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Valorisation of food waste to biogas
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VALORGAS

AD waste input energy model

An energy and emissions based tool for anaerobic digestion from waste inputs

Manual for use of the spreadsheet based tool

Revision [W7]

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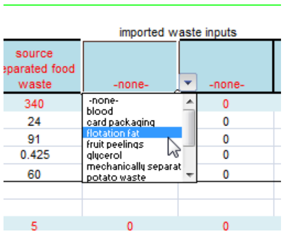
Introduction

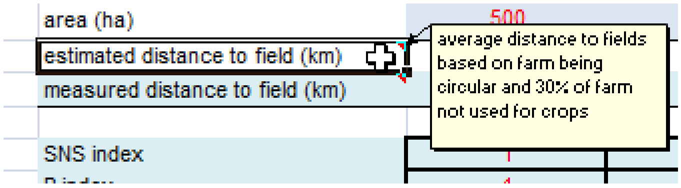
The various aspects of the energy tool have been combined into a spreadsheet based tool in order to allow for the calculation of potential energy balances and emissions using a waste based AD system. The tool enables the user to get a 'snap shot' view based on a single year but with the flexibility to easily change feedstock materials.

User inputs are indicated in the tool by red text

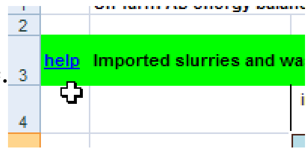
or drop down lists (red text, blue background and thick border).



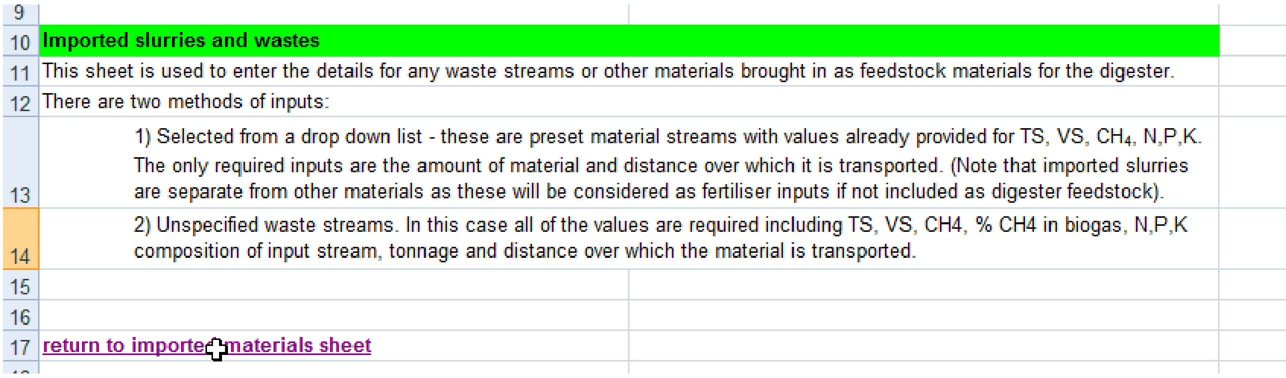
Some cells have a small red triangle in the top right corner. Placing the mouse pointer over the cell will cause a comment box to appear proving some help regarding the information in that row.



There are also various 'help' links which when selected lead to a help page.



Clicking on the relevant 'return' link from this page returns the user to the selected input sheet.



Further detail regarding the theoretical basis of the tool and associated data sources is available in VALORGAS Deliverable D6.3.

Imported materials

A number of specified import streams including wastes can be entered (Figure 1). Selection can be made from a range of animal slurries including cattle pigs and poultry. Once selected the only other inputs required are the amount and the distance. A range of preselected crop and other waste streams are also available. These also require tonnage and distance.
Finally the user is able to enter up to 5 waste streams of their own specification in which case the user is required to specify the amount, total solids, volatile solids (as proportion of total solids), methane yield and %methane in biogas. Anticipated nutrient values (N, P and K) for these streams are also required in order to provide information for the digestate analysis.

	A	B	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1		AD waste energy balanc					general help										
2																	
3	help	Imported slurries and w															
4			nported crop inputs			imported waste inputs				user inputs							
5		select type	-none-	-none-	source separated food waste	-none-	-none-	-none-	digestate liquor	1	2	3	4	5	total (excluding animal slurries & liquor)		
6		tonnage	0	0	30496	0	0	0	3,531	0	0	0	0	0	30496	tonnes	
7		TS (%)	0	0	24	0	0	0	2	0	0	0	0	0	24.0	%	
9		VS (% of TS)	0	0	92	0	0	0	54	0	0	0	0	0	92	% of TS	
11		methane yield	0	0	0.42	0	0	0	0	0	0	0	0	0	0.420	$m^3/kgVS_{added}$	
13		% methane in biogas	0	0	58	0	0	0	0	0	0	0	0	0	58	%	
15								waste type		solid	liquid	liquid	liquid	liquid			
16																	
17		pretreat before digestion	yes	yes	yes	no	yes	yes	no	yes	yes	yes	no	no			
18			0	0	30496	0	0	0	0	0	0	0	0	0	30496	tonnes	
19		pasteurise	yes	yes	yes	no	yes	yes	no	yes	yes	yes	no	no			
20			0	0	30496	0	0	0	0	0	0	0	0	0	30496	tonnes	
21																	
22		transport distance (km)	0	0	15	0	0	0		0	0	0	0	0			
23		transport method	select	select	Rigid <7.5t	select	select	select		Artic <33t	select	select	select	select			
24		**energy for transport**	**0.0**	**0.0**	**4081.7**	**0.0**	**0.0**	**0.0**		**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**4081.7**	**GJ**	
25																	
26		digestate values															
27		N	0	0	8	0	0	0	4.70	0	0	0	0	0	8.00	g/kg fresh weight	
28		P	0.00	0.00	1.3	0	0	0	0.35	0	0	0	0	0	1.30	g/kg fresh weight	
29		K	0.00	0.00	3.33	0	0	0	1.75	0	0	0	0	0	3.33	g/kg fresh weight	
30																	
31		N	0	0	8	0	0	0	4.70	0	0	0	0	0	8.00	kg/t fresh weight	
32		P_2O_5	0	0	2.99	0	0	0	0.80	0	0	0	0	0	2.99	kg/t fresh weight	
33		K_2O	0	0	3.996	0	0	0	2.10	0	0	0	0	0	4.00	kg/t fresh weight	

Figure 1: Imported material streams

If the user input waste stream is used, the type of waste (liquid or solid) should be selected (Figure 2). This is used in defining the parasitic electrical energy requirements.

	1	2	3
e-			
	23707	0	0
	11.26	0	0
	88	0	0
	0.416	0	0
	61	0	0
	liquid	iquid	liquid
	liquid solid		
	0	0	0
ct	select	select	select
	0.0	**0.0**	**0.0**

Figure 2: Manually inputted waste stream type

Options are available for pasteurisation and pre-treatment for each waste stream, these will have effect on the digester sheet. Select pre-treatment if the waste requires pre-sorting before entering the digestion system, This gives an energy value separate from the parasitic energy requirement for pre-treatment.

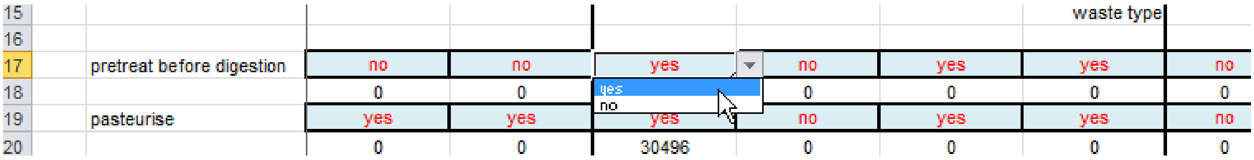


Figure 3: pre-treatment

Different waste streams may or may not require pasteurisation. Select if it is required for that stream Figure 3.

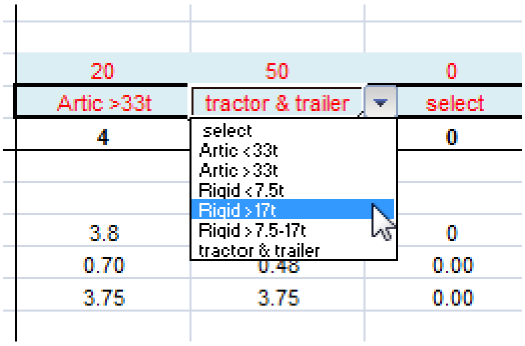


Figure 4: Selecting transport type

If transport energy is to be considered then distance over which the waste is transported to the digester can be specified. The amount of energy required will vary according to the type of transport used. It is possible to select from a range of lorry types based on the DEFRA/DECC guidelines for GHG factors for company reporting (DEFRA, 2009, AEA, 2010). Energy requirements for tractor transport are based on values from KTBL (2009). The type of transport is selected using the relevant drop down list as shown in Figure 4.

The digesters

From the amount of feedstock materials specified, the tool calculates the required digester size and energy requirements as shown in Figure 5.

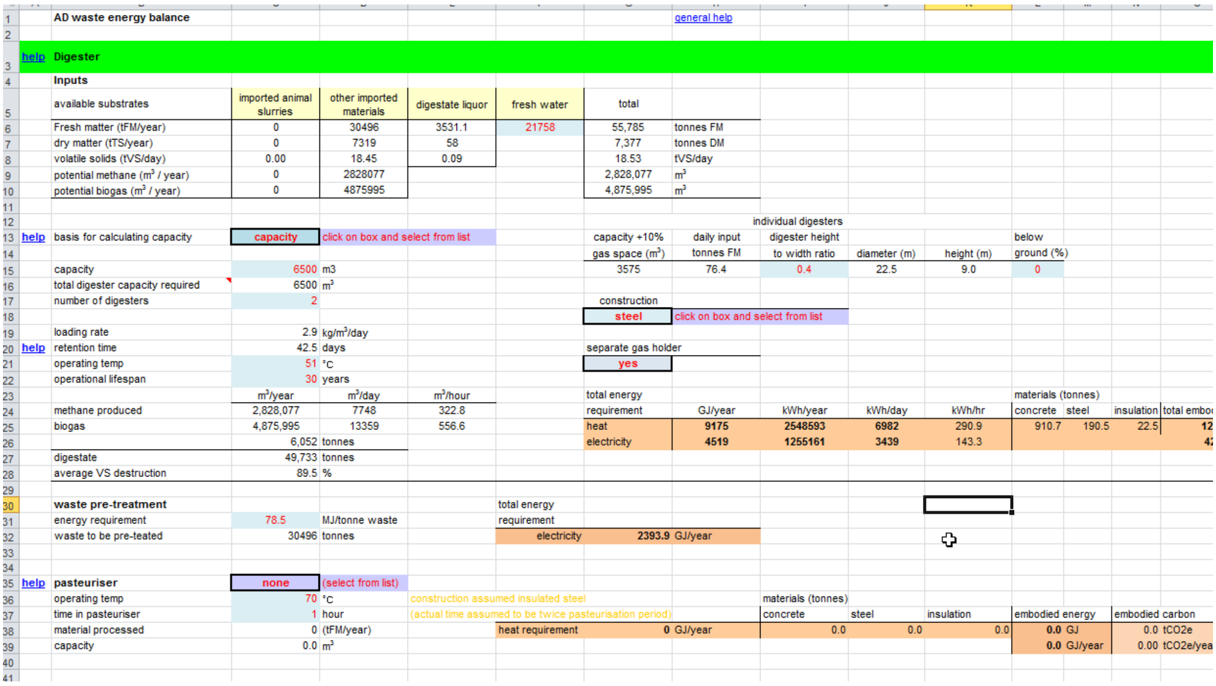


Figure 5: Digester capacity and energy requirements

Overall digester capacity here is calculated based on three options; capacity, loading rate or retention time. Research has shown that a loading rate in the region of 3kg VS/m^3/day is good for CSTR digesters using these types of feedstock materials. Overloading the digester can lead to a reduction in efficiency, methane output and stability. Retention time is also important because it determines the average length of time over which the material is held in the digester. If the retention time is too short then not all of the potential biogas will be released, leading to biogas being produced in the following stages of digestion, storage or after the digestate has been applied to fields. The capacity, loading rate or retention time can be selected as shown in Figure 6. If the selection criteria leads to unreasonable values these are indicated by warning messages. The values should then be reconsidered.

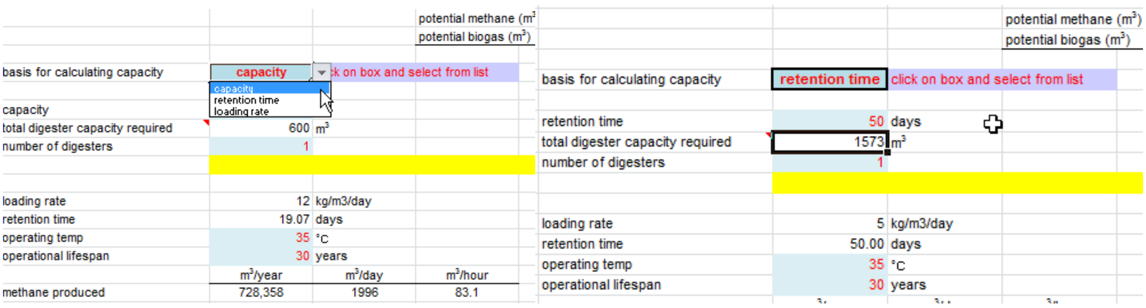


Figure 6: Selection of capacity criteria

The number of digesters over which this capacity is spread can also be specified, typically a single digester will not be larger than 3500 m^3. The user can specify if the digester is of steel or concrete construction and whether a pasteuriser is included. Energy requirement will be affected by the temperature the digester is operated at (which can be specified), embodied energy is calculated per year based on expected lifespan (which can also be specified).

A number of design options are available using the various input boxes.

The construction materials for the digester can be selected as either concrete based or steel based. A concrete digester is modelled as having a reinforced concrete wall and floor surrounded by an insulation layer and protective sheet metal skin. A flexible gas dome is modelled as the roof for the digester. A steel digester is modelled as a cylinder constructed of two layers of steel separated by a layer of insulation. The floor of the digester is constructed from reinforced concrete. In both designs 10% of the volume is added to the working volume for gas storage.

The height to width ratio and amount of digester buried below ground level can be input.

		individual digesters			
capacity +10% gas space (m³)	daily input tonnes FM	digester height to width ratio	diameter (m)	height (m)	below ground (%)
2731	31.5	0.25	24.0	6.0	0
construction					
concrete	click on box and select from list				

Figure 7: inputs for digester dimensions

Pasteurisation is an option either before digestion for materials selected as requiring pasteurisation in the imported materials sheet or for after digestion in which case all of the digestate is pasteurised. The heat requirements are calculated based on the different options, in the case of pre-pasteurisation it is assumed that the material requires no further heat before being added to the digester.

33												
34												
35	help	pasteuriser	none	elect from list)								
36		operating temp	none		construction assumed insulated steel			materials (tonnes)				
37		time in pasteuriser	pre	r	(actual time assumed to be twice pasteurisation period)			concrete	steel	insulation	embodied energy	embodied carbon
38		material processed	0	(tFM/year)		heat requirement	0 GJ/year	0.0	0.0	0.0	0.0 GJ	0.0 tCO2e
39		capacity	0.0	m³							0.0 GJ/year	0.00 tCO2e/yea
40			post									

Figure 8: Pasteurisation

Biogas storage can be done either in the digester, in which case 30% is added to the digester volume to allow for this or in a separate gas storage unit, in which case 10% is added to the working volume of the digester as freeboard. If a separate gas storage unit is specified then it is assumed to be spherical, constructed of two layers of PVC and situated on a reinforced concrete base. The size of the unit is determined by the maximum storage period required.

Separate gas storage							
storage period	2	hours		materials (tonnes)			
volume	166	m³	(spherical gas holder on concrete base)	concrete	steel	PVC	embodied energy
				23.0	2.0	31.8	56.7 GJ
							1.9 GJ/year

Figure 9: Biogas storage

Digestate storage facilities can also be specified. The storage period determines the volume of storage required and it is possible to specify the construction materials and whether a roof is included and, if so, its construction. The digestate storage is taken to be a cylindrical tank on a reinforced concrete base without insulation or heating.

Digestate storage									
storage period	6	months			materials (tonnes)			embodied energy	
storage requirement	4901	m^3	(digestate - assumes production even throughout year)		concrete	steel	PVC	GJ	GJ/year
number of tanks	1		individual tank height to width ratio	tank	535.2	34.6		1283.4	42.8
construction	steel		0.2	roof		0.0	175.0	175.0	0.5
roof	membrane						total	1458.3	43.3

Figure 10: Digestate storage

If pre-treatment of wastes has been selected (on the input materials sheet) then the total energy required for treatment is calculated based on a user input value (given initially as 78.5 MJ $tonne^{-1}$ waste).

29					
30	waste pre-treatment			total energy	
31	energy requirement	78.5	MJ/tonne waste	requirement	
32	waste to be pre-teated	30496	tonnes	electricity	2393.9 GJ/year
33					

Figure 11: pre-treatment

Many plants processing meat or animal based waste products will require compliance with animal by-product regulations including the provision of a building which separates input waste materials from digestates produced. The embodied energy of the building required is calculated based on user specified dimensions and assuming construction is a steel frame covered with corrugated steel cladding.

62	ABPR building							
63	length	20	L					
64	width	25	W	materials (tonnes)				
65	height (centre)	5	Hc	concrete	steel	galv steel	embodied energy	embodied carbon
66	height (walls)	3	H	294.8	10.01	5.9	542.2 GJ	61.73 tCO2e
67							18.1 GJ/year	2.06 tCO2e/year
68								
69								

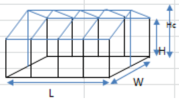


Figure 12: ABPR building

Digestate

The fertiliser value of the digestate is calculated on the basis of nutrients contained in the materials used for digestion with no losses.

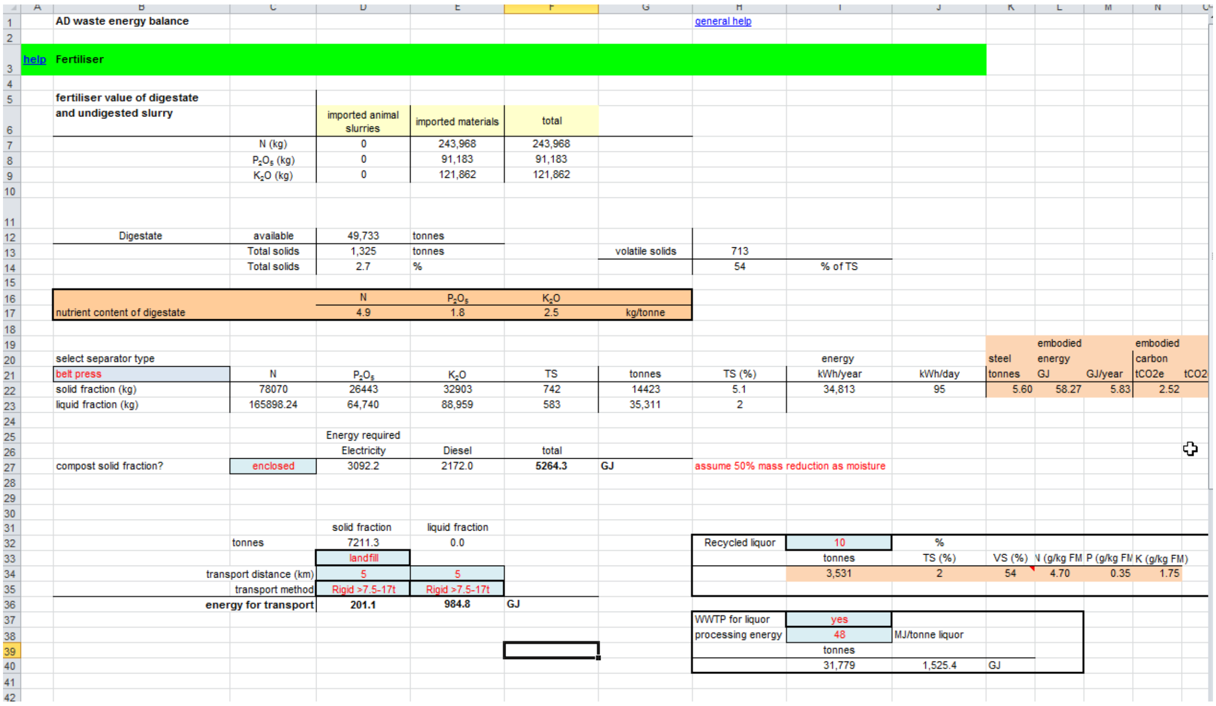


Figure 13: Digestate output

If on site separation is available then the potential separation of solids and nutrients can be determined using different types of separators. This also includes the energy requirement for the separator and embodied energy.

If separation is selected then this can be followed by composting for the fibre fraction. The composting can be either in open windrows or enclosed, each having different requirements for diesel and electricity as shown in

Table 1.

Table 1. Composting energy requirement

	electricity (MJ/t)	diesel (MJ/t)
enclosed	214.4	150.6
none	0	0
open	28.4	275.7

The separated liquor has three paths of use.

a) transported to fields for application

b) recycled to the digester to assist in the dilution of input feedstock, for this use the % of liquor recycled must be specified.

c) any liquor not recycled can be sent to a waste water treatment plant (WWTP) for treatment where it is assumed 48.3 MJ $tonne^{-1}$ liquor is required for the treatment process.

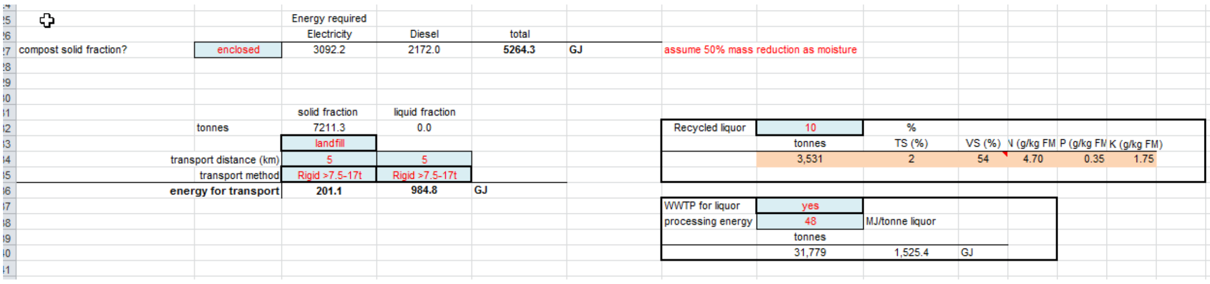


Figure 14. digestate treatment options

Energy requirement for the transport of each fraction of the digestate is calculated based on the type of transport and distance to be travelled.

Biogas use

Energy production is determined from the production and use of the biogas. Electrical energy requirement on-site can be supplied from the grid or through the use of on-site combined heat and power (CHP). The user can specify if the biogas is upgraded or upgraded and compressed. If on-site CHP is selected and no upgrading then it is assumed that all of the biogas is used for CHP (Figure 15).

Heat energy required can be supplied via an on-site boiler. If CHP is selected then there is the potential for heat generated to be used. The tool assumes that heat will initially be used for maintaining digester temperature and heating feedstock materials – any remaining heat is available for export. In this case it is possible to specify the expected heat utilisation (as a percentage of the heat available for export). If no on-site biogas use is selected then heat must be generated from other, imported fuel sources which can be selected.

Process losses (biogas lost before use in the CHP/upgrading) can be entered and are deducted from the potential total available.

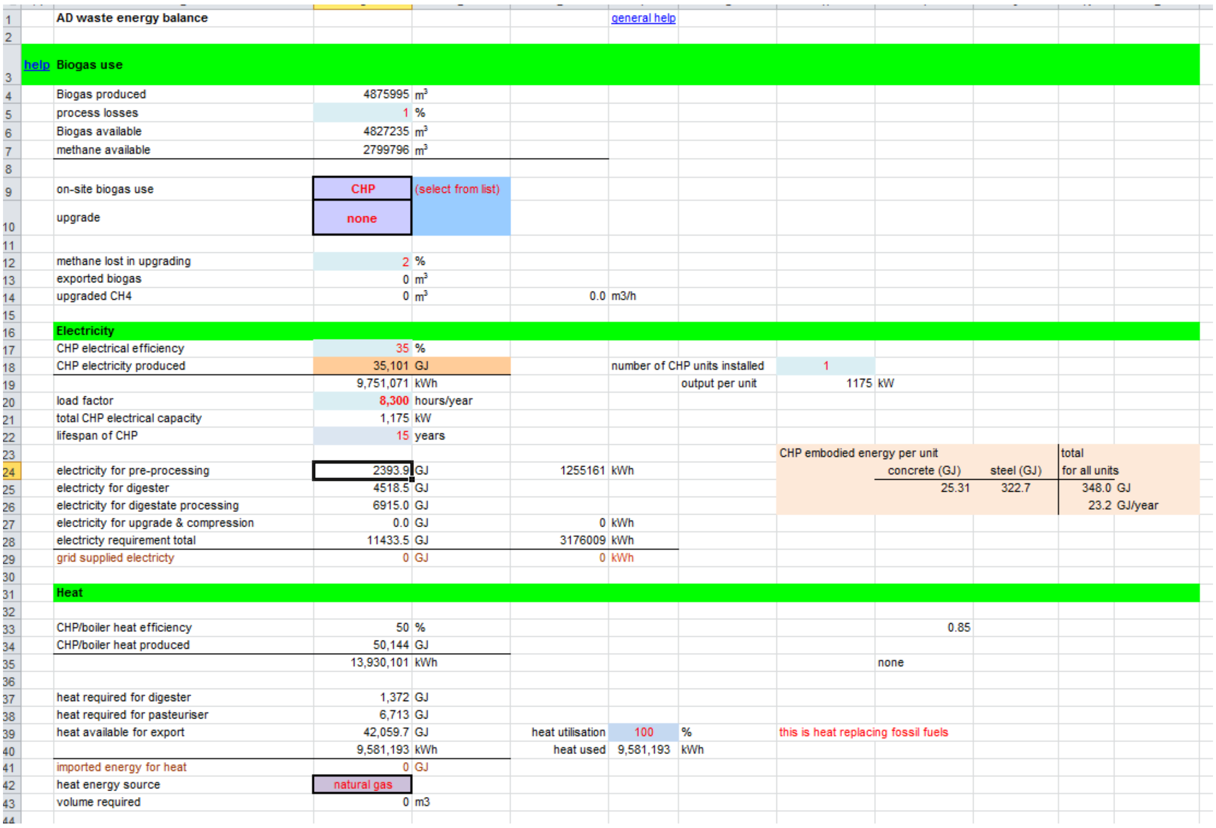


Figure 15: Use of biogas

Where CHP is not included it is assumed that heat and electricity are imported. In the case of electricity this is assumed to be from the national grid, in the case of heat the source can be selected from the drop down list (Figure 16).

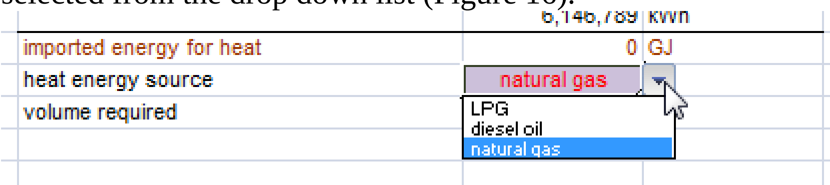


Figure 16: Heat energy sources

If upgrading is selected then the energy required for upgrading and for compression of the upgraded gas can be selected. These are user input with an initial value of 1.08 MJ m^{-3} gas.

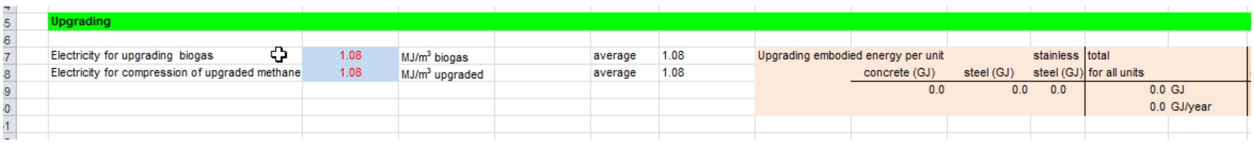


Figure 17: Upgrading and compression

Summary sheet

Finally, a summary is given of the energy requirements and balances and emissions produced and potentially saved (Figure 18).

help Summary

Energy		
digester input	55785	tonnes
digester loading rate	2.9	kg/m3/day
total digester capacity required	3575	m^3
retention time	43	days
methane produced	2828077	m^3
methane available	2799796	m^3
biogas	4875995	m^3
=	6052	tonnes
digestate	49733	tonnes
Energy balance (/year)		
pre-processing electricity	2393.9	GJ
digester electricity requirement	4519	GJ
electricity for upgrading	0.0	GJ
electricity for composting	6915.0	GJ
heat for digester	1372.1	GJ
heat for pasteuriser	6712.6	GJ
diesel for composting	2172.0	GJ
total	24084.2	GJ
embodied energy		
digester embodied	428.3	GJ
pasteuriser embodied	3.8	GJ
CHP embodied	23.2	GJ
upgrading embodied	0.0	GJ
gas holder embodied	6.7	GJ
ABPR building embodied	18.1	GJ
digestate storage	126.4	GJ
seaprator embodied	5.8	GJ
feedtank embodied	0.6	GJ
total	613	GJ
on-site boiler/CHP	CHP	
CHP electrical capacity	1,175	kW
energy in methane produced	101302	GJ
generated electricty	35101	GJ
generated heat	50144	GJ
imported electricity	0	GJ
imported heat	0	GJ
exported electicty	21274	GJ
	5910	MWh

Carbon		
diesel for composting	162.41	t CO_2 eq
embodied carbon (/year)		
digester embodied	15.58	t CO_2 eq
pasteuriser embodied	0.26	t CO_2 eq
CHP embodied	1.20	t CO_2 eq
upgrading embodied	0.00	t CO_2 eq
gas holder embodied	0.59	t CO_2 eq
ABPR building embodied	2.06	t CO_2 eq
digestate storage	14.00	t CO_2 eq
seaprator embodied	0.25	t CO_2 eq
feedtank embodied	0.08	t CO_2 eq
total	34.02	**t CO_2 eq**
process loss	547.2	t CO_2 eq
CHP emissions	5550.5	t CO_2 eq
grid electricity source	All fuels (including nuclear and renewables)	
imported heat source	natural gas	
imported electricity	0.0	t CO_2 eq
imported heat	0.0	t CO_2 eq
electricity generation replaced	2671.0	t CO_2 eq
export heat source replaced	natural gas	
	2401.9	t CO_2 eq
exported nitrogen	0	kg
potential emission savings	0.0	t CO_2 eq
upgraded gas		
energy source replaced	diesel oil	
	0	t CO_2 eq

Figure 18: Energy balances

If no CHP is provided it is assumed that all heat and electricity for the AD plant is imported from the national grid for electricity and selectable source for the heat (i.e natural gas, LPG, or diesel oil). When calculating the emissions resulting from the generation of electricity for the national grid, various options can be selected including generation from coal to all sources including renewable (Figure 19). Values used in the tool are based on UK electricity production and will vary for other countries according to the fuel sources used.

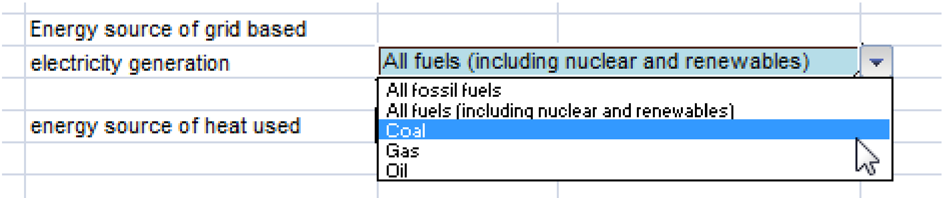


Figure 19: Sources for electricity generation

The emissions saved from exported energy are based on the same selected fuel sources. Emissions saved from the use of heat captured from the CHP are based on the amount of heat utilised as determined on the biogas use sheet. In both the case of electricity and heat the amount available for export is assumed to be that generated les the amount required for use at the AD plant including any biogas upgrading specified.

Temperatures

The temperatures sheet contains information relating to average monthly temperatures for the chosen location. The values used are those contained in column B. These values can be altered to match the users location. If the soil temperatures are unknown then a close estimate can be made by using the average air temperatures.

References for manual

AEA (2010) 2010 Guidelines to Defra / DECC's GHG Conversion Factors for Company Reporting. London, DEFRA.

DEFRA (2009) Guidance on How to Measure and Report Your Greenhouse Gas Emissions. London, DEFRA.

KTBL (2009) *Betriebsplannung Landwirtschaft 2008/09,* Darmstadt, KTBL.

Appendix: Calculation guide for spreadsheet version of AD modelling tool

AD tool calculation methods

Note: values in blue are pre-set default values
values in red are user specified

Feedstock

There are a number of pre-set feedstock streams. These can be edited but original values will not be remembered. Red values in the tables are estimates.

slurries_table

animal manure	TS%	VS%	CH4 (m^3/kg VS)	biogas CH_4 %	proportion fixed carbon	proportion converted	residual TS (%)	N (g/kg FM)	P (g/kg FM)	K (g/kg FM)	parasitic (kWh/t FM)
-none-	**0**	**0**	**0**	**0**	**0**	**0.00**	**0.0**	**0**	**0**	**0**	0
cattle - FYM	25	80	0.19	60	0.5	0.34	18.2	6	1.5	6.7	8
cattle - slurry	9	83	0.185	60	0.5	0.33	6.5	5.1	0.9	4.3	4
Pigs	5.5	82	0.26	60	0.5	0.46	3.4	5.0	2.2	3.3	8
poultry - broiler	60	75	0.3	60	0.5	0.54	35.9	30.0	4.7	12.5	8
poultry - layer	30	75	0.325	65	0.5	0.54	17.9	16.0	2.5	6.3	8

waste_table

	digestion values							nutrient content			
import stream	TS%	VS%	CH4 (m^3/kg VS)	biogas CH_4 %	proportion fixed carbon	proportion converted	residual TS (%)	N (g/kg FM)	P (g/kg FM)	K (g/kg FM)	parasitic (kWh/t FM)
-none-	**0**	**0**	**0**	**0**	**0**	**0.00**	**0.0**	**0**	**0**	**0**	**0**
blood	20	96	0.42	60	0.5	0.75	5.6	30	0.16	0.73	4
card packaging	93.9	83.6	0.266	60	0.5	0.48	56.6	1.35	0.126	0.21	20
flotation fat	21	93	0.59	60	0.6	0.88	3.9	16.1	1.7	2.27	4
fruit peelings	14.4	94.1	0.4	60	0.5	0.71	4.7	1.22	0.21	2.48	10
glycerol	99.5	99.5	0.425	60	0.5	0.76	24.4	0	0	0	4
mechanically separated BMW	53	63.5	0.35	60	0.5	0.63	32.0	8	1.15	2.25	40
potato waste	25	93	0.35	60	0.5	0.63	10.5	3.8	0.88	5.9	10
pre past SS food waste	24	92	0.42	58	0.45	0.86	5.0	8	1.3	3.33	4
rapeseed cake	90.3	94.7	0.43	60	0.5	0.77	24.6	38.2	6.2	8.14	10
salad waste	3	76	0.3	60	0.5	0.54	1.8	3.96	0.27	2.24	10
sewage sludge	6	65	0.26	60	0.5	0.46	4.2	1.5	0.42	0.2	10
source separated food waste	24	92	0.42	58	0.45	0.86	5.0	8	1.3	3.33	40
whey	6.1	90	0.45	51	0.5	0.95	0.9	1.5	0.46	1.65	4

crop_data table

	digestion values							nutrient removal			
	TS%	VS%	CH4 (m^3/kg VS)	biogas CH_4 %	proportion fixed carbon	proportion converted	residual TS (%)	N (g/kg FM)	P (g/kg FM)	K (g/kg FM)	parasitic (kWh/t FM)
-none-	**0**	**0**	**0**	**0**	0.5	0.00	0.0	**0**	**0**	**0**	**0**
fodder beet	20	88	0.4	55	0.5	0.78	6.3	1.8	0.4	4.2	10
fodder beet - leaves	16	82	0.37	55	0.5	0.72	6.5	3	0.3	4.2	8
grass silage (3 cut)	19.9	90.1	0.32	55	0.5	0.62	8.7	3.8	0.7	3.8	8
maize silage	30	94	0.35	55	0.5	0.68	10.8	3.8	0.7	3.8	10
spring barley wholecrop	35	94	0.35	55	0.5	0.68	12.6	3.5	0.5	3.8	10
sugar beet - beet	22	94	0.37	55	0.5	0.72	7.1	1.8	0.4	2.1	10
sugar beet - leaves	13	81	0.306	55	0.5	0.60	6.7	2.8	0.3	4.2	8
swedes - leaves	12	84	0.31	55	0.5	0.60	5.9	3.5	0.5	3.8	8
triticale wholecrop	39	94	0.335	55	0.5	0.65	15.1	3.9	0.9	4.0	10
winter oats wholecrop	30	86	0.295	55	0.5	0.57	15.2	5.3	1.0	7.8	10
winter rye wholecrop	31.7	93.2	0.32	55	0.5	0.62	13.3	3.5	0.5	3.8	10
winter wheat - wholecrop	35	94	0.35	55	0.5	0.68	12.6	3.5	0.5	3.8	10

note: keep firs column of each table in alphabetical order

Note: proportion of fixed carbon, proportion converted and residual TS are not used in this version.

Users can specify their own waste streams and need to select if they are liquid or solid (for parasitic energy requirements). Solid requires 40 kWh $tonne^{-1}$ and liquid 10 kWh $tonne^{-1}$ (default values).

Pre-treatment before digestion requires a (user specified) electrical energy requirement (default value 78.5 MJ $tonne^{-1}$ waste). This is separate to the parasitic electrical requirement for waste processed through the digester.

Whether the material needs to be pasteurised or not is selected and will affect the size of the pasteuriser (for pre-pasteurisation).

Transport energy can be calculated based on transport type and distance travelled.

fuel use in transport	$MJtonne^{-1}$ km^{-1}	$Ltonne^{-1}$ km^{-1}
select	0	
Artic <33t	2.07	0.058
Artic >33t	1.18	0.033
Rigid <7.5t	8.92	0.250
Rigid >17t	2.71	0.076
Rigid >7.5-17t	5.58	0.156
tractor & trailer	1.91	

Digester

The size, loading rate and retention time of the digester are interlinked and can be calculated based oneach of three variables:

***volatile solids loading*:**
total working capacity (m^3) = VS in feedstock (kg day^{-1}) / VS loading rate (kg m^{-3} day^{-1})
retention time (days) = capacity (m^3) / feedstock added (tonnes day^{-1})
(it is assumed feedstock has a density of $1tonnem^{-3}$)
***retention time*:**
total working capacity (m^3) = feedstock (tonnes day^{-1}) * required retention time (days)
VS loading rate (kg m^{-3} day^{-1})= VS (tonnes day^{-1}) * 1000 / capacity (m^3)
***total working capacity*:**
VS loading rate (kg m^{-3} day^{-1})= VS (tonnes day^{-1}) * 1000 / capacity (m^3)
retention time (days) = capacity (m^3) / feedstock added (tonnes day^{-1})

The operational capacity (actual digester vessels total volume) is then calculated based on the number of digesters (user specified) and the requirement for external biogas storage.
Individual working capacity of digesters (WCi) = total working capacity / number of digesters.
External biogas storage
individual operational capacity (m^3) = individual working capacity * 1.1
Internal biogas storage
individual operational capacity (m^3) = individual working capacity * 1.3

Individual digester dimensions:
The digester is assumed to be cylindrical with a height to width ratio (HWr) specified by the user (height of the working capacity, not the vessel height).
Digester diameter (m) = $(((\text{individual working capacity}/\pi)*(1/HW_r)/2)^{1/3})*2$
Digester height (m) = digester diameter/ $(1/HW_i)$
digester wall area (m^2) = π * digesterdiameter * digesterheight
digesterfloorarea (m^2) = $\pi * (\text{digesterdiameter}/2)^2$

digester roof area depends on selected construction type. A steel construction digester is assumed to have a circular, flat roof of the same construction as the digester; a concrete construction digester is assumed to have conical, membrane roof made of 2 layers of neoprene rubber.

Steel construction
digesterroofarea(m^2) = π * (digesterdiameter/2)^2

Concrete construction
roof height to width ratio = 0.2
digesterroofarea (m^2) = π*(digesterdiameter / 2)*√((digesterdiameter*0.2)^2+(digesterdiameter/2)^2)

Digester construction
Is user selected from either steel or concrete.
Steel - is assumed to be 6mm stainless steel surrounded by 300mm of polyurethane foam insulation and 3mm galvanised steel cladding on a square reinforced concrete base 300mm thick.
Concrete - is assumed to be 300mm of reinforced concrete, surrounded by 300mm polyurethane foam insulation and 0.7mm galvanised steel cladding on a square reinforced concrete base 300mm thick.

Embodied energy is based on volume of materials used and embodied energy values.

embodied energy and density	GJtonne^{-1}	Tonne m^{-3}	tonneCO2eq tonne^{-1}
concrete	1.03	2.4	0.163
reinforcing steel	10.4	7.8	0.45
sheet steel (galvanised)	22.6	7.8	1.54
stainless steel	56.7	8	6.15
insulation (polyurethane rigid foam)	101.5	0.036	4.26
neoprene rubber	90	1.23	2.85
PVC	77	1.41	3.1

(Hammond and Jones, 2011)

The embodied energy is calculated as a total for the digester then divided by a user defined lifespan to give an annual value. The embodied energy does not include construction or demolition of the digester.

Steel construction

walls
Stainlesssteel= π*digesterdiameter*digesterheight*(6/1000)* density [8 tonne m^{-3}] * energy [56.7 GJ tonne^{-1}]

insulation= π*(digesterdiameter +0.3)*digesterheight*0.3* density [0.036 tonne m^{-3}] * energy [101.5 GJ $tonne^{-1}$]
claddingsteel= π*(digester diameter+0.6)*digesterheight*(3/1000) * density [7.8 tonne m^{-3}] * energy [22.6 GJ $tonne^{-1}$]

roof
Stainlesssteel= π*$(digesterdiameter/2)^2$*(6/1000)* density [8 tonne m^{-3}] * energy [56.7 GJ $tonne^{-1}$]
insulation= π*$(digesterdiameter/2)^2$ *0.3* density [0.036 tonne m^{-3}] * energy [101.5 GJ $tonne^{-1}$]
claddingsteel= π*$(digesterdiameter/2)^2$*(3/1000)*density [7.8 tonne m^{-3}] * energy [22.6 GJ $tonne^{-1}$]

Concrete construction

walls
concrete= π*(digester diameter+0.3)*0.3*digesterheight * density [2.4 tonne m^{-3}] * energy [1.03 GJ $tonne^{-1}$]
reinforcing steel (2 layers = 20 rods per m height and 20 rods per m circumference, 12mm diameter)
= 2 * 20 * (π * digesterdiameter * digesterheight) * ((12/2)/1000)^2*π * density [7.8 tonne m^{-3}] * energy [10.4 GJ $tonne^{-1}$]
insulation= π*(digesterdiameter +0.6 + 0.3)*digesterheight*0.3* density [0.036 tonne m^{-3}] * energy [101.5 GJ $tonne^{-1}$]
claddingsteel= π*(digester diameter+1.2)*digesterheight*(0.7/1000) * density [7.8 tonne m^{-3}] * energy [22.6 GJ $tonne^{-1}$]

roof
neoprene rubber = roof area * 0.003 * density [1.23 tonne m^{-3}] * energy [90 GJ $tonne^{-1}$]

Base - for both constructions the base is assumed to be a reinforced concrete square, 300mm thick with 2 layers of 12mm reinforcing rod (40m m^{-2})at 100mm centres. 25% of the area is added as concrete for ancillary equipment.
concrete= digester $diameter^2$ *1.25*digesterheight*density [2.4 tonne m^{-3}] * energy [1.03 GJ $tonne^{-1}$]
reinforcingsteel= 40 * digesterdiameter * density [7.8 tonne m^{-3}] * energy [10.4 GJ $tonne^{-1}$]

Heat loss is based on the areas (m^2), temperature difference (ΔT in degrees K))between digester (user specified) and ambient (user specified) and heat transfer coefficients.

$hl = UA\Delta T$ where hl = heat loss, (kW)
U = overall heat transfer coefficient (W $m^{-2}K^{-1}$)
A = cross-sectional area through which heat loss is occurring (m^2)
ΔT = temperature drop across surface in question (K).

Heat transfer coefficients

construction materials	U (W m^{-2} K^{-1})
reinforced, insulated concrete	0.734
insulated steel	0.35
membrane roof	1.00

Heat loss is calculated on a monthly basis (using monthly averages for ambient temperature) and these are summed to give a total for the year.

Feedstock heat

The amount of heat required to raise the temperature of the feedstock to that of the digester depends on whether pasteurisation is included. The equation for calculating the heat required is:

heat required [GJ] = feedstock [tonnes day^{-1}] * 4.2 * ΔT [K] * days in month / 1000

where ΔT is the difference in temperature between the temperature required and ambient.

If there is no pasteurisation then the feedstock is heated to digester temperatureΔT = digester temp - ambient .

If there is post pasteurisation, the feedstock is heated to digester temperatureΔT = digester temp - ambient then the digestate is heated to pasteuriser temperatureΔT = pasteuriser temp - digester temp.

If there is pre pasteurisation then the feedstock is heated to pasteuriser temperature and no extra heat is requiredΔT = pasteuriser temp - ambient.

digester temperature (user specified)

pasteuriser temperature (user specified)

Pasteuriser

The pasteuriser is assumed to be a steel based insulated tank on a square concrete base 300mm thick reinforced with 14m m^{-2} steel rod 10mm in diameter. The volume is calculated by assuming that the pasteurised material is held at temperature for user defined period and that it takes the same period to load and unload the pasteuriser.

volume (m3) = daily load (tonnes day^{-1}) / (24 / (2 * pasteurisation period [hours])

Embodied energy calculations are then the same as those for a steel based digester.

Biogas holder

The biogas holder is assumed to be spherical and composing two layers of PVC 1mm thick, based on a concrete base 200mm thick reinforced with 10mm steel bars at 150mm spacing.

volume (m^3) = biogas production (m^3 $hour^{-1}$) * hours storage (user specified)

radius (m) = $((3*\text{volume})/(4*\pi))^{1/3}$

wall volume (m^3) = 4 * π * $radius^2$ * 0.002

embodied energy

PVC walls(GJ) =wall volume * density [1.41 tonne m^{-3}] * energy [77 GJ $tonne^{-1}$]

concrete base(GJ)= 0.2 * $(2 * radius)^2$ * density [2.4 tonne m^{-3}] * energy [1.03 GJ $tonne^{-1}$]

reinforcing steel(GJ) = 2 * (2 * radius)/0.15 * (π*0.005^2) * density [7.8 tonne m^{-3}] * energy [10.4 GJ $tonne^{-1}$]

Biogas use

The amount of biogas available is determined from the input materials. Process losses can be taken into account with a (user specified) percentage of biogas removed before usage calculations.
Biogas use is defined in two sections - on-site use and upgrading.

On-site use
there are three options, none, boiler and CHP

none - electricity is imported from the national grid, heat is provided by a (user selected) source: diesel oil, LPG, natural gas, petrol.
boiler - biogas is burnt with a combustion efficiency of 85% (default value) to provide heat. All electricity is imported from the national grid.
CHP - size calculated based on electrical efficiency (user specified).
electricity produced (GJ year $^{-1}$) = methane available (m^3 year $^{-1}$) * electrical efficiency (%) * 35.82 (MJ m^{-3}) / 1000
CHP electrical capacity (kW) = electricity produced (GJ year $^{-1}$) * 277.8 (kWh GJ^{-1}) / load factor (hours year $^{-1}$user specified)
CHP heat efficiency (%) = 85 [% default] - CHP electrical efficiency [% user specified]
heat produced (GJ year $^{-1}$) = methane available (m^3 year $^{-1}$) * heat efficiency (%) * 35.82 (MJ m^{-3}) / 1000

The CHP electrical capacity can be divided between a (user specified) number of units.
The electrical requirements of the site are summed and subtracted from the amount produced by the CHP unit. If the requirement is greater than supplied the difference is assumed to be imported from the national grid. The site requirement includes, pre-treatment of the waste, digester parasitic requirement, digestate processing, and upgrading and compression (if selected).

Grid supplied electricity (GJ) = CHP electrical output (GJ) - site electrical requirement (GJ)
Embodied energy of the CHP unit is based on weight of the unit calculated from the electrical generation capacity. The construction is assumed to be all steel and the unit stands on a concrete base 225mm thick and reinforced with two layers of 10mm diameter steel rod at 300mm centres (default values). The length and width (default values) of the base depend on CHP capacity:

CHP electrical capacity	<= 500kW	>500kW
length (m)	7	13
width (m)	3	3.5

CHP weight (tonnes) = (19.869 [kg/kW] * (electrical capacity [kW]/number of CHP units) + 7497 kW) / 1000

Concrete base

Embodied energy

CHP (GJ) = CHP weight [tonne] * energy [10.4 GJ tonne^{-1}]

concrete (GJ) = length[m] * width[m] * 0.225[m] * density [2.4 tonne m^{-3}] * energy [1.03 GJ tonne^{-1}]

reinforcing rod (GJ) = (width * (length/0.3) + length * (width/0.3)) * (π*0.005^2) * density [7.8 tonne m^{-3}] * energy [10.4 GJ tonne^{-1}]

Upgrading and compression

Can be selected as upgrading only or upgrading and compression and is independent of the on-site use.

No on-site use: all of the available biogas can be upgraded.

Biogas available (m^3) = total available (m^3)

*Boiler only use:*the amount of biogas required to provide the parasitic heat for digestion and pasteurisation is deducted from the total available

Biogas available (m^3) = total available (m^3) - ((parasitic heat[GJ]*1000/boiler efficiency [85%])/35.82 [MJ m^{-3}]) / methane in biogas (%)

CHP use: the CHP unit is sized electrically to deliver all of the on-site electricity demand including the upgrading and compression assuming a (user specified) conversion efficiency. CHP size is determined in 3 stages:

i) parasitic energy requirement

electrical requirement (GJ) = digester parasitic (GJ) + digestate processing (GJ) + pre-processing (GJ)

parasitic methane requirement (m^3) =

(electrical requirement (GJ)*1000/electrical efficiency (%))/35.82 [MJ m^{-3}]

biogas available (m^3) =

total available (m^3) - methane requirement (m^3) / methane in biogas (%)

ii) upgrading energy requirement

energy for upgrading (MJ) = biogas available (m^3) * 1.08 [MJ m^{-3}]

upgrading methane requirement (m^3) = energy for upgrading (MJ) / 35.82 [MJ m^{-3}]

upgradedbiomethane (m^3)= available methane (m^3) - parasitic methane requirement (m^3) - upgrading methane requirement (m^3)

iii) compression energy requirement

energy for compression (MJ) = upgraded biomethane (m^3) * 1.08 [MJ m^{-3}]

compression methane requirement (m^3) = energy for compression (MJ) / 35.82 [MJ m^{-3}]

Biomethane available after upgrading & compression (m^3) = upgraded biomethane (m^3) - compression methane requirement (m^3)

A user specified % of methane lost during upgrading & compression is applied to give a final, available biomethane value.

Biomethane available (m^3) = Biomethane available * (100 - % lost) (m^3)

Total CHP electrical requirement (GJ) = parasitic + upgrading + compression
CHP electrical capacity (kW) = Total CHP electrical requirement (GJ year^{-1}) * 277.8 (kWh GJ^{-1}) / load factor (hours year^{-1}user specified)

Embodied energy
Embodied energy is calculated based on the weight of the CHP unit, determined from the flow rate. The construction is assumed to be 50% steel and 50% stainless steel and the unit sits on a concrete base 225mm thick reinforced with 10mm diameter steel rod at 300mm centres.

upgrading capacity	<600 m^3 hour^{-1}	>600 m^3 hour^{-1}
length (m)	7	20
width (m)	3	3

Weight of upgrading unit (tonnes) = 30.1 * flow rate [m^3 hour^{-1}] + 6205
steel (GJ) = 0.5 * weight [tonnes] * energy [10.4 GJ tonne^{-1}]
stainless steel (GJ) = 0.5 * weight [tonnes] * energy [56.7GJ tonne^{-1}]
concrete (GJ) = length[m] * width[m] * 0.225[m] * density [2.4 tonne m^{-3}] * energy [1.03 GJ tonne^{-1}]
reinforcing rod (GJ) = (width * (length/0.3) + length * (width/0.3)) * (π*0.005^2) * density [7.8 tonne m^{-3}] * energy [10.4 GJ tonne^{-1}]

Digestate
The amount of digestate is based on what passes through the digester:
digestate (tonnes) = feedstock (tonnes) - biogas (tonnes).
The nutrient content of the digestate is assumed to be the total of nutrients in the feedstock including those in the recycled liquor.
nutrient (kg) = imported animal slurries (kg) + imported materials (kg) + digestate liquor (kg)
nutrient content (kg tonne^{-1}) = nutrient (kg) / digestate (tonnes)
There are a number of separation methods available with various efficiencies and energy requirements:

		separation efficiency	% of nutrient in solid fraction				
	flowrate	dry matter	N	P	K	volume reduction	specific energy
	m^3/h	%	%	%	%	%	kWh/m^3
belt press	3.3	56	32	29	27	29	0.7
decanter centrifuge	10	61	30	65	13	25	3.7
none	0	0	0	0	0	0	0
screw press	11	45	17	20	12	15	1.3
sieve centrifuge	3.7	33	18	15	21	17	4.5
sieve drum	14	41	18	18	17	18	1

The separator splits the digestate into fibre and liquor fractions with the solids and nutrients being divided according to the table.
Energy for separation (GJ) = digestate (tonnes) * specific energy (kWh tonne^{-1}) * 3.6/1000
Embodied energy is calculated based on the weight of the separator and assuming it is all made of steel. Weight is based on throughput in tonnes hour^{-1}.

It is assumed that the separator processes all of the digestate and works for 8 hours per day, 5 per week for 50 weeks = 2000 hours.
belt press weight (tonnes) = digestate (tonnes) / 2000 * 225.3 kg/1000
decanter centrifuge weight (tonnes) = (32.75 * digestate (tonnes) / 2000 + 1217) / 1000
screw press weight(tonnes) = (108.8 * digestate (tonnes) / 2000 + 404) / 1000
sieve centrifuge weight (tonnes) = assumed same as for decanter centrifuge
sieve drum weight (tonnes) = (11.74 * digestate (tonnes) / 2000 + 1913) / 1000
details of data used to derive these equations is in a separate excel workbook.
Embodied energy (GJ) = decanter weight (tonnes) * 10.4 GJ tonne^{-1}

If the digestate is separated, some of the liquor can be recycled back to the digester as feedstock. This leads to recalculation of the digestate contents. It is assumed that the liquor contains no digestible volatile solids so does not contribute to the biogas production.
Any liquor which is not recycled can be sent to a waste water treatment plant . The energy requirement for this is user specified with an initial value of 48 MJ tonne^{-1} liquor treated.
If the liquor is not treated it can be returned to the field as biofertiliser, energy requirement for transport is based on a user selected transport method and user specified distance using the same data for transport energy as for imported materials.
Separated fibre can be composted to reduce the amount of material that needs to be transported. The composting can be either in open rows or enclosed (user selected) and requires electricity and diesel.

composting energy requirement		
	electricity (MJtonne^{-1})	diesel (MJtonne^{-1})
enclosed	214.4	150.6
none	0	0
open	28.4	275.7

Energy required (GJ) = solid fraction (tonnes) * (electricity [MJ tonne^{-1}] + diesel [MJ tonne^{-1}]) / 1000
Unseparated digestate or separated fibre can be transported to fields for application or landfill using the same energy requirement criteria.

References

HAMMOND, G. & JONES, C. 2011. Inventory of Carbon & Energy (ICE). University of Bath.