balance traces the flow of materials from feedstock to biomethane, so it is essential to ensure that no inputs or outputs have been omitted. As the ultimate outputs of AD are energetic it is also essential to balance the flow of energy. Energy use within the system (e.g. for process energy) must also be balanced, whether it comes from biogas or from external sources.

In both actual mode and model mode, calculations are run based on site configuration and capacity. In actual mode, data is entered. In model mode, the equivalent cell is automatically populated based on a selected scenario.

This section provides information on the methodology and calculations used in the tool, with discussion on key input parameters and assumptions.

Design and Operation

Sites are sized in this tool based on their capacity to produce useful products.

In actual mode, the biomethane capacity (typically the capacity of the grid injection unit to inject gas into the grid) must be entered (in 'Actuals'), along with the capacity of the boiler and CHP, if present.

In model mode, these cells are automatically populated when a scenario is selected for 'size' (see **Error! Reference source not found.** in Annex), as explained in the instructions above.

Biogas CHP

In both modes, biogas required for CHP is based on the installed capacity of the CHP.

$$E_{LHV\ biogas\ for\ CHP} = C_{CHP} * \%_{achieved} * 8760 * 3.6 / \eta_{electrical}$$

Where:

$E_{LHV\ biogas\ for\ CHP}$ = biogas required for CHP in MJ (LHV)
C_{CHP} = installed capacity of the CHP in $kW_{electric}$
$\%_{achieved}$ = percentage of capacity actually achieved
8,760 = number of hours in a year (h/year)
3.6 = conversion factor MJ/kWh
$\eta_{electrical\ efficiency}$ = the electrical efficiency of the CHP

The amount of electricity generated in the CHP can then be calculated.

$$E_{electricity\ generated} = E_{LHV\ biogas\ for\ CHP} * \eta_{electrical} / 3.6$$

Where:

$E_{electricity\ generated}$ = electricity generated in kWh/year

In ***model*** mode:

- $E_{LHV\ biogas\ for\ CHP}$ is calculated
- C_{CHP} is selected via 'Useful products', 'Size' and 'Energy supply'. If the selected useful products indicate that the site generates electricity but not biomethane, the tool choses from one list of relevant CHP sizes. If the selected outputs indicate that a site generates both electricity and biomethane, or if the electricity demand is mainly provided by biogas, a second list of relevant CHP sizes is referenced, based on typical site configurations used in recent plants.
- $\%_{achieved}$ is selected under Operation > Outputs performance.
- $\eta_{electrical\ efficiency}$ is set at 36%.
- $E_{electricity\ generated}$ is calculated.

In ***actual*** mode:

- $E_{LHV\ biogas\ for\ CHP}$ is calculated.
- C_{CHP} is input by the user (typically found on the CHP nameplate or in accompanying documentation).
- $\%_{achieved}$ is calculated
- $\eta_{electrical\ efficiency}$ can be estimated from the CHP unit's documentation and is typically between 0.3 and 0.4.
- $E_{electricity\ generated}$ is input by the user.

Biogas supply to biogas upgrading unit (BUU)

The biogas required for upgrading to biomethane should take account any losses prior to or during upgrading (e.g. slip from the biogas upgrading unit). This is accounted for as follows:

$$E_{LHV\ biogas\ for\ upgrading} = E_{LHV\ upgraded\ biogas} / (1 - \%_{BUU\ loss}/100)$$

Where:

$E_{LHV\ biogas\ for\ upgrading}$ = the energy contained within biogas sent to upgrading in MJ/year (LHV)
$E_{LHV\ upgraded\ biogas}$ = the energy contained within the upgraded biogas in MJ/year (LHV)
$\%_{BUU\ loss}$ = the losses of methane in the biogas upgrading unit in %

This can be converted to volume of biogas required for upgrading using the LHV of methane and the percentage of methane in the biogas:

$$V_{biogas\ for\ upgrading} = E_{LHV\ biogas\ for\ upgrading} / 35.82 / \%_{methane\ in\ biogas}$$

Where:

$V_{biogas\ for\ upgrading}$ = the volume of biogas needed by the biogas upgrading unit (not listed)
35.82 = the LHV of methane in MJ/Nm³
$\%_{methane\ in\ biogas}$ = the percentage of methane in biogas

Depending on whether the percentage methane in biogas is calculated or measured, this may be an underestimate of the biogas needed. This is because the calculated percentage of methane in biogas is often higher than actual, owing to the presence of nitrogen, caused by accidental or intentional addition of air.

In ***model*** mode:

- $E_{LHV\ biogas\ for\ upgrading}$ is calculated.
- $E_{LHV\ upgraded\ biogas}$ is calculated.
- $\%_{BUU\ loss}$ = the losses of methane in the biogas upgrading unit in %
- $V_{biogas\ for\ upgrading}$ is calculated.
- $\%_{methane\ in\ biogas}$ is calculated, based on feedstocks used.

In ***actual*** mode:

- $E_{LHV\ biogas\ for\ upgrading}$ is calculated.
- $E_{LHV\ upgraded\ biogas}$ is calculated.
- $\%_{BUU\ loss}$ can be estimated from the biogas upgrading unit's documentation and is typically between 0% and 5%
- $V_{biogas\ for\ upgrading}$ is calculated.
- $\%_{methane\ in\ biogas}$ is calculated, based on feedstocks used.

Biogas CHP & CHP efficiency

The amount of electricity exported is linked with the amount of electricity generated and the on-site (parasitic) demands.

$$E_{electricity\ exported} = E_{electricity\ generated} - E_{parasitic\ electricity}$$

Where:

$E_{electricity\ exported}$ = electricity used for a purpose other than AD, for example for export to grid or a third party, in kWh/year
$E_{parasitic\ electricity}$ = electricity used in the AD process itself, in kWh/year

In ***model*** mode:

If electricity is selected as a useful product:

- $E_{electricity\ exported}$ is calculated.
- $E_{parasitic\ electricity}$ is calculated.

In ***actual*** mode:

- $E_{electricity\ exported}$ is input by the user.
- $E_{parasitic\ electricity}$ is calculated.

Biogas from digesters

The total biogas required by the site can be calculated from the biogas needed for all applications (biogas upgrading, CHP and boiler). The simplest way to calculate this is using the energy of the biogas.

$$E_{LHV\ total\ biogas} = (E_{LHV\ biogas\ for\ upgrading} + E_{LHV\ biogas\ for\ CHP} + E_{LHV\ biogas\ for\ boiler}) / (1 - \%_{fugitive\ methane\ digestion}/100)$$

Where:

$\%_{fugitive\ methane\ digestion}$ = the percentage of total biogas generated that is lost in leaks from the digesters

This is the energy content of the biogas and resultant biomethane. This can be converted to volume of methane required by multiplying by the energy content of methane.

$$V_{total\ methane} = E_{LHV\ total\ biogas} / 35.82$$

Where:

$V_{total\ methane}$ = the volume of methane needed to generate the outputs in Nm^3/year
35.82 = the lower heating value (LHV) of methane in MJ/Nm^3

It is important to note that the volume of methane required is purely for calculation purposes, as it is biogas that is generated, not methane. In order to calculate the volume of biogas required, this must be multiplied by the fraction of methane in the biogas.

$$V_{total\ biogas} = V_{total\ methane} / \%_{biomethane}$$

Where:

$V_{total\ biogas}$ = the volume of biogas needed to generate the outputs in Nm^3/year
$\%_{biomethane}$ = the percentage of methane in the biogas

CO_2 yield

The amount of CO_2 recovered is typically accounted for by weight, as the CO_2 is liquified and the volume varies with pressure. The amount of CO_2 recovered can be calculated from the

amount of biomethane sent to the biogas upgrading unit, along with the % of methane in the biogas.

$$M_{CO_2\ recovered} = V_{biogas\ for\ upgrading} * (100 - \%_{methane\ in\ biogas}) * (1 - \%_{CO_2\ lost}) * 0.00187$$

Where:

$M_{CO_2\ recovered}$ = the mass of CO_2 recovered in t/year
$\%_{CO_2\ lost}$ = the amount of CO_2 lost during CO_2 recovery
0.00187 = the density of CO_2 in t/Nm³

N.B. An approximation has been used here, that the CO_2 volume is the biogas volume minus the methane volume. However, in practice, small amounts of nitrogen are often also present in biogas, either from accidental or intentional introduction of air.

In ***model*** mode:

Calculations on CO_2 recovery will only be carried out if CO_2 has been selected as a product under 'Useful products'..

- $M_{CO_2\ recovered}$ is calculated.
- $\%_{CO_2\ lost}$ is fixed at 20%, based on stakeholder feedback.

In ***actual*** mode:

- $M_{CO_2\ recovered}$ is available from the biomethane producer.
- $\%_{CO_2\ lost}$ is calculated.

Grid injection

In ***model*** mode, if biomethane is selected as product and an AD capacity has been entered or selected, the annual amount of gas produced for injection is calculated. The annual amount of gas injected is calculated from the % efficiency achieved and the hours in a year. In addition, the units of gas are converted from standard cubic metres (scm) (the convention in the UK gas grid) to normalised cubic metres (at standard temperature and pressure) (Nm³) (the convention in the biogas industry).

$$V_{gas\ for\ grid} = C_{gas\ for\ grid} * \%_{achieved}/100\% * 8760 * 0.95$$

Where:

$V_{gas\ for\ grid}$ = volume of gas generated for grid injection in Nm³/year
$C_{gas\ for\ grid}$ = capacity of the grid entry unit to inject gas in scm/h
$\%_{achieved}$ = percentage of capacity actually achieved
8,760 = number of hours in a year in h/year
0.95 = conversion factor Nm³/scm

It is important to note that not all gas injected is biomethane; almost all sites carry out some defined propane blending to meet grid standard, and there is typically some contaminating gas (usually CO_2) remaining in the upgraded biomethane. The values calculated for grid injection exclude propane addition, but the latter is taken into account for the LCA calculation.

In ***actual*** mode:

- $V_{gas\ for\ grid}$ is input by the user. In cases where there is significant biomethane flaring at the site, this number should be the gas generated for injection *before* flaring. If the volume is not known, proceed using the same value for 'Actual injected' and 'Before flared biomethane'. If significant flaring has occurred, using the 'Actual injected' value for 'Before flared biomethane' will inflate the carbon intensity of the biomethane and it is therefore advisable to use actual flare data where possible.
- $C_{gas\ for\ grid}$ is available from the biomethane producer
- $\%_{achieved}$ is calculated

Energy content of injected gas

Gas injected into the grid, although commonly referred to as biomethane, is typically a mix of biomethane, residual CO_2 or nitrogen, and blended propane; therefore, the energy content depends on the specific composition of the gas. The convention of the UK gas grid is to give the energy content of gas as gross calorific value (GCV), also known as higher heating value (HHV).

$$E_{HHV\ injected\ gas} = V_{gas\ for\ grid} * GCV_{required}$$

Where:

$E_{HHV\ injected\ gas}$ = the energy content of the injected gas as GCV (HHV) in MJ/year
$GCV_{required}$ = the GCV (HHV) required by the gas grid (in this tool, this is assumed to be the same as the GCV achieved) in MJ/Nm³

In ***model*** mode:

- $E_{HHV\ injected\ gas}$ is calculated.
- $GCV_{required}$ is selected under Constraints > Grid-required GCV. GCV options are based on stakeholder engagement and typical GCV requirements in the UK.

In ***actual*** mode:

- $E_{HHV\ injected\ gas}$ is input by the user.
- $GCV_{required}$ is calculated.

Propane blended

At almost all biomethane sites, propane must be blended with upgraded biogas to match the gross calorific value (GCV) of the gas grid prior to injection. The GCV required by the grid varies but is typically around 39 MJ/Nm³, while the GCV of upgraded biogas is typically lower, often around 36 MJ/Nm³. The amount of propane required to be blended is calculated based on the required GCV at grid and the actual GCV.

$$\%_{propane} = 100 * 1 - 1 / (1+ (GCV_{required} - GCV_{upgraded\ biogas}) / GCV_{propane})$$

Where:

$\%_{propane}$ = the percentage of propane required in the gas for injection
$GCV_{upgraded\ biogas}$ = the required GCV of the upgraded biogas, typically around 36 MJ/Nm³
$GCV_{propane}$ = the GCV of propane, currently fixed as 93.99 MJ/Nm³

The volume of propane required can then be calculated.

$$V_{propane} = \%_{propane} * V_{gas\ for\ grid}$$

Where:

$V_{propane}$ = volume of propane blended into gas for grid injection (Nm³/year)

In ***model*** mode:

- $\%_{propane}$ is calculated.
- $GCV_{upgraded\ biogas}$ is currently set at 36 MJ/Nm³
- $GCV_{propane}$ is fixed at 93.99 MJ/Nm³
- $V_{propane}$ is calculated

In ***actual*** mode:

- $\%_{propane}$ is calculated
- $GCV_{upgraded\ biogas}$ is input by the user
- $GCV_{propane}$ is fixed at 93.99 MJ/Nm³
- $V_{propane}$ is input by the user.

Gas supply to grid entry unit (GEU)

The amount of upgraded biogas required for blending at the GEU can be calculated from the % propane and the volume of gas injected.

$$V_{upgraded\ biogas} = V_{gas\ for\ grid} * (1 - \%_{propane}/100)$$

Where:

$V_{upgraded\ biogas}$ = the volume of upgraded biogas from the biogas upgrading unit in Nm^3/year

The energy contained in the upgraded biogas can be calculated from the GCV of the upgraded biogas and converted into LHV (NCV) if desired using the conversion factor of 0.9 (HHV/LHV).

$$E_{LHV\ upgraded\ biogas} = V_{upgraded\ biogas} * CGV_{upgraded\ biogas} * 0.9$$

Where:

$E_{LHV\ upgraded\ biogas}$ = the total energy content of the upgraded biogas in MJ/year (as LHV)
0.9 = the conversion factor for methane LHV/HHV (aka NCV/GCV)

In ***model*** mode:

- $V_{upgraded\ biogas}$ is calculated
- $E_{LHV\ upgraded\ biogas}$ is calculated

In ***actual*** mode:

- $V_{upgraded\ biogas}$ is calculated
- $E_{LHV\ upgraded\ biogas}$ is calculated

Flare

Gas is sometimes rejected at the grid entry point because of quality of capacity constraints. This gas may be recirculated, stored or flared. The actual volume of gas injected to the grid is the total presented for injection minus the fraction that is flared.

$$V_{gas\ injected} = V_{gas\ for\ grid} * (1 - \%_{flared}/100)$$

Where:

$V_{gas\ injected}$ = volume of gas actually injected in Nm^3/year
$\%_{flared}$ = percentage of biomethane flared

In ***model*** mode:

- $V_{gas\ injected}$ is calculated
- $\%_{flared}$ is selected under Operation > Flared gas

In ***actual*** mode:

- $V_{gas\ injected}$ is available from the biomethane producer.
- $\%_{flared}$ is calculated

Feedstocks & digestate

Feedstock calculations

The previous section calculates the total amount of biogas needed by the site, given its capacity and the level at which it is operating. The feedstock calculations are separate and depend on whether model or actual mode is selected.

In ***model*** mode**,** the tool uses the biomethane potential of the feedstocks and the proportions of each feedstock (as a percentage of the biogas yield, rather than as a percentage of weight – as per current sustainability reporting) to calculate back to the amount of feedstock required. As not every site is able to achieve the full biomethane potential, this calculation also takes account of the percentage of the potential that sites typically achieve.

$M_{feedstock\ n} = (\%_{digestion\ yield\ achieved} * V_{total\ methane} * \%_{feedstock,\ n}) / (BMP_{feedstock,\ n} * DM_{feedstock,\ n} * VS_{feedstock,\ n})$

Where:

$M_{feedstock\ n}$ = mass of feedstock n required, in t/year
$\%_{digestion\ yield\ achieved}$ = the achieved biogas yield as a percentage of the theoretical biogas yield (based on literature values)
$\%_{feedstock,\ n}$ = the fraction of gas generated from feedstock n
$BMP_{feedstock,\ n}$ = the biomethane potential (BMP) of feedstock n in Nm^3/t_{VS}
$DM_{feedstock,\ n}$ = the dry matter (DM) content of feedstock n as a % of total weight
$VS_{feedstock,\ n}$ = the volatile solids (VS) content of feedstock n as a % of DM

The total amount of feedstock needed can be calculated by summing the amount of each individual feedstock.

$$M_{feedstock} = \sum_{1}^{n} M_{feedstock,n}$$

Where:

$M_{feedstock}$ = the total mass of feedstock required, in t/year

In ***actual*** mode, the feedstock volumes are entered manually, along with feedstock names and characteristics. In this case, the theoretical biomethane yield is calculated for each feedstock.

$V_{methane,\ n} = M_{feedstock\ n} * BMP_{feedstock,\ n} * DM_{feedstock,\ n} * VS_{feedstock,\ n})$

Where:

$V_{methane,\ n}$ = the volume of methane generated from feedstock n in Nm^3/year

As the tool also back-calculates the amount of gas needed to deliver the outputs, the achieved biogas yield as a percentage of the theoretical biogas yield can be calculated. This number

would be expected to be less than 100%, as it is rare to get full conversion of biomass to biogas. However, if the number is over 100%, this can indicate that the BMP estimate was inaccurate and should be adjusted.

Digestate calculations

The volume of digestate generated during AD is very similar to the volume of feedstock used, with only part of the feedstock being converted to biomethane, and the majority of the feedstock (in particular, the water content, the ash content and the recalcitrant organic fraction) remaining after digestion. Therefore, the volume of digestate generated is often approximated to the volume of feedstock used. However, this is a simplification, as liquids may be recirculated in the digestate, and water is sometimes added to improve fluidity (if feedstocks with high dry-matter (DM) content are used. In this tool, the DM of digestate has been considered instead. It has been assumed that the DM of the digestate is approximately 50% of the DM of the feedstock[2].

$$M_{DM\ digestate} = 0.5 * \sum_{1}^{n} m_{feedstock,n} * DM_{feedstock,n}$$

Where:

$M_{DM\ digestate}$ = the amount of digestate as t_{DM}/year

In ***model*** mode**,** the volume of digestate generated is then back calculated from the dry matter content of the digestate, which has been set at 10%, with an assumption that the site carries out solid-liquid separation of digestate (for example in a screw press). It is then assumed that 75% of the mass goes to the liquid fraction, with a DM of 5%, and 25% of the mass goes to the solid fraction, with a DM of 25%. These assumptions are based on information from screw press manufacturers and evidence from operating sites.

In ***actual*** mode**,** this number ($M_{DM\ digestate}$) is only provided for reference and the volume and dry matter content of digestate should be entered manually.

Energy balance

Anaerobic digestion plants require heat and electricity to operate, which can be provided by various sources, including biogas, natural gas and grid electricity.

Electricity requirements

The total electricity required is calculated as follows:

$E_{AD} = E_{digesters} + E_{upgrading\&injection} + E_{CO_2\ compression}$

[2] Chastain & Smith (2015) Determination of the Anaerobic Volatile Solids Reduction Ratio of Animal Manure Using a Bench Scale Batch Reactor. ASABE Annual International Meeting 152189216 (doi:10.13031/aim.20152189216)

Where:

E_{AD} = total electricity required in kWh/year
$E_{digesters}$ = electricity required for digestion, including pumps and mixing, in kWh/year
$E_{upgrading\&injection}$ = electricity required for biogas upgrading and grid injection, including compression (only required if the site upgrades biogas to biomethane) in kWh/year
$E_{CO_2\ compression}$ = electricity required for the compression of CO_2 (only required if the site upgrades biogas to biomethane and compressed CO_2 for further use or storage) in kWh/year

Electricity supply

Electricity can be provided in different ways. Electricity is typically provided by a biogas CHP, a natural gas CHP or from the electricity grid. Other sources of electricity are possible, such as a diesel generator (typically only used as backup) or locally generated solar or wind. Heat is typically provided by a biogas CHP and/or boiler, a natural gas CHP and/or boiler, or an electric heater. Heat pumps have been proposed to provide heat to an AD plant, although this technology is not currently commonly used. Recovered industrial heat may also be used in AD plants. A number of configurations are made possible in the tool, to reflect differing options.

Electricity use from an in-house CHP (whether biogas or natural gas) is calculated from the electricity generated and the electricity exported.

$$E_{demand,CHP} = E_{generated\ electricity} - E_{exported\ electricity}$$

Where:

$E_{demand,CHP}$ = electricity demand of the AD site supplied from a CHP, in kWh/year
$E_{generated\ electricity}$ = electricity generated by the CHP, in kWh/year
$E_{exported\ exported}$ = electricity exported (beyond the AD system) in kWh/year

Any electricity not provided by a CHP is assumed to be supplied by the grid.

$$E_{imported} = E_{AD} - E_{demand,CHP}$$

Where:

$E_{imported}$ = electricity demand of the AD site, supplied from the electricity grid

Transport

Transport emissions are calculated based on km travelled, fuel used and mode of transport, as shown in the *Crop*, *Residue*, *Waste* and *Manure* worksheets. Fuel needed for transport is calculated in MJ from the amount of feedstock and the distance travelled, taking into account the fuel used and the transport efficiency of the vehicle, as well as any losses.

$$E_{transport\ fuel,n} = \eta_{transport\ efficiency,n} * D_n * M_{feedstock,n} * (1 - \%_{loss,transport,n})$$

Where:

$E_{transport\ fuel,n}$ = the energy content of the fuel needed for the transport of feedstock n, in MJ/tonne
$\eta_{transport\ efficiency,n}$ = the transport fuel efficiency of the vehicle used to transport feedstock n, as a fraction, based on literature values.
D_n = the distance travelled by feedstock n, in km
$\%_{loss,transport,n}$ = the fraction of feedstock lost during transport

Feedstock ensiling

The amount of crop required for silage production is calculated, taking into account losses from transport and ensiling, as shown in the *Crop* worksheet.

$$M_{crop,feedstock,n} = M_{feedstock,n} * (1 - \%_{loss,transport,n}) * (1 - \%_{loss,silage,n})$$

Where:

$M_{crop,feedstock,n}$ = the mass of crop (from which feedstock n derives) needed for feedstock n, in tonnes/year
$\%_{loss,silage,n}$ = the fraction of feedstock lost during the ensiling process

The amount of diesel needed for the ensiling process is fixed in this tool at 3.881 kWh/t, based on literature values.

Default crop data

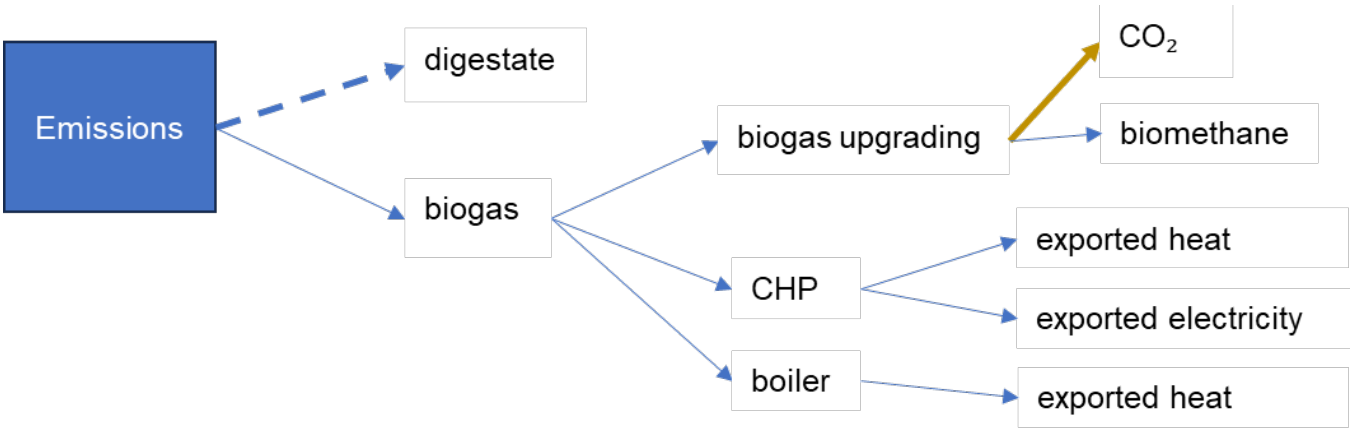
Cultivation input data from crop feedstocks (e.g. chemical and fuel use) is reported per hectare (by weight or volume), as set out in the *Crop defaults* worksheet. This includes information on:

- Fertiliser use, including:
  - nitrogen fertiliser
  - organic fertiliser (digestate or manure)
  - phosphorus fertiliser
  - potassium fertiliser
  - lime
- Pesticide use
- Seed use
- Fuel consumption
  - usually diesel in a tractor for tilling, sowing and harvesting

In order to link this to the feedstock demand, the crop yield is used in t/ha. The dry matter content of the crop at harvest is also taken into account, as set out in the *Crop defaults* worksheet.

Allocation

Anaerobic digestion is a multifunctional system: there are multiple valuable outputs that must be considered. Possible valuable outputs include biomethane, electricity, heat, digestate and CO_2.



Multifunctional co-product delivery by AD means that upstream emissions can be allocated to a mix of different coproducts via 'allocation' Most regulatory GHG reporting in the renewable energy sector adopts allocation by energy content (LHV) (following RED III principles) and this is also the approach used in this tool.

Allocation by energy content takes into account the efficiency of energy conversion for each output. For example, 1 MJ of biogas combusted in a CHP will typically only yield around 0.36 MJ of electricity, whereas 1 MJ of biogas sent for upgrading will generate close to 1 MJ of biomethane. Therefore, if an AD site generates 1 MJ of biomethane and 1 MJ of electricity, the allocation between the two products should not be 50:50 since the amount of biogas used to generate each is not split 50:50.

Allocation between co-products is shown under the *Digestion* worksheet. This is calculated from the biogas required to drive each product output divided by the total biogas generated in the system.

Digestate allocation

Emissions allocation between digestate and biogas is carried out as a first step in this tool, and then again between the biogas outputs (e.g. biomethane and exported electricity). Allocation is applied at the point a co-product is generated in a system and affects all emissions upstream from that point.

Allocation by energy content. Digestate can, in theory and after drying, be used as a solid fuel and would have an energetic value. This energetic value is used for allocation of digestate as a co-product, regardless of whether the digestate is used as a solid fuel or not.

The energetic value of digestate is calculated from the LHV of the dry matter, minus the energy needed to evaporate off the moisture[3]. This is sometimes referred to as the wet LHV.

Where the energy required to evaporate moisture in digestate is higher than the energy improvement gained from the dry matter content, this would generate a negative energy content. This is the case for digestate where the dry matter content is commonly below 12.04%. In these cases, the energy content is considered to be zero[4] and there can be no emissions allocation. It is typical for digestate to have a dry matter content below 12.04%, unless it is separated (e.g. by screw press or other techniques) into a solid and liquid fraction.

For this reason, the tool only considers allocation when the solid fraction of the digestate has an equivalent dry matter content of 25%. In this case, the solid fraction refers only to the fraction containing most of the aggregated dry matter (typically 25-35% DM). The dry matter of digestate refers to a theoretical fraction excluding any water content.

$$E_{LHV\ solid\ digestate} = (LHV_{dry} * M_{solid\ digestate} * \%_{DM\ solid\ digestate}) - (2.441 * M_{solid\ digestate} * (1 - \%_{DM\ solid\ digestate}/100\%)$$

Where:

$E_{LHV\ solid\ digestate}$ = the energy value of the solid fraction digestate (LHV) in MJ/year (cell E59)
LHV_{dry} = the LHV of the dry matter in a digestate, fixed in this work as 17.8333 MJ/kg_{DM}
$\%_{DM\ solid\ digestate}$ = the dry matter content of the solid fraction of digestate
2.441 = the latent heat of vaporisation of water at 25 °C in MJ/kg

An IF equation is used in the tool to ensure this defaults to zero in this case (cell E59).

Allocation by energy between biogas and digestate is then carried out as follows:

$$A_{digestate,\ energetic} = E_{LHV\ solid\ digestate} / (E_{LHV\ solid\ digestate} + E_{LHV\ total\ biogas})$$

Where:

$A_{digestate,\ energetic}$ = the energetic allocation factor, expressed in the Excel tool in %

This energetic allocation factor is shown in cell E60, if 'Allocation by energy content' is selected in the *LCA* worksheet (cell D10). However, a number of other approaches can also be modelled in ***Model*** mode, as explained below.

Surplus. Energetic allocation of GHG emissions between biogas and digestate can lead to very high allocations to digestate. It could be argued that the allocation to digestate is unfairly high, since biogas is the primary output (intention) of the process and the value of digestate is low in comparison. An alternative is to consider digestate as a waste or residue and ineligible

[3] Edwards et at (2017) Definition of input data to assess GHG default emissions from biofuels in EU legislation. European Commission JRC EUR 28349 EN, doi:10.2790/658143
[4] Edwards et at (2017) Definition of input data to assess GHG default emissions from biofuels in EU legislation. European Commission JRC EUR 28349 EN, doi:10.2790/658143

for emissions allocation. This is the 'Surplus' scenario, where in the first allocation step, zero emissions are allocated to digestate.

Allocation by economic value. Although not permitted in REDII or current RHI/GGSS GHG reporting, an alternative allocation method for digestate would be based on the economic market value of outputs, which can address issues associated with low intrinsic energy value. However, the downside to this approach is that the market value of outputs can change, so the analysis becomes very time/period specific.

Economic allocation of upstream GHG emissions is undertaken based on the market value of all the digestate generated, versus the market value of all the biogas outputs generated (i.e. biomethane, exported electricity and exported heat).

$$A_{digestate,\ economic} = £_{digestate} / (£_{digestate} + £_{biomethane} + £_{CO_2} + £_{electricity} + £_{heat})$$

Where:

$A_{digestate,\ economic}$ = the economic allocation factor for digestate, expressed in the tool as a %
$£_{digestate}$ = the value of digestate in £/year
$M_{digestate}$ = the mass of digestate generated in t/year
$£_{biomethane}$ = the value of biomethane generated in £/year
$£_{CO_2}$ = the value of CO_2 generated in £/year
$£_{electricity}$ = the value of electricity exported in £/year
$£_{heat}$ = the value of heat exported in £/year

Avoiding allocation

One approach recognised by LCA practitioners that can be adopted as an alternative to allocation of emissions is the substitution method, which involves identifying the products that are substituted by the co-product(s) and quantifying the environmental burdens associated with those products. The avoidance of these burdens is then credited to the main product under study. This method is also known as the 'avoided burden' approach or 'system expansion'

The credit for digestate needs to be manually added in the tool, based on the environmental impact of being substituted.

Allocation to biogas (as biomethane, heat or power)

To allocate emissions between biogas and digestate, the same approach is applied to each output, as shown in the *Digestion* worksheet. Allocation to biogas is not an option that can be independently selected in the tool, it will automatically follow the allocation scenario selected for digestate, though with some specific changes under certain scenarios as detailed below.

- Where allocation to digestate is by 'energy content', allocation to biogas is by energy content.
- Where allocation to digestate is 'surplus', 100% of emissions are allocated to biogas.

- Where allocation to digestate is by 'economic value', allocation to biogas is also economic (as is allocation to all associated biogas outputs – i.e. to biomethane, electricity or heat, which results in subdivision of upstream emissions reflecting the ratio of total economic output of each output).
- Where allocation to digestate is by substitution, 100% of upstream emissions are allocated to biogas and the substitution is handled as a separate issue in calculation of total emissions.

Allocation by energy content

$$A_{biogas,\ energetic} = E_{LHV\ total\ biogas} / (E_{LHV\ digestate} + E_{LHV\ total\ biogas}) = 1 - A_{digestate,\ energetic}$$

Where:

$A_{biogas,\ energetic}$ = the economic allocation factor, expressed in the tool as a %

Allocation by economic value

$$A_{biogas,\ economic} = (£_{biomethane} + £_{CO_2} + £_{electricity} + £_{heat}) / (£_{digestate} + £_{biomethane} + £_{CO_2} + £_{electricity} + £_{heat}) = 1 - A_{digestate,\ economic}$$

Where:

$A_{biogas,\ economic}$ = the economic allocation factor for biogas, expressed in the tool in %

Allocation of biogas to its products

Allocation of biogas emissions between its potential co-products is primarily based on allocation by energy in this tool (as per RED II and subsequent GGSS methodology). This therefore excludes any accounting for CO_2.where captured as a potential co-product when considering emissions allocation, although a CCS or CCU credit can be accounted for.

CO_2 as a co-product

As there is a commercial market for CO_2, there is also the potential to examine the impacts of allocations of upstream emissions to co-products of biogas upgrading, including any CO_2. Where emissions are partially allocated to CO_2 (i.e. by economic allocation), the remaining emissions are still allocated between the other biogas products by energy. This is possible because allocation to CO_2 only involves CO_2 and biomethane at the upgrading step, with other outputs (i.e. electricity and/or heat) unaffected.

Biogas, heat and electricity as co-products

For allocation of emissions by energy, there are several considerations where a biogas CHP and/or boiler is used on site. Firstly, for CHPs with exported electricity and exported heat, apportioning must take into account the efficient use of that heat[5]. Secondly, where some of

[5] For more information, see REDII Annex VI, B (Methodology), (d), (iii) & (iv)

the CHP or boiler energy is used for the AD process itself, this parasitic demand must be allocated correctly between the outputs.

In order to correctly allocate between exported electricity and heat from a biogas CHP, a CHP allocation factor is used.

$$A_{CHP\ (electricity)} = E_{electricity\ exported} / (E_{electricity\ exported} + (E_{CHP\ heat\ exported} * C_h))$$

$$A_{CHP\ (heat)} = (E_{CHP\ heat\ exported} * C_h) / (E_{electricity\ exported} + (E_{CHP\ heat\ exported} * C_h))$$

Where:

$A_{CHP\ (electricity)}$ = CHP-specific allocation factor for exported electricity (cell O46)
$A_{CHP\ (heat)}$ = CHP-specific allocation factor for exported heat (cell O47)
C_h = Carnot efficiency (fraction of exergy in the useful heat), which is 0.3546 for heat systems below 150 °C.

This CHP allocation factor is used to determine the amount of biogas required to generate the exported electricity and exported heat ouputs.

$$E_{LHV\ biogas\ for\ exported\ electricity} = A_{CHP\ (electricity)} * E_{LHV\ biogas\ for\ CHP} * (E_{electricity\ exported} / E_{electricity\ generated})$$

$$E_{LHV\ biogas\ for\ exported\ CHP\ heat} = A_{CHP\ (heat)} * E_{LHV\ biogas\ for\ CHP} * (E_{CHP\ heat\ exported} / E_{CHP\ heat\ generated})$$

Where:

$E_{LHV\ biogas\ for\ exported\ electricity}$ = the biogas required for exported electricity (LHV) in MJ/year
$E_{LHV\ biogas\ for\ exported\ CHP\ heat}$ = the biogas required for exported CHP heat (LHV) in MJ/year

The biogas required for exported CHP heat and electricity then allows the parasitic biogas demand to be calculated.

The amount of parasitic biogas is calculated from the total biogas going to the boiler and the CHP, minus the biogas that has been used to generate the exported outputs and minus the amount of electricity that was specifically used for biogas upgrading rather than the AD process in general.

$$E_{LHV\ biogas,\ parasitic} = E_{LHV\ biogas\ to\ boiler} + E_{LHV\ biogas\ for\ CHP} - E_{biogas\ for\ BUU\ electricity} - E_{biogas\ for\ boiler\ exported\ heat} - E_{LHV\ biogas\ for\ CHP\ exported\ heat} - E_{LHV\ biogas\ for\ exported\ electricity}$$

Where:

$E_{LHV\ biogas,\ parasitic}$ = the parasitic biogas used, in MJ/year (LHV)
$E_{LHV\ biogas\ for\ BUU\ electricity}$ = the biogas needed to generate the electricity used in the BUU

Allocating parasitic energy demand

Allocation factors are used to allocate the parasitic biogas and associated GHG emissions between different outputs. The allocation factors are calculated as the useable exported energy divided by the total exported energy. The total exported energy is calculated as follows:

$$E_{\text{total exported products}} = E_{\text{LHV upgraded biogas}} + E_{\text{exported electricity}} + (E_{\text{exported CHP heat}} * C_h) + (E_{\text{exported boiler heat}} * C_h)$$

Where:

$E_{\text{total exported products}}$ = the total energy in exported products in MJ/year.

The allocation factors are calculated as follows:

$$A_{\text{upgraded biogas}} = E_{\text{LHV upgraded biogas}} / E_{\text{total exported products}}$$

$$A_{\text{electricity exported}} = E_{\text{exported electricity}} / E_{\text{total exported products}}$$

$$A_{\text{CHP heat exported}} = E_{\text{exported CHP heat}} / E_{\text{total exported products}}$$

$$A_{\text{boiler heat exported}} = E_{\text{exported boiler heat}} / E_{\text{total exported products}}$$

Where:

$A_{\text{upgraded biogas}}$ = the allocation factor for upgraded biogas (biomethane for injection)
$A_{\text{electricity exported}}$ = the allocation factor for exported electricity
$A_{\text{CHP heat exported}}$ = the allocation factor for exported CHP heat
$A_{\text{boiler heat exported}}$ = the allocation factor for exported boiler heat

The biogas energy demand for each output, including the parasitic biogas demand, is calculated as follows:

$$E_{\text{LHV biogas allocated to electricity}} = E_{\text{LHV biogas for exported electricity}} + (E_{\text{biogas, parasitic}} * A_{\text{electricity exported}})$$

$$E_{\text{LHV biogas allocated to CHP heat}} = E_{\text{LHV biogas for exported CHP heat}} + (E_{\text{biogas, parasitic}} * A_{\text{CHP heat exported}})$$

$$E_{\text{LHV biogas allocated to exported boiler heat}} = E_{\text{LHV biogas for boiler heat}} + (E_{\text{biogas, parasitic}} * A_{\text{boiler heat exported}})$$

$$E_{\text{LHV biogas allocated to biomethane}} = E_{\text{LHV biogas for upgrading}} + (E_{\text{biogas, parasitic}} * A_{\text{upgraded biogas}})$$

In order to carry out the final allocation, a net efficiency factor is applied to the emissions associated with biogas.

$$\mu_{\text{exported electricity}} = E_{\text{electricity exported}} / E_{\text{LHV biogas allocated to electricity}}$$

$$\mu_{\text{CHP heat exported}} = E_{\text{CHP heat exported}} / E_{\text{LHV biogas allocated to CHP heat}}$$

Allocation of biogas for the biogas upgrading unit

Allocation of emissions to biomethane where no CO_2 is captured and stored/used, or where CO_2 storage/use is either disregarded (surplus) or treated as a credit (allocation by substitution) simply takes into account the net efficiency of conversion of biogas to methane.

$$A_{biomethane} = E_{LHV\ biogas\ for\ upgrading} / E_{LHV\ total\ biogas}$$

Where:

$A_{biomethane}$ = allocation to biomethane (shown as %)

Allocation to CO_2 as a co-product

As CO_2 has no calorific value, allocation of emissions to CO_2 as a co-product based on energy value is not possible.

Substitution. In REDII, the use of CO_2 as a co-product is addressed through substitution. Where the captured CO_2 is diverted to permanent storage (carbon capture and storage, CCS), or where it replaces fossil CO_2 (for example in carbonated beverages or dry ice), the mass of the CO_2 is deducted from the carbon footprint, thus it becomes a carbon credit.

In this case, the carbon credit from CO_2 is the same as the weight of CO_2 captured and stored or used. The weight of CO_2 captured is given in the *Models* and *Actuals* worksheets in tonnes, and converted into grams of CO_2 in the *Digestion* worksheet in cell E60.

Surplus. An alternative approach is to ignore CO_2 as a co-product; this is the 'Surplus' scenario. In this scenario there are zero emissions allocated to CO_2 and there is no carbon credit.

Allocation by economic value. Although not permitted in REDII or current GGSS reporting, an alternative GHG allocation method for any CO_2 capture would be economic allocation. Here, the emissions for energetic outputs are allocated by energy content, but the emissions for biomethane and between biomethane and CO_2 (from the upgrader unit) are based on economic value.

Economic allocation is carried out by considering the market value of all the CO_2 generated, versus the value of all the biomethane generated.

$$A_{CO_2,\ economic} = (£_{CO_2} * M_{CO_2}) / ((£_{CO_2} * M_{CO_2}) + (£_{biomethane} * E_{biomethane}))$$

Where:

$A_{CO_2,\ economic}$ = the economic allocation factor, expressed in the tool in %

Final allocation is as follows:

First, emissions per year are split between digestate and biogas. Allocation to digestate is not shown in the tool.

Allocation to biogas: this is carried out in the top section of the *Digestion*, *Manure*, *Waste*, *Residues* and *Crops* worksheets

$$e_{biogas} = e_{total\ annual} * (1 - (E_{LHV\ digestate} / E_{LHV\ digestate} + E_{LHV\ total\ biogas}) / E_{LHV\ total\ biogas}$$

Where:

e_{biogas} = the emissions attributed to biogas, in gCO_2eq/MJ_{biogas}
$e_{total\ annual}$ = the emissions from the whole process, in gCO_2eq/year

Allocation to biomethane:

$$(1 - A_{CO_2}) * e_{biogas} * \text{net efficiency biomethane}$$

Where:

$A_{CO_2} * e_{biogas} * \text{net efficiency biomethane}$

Glossary

AD – anaerobic digestion, a biological process that breaks down organic matter in the absence of oxygen and generates a biogas consisting largely of methane and CO_2.

Biogas – the unprocessed gas generated from AD, consisting of methane, CO_2 and other gases such as water vapour, nitrogen, ammonia and hydrogen sulphide.

CCU – carbon capture and use, sometimes called carbon capture and replacement (CCR). In AD, an example would be the capture of CO_2 from the biogas upgrading unit and its use in the manufacture of carbonated beverages.

CCR – carbon capture and replacement, see CCS.

CCS – carbon capture and storage. In AD, an example would be the capture of CO_2 from the biogas upgrading unit and its permanent storage (e.g. in a geological CO_2 storage site).

CI – carbon intensity [of a fuel, product or service], which is the greenhouse gas emissions associated with a fuel, product or service, expressed as their global warming potential in terms of equivalent weight of carbon.

GCV – gross calorific value, also referred to as HHV; see HHV.

GHG – greenhouse gas, a gas that contributes to global warming via the greenhouse effect.

GWP – global warming potential, a method of comparing greenhouse gases by their impact.

HHV – higher heating value, also referred to as GCV; the energy content of a fuel, described as ‘higher’ because it does not consider the fact that some heat is lost when condensing the water vapour generated during combustion of the fuel. See also LHV.

kWh – kilo Watt-hours, equivalent to

Nm³ – cubic meters of gas under normal conditions

LCFS – [California] Low Carbon Fuel Standard

LHV – lower heating value, also referred to as NCV; the energy content of a fuel, described as ‘lower’ because it considers the fact that some heat is lost when condensing the water vapour generated during combustion of the fuel. See also HHV.

MJ – megajoules

NCV – net calorific value, also referred to as LHV; see LHV.

RED – Renewable Energy Directive (2009)

REDII – The 2018 recast Renewable Energy Directive

scm – cubic meters of gas under standard conditions

upgrading – the process of removing contaminating gases from biomethane, mainly water vapour, CO_2 and hydrogen sulphide.

Definitions for equations

Percentage: yields, losses or compositions

$\%_{achieved}$ = percentage of capacity actually achieved (AD29)

$\%_{achieved}$ = percentage of capacity actually achieved (R25)

$\%_{biomethane}$ = the percentage of methane in the biogas (Q33)

$\%_{BUU\ loss}$ = the losses of methane in the biogas upgrading unit in % (Y28)

$\%_{CO_2\ lost}$ = the amount of CO_2 lost during CO_2 recovery (Y24)

$\%_{digestion\ yield\ achieved}$ = the achieved biogas yield as a percentage of the theoretical biogas yield

$\%_{DM\ digestate}$ = the dry matter content of the digestate

$\%_{feedstock,\ n}$ = the fraction of gas generated from feedstock n

$\%_{flared}$ = percentage of biomethane flared (AD21)

$\%_{fugitive\ methane\ digestion}$ = the percentage of total biogas generated that is lost in leaks from the digesters (Q35)

$\%_{loss,silage,n}$ = the fraction of feedstock lost during silage making

$\%_{loss,transport,n}$ = the fraction of feedstock lost during transport

$\%_{methane\ in\ biogas}$ = the percentage of methane in biogas (Q32)

$\%_{propane}$ = the percentage of propane in the gas for injection (AC37)

Greek letter eta: efficiency

$\eta_{transport\ efficiency,n}$ = the transport fuel efficiency of the vehicle used to transport feedstock n, as a fraction

$\eta_{electrical\ efficiency}$ = the electrical efficiency of the CHP (U22)

A: allocation factor

$A_{biogas,\ energetic}$ = the economic allocation factor, expressed in the Excel tool in %

$A_{biogas,\ economic}$ = the economic allocation factor for biogas, expressed in the tool in %

$A_{digestate,\ energetic}$ = the energetic allocation factor, expressed in the Excel tool in %

$A_{digestate,\ economic}$ = the economic allocation factor for digestate, expressed in the Excel tool in %

$A_{CHP\ (electricity)}$ = CHP-specific allocation factor for exported electricity (O52)

$A_{CHP\ (heat)}$ = CHP-specific allocation factor for exported heat (O53)

C_h = Carnot efficiency (fraction of exergy in the useful heat), which is 0.3546 for heat systems below 150 °C.

BMP: biomethane potential

$BMP_{feedstock,\ n}$ = the biomethane potential (BMP) of feedstock n in Nm^3/t_{VS}

C: capacity

C_{CHP} = installed capacity of the CHP in $kW_{electric}$ (R26)

$C_{gas\ for\ grid}$ = capacity of the grid entry unit to inject gas in scm/h (AD28)

DM: dry matter content

$DM_{digestate}$ = the dry matter content of the digestate in %

$DM_{feedstock,\ n}$ = the dry matter (DM) content of feedstock n as a % of total weight

D: distance

D_n = the distance travelled by feedstock n, in km

E (capitalised): energy

E_{AD} = total electricity required in kWh/year

$E_{LHV\ biogas\ for\ exported\ electricity}$ = the biogas needed for exported electricity (LHV) in MJ/year (F52)

$E_{LHV\ biogas\ for\ exported\ CHP\ heat}$ = the biogas needed for exported CHP heat (LHV) in MJ/year (F53)

$E_{LHV\ biogas,\ parasitic}$ = the parasitic biogas used, in MJ/year (LHV)

$E_{total\ exported\ products}$ = the total energy in exported products in MJ/year.

$E_{CO_2\ compression}$ = electricity required for the compression of CO_2 (only required if the site upgrades biogas to biomethane and compressed CO_2 for further use or storage) in kWh/year

$E_{demand,CHP}$ = electricity demand of the AD site supplied from a CHP, in kWh/year

$E_{digesters}$ = electricity required for digestion, including pumps and mixing, in kWh/year

$E_{ensiling}$ = emissions from ensiling in gCO_2eq/year

$E_{ensiling\ fuel,n}$ = the energy content of the fuel used for ensiling crop for feedstock n, in MJ/t (or l/t)

$E_{exported\ electricity}$ = electricity exported (beyond the AD system) in kWh/year

$E_{generated\ electricity}$ = electricity generated by the CHP, in kWh/year

$E_{HHV\ injected\ gas}$ = the energy content of the injected gas as GCV/HHV in MJ/year (AD35)

$E_{imported}$ = electricity demand of the AD site, supplied from the electricity grid

$E_{LHV\ biogas\ for\ upgrading}$ = the energy contained within biogas sent to upgrading in MJ/year (LHV) (T29)

$E_{LHV\ biogas\ for\ CHP}$ = biogas required for CHP in MJ (LHV) (R24)

$E_{LHV\ solid\ digestate}$ = the energy value of the digestate (LHV) in MJ/year (E59)

$E_{LHV\ upgraded\ biogas}$ = the energy contained within the upgraded biogas in MJ/year (LHV) (Y36)

$E_{LHV\ upgraded\ biogas}$ = the total energy content of the upgraded biogas in MJ/year (as LHV) (Y37)

$E_{parasitic\ electricity}$ = electricity used in the AD process itself, in kWh/year

$E_{transport\ fuel,n}$ = the energy content of the fuel needed for the transport of feedstock n, in MJ/tonne

$E_{upgrading\&injection}$ = electricity required for biogas upgrading and grid injection, including compression (only required if the site upgrades biogas to biomethane) in kWh/year

e (not capitalised): emissions

$e_{transport,n}$ = emissions from transport of feedstock n, in gCO_2eq/t

$e_{transport\ fuel,n}$ = emissions from the transport fuel used for feedstock n, in gCO_2eq/t

$e_{exhaust\ transport\ fuel,n}$ = emissions from the exhaust from the use of transport fuel n, in gCO_2eq/t

EF: Emissions factor

$EF_{fuel,n}$ = the emissions factor of the fuel used to ensile crop for feedstock n, in gCO_2eq/MJ

$EF_{transport\ fuel,n}$ = the emissions factor of the fuel used in the transport of feedstock n, in gCO2eq/MJ

$EF_{exhaust,n}$ = emissions factor from exhaust of the vehicle used to transport feedstock n, in gCO_2eq/km

GCV: energy content as gross calorific value

$GCV_{required}$ = the GCV (HHV) required by the gas grid (in this tool, this is assumed to be the same as the GCV achieved) in MJ/Nm^3

$GCV_{upgraded\ biogas}$ = the GCV of the upgraded biogas, typically around 36 MJ/NM^3 (Y34)

$GCV_{propane}$ = the GCV of propane

LHV: energy content as lower heating value

LHV_{dry} = the LHV of the dry matter in digestate, fixed in this work as 17.8333 MJ/kg_{DM}

M: mass

$M_{CO_2\ recovered}$ = the mass of CO_2 recovered in t/year (Y22)

$M_{crop,feedstock,n}$ = the mass of crop (from which feedstock n derives) needed for feedstock n, in tonnes/year

$M_{digestate}$ = the total mass of digestate required, in t/year

$M_{feedstock\ n}$ = mass of feedstock n required, in t/year

$M_{feedstock}$ = the total mass of feedstock required, in t/year

V: volume

$V_{biogas\ for\ upgrading}$ = the volume of biogas needed by the biogas upgrading unit (not listed)

$V_{gas\ for\ grid}$ = volume of gas generated for grid injection in Nm^3/year (AD31)

$V_{gas\ injected}$ = volume of gas actually injected in Nm^3/year (AD32)

$V_{propane}$ = volume of propane blended into gas for grid injection (Nm^3/year) (AC40)

$V_{upgraded\ biogas}$ = the volume of upgraded biogas from the biogas upgrading unit in Nm^3/year (Y34)

$V_{total\ methane}$ = the volume of methane needed to generate the outputs in Nm^3/year (Q38)
35.82 = the lower heating value (LHV) of methane in MJ/Nm^3

$V_{total\ biogas}$ = the volume of biogas needed to generate the outputs in Nm^3/year (Q36)

VS: volatile solids content

$VS_{feedstock,\ n}$ = the volatile solids (VS) content of feedstock n as a % of DM

$£_{digestate}$ = the amount of money an AD plant gets for digestate, in £/t
$M_{digestate}$ = the mass of digestate in t/year
$£_{biogas}$ = the value of biogas in £

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