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VALORGAS

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D6.3: Output from an energy and carbon footprint model verified against primary data collected as part of the research

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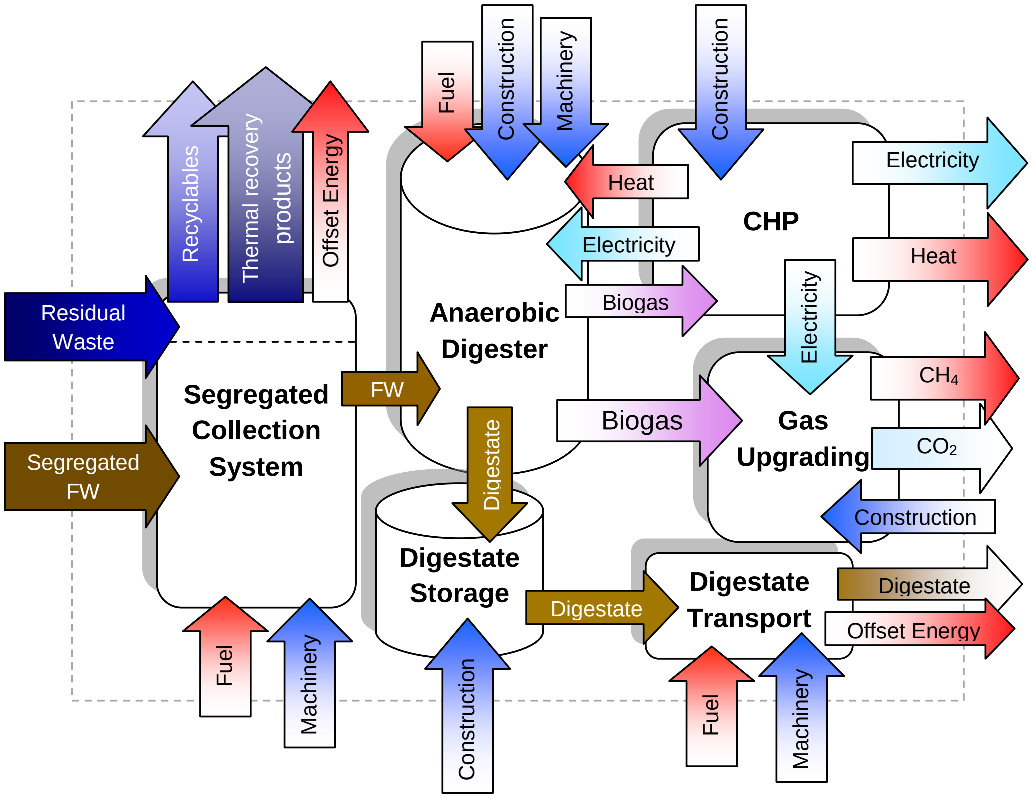


Contents

D6.3: Output from an energy and carbon footprint model verified against primary data collected as part of the research

1 Introduction

The aims of the work described in this deliverable report were firstly to provide a means for assessing the overall energy balance from collection, pre-processing and anaerobic digestion of food waste, through to utilisation of the digestate and the biogas fuel product; and secondly to apply this to selected scenarios to determine the benefits or otherwise from valorisation of source segregated domestic food waste to biogas.

For this purpose two tools were used: the collections model developed in deliverable D2.7 (VALORGAS 2013a), and a modelling tool for anaerobic digestion of organic wastes. The former was run with a range of scenarios to identify a 'typical' value for the extra energy requirement of source segregated food waste collection, which could then be used in assessing the energy balance for the whole system. The latter was based on a model originally developed in the FP6 CROPGEN project, and extended in the current research. The work made use both of literature data, and of results and experience gained during the VALORGAS project. Results from the two models were then combined to give a whole system assessment.

As VALORGAS is part of the FP7 Energy programme the modelling tools were primarily designed to calculate energy balances, while also considering some other resource and environmental parameters. A decision had been made at the project proposal stage not to attempt a full life cycle assessment (LCA) approach; the wisdom of this was confirmed by the results of deliverable D2.7. Energy, nutrients and greenhouse gas (GHG) emissions were selected, however, as capturing the most quantifiable components of LCA. The modelling outputs did not include economic costing, since this is highly subject to change with both time and location. Instead the main goal was to produce robust and reliable output data that could form a basis for economic and life cycle assessment, taking into account the specific conditions of a particular scheme.

The modelling work was not intended to identify a single 'optimum' configuration for collection and processing of source separated food waste: each scheme and location has particular characteristics and, while some options may generally be more efficient, it is unlikely that one ideal solution exists. In addition, the choice between different collection and processing options is rarely based on the energy balance alone, but must take into account many other societal and environmental factors. The purpose of the combined modelling tools is to provide a means of exploring the consequences of different options in terms of the key parameters of energy, GHG emissions and nutrients; and thus to support informed decision-making. The approaches adopted can also be used for research purposes, to identify areas where changes, in both engineering and policy terms, could bring about significant improvements in performance.

The main outputs from the research are thus the modelling tools themselves, and the conclusions from the typical scenarios considered. This deliverable report describes the second tool and presents examples of the use the two tools in combination to model selected scenarios: the results are not exhaustive or definitive, however, and it is hoped that these tools will be widely used in future to enable whole system analysis of energy production from anaerobic digestion of organic wastes.

2 Modelling energy consumption in source segregated food waste collections

In this part of the work, the WasteCAT tool developed in deliverable D2.7 (VALORGAS, 2013a) was used to determine the 'extra' energy requirement and GHG emissions for collection of source segregated domestic food waste under a variety of scenarios.

2.1 Assumptions

The case study carried out was based on a hypothetical group of 25,000 households, corresponding to a typical medium-sized town (Flacke, 2004). Each household was assumed to generate 2.5 kg day^{-1} of kerbside-collected waste, not including garden waste which was assumed to be composted or collected separately. The quantity of food waste, recyclables and residual waste collected was based on the percentage composition of kerbside-collected household waste, the capture rate and the set out rate for each waste, as described in deliverable D2.7. The values used are shown in Table 1: these were taken from a UK data source but it should be noted that the proportion varies and is typically higher in Mediterranean countries, making this a reasonably conservative assumption. For the current study, it was assumed that recyclable waste including paper, card, plastics, glass and metals were collected co-mingled, i.e. in a single recycling bin. Any waste not captured and set out for recycling or recovery is assumed to go into the residual waste bin: for example, when there is no source separated food waste collection all food waste goes in with residual waste.

Table 1. Assumed composition of kerbside-collected household waste used in the study (Adapted from Defra, 2009)

	Proportion in waste % weight	Capture rate [a] %	Set-out rate [b] %
Food waste	24.1	70	65
Co-mingled recyclables	45.3	75	100
Residual waste	17.15	100	100
Green waste	13.45	0	0

[a] Capture = waste presented for separate collection as a proportion of total household waste put out at the kerbside (WRAP, 2009); [b] Set out = proportion of households participating in the scheme

2.1.1 Collection scenarios

Seven collection scenarios were considered. Scenarios C1 and C2 are household waste collection without separate collection of food waste, at weekly or fortnightly intervals. Scenarios C3-C7 are household waste collection with separate food waste collection, with Scenarios C3 and C4 employing separate vehicles for each collection type and Scenarios C5-C7 adopting co-collection of different waste streams in twin-compartment vehicles. In all cases weekly collection of food waste was assumed, though in practice the necessary frequency will vary both from country to country and seasonally. These scenarios are only a small fraction of the range of options that can be modelled using WasteCAT, but were chosen to represent some commonly used schemes for waste collection. Details of the scenarios are shown in Table 2 and specifications for the collection vehicles chosen are given in Table 3.

Table 2. Collection scenarios

Scenario	Collection vehicle	Waste type	Frequency
C1	26t single	Residual waste	Weekly
	26t single	Co-mingle recyclables	Weekly
C2	26t single	Residual waste	Fortnightly
	26t single	Co-mingle recyclables	Fortnightly
C3	7.5t single	Food waste	Weekly
	26t single	Residual waste	Weekly
	26t single	Co-mingle recyclables	Weekly
C4	7.5t single	Food waste	Weekly
	26t single	Residual waste	Fortnightly
	26t single	Co-mingle recyclables	Fortnightly
C5	Twin 3	Food waste	Weekly
		Residual waste	Fortnightly
	Twin 3	Food waste	Weekly
		Co-mingle recyclables	Fortnightly
C6	7.5t single	Food waste	Weekly
	Twin 1	Residual waste	Fortnightly
		Co-mingle recyclables	Fortnightly
C7	26t single	Food waste	Weekly
	Twin 1	Residual waste	Fortnightly
		Co-mingle recyclables	Fortnightly

Table 3. Specification of the collection vehicles

	GVW (tonnes)	Payload (tonnes)	No. of compartments	Compartment size	
				Small (m^3)	Large (m^3)
7.5t single	7.5	3.58	1	5	--
26t single	26	12.84	1	25	--
Twin 1	26	10.58	2	10	10
Twin 3	26	10.88	2	6	14

2.1.2 Description of the household waste collection

For this study the waste collection activity was assumed to start at the depot, followed by travel to the designated collection area. Once the collection vehicle is full or the maximum service time is reached, it returns to a waste transfer station for bulking of the collected material. The exception to this is the case of a single collection vehicle collecting residual waste, which is assumed to take the material directly to a landfill site / incinerator and then return to the depot after unloading; a compartmentalised vehicle collecting residual waste is assumed to go to the transfer station for bulking of the waste before it is sent to the landfill/incinerator. It is assumed that all collected food waste is bulked at the transfer station and sent to the anaerobic digestion plant by lorry. A schematic of collection options indicating the vehicles used in different stages is presented in Figure 1.

2.1.3 Input values and embodied energy

The input values used in the WasteCAT modelling tool are shown in Table 4. For the current study it was assumed that the collection crew works 6 hours per day and five days a week. The average pick-up times for containers for food waste and for mixed recyclables or residual wastes were taken as 21.6 and 33 seconds per location, respectively (WRAP, 2009). The distance from the depot to the first and last collection points and from the last collection point to the landfill site was set at 5 km. The bulking point (transfer station) was assumed to be located at the depot.

Table 4. Input values used in modelling

	Values	Unit
Time		
Working hours	6	hour
Break	30	min
Traffic congestion	0	min
Pick up crew members	5	min
Fuel filling	10	min
Depot to first collection point	6	min
Last collection point to depot	6	min
At unloading site	30	min
Collection point to bulking when full	6	min
Bulking point to depot	0	min
Unloading at landfill site	15	min
Pick-up time for biowaste (i.e. food waste)	21.6	s
Pick-up time for mixed recyclables	33	s
Pick-up time for residual waste	33	s
Distance		
From depot to first collection point	5	km
From last collection point to depot	5	km
Between collection points	0.02	km
From last collection point to landfill site	5	km
Bulking to AD plant	15	km
Speed		
In collection	10	km $hour^{-1}$
In transportation	50	km $hour^{-1}$

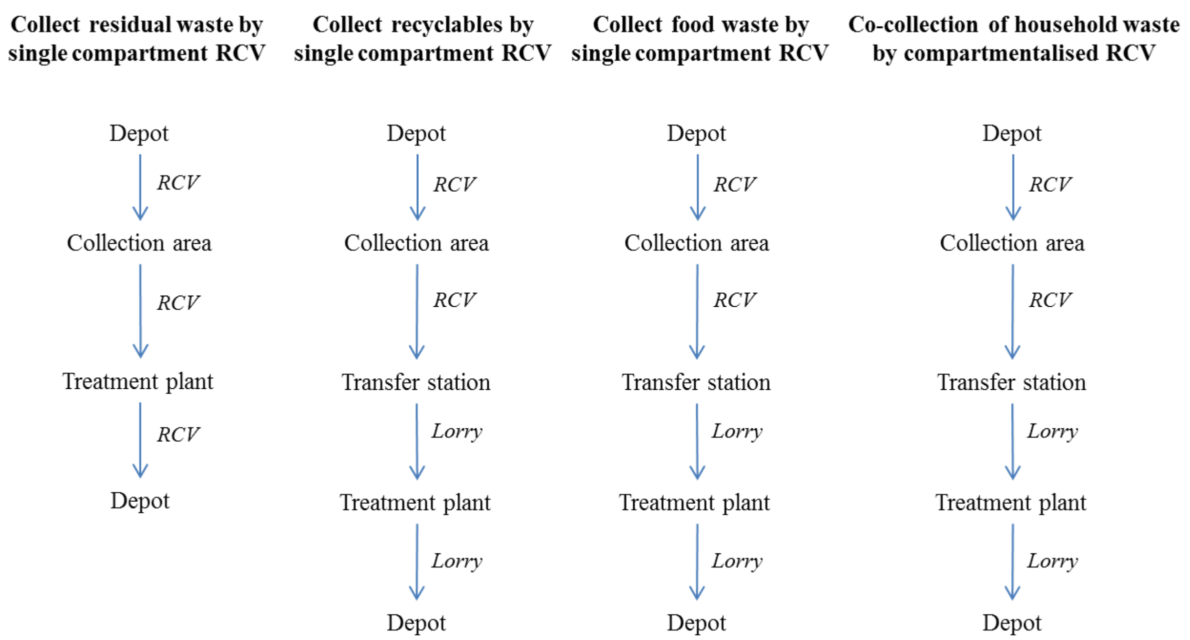


Figure 1. Schematic showing vehicle movements in household waste collection (RCV = refuse collection vehicle)

2.2 Results and discussion of WasteCAT collections modelling

The total amount of food waste collected and available for anaerobic digestion in the selected conditions is 2500 tonnes per year, equivalent to 45.5% of the total food waste generated and 11% of the total waste stream.

Energy difference with and without source separated food waste collection
Table 5 shows the number of vehicles required, service time, energy consumed as fuel and fuel-related GHG emissions in kerbside collection of the household waste stream. Scenarios C1 and C2 are the baseline values without separate food waste collection. The difference between the value for Scenario C1 or C2 and for Scenarios C3-C7 which include separate collection of food waste can thus be taken to represent the additional energy cost of separate collection for each set of conditions considered.

When compared with Scenario C2, based on fortnightly collections of recyclables and residual waste, the additional energy required to provide separate food waste collection in Scenarios C4-C7 was between 377.8-762.6 GJ $year^{-1}$. This is a 'like for like' comparison, providing the same level of service to customers in terms of the frequency of collection of recyclables and residual waste but with the addition of a weekly food waste collection. It should be noted, however, that when Scenarios C4-C7 are compared with Scenario C1 the introduction of a separate food waste collection leads to a decrease in the total energy required for collection of the household waste stream, because of the greater overall efficiency of the new system. When Scenario C1 is compared with the Scenario C3 an additional 776 GJ $year^{-1}$ is required to operate the same weekly service for residual waste and recyclables with the addition of separate food waste collection. In comparison with Scenario C2, with fortnightly collection of recyclables and residual wastes, Scenario C3 requires 80% more energy. One of the motives for introducing separate weekly food waste collections, however, is that it may allow a reduction in the frequency of collections of other wastes, which would clearly offer energy savings. Scenario C3 is therefore only likely to be chosen if there are other compelling reasons to offer weekly collection of recyclables and residual wastes, such as an acute shortage of storage space at the household in very densely-populated urban areas; and in this case Scenario C1 offers the best like-for-like comparison.

While this study considers only one set of scenarios out of a huge number of potential collection configurations and parameters, the model clearly provides a useful tool for investigating both specific cases and general performance. The results suggest that the 'additional' fuel energy requirement associated with the introduction of a separate food waste collection system of this scale and type is likely to be on the order of 500 GJ $year^{-1}$, or around 0.2 GJ $tonne^{-1}$ FW collected.

Fuel-based CO_2 emissions are directly proportional to the fuel use in collection and therefore present a similar pattern of increase or decrease as seen for energy use (Table 5). The additional fuel-based CO_2 emissions associated with the introduction of the separate food waste collection scheme in the study are on the order of 0.01-0.02 $tonne^{-1}$ FW collected.

The fuel consumption, number of vehicles and staff time determined in the modelling can be used directly as a basis for economic comparison of the different options according to the applicable labour costs, fuel prices and capital financing charges.

Table 5. Summary of fuel energy consumption, number of vehicles and time required for kerbside collection of the whole household waste stream

	Scenario						
	1	2	3	4	5	6	7
Basic output parameters							
Total no. of refuse collection vehicles required	13	11	18	12	14	10	9
Total time spent on collection and transfer (hours $year^{-1}$)	18749.2	10643.0	25606.2	16616.0	20948.7	14163.9	12963.8
Energy consumed from depot to transfer station (GJ $year^{-1}$)	2325.3	1509.4	2946.5	1839.8	1144.7	1276.6	1529.5
Energy consumed from transfer station to plant (GJ $year^{-1}$)	479.6	479.6	634.4	634.4	1222.1	1222.1	1222.1
Total energy consumed in collection and transfer (GJ $year^{-1}$)	2804.9	1989.0	3580.9	2474.2	2366.9	2498.7	2751.6
Total GHG emissions from fuel consumption (tonnes CO_{2eq} $year^{-1}$)	209.7	148.7	267.8	185.0	177.0	186.8	205.8
Extra time needed for separate FW collection							
Compared to Scenario 1 (hours $year^{-1}$)	-	-	6857.1	-2133.2	2199.5	-4585.3	-5785.3
Compared to Scenario 2 (hours $year^{-1}$)	-	-	14963.3	-8990.2	4332.6	-6784.8	-1200.0
Extra fuel energy needed for separate FW collection							
Compared to Scenario 1 (GJ $year^{-1}$)	-	-	776.0	-330.7	-438.1	-306.2	-53.3
(GJ $tonne^{-1}$ FW collected $year^{-1}$)	-	-	0.31	-0.13	-0.18	-0.12	-0.02
% of Scenario 1 collection energy	-	-	28%	-12%	-16%	-11%	-2%
Compared to Scenario 2 (GJ $year^{-1}$)	-	-	1591.9	485.2	377.8	509.7	762.6
(GJ $tonne^{-1}$ FW collected $year^{-1}$)	-	-	0.64	0.19	0.15	0.20	0.31
% of Scenario 2 collection energy	-	-	80%	14%	15%	22%	31%
Extra GHG emissions from fuel use in separate FW collection							
Compared to Scenario 1 (tonne CO_{2eq} $year^{-1}$)	-	-	58.0	-24.7	-32.8	-22.9	-4.0
Compared to Scenario 2 (tonne CO_{2eq} $year^{-1}$)	-	-	119.0	36.3	28.3	38.1	57.0

2.3 Embodied energy in collection vehicles and bins

The WasteCAT model does not include the embodied energy or GHG emissions in refuse collection vehicles or bins, since it is primarily intended as a tool for comparison of the 'costs' of collection schemes in terms of fuel usage and staff time (as running costs) and of vehicle numbers (capital costs), rather than for life cycle assessment. The additional embodied energy and GHG emissions associated with food waste collection can, however, be calculated and added into the overall energy balance.

Vehicles. Embodied energy and GHG emissions in the vehicles were estimated using the methods described in deliverable D2.7 and the values in Table 6.

Table 6. Energy and emissions factors for materials and assumed proportion of vehicle weight

Material	Energy factor MJ kg^{-1} material	GHG emissions factor kg CO_{2eq} kg^{-1} material	Assumed proportion of vehicle weight
Plastic	80.5	3.31	9.2%
Steel	35.4	2.89	75.6%
Glass	15	0.91	0.8%
Aluminium	155	9.16	14.4%

Energy and emissions factors shown in Table 6 were increased by 5% to allow for materials missing from the inventory, and by 20% for vehicle maintenance. To take account of the energy used in vehicle manufacture a further 80 GJ $vehicle^{-1}$ was added, equivalent to 13.71 tonnes CO_{2eq} $vehicle^{-1}$ based on the relevant UK electricity mix (VALORGAS, 2013a). For the purpose of this study the vehicles were assumed to have a 7-year lifespan typical of European conditions, although much longer working lives may be applicable elsewhere (UNEP, 2005; EUNOMIA, 2007). This gave the estimated values for embodied energy and GHG emissions shown in Table 7 and 8. It was assumed that a separate lorry would be used for each waste stream requiring transport from the transfer station.

Table 7. Estimated embodied energy and GHG emissions for each vehicle type

	7.5t Single	26t Single	26t Split	Lorry
Embodied energy of vehicle (GJ $vehicle^{-1}$)	359.7	1018.9	1158.8	919.0
GHG emission (tonne CO_{2eq} $vehicle^{-1}$)	32.6	77.0	86.4	70.3

Table 8. Estimated embodied energy and GHG emissions for each scenario

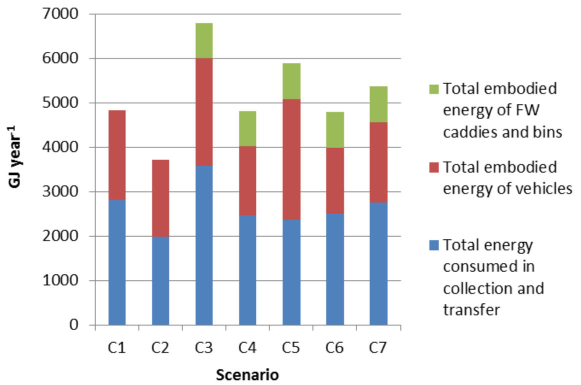
	C1	C2	C3	C4	C5	C6	C7
Embodied energy of vehicles (GJ $vehicle^{-1}$ $year^{-1}$)							
Collection vehicles	1892.28	1601.16	2149.19	1275.83	2317.52	1084.60	1409.93
Transfer lorries	131.29	131.29	262.58	262.58	393.87	393.87	393.87
Total for vehicles	2023.57	1732.45	2411.78	1538.42	2711.39	1478.47	1803.80
GHG emission (tonnes CO_{2eq} $vehicle^{-1}$ $year^{-1}$)							
Collection vehicles	143.02	121.02	166.28	100.27	172.88	85.01	105.75
Transfer lorries	10.04	10.04	20.08	20.08	30.12	30.12	30.12
Total for vehicles	153.06	131.06	186.36	120.35	203.00	115.12	135.87

Bins. In scenarios with separate food waste collection it is assumed that each household is provided with two polypropylene bins: a kerbside bin and a kitchen caddy. The assumed characteristics of the bins are shown in Table 9. These were based on those used in deliverable D2.7, except that the bin life time was taken as 7 years (Environment Agency, 2006; EUNOMIA, 2007) and energy used in distribution of the bins to households was not included. These values were used to calculate the total embodied energy and GHG emissions of the additional food waste bins.

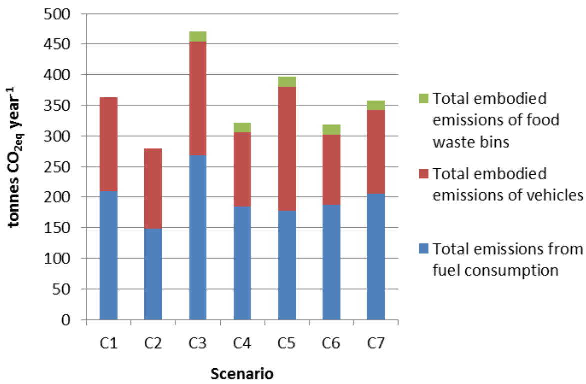
Table 9. Characteristics of bins

Parameter	unit	value
Weight of kerbside bin	kg	1.383
Weight of kitchen caddy	kg	0.398
Energy factor for polypropylene	MJ kg^{-1}	115.1
Embodied GHG emissions for polypropylene kerbside bin	kg CO_{2eq} kg^{-1}	4.49
Additional energy and emissions in manufacturing of bins	%	10
Embodied GHG emissions for polypropylene kerbside bin	kg CO_{2eq}	4.49
Assumed lifetime of bins	years	7

Figure 2 shows the energy used and GHG emissions for kerbside collection of the whole household waste stream including the embodied energy of vehicles and of food waste bins under different scenarios, while Table 10 presents the 'additional' energy required for separate food waste collection. In Scenarios C4-C7 the additional energy required is between 1061.0-2162.1 GJ $year^{-1}$. The embodied energy in additional food waste bins forms a large proportion of this, at 805.3 GJ $year^{-1}$. This result was also noted in deliverable D2.7 and confirms the view that the use of recycled plastic for bins could have a noticeable effect on overall energy balances. The 'additional' energy is also quite sensitive to assumptions made about collection vehicle type, number of lorries used in transport, vehicle lifespan etc: the current assumptions are reasonably conservative and as far as possible in accordance with common literature values and industry or manufacturers' data, but may not be applicable in all locations.



(a) collection scheme energy



(b) collection scheme emissions

Figure 2. Energy and emissions for whole waste collection scheme (including embodied energy of vehicles and additional food waste bins but excluding bins for recyclables and residual waste)

From Table 10, the 'additional' energy requirement for an efficient system in the conditions studied is around 1100 GJ $year^{-1}$; while the average for Scenarios 4-7 is on the order of 1500 GJ $year^{-1}$ or 0.6 GJ $tonne^{-1}$ FW collected. The corresponding 'additional' GHG emissions from the introduction of separate food waste collections are around 70 tonnes CO_{2eq} $year^{-1}$.

Best and worst collection systems for separate and co-collection of household waste
In terms of the additional energy required for separate food waste collection, Scenario C3 with weekly separate collection of food waste, residual waste and recyclables had the worst performance, using about 85% more energy than Scenario C6 which was the best system in this respect. The results for Scenario C4 provide a baseline for determining the difference between separate collection and co-collection of household waste.

For the purposes of this study, values of 1500 GJ $year^{-1}$ and 70 tonnes CO_{2eq} $year^{-1}$ will be taken forward to the next stage of the assessment as potentially typical of the 'additional' energy requirement and GHG emissions associated with introducing a separate food waste collection system of this scale and type. If recycled material is substituted for new plastic in the bins, the additional energy required could reduce to around 1100 GJ $year^{-1}$; the change in GHG emissions would be much lower. It is important to note, however, that values for both the total and 'additional' collection energy are dependent on the assumptions used in modelling, such as the housing density (distance between properties) and the distance to the AD plant. These are properties of the scheme considered, and cannot necessarily be improved or optimised: it is clear that collection and transportation of food waste will consume a higher amount of energy in a less densely populated area where travel distances are larger, or where the AD plant is located far away the collection scheme. The value of the WasteCAT tool is that it allows rational estimation of energy usage and other parameters in a given case, and comparison of the performance of a wide range of collection options. The total and 'additional' values including embodied energy and GHG emissions for vehicles and bins are considerably more speculative and depend on fundamental assumptions in the life cycle assessment approach.

2.4 Conclusions from collections modelling

To assess the energy demand associated with separate collection of food wastes it is necessary to analyse the collection of the whole waste stream, so that any collection energy saved through reduction in the quantity of residual waste is taken into account. This part of the study demonstrated the usefulness of the WasteCAT model as a tool for estimating the absolute and comparative energy consumption of schemes involving separate collection of food waste. The output from the model can be combined with literature data on the embodied energy and GHG emissions of waste collection vehicles and bins, to provide an estimate of the total 'additional' energy required for separate food waste collection. For the scenarios modelled in the current study, typical values for 'additional' collection energy and GHG emission were estimated as 1500 GJ $year^{-1}$ and 70 tonnes CO_{2eq} $year^{-1}$, and these will be taken forward to contribute to a whole system energy balance.

Table 10. Summary of energy and GHG emissions for kerbside collection of the whole household waste stream including embodied energy of collection vehicles and additional food waste bins

	Scenario						
	C1	C2	C3	C4	C5	C6	C7
Total energy consumed in collection and transfer (GJ $year^{-1}$)	2804.9	1989.0	3580.9	2474.2	2366.9	2498.7	2751.6
Total embodied energy of vehicles (GJ $year^{-1}$)	2023.6	1732.5	2411.8	1538.4	2711.4	1478.5	1803.8
Total embodied energy of FW caddies and bins (GJ $year^{-1}$)	0.0	0.0	805.3	805.3	805.3	805.3	805.3
Total energy used by collection system (GJ $year^{-1}$)	4828.5	3721.5	6798.0	4817.9	5883.6	4782.5	5360.7
Total GHG emissions from fuel consumption (tonnes CO_{2eq} $year^{-1}$)	209.7	148.7	267.8	185.0	177.0	186.8	205.8
Total embodied GHG emissions of collection vehicles (tonnes CO_{2eq} $year^{-1}$)	153.1	131.1	186.4	120.4	203.0	115.1	135.9
Total embodied GHG emissions of FW caddies and bins (tonnes CO_{2eq} $year^{-1}$)	0.0	0.0	16.4	16.4	16.4	16.4	16.4
Total GHG emissions of collection system (tonnes CO_{2eq} $year^{-1}$)	362.8	279.8	470.6	321.8	396.4	318.4	358.0
Extra energy needed for separate FW collection							
Compared to Scenario 1 (GJ $year^{-1}$)	-	-	1969.5	-10.6	1055.1	-46.0	532.2
(GJ $tonne^{-1}$ FW collected $year^{-1}$)	-	-	0.79	0.00	0.42	-0.02	0.21
% of Scenario 1 collection energy	-	-	41%	0%	22%	-1%	11%
Compared to Scenario 2 (GJ $year^{-1}$)	-	-	3076.5	1096.5	2162.1	1061.0	1639.2
(GJ $tonne^{-1}$ FW collected $year^{-1}$)	-	-	1.23	0.44	0.86	0.42	0.66
% of Scenario 2 collection energy	-	-	83%	29%	58%	29%	44%
Extra GHG emissions for separate FW collection							
Compared to Scenario 1 (tonne CO_{2eq} $year^{-1}$)	-	-	107.8	42.0	-74.1	-3.4	-38.4
Compared to Scenario 2 (tonne CO_{2eq} $year^{-1}$)	-	-	190.8	42.0	116.6	38.6	78.3

3 Energy balance modelling in anaerobic digestion – model description

Each part of the anaerobic digestion process has an energy requirement and related GHG emissions. By considering these it is possible to determine the net energy output and therefore the potential replacement of fossil fuel derived energy sources, with the associated reduction in long term GHG emissions. Modelling of the process allows comparison of the various options without extensive laboratory trials or expensive prototype and full-scale development.

The current project built upon previous work carried out in the EU FP6 CROPGEN project (www.cropgen.soton.ac.uk) and the RELU programme (www.AD4RD.soton.ac.uk), and reported in Salter and Banks 2009 and Salter et al. (2011), to derive a tool specifically for modelling the anaerobic digestion of organic wastes (Salter, 2013). This section of the report describes the model. The output was then validated by comparison with data from two full-scale AD plants monitored in the VALORGAS project; and the tool was subsequently applied to modelling a number of scenarios for anaerobic digestion of source segregated food waste based on information gathered in VALORGAS workpackages.

Once the collected waste has been delivered the waste processing system can be divided into four components (Figure 3), each of which can assume varying levels of complexity:

- pre-processing (waste sorting)
- digester (including feeding, mixing and emptying)
- biogas use
- digestate (including separation and composting).

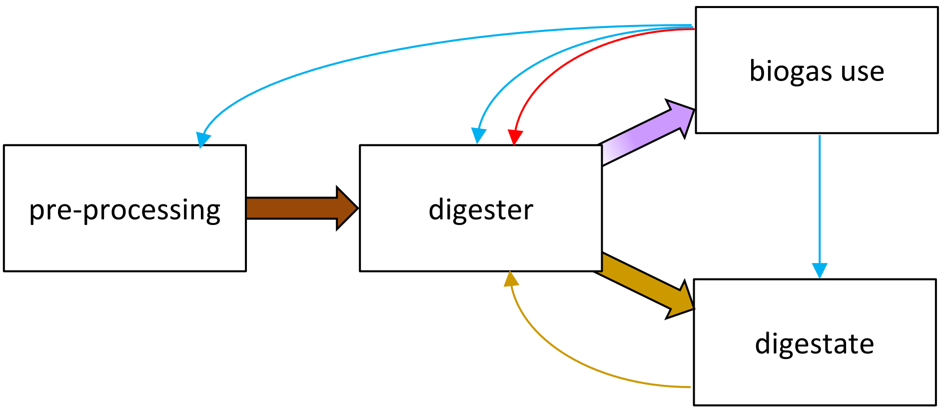


Figure 3. Main components of the waste processing system

Each of these can be divided into a number of sub-components for which energy requirements can be calculated. By comparing the energy requirements for the system against energy production it is possible to develop an energy balance, either as an overall total or per tonne of input material (waste). The basic input and output streams can be divided into energy (electricity, heat and embodied energy), plus material streams (feedstock and digestate) as shown in Figure 4.

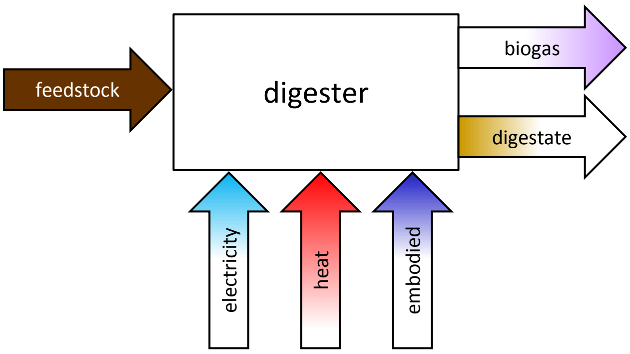


Figure 4. Inputs and outputs for a digester sub-system

Electricity is required to operate pumps, macerators, mechanical mixing systems, biogas upgrading, digestate separators etc. Heat is required to raise the temperature of the feedstock to that of the digester (and/or pasteuriser) and to maintain the digester at the required operating temperature. The embodied energy is that contained in the equipment and structures that make up the digestion plant. This will include concrete and steel for structure bases, reinforced concrete or steel and rubber or PVC used in digester construction and materials included in CHP units, upgrading plant and digestate separators. In order to give an annual embodied energy value the total for the relevant equipment is divided by the life expectancy of the equipment.

The tool allows modelling of different anaerobic digestion scenarios, including the processing of municipal solid waste. The application contains a range of pre-determined values (taken from personal communications and the literature) and calculations which enable the production of a potential energy balance for the input waste stream.

3.1 Input waste stream

A number of pre-determined waste streams are available for selection. These include source separated food waste, the key component in the current project; and also card packaging and biodegradable municipal waste (BMW), with values derived from Zhang et al. (2010). The default food waste characteristics are: TS 24% of FM, VS = 92% of TS, methane yield 0.42 m^3 CH_4 kg^{-1} VS_{added}, 8 g N kg^{-1} FM, 1.3 g P kg^{-1} FM and 3.33 g K kg^{-1} FM. These values were compared with those reported in deliverable D2.1 (VALORGAS, 2011) for food waste samples from Finland, Italy, Portugal and the UK, and were accepted as representative.

Each waste stream has an associated parasitic energy requirement for digestion, including any maceration and pumping required to get the feedstock into the digester. Values for this range from 4 to 40 kWh $tonne^{-1}$ fresh matter (FM) depending on the nature of the material (Chesshire pers. comm. 2012, Börjesson and Berglund, 2006).

3.2 Digester

Once the quantity and type of input materials have been selected the required working volume of the digester(s) can be calculated. This can be done on the basis of volatile solids loading, retention time or capacity.

volatile solids loading:
capacity (m^3) = VS in feedstock (kg day^{-1}) / VS loading rate (kg m^{-3} day^{-1})

retention time:
capacity (m^3) = feedstock (tonnes day^{-1}) * required retention time (days)

capacity:
as specified, loading rate and retention time are then calculated on this basis.

For construction and operational reasons digesters typically have a volume less than 3500 m^3. To control the volume of individual digesters, the number of digesters to be used for feedstock processing can be specified. The digesters are assumed to be all of the same size and construction, and the working volume is calculated by dividing the required capacity by the number of digesters. Having determined the working volume of a digester a decision is made on whether the biogas will be stored within the digester or separately. If separately then 10% of the working volume is added to allow some freeboard within the digester. If the gas is to be stored within the digester then 30% of the working volume is added for gas storage.

Digesters are assumed to be cylindrical with a user-specified height to width ratio. The main construction materials are either reinforced concrete surrounded with polyurethane foam insulation and protective galvanised steel; or stainless steel surrounded by polyurethane foam with a galvanised steel cover. Both types are assumed to have a reinforced concrete base. In the case of a concrete digester the roof is assumed to be a membrane cover constructed from two layers of neoprene rubber. From the dimensions and materials used in construction the embodied energy and carbon is calculated based on the information given in Table 11 (adapted from Hammond and Jones, 2011). A value of 25% of the calculated embodied value is added to allow for ancillary infrastructure.

Table 11. Embodied energies (Hammond and Jones, 2011)

	embodied energy (GJ $tonne^{-1}$)	density (tonne m^{-3})	embodied carbon (tonne CO_2eq $tonne^{-1}$)
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

Given the digester volume, shape and construction the heat loss can be determined. Heat requirements for digestion are made up of two components: heat required to raise the temperature of the feedstock to the digester operating temperature, and heat required to replace that lost through the surfaces of the digester. Heat loss is calculated using the equation

$hl = UA\Delta T$ where hl = heat loss, (kJ s^{-1})
U = overall coefficient of heat transfer, (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).

The coefficients of heat transfer used are shown in Table 12.

Table 12. Heat transfer coefficients

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

The energy required to raise the temperature of the feedstock to that of the digester depends on the ambient and digester operating temperatures and on whether pasteurisation is required. Pasteurisation can occur either before digestion or after. If before, it is assumed that any materials requiring pasteurisation are heated to 70 °C and require no further heating before being added to the digester. Any materials not requiring pasteurisation are added directly to the digester and require heating only to the digester operating temperature. In the case of post digestion the temperature of all of the digestate must be increased from digester operating to pasteurisation temperature. The heat energy required is calculated using the equation

$q = CQ\Delta T$ where q = heat required to raise feedstock to digester temperature, (kJ s^{-1})
C = specific heat of the feedstock (kJ kg^{-1} K^{-1})
Q = volume to be added (m^3)
ΔT = temperature difference, (K).

Pasteurisation is assumed to be a batch process. The material must be heated to 70 °C and maintained at this temperature for one hour. One further hour is allowed for loading and unloading the pasteuriser. The volume of the pasteuriser is therefore calculated as the daily feedstock volume requiring pasteurisation divided by 12. Pasteuriser construction is assumed to be insulated steel on a reinforced concrete base.

If a separate biogas holder is specified the volume is calculated on a user specified number of hours with a default value of 2 (Lewis, pers comm, 2013). The gas holder is assumed to be spherical in shape and constructed from two layers of PVC 1 mm thick on a reinforced concrete base 200 mm thick.

Some digester systems have a separate mixing tank installed before the digester. Users can specify the size of the tank by giving the number of days' feedstock supply to be held by the tank. The tank itself is assumed to be an unheated reinforced concrete tank in the shape of a cube.

If the Animal by-products Regulation (EC 1069/2009) (ABPR) applies then an ABPR-compliant building may be required. This is assumed to be a steel-clad on steel frame building standing on a reinforced concrete pad. The building is rectangular in shape with a central peaked roof. Length, width and height dimensions can be specified.

3.3 Biogas use

The amount of biogas produced is determined from information provided for the imported materials used for feedstock. Methane production is calculated based on the equation methane volume (m^3) = feedstock (kg) * TS (%) * VS (% of TS) * specific methane production (m^3 kg^{-1} VS added).

In this version of the AD tool it is assumed that the full methane potential as specified by the user is created and captured. Depending on the input values this may lead to an overestimate of total methane production, for example if biochemical methane potential values obtained from long-term batch testing are used.

The amount of biogas is then calculated by dividing the methane volume by the predicted methane in biogas percentage. Some biogas may be lost in the AD process before upgrading or combustion in the CHP unit, for example due to leaks between pipes or from the biogas storage; this is accounted for in the calculations through a user specified percentage biogas loss.

Various energy options are available in terms of how the biogas is used as shown in Table 13.

Table 13. Biogas use

		upgrading		
		none	upgrading only	upgrading & compression
energy generation	none	all of the biogas is flared, heat and electricity for the digester and upgrading processes, if selected, are imported		
	boiler	all of the biogas is burnt in a boiler to produce heat. The default value for efficiency is 85%. Excess heat can be exported	sufficient biogas is burnt in a boiler to provide the heat required by the digester and pasteuriser and the rest is upgraded. Electricity for the digester and upgrading processes are imported	
	CHP	All of the biogas is used in the CHP unit which is sized according to potential electrical output. Excess heat and electricity can be exported	Biogas is used in CHP unit which is sized to provide enough electricity for the digester and upgrading requirements. Excess heat can be exported. The rest of the biogas is upgraded.	

In the case of no upgrading, CHP units are sized according to electrical production based on the methane available, the load factor (number of hours per year in which the CHP unit is operational allowing for repairs and maintenance) and electrical conversion efficiency according to the equation:

CHP unit size (kW) = methane (m^3) * 35.82 (MJ m^{-3}) * 0.2778 (kWh MJ^{-1}) * conversion efficiency (%) / load factor (hours $year^{-1}$)

Conversion efficiency is user specified (default value 35%).

Where upgrading and/or compression occurs the CHP unit (if selected) is sized according to the parasitic requirements of the digester (based on CHP unit electrical efficiency) and electrical energy requirements for upgrading and compression. For biogas upgrading the energy requirement can be divided into two parts: upgrading to remove the impurities and compression if the upgraded gas is to be used for vehicle fuel. The energy requirement is in the form of electricity for pumps and the compressor. Values for upgrading vary from 0.3 to 0.67 kWh m^{-3} biogas (Electrigaz Technologies Inc, 2008) and between 3 to 6% energy in upgraded gas (Persson, 2003). Total energy for upgrading and compression has been given as

0.6 kWh m^{-3} upgraded gas (Kalmari, H, pers comm. Aug 2008 and VALORGAS, 2013b) and 0.75 kWh m^{-3} upgraded gas (Murphy et al., 2004). The default values used are 0.3 kWh m^{-3} biogas for the upgrading and 0.3 kWh m^{-3} gas for compression (Nijaguna, 2002, VALORGAS, 2013b). The modelling tool also allows input of user-specified values.

Energy output from gas upgrading is expressed in the form of upgraded biomethane (GJ or m^3) and of diesel equivalent (GJ or litres) where the net calorific value of diesel is taken as 35.73 MJ l^{-1} (AEA, 2010). It is assumed here that a user specified percentage (default 2%) of the methane is contained in the off-gas produced during the upgrading process. This leads to an equivalent reduction in the energy available as biomethane.

Where the electrical energy production is lower than that needed for the digester parasitic energy requirements (for example when the biogas is consumed in a boiler), electricity is assumed to be imported from the national grid.

Heat requirements for the digester and pasteuriser can be produced by combustion of the biogas in the CHP unit or boiler. In the case the overall efficiency of energy conversion of the CHP unit is assumed to be 85%. Heat energy produced is therefore calculated as 0.85 - electrical efficiency * energy value of methane available. Where the heat supply is insufficient extra heat is assumed to be provided by combustion of a user specified fuel in a boiler at an efficiency of 85%.

The embodied energy of the CHP unit is estimated based on example weights and power provided in the literature (GE-energy, 2013, MAN, 2013, Primas, 2007). Using this information the mass can be derived as a function of the electrical capacity using the equation

mass (kg) = 19.869 * capacity (kW) + 7497

This value includes a transport container and for simplicity it is assumed that the mass is all steel.

The container is assumed to stand on a reinforced concrete pad.

A similar process is applied where upgrading is included, based on literature values (HyGear, 2013, BioSling, 2013, Greenlane, 2013, Persson, 2003, Persson et al., 2006). In this case the mass of the upgrading unit is proportional to the capacity of the unit

mass (kg) = 30.1 * capacity (Nm^3 h^{-1}) + 6205

It is assumed that the upgrading unit is containerised, that the mass is half steel and half stainless steel, and that it also stands on a reinforced concrete pad.

3.4 Digestate processing

The amount of digestate produced is calculated from the total feedstock input minus the mass of biogas produced. The digestate is assumed to contain all of the nutrients (N, P, K) that were in the original feedstock material. The total solids content of the digestate is calculated on the basis that all of the biogas is produced from volatile solids, which themselves were part of the original total solids. The digestate solids content is calculated using the equation

digestate solids (%) = (feedstock (tonnes) * TS (%) - biogas (tonnes)) / digestate (tonnes)

The digestate can be left untreated or separated to reduce the moisture content, splitting the digestate into fibre and liquor fractions. The methods available for this include:

- belt press
- decanter centrifuge
- screw press
- sieve centrifuge
- sieve drum

each having an operational efficiency and energy requirement as shown in Table 14 (Burton and Turner, 2003). Embodied energy is determined based on a predicted weight for the separator derived from details given by manufacturers (Bernstad et al., 2013, Ekofinn, 2013, Vincent corp., 2013, EYS, 2013, PBS Velká Bíteš, 2013, GN Solids Control, 2013) and assuming that the construction is all steel. The separator is assumed to have an operating life of 10 years.

Table 14. Separator efficiencies and energy requirement

	flowrate	separation efficiency dry matter	N	P	K	volume reduction	specific energy
	m^3 $hour^{-1}$	%	%	%	%	%	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 fibre fraction of the digestate may be further processed by composting. This involves an energy requirement supplied by electricity and diesel, which is proportional to the amount of material processed and dependent on the type of composting, open windrow or closed vessel (van Haaren, 2009, Cabaraban et al., 2008, White, 2012, Martínez-Blanco et al., 2009, Finnvedan et al., 2000, Cadena et al., 2009, ROU, 2003). Values used are shown in Table 15. It may not be possible to return fibre fraction to land as a fertiliser/conditioner, due to quality standards or for other regulatory reasons. In this case the fibre fraction must be disposed of e.g. to landfill, which may involve a further requirement for transport.

Table 15. Energy requirement for composting

	electricity (MJ $tonne^{-1}$)	diesel (MJ $tonne^{-1}$)
open windrow	28.4	275.7
closed vessel	214.4	150.6

The liquor fraction may receive further processing in order to make it suitable for recycling or disposal to sewer, if land application is not possible. This has an energy requirement, which can be specified by the user based on the treatment applied.

3.5 GHG emissions

Where energy is expended there will be emission of greenhouse gases. The emissions in this report are presented as CO_2 equivalent which takes into account CO_2, CH_4 and N_2O. Each of these gases has a different global warming potential which can be converted to a CO_2 equivalent by multiplying the mass of each gas by a conversion factor. The relative global warming potentials are shown in Table 16, adapted from IPCC (2007) .

Table 16. Global warming potentials

CO_2	CH_4	N_2O
1	25	298

The emissions produced in the manufacture and supply of each of the embodied materials considered are shown in Table 11. The emission factors used for fuels and energy sources; where electricity, heat or transport fuels are required are shown in Tables 17 and 18.

Table 17. Energy values and emissions (AEA, 2010)

emissions from consumption of fuels	kg CO_{2eq} MJ^{-1}	NCV MJ l^{-1}
diesel oil	0.075	35.73
LPG	0.064	23.33
natural gas	0.057	35.50
Petrol	0.071	32.85

Table 18. GHG emissions for electricity generation (DECC, 2010)

	tonne CO_{2eq} GWh^{-1}	kg MJ^{-1}
All fossil fuels	598	0.166
All fuels (including nuclear and renewables)	452	0.126
Coal	915	0.254
Gas	405	0.113
Oil	633	0.176

The emission factor for the CHP unit is taken as 0.0553 tonne CO_{2eq} GJ^{-1} biogas consumed (IPCC, 2006). This is mainly CO_2 resulting from combustion plus some unburnt CH_4 and N_2O. The off-gas from the upgrading unit is assumed to be added to the biogas supplied to the CHP unit so does not contribute further to GHG emissions.

Digestate provides a source of nutrients which can be used in crop production. Unlike animal slurries, which are returned to land as part of the farming operation, food waste has not generally been applied to land, but has typically been deposited in landfill or destroyed. In these cases the nutrients removed from the soil are not returned and must be replaced using alternative sources, usually in the form of fossil fuel based mineral fertilisers. The digestate can therefore be considered as a replacement for mineral fertilisers and can substitute the GHG emissions produced during their manufacture. The values of energy required and GHG emissions resulting from the manufacture of mineral fertilisers are shown in Table 19.

Table 19. Fertiliser energy and emissions

	N	P_2O_5	K_2O
GHG (kg CO_2eq kg^{-1})	7.01	1.665	1.735
production energy (MJ kg^{-1} product)	40.3	3.4	7.3
packing & transport (MJ kg^{-1} product)	2.595	2.595	2.595

4 Validation of anaerobic digestion energy balance model

Validation of the anaerobic digestion energy balance modelling tool was carried out by comparing its output with the results from two full-scale AD plants monitored in the VALORGAS project.

4.1 Validation of mesophilic simple AD plant

The tool was used to model a mesophilic, simple AD system which could be compared with the South Shropshire biodigester reported in deliverable D4.2 (VALORGAS, 2012b). Default values were used, apart from for the annual tonnage of source separated food waste (3572 tonnes), the digester size (801 m^3 working volume), the operating temperature (40.2 °C) and the electrical efficiency of the CHP unit (32%). Ambient temperatures for the town of Ludlow were taken from Meoweather.com (2013). A comparison of the results of the modelling with those presented in deliverable D4.2 is given in Table 20.

Table 20. Model of South Shropshire biodigester

	units	model	D4.2	model with reported data
waste	tonne $year^{-1}$	3572	3572	3572
TS	% of FM	24	27.8	27.8
VS	% of TS	92	88.5	88.5
methane yield	m^3 CH_4 kg^{-1} VS	0.42	0.422	0.422
loading rate	kg VS m^{-3} day^{-1}	2.7	2.9	3.0
methane yield	m^3 $year^{-1}$	332830	355342	368766
CHP electrical capacity	kW	128	195	141
Parasitic electricity	GJ $year^{-1}$	514	768.3	514
parasitic heat	GJ $year^{-1}$	1146	1397	1146

The results show good agreement with those recorded in deliverable D4.2. The parasitic electrical requirement is higher in deliverable D4.2 as it includes electricity for offices and demonstration rooms not included in the modelling. The parasitic heat requirement in the model is slightly lower than that reported. Electrical capacity at the plant is higher but this is due to a difference in the method of calculation. The plant has a fixed-capacity installed unit, the size of which will have been based on predicted biogas production allowing for temporal variation and changes in the feedstock. The model does not take these factors into account, but works on the basis of a continuous potential methane yield with no allowance for day-to-day variation. The electrical capacity required based on modelling is also based on 95% CHP availability. Using the reported values for feedstock characteristics in the model increases the methane yield to 368766 m^3, and the CHP unit to 141 kW.

4.2 Validation of thermophilic complex AD plant

The tool was used to model a complex thermophilic system as reported for Lisbon, Portugal in VALORGAS deliverable D4.3 (VALORGAS, 2012a). This system involves pre-processing, digesters operating at 50 °C and post digestion processing including dewatering and composting. Temperatures in the model were set to average Lisbon values (World Weather online, 2013) and the digester capacity was defined by specifying it as equal to that of the Valorsul plant, with two digesters of 3800 m^3 each. A comparison of the results is presented in Table 21.

Table 21. A thermophilic, complex plant

	units	model	D4.3	model with reported data
waste	tonne $year^{-1}$	30496	30496	30496
added water	tonne $year^{-1}$	21758	21758	21758
TS	% of FM	24	28	28
VS	% of TS	92	87.3	87.3
methane yield	m^3 CH_4 kg^{-1} VS	0.42	0.408	0.408
loading rate	kg VS m^{-3} day^{-1}	2.8	1.6 [a]	3.1
methane yield	m^3 $year^{-1}$	2828077	3042459	3041412
CHP electrical capacity	kW	1175	1600	1263
Electricity produced	GJ	35101	30456	37749
Parasitic electricity	GJ $year^{-1}$	13280	11588	13410
parasitic heat	GJ $year^{-1}$	8681	7904	8681
diesel for composting	GJ $year^{-1}$	3207	0	0

[a] Based on post-processed feed to digester (VS lower due to solubilisation); equivalent to 2.94 kg VS m^{-3} day^{-1} based on gross VS input to plant

The parasitic heat requirement in the model is slightly higher than that reported for the plant, due to the fact that the model currently does not include heat recirculation. The Valorsul plant uses electricity only in its composting so there is no diesel requirement (Vaz, pers comm 2013). As with the mesophilic plant, the modelled CHP electrical capacity is lower than the installed capacity. This reflects the fact that the size of the plant in the model is based the assumption of uniform biogas production throughout the year. Using the feedstock characteristics reported for the plant rather than the default values, the methane production values are very similar. The differences between loading rates are due to the fact that the liquid volume of the Valorsul digester is slightly greater than the 90% assumed in the model, and to solubilisation during the pre-processing stages. The modelled electricity production is higher than that reported, reflecting the assumption of 95% CHP availability. In general, however, the modelled values are a good match to those reported for the plant.

4.3 Conclusions from validation

Validation of modelled output against the data sets from two full-scale plants indicated that the modelling tool was capable of accurately simulating their performance, and by extension of a range of anaerobic digestion plants of this or similar types.

5 Anaerobic digestion scenario modelling

The energy balance modelling tool was used to simulate a number of scenarios, as described below.

5.1 Main scenarios

Two sets of scenarios were developed, based on the production of electricity and heat in a CHP unit, and of methane through biogas upgrading. In each case these were run with two alternative assumptions from the three options below:

i) Feedstock quantities of 2,500 or 10,000 tonnes year^{-1}. The first of these is equivalent to the food waste from a population of around 25,000 households, as used in the collections modelling in section 2. The second was chosen to correspond to a medium-size city, or e.g. to four separate towns of 25,000 households, with the aim of indicating any significant differences in the energy balance at these different scales of operation.

ii) Operation of the AD plant at mesophilic (35 °C) or thermophilic (55 °C) temperatures.

iii) Simple or complex digestion process. The simple process consists only of a digester followed by a pasteuriser, with biogas stored in a separate gas-holder and then burnt in a CHP unit, and with digestate storage. The complex process includes pre-processing (assuming e.g. a contaminated initial waste stream which needs to be sorted before digestion), digestate separation and composting. For pre-processing a value of 78.5 MJ tonne^{-1} waste was used, derived from that measured at the Valorsul plant as reported in deliverable D4.3 (VALORGAS, 2012a). This pre-processing energy consumption is in addition to the parasitic energy requirements determined by the waste type digested, and falls within the range of values reported by Bernstad et al. (2013) as shown in Table 22. Where applicable, digestate separation was assumed to be by belt press (Table 14).

Table 22. Pre-treatment energy requirements (adapted from Bernstad et al., 2013)

facility	Energy use (MJ tonne^{-1} waste)	Water use (m^3 tonne^{-1} waste)	reference
A	99.7	0.6	
B	32.8	0.1	(Bernstad et al., 2013)
C	17.6	0	
D	300.6	1.1	
Valorsul plant	78.5	0.7	(VALORGAS, 2012a)

Energy required for transport of the feedstock from a central collection point (e.g. transfer station) to the digestion plant was not included: this option is available in the modelling tool, but in the current study this component of the energy balance was taken into account in the collections modelling in section 2. Energy for transport and application of the digestate as a fertiliser replacement, or for any extra processing where digestate cannot be returned to land, is also not included: these cases are considered separately in section 6.

It was assumed in all cases that the digesters are of steel construction with a separate gas holder (capacity for 2 hours production of biogas). Other assumptions were that pasteurisation occurs after digestion, there is 1% process loss of biogas and the biogas generated is used in CHP units to produce electricity (at 35% conversion efficiency) and heat. The CHP unit has a load factor of 8300 hours. Digestate storage in a steel tank for up to 6 months is included, as is a steel clad building measuring 20 m by 25 m with 3 m walls and 5 m high ridge, to comply with ABPR requirements. Ambient temperatures were based on Southampton (UK).

Scenarios/examples are identified using the following codes:
M = mesophilic, T = Thermophilic
S = simple process, C = complex process
2 = 2500 tonnes waste year^{-1}, 10 = 10,000 tonnes waste year^{-1}
e = biogas used in CHP unit for electricity/heat generation, u = biogas upgraded to biomethane

So for example MS2e is a mesophilic digester in a simple process plant processing 2,500 tonnes of waste and producing electricity for export.
Unless specified, all loading rates are 4 kg VS m^{-3} day^{-1}.

5.2 Energy balances for electricity and heat production

Summary energy balances for the scenarios based on production of electricity and heat in a CHP unit are shown in Table 23, while detailed results are presented in Tables 24 and 25.

Table 23. Summary energy balances for electricity and heat production

2,500 tonne scenarios		MS2e	MC2e	TS2e	TC2e
energy balance total	GJ year^{-1}	4820	4232	4545	3957
	GJ tonne^{-1} waste	1.93	1.69	1.82	1.58
energy balance electrical	GJ year^{-1}	1386	798	1249	660
	GJ tonne^{-1} waste	0.55	0.32	0.50	0.26
10,000 tonne scenarios		**MS10e**	**MC10e**	**TS10e**	**TC10e**
energy balance total	GJ year^{-1}	19820	17466	19009	16656
	GJ tonne^{-1} waste	1.98	1.75	1.90	1.67
energy balance electrical	GJ year^{-1}	5903	3549	5498	3144
	GJ tonne^{-1} waste	0.59	0.35	0.55	0.31

Greater complexity leads to an increase in energy requirement for processing, and increased temperature leads to an increasing demand for heat. In all eight cases the energy available from digesting the waste is sufficient to provide both the electrical and heat energy required for operating the plant with some remaining electricity and heat that can be exported to provide an alternative to fossil fuel based energy sources.

In each case the larger plants (10,000 tonnes) show a slightly higher net energy balance due to the higher volume to surface ratio of the digesters, which thus have smaller heat losses in proportion to the heat supplied. The difference for a 4-fold increase in feedstock volume is not large, however, being equivalent to around 4% of the total: this suggests that smaller local AD plants can be reasonably efficient.

5.3 Energy balances for upgrading to biomethane

Table 26 shows the energy inputs and outputs and process details for AD with upgrading and compression of the biogas. The size of the on-site CHP unit used to provide electricity for the site and heat for the digester and pasteuriser varies according to site requirements. The larger the CHP unit needed for the on-site requirement, the smaller the amount of biogas available for upgrading.

In other respects the trends seen are similar to those for electricity production, as expected, with larger plants appearing slightly more efficient than small ones and more complex plants having a lower net energy output than simple.

Table 24. Energy inputs and outputs for electricity and heat production at 2,500 tonnes waste input

details		MS2e	MC2e	TS2e	TC2e
digester input	tonnes	2500	2500	2500	2500
digester loading rate	kg m^{-3} day^{-1}	4	4	4	4
total digester capacity required	m^3	416	416	416	416
retention time	days	55	55	55	55
methane produced	m^3	231840	231840	231840	231840
methane available	m^3	229522	229522	229522	229522
biogas	m^3	386400	386400	386400	386400
=	tonnes	470	470	470	470
digestate	tonnes	2030	2030	2030	2030
Energy balance ($year^{-1}$)					
pre-processing electricity	GJ	0	196.25	0	196.25
digester electricity requirement	GJ	360	360	360	360
electricity for upgrading	GJ	0.0	0.0	0.0	0.0
electricity for composting	GJ	0.0	16.7	0.0	16.7
heat for digester	GJ	375.7	375.7	683.9	683.9
heat for pasteuriser	GJ	300.9	300.9	130.4	130.4
diesel for composting	GJ	0.0	162.3	0.0	162.3
total	**GJ**	**1036.7**	**1411.9**	**1174.3**	**1549.6**
embodied energy					
digester embodied	GJ	51.2	51.2	51.2	51.2
pasteuriser embodied	GJ	0.7	0.7	0.7	0.7
CHP embodied	GJ	7.4	7.4	7.4	7.4
upgrading embodied	GJ	0.0	0.0	0.0	0.0
gas holder embodied	GJ	1.6	1.6	1.6	1.6
ABPR building embodied	GJ	18.1	18.1	18.1	18.1
digestate storage	GJ	15.4	15.4	15.4	15.4
separator embodied	GJ	0.0	0.2	0.0	0.2
feedtank embodied	GJ	0.2	0.2	0.2	0.2
total	**GJ**	**95**	**95**	**95**	**95**
on-site boiler/CHP		CHP	CHP	CHP	CHP
CHP electrical capacity	kW	96	96	96	96
energy in methane produced	GJ	8305	8305	8305	8305
generated electricity	GJ	2878	2878	2878	2878
generated heat	GJ	4111	4111	4111	4111
imported electricity	GJ	0	0	0	0
imported heat	GJ	0	0	0	0
exported electricity	GJ	2518	2305	2518	2305
	MWh	699	640	699	640
exported heat	GJ	3434	3434	3296	3296
	MWh	954	954	916	916

Table 25. Energy inputs and outputs for electricity and heat production at 10,000 tonnes waste input

		MS10e	MC10e	TS10e	TC10e
details					
digester input	tonnes	10000	10000	10000	10000
digester loading rate	kg m^{-3} day^{-1}	4	4	4	4
total digester capacity required	m^3	1664	1664	1664	1664
retention time	days	55	55	55	55
methane produced	m^3	927360	927360	927360	927360
methane available	m^3	918086	918086	918086	918086
biogas	m^3	1545600	1545600	1545600	1545600
=	tonnes	1880	1880	1880	1880
digestate	tonnes	8120	8120	8120	8120
Energy balance ($year^{-1}$)					
pre-processing electricity	GJ	0	785	0	785
digester electricity requirement	GJ	1440	1440	1440	1440
electricity for upgrading	GJ	0.0	0.0	0.0	0.0
electricity for composting	GJ	0.0	66.8	0.0	66.8
heat for digester	GJ	1325.7	1325.7	2413.2	2413.2
heat for pasteuriser	GJ	1200.0	1200.0	517.9	517.9
diesel for composting	GJ	0.0	649.3	0.0	649.3
total	**GJ**	**3965.7**	**5466.8**	**4371.1**	**5872.1**
embodied energy					
digester embodied	GJ	128.7	128.7	128.7	128.7
pasteuriser embodied	GJ	1.7	1.7	1.7	1.7
CHP embodied	GJ	11.3	11.3	11.3	11.3
upgrading embodied	GJ	0.0	0.0	0.0	0.0
gas holder embodied	GJ	3.1	3.1	3.1	3.1
ABPR building embodied	GJ	18.1	18.1	18.1	18.1
digestate storage	GJ	38.2	38.2	38.2	38.2
separator embodied	GJ	0.0	1.0	0.0	1.0
feedtank embodied	GJ	0.4	0.4	0.4	0.4
total	**GJ**	**201**	**202**	**201**	**202**
on-site boiler/CHP		CHP	CHP	CHP	CHP
CHP electrical capacity	kW	385	385	385	385
energy in methane produced	GJ	33218	33218	33218	33218
generated electricity	GJ	11510	11510	11510	11510
generated heat	GJ	16443	16443	16443	16443
imported electricity	GJ	0	0	0	0
imported heat	GJ	0	0	0	0
exported electricity	GJ	10070	9218	10070	9218
	MWh	2797	2561	2797	2561
exported heat	GJ	13917	13917	13512	13512
	MWh	3866	3866	3754	3754

Table 26. energy inputs and outputs including biogas upgrading and compression

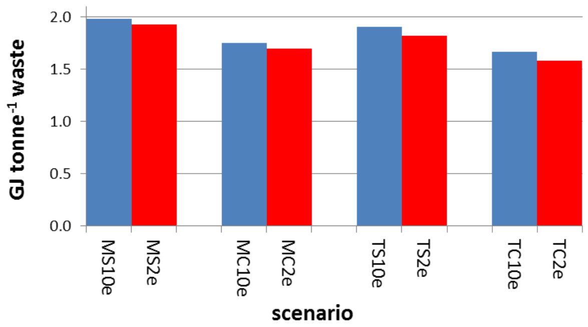
		MS2u	MC2u	TS2u	TC2u	MS10u	MC10u	TS10 u	TC10 u
Energy									
digester input	tonnes	2500	2500	2500	2500	10000	10000	10000	10000
Energy balance (year^{-1})									
pre-processing electricity	GJ	0	196.25	0	196.25	0	785	0	785
digester electricity requirement	GJ	360	360	360	360	1440	1440	1440	1440
electricity for upgrading	GJ	546.8	463.9	546.8	463.9	2187.3	1855.5	2187.3	1855.5
electricity for composting	GJ	0	184.1	0	184.1	0	736.5	0	736.5
heat for digester	GJ	375.7	375.7	683.9	683.9	1325.7	1325.7	2413.2	2413.2
heat for pasteuriser	GJ	300.9	300.9	130.4	130.4	1200	1200	517.9	517.9
diesel for composting	GJ	0	162.3	0	184.1	0	649.3	0	649.3
total	**GJ**	**1583.5**	**2043.3**	**1721.1**	**2202.7**	**6153**	**7992.1**	**6558.3**	**8397.4**
embodied energy									
total	**GJ**	**111**	**111**	**111**	**111**	**223**	**223**	**223**	**223**
CHP electrical capacity	kW	30	40	30	40	121	161	121	161
energy in methane produced	GJ	8305	8305	8305	8305	33218	33218	33218	33218
generated electricity	GJ	907	1204	907	1204	3627	4817	3627	4817
generated heat	GJ	1295	1720	1295	1720	5182	6882	5182	6882
exported heat	GJ	619	1044	481	906	2656	4356	2251	3950
	MWh	172	290	134	252	738	1210	625	1097
upgraded biomethane	m^3	153808	130479	153808	130479	615233	521916	615233	521916
energy in upgraded CH_4	GJ	5509.4	4673.8	5509.4	4673.8	22037.6	18695	22037.6	18695
diesel equivalent of CH_4	litres	154176	130791	154176	130791	616704	523164	616704	523164
energy balance total [a]	GJ year^{-1}	4434	3563	4158	3266	18318	14836	17507	14025
	GJ tonne^{-1} waste	1.77	1.43	1.66	1.31	1.83	1.48	1.75	1.4
energy balance biomethane [b]	GJ year^{-1}	3815	2520	3677	2360	15662	10480	15256	10075
	GJ tonne^{-1} waste	1.53	1.01	1.47	0.94	1.57	1.05	1.53	1.01

[a] including upgraded biomethane, exported heat
[b] including upgraded biomethane but not exported heat

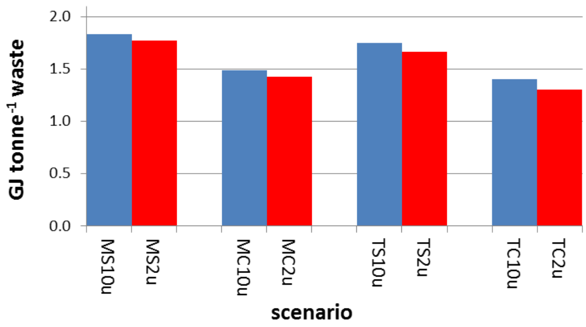
5.4 Comparison of energy balances for electricity and biomethane production

The total exportable energy is slightly higher for scenarios involving electricity and heat production than for biomethane and heat, due to the assumed overall energy conversion efficiencies and embodied energies for the two technologies (Figure 5a and b). In many locations, however, finding a use for surplus heat is highly problematic. Figure 5c and d show the exportable energy in terms of electricity and biomethane only, not taking heat into account.

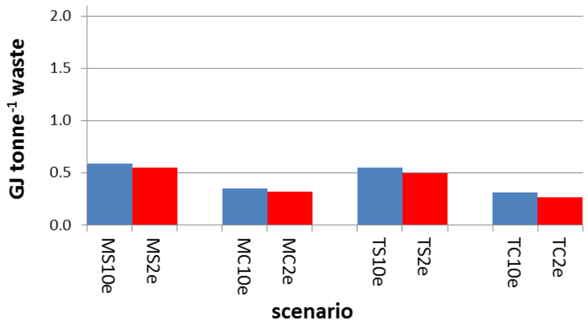
The net energy output for the electricity options is much lower, as electricity produced via CHP accounts for only 35% of the energy in the consumed biogas due to the inefficiency of the CHP unit and the heat produced. Upgrading is more efficient in terms of the energy produced and provides a better source of energy production if there is no use for the heat produced by the CHP unit.



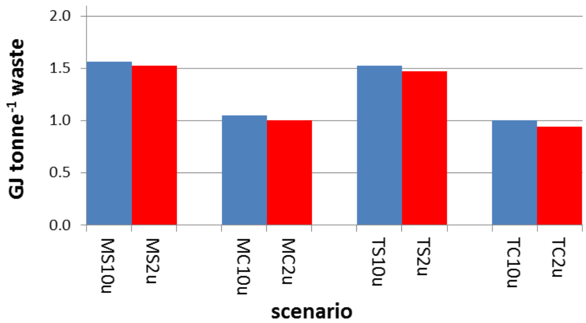
(a) electrical energy and heat



(b) biomethane and heat



(c) electrical energy only



(d) biomethane only

Figure 5. comparison of energy balances for electricity and biomethane production

5.4 GHG emissions

Emissions balances for the four scenarios with electricity production at 2,500 tonnes waste input are given in Table 27, while Figure 6 and Table 28 show the relative emissions savings from various sources at 2,500 and 10,000 tonnes waste input.

The values shown do not include emissions from combustion in the CHP unit since the biogas is produced from a waste source, rather than being a fossil fuel; it is therefore considered to be part of the short carbon cycle and not a net contributor to GHG emissions.
Two potential sources of emissions savings are considered here: replacement of electricity generated from fossil and other fuels and replacement of heat generated from fossil fuels. As noted above, however, not all digesters will be located in situations in which the heat can be used.

The high GWP of the methane component means that process losses of biogas are the major component in GHG emissions, and thus an important issue in plant design and operation. They are equivalent to 7% of the emissions savings (Table 27) and their reduction would make a considerable contribution to the effectiveness of the plant in GHG terms.

Emissions savings from the 10,000 tonnes scheme are much higher than from the 2,500 tonne (Figure 6), but the values per tonne of waste processed are very similar (Table 28) indicating that small-scale systems are not necessarily inefficient in this respect.

Table 27. Emissions inputs and outputs for electricity production in the 2,500 tonne scenarios

tonne CO_2eq	MS2e	MC2e	TS2e	TS2e
diesel for composting	0.00	12.14	0.00	12.14
embodied carbon ($year^{-1}$)				
digester embodied	3.72	3.72	3.72	3.72
pasteuriser embodied	0.05	0.05	0.05	0.05
CHP embodied	0.41	0.41	0.41	0.41
upgrading embodied	0.00	0.00	0.00	0.00
gas holder embodied	0.13	0.13	0.13	0.13
ABPR building embodied	2.06	2.06	2.06	2.06
digestate storage	1.69	1.69	1.69	1.69
separator embodied	0.00	0.01	0.00	0.01
feedtank embodied	0.03	0.03	0.03	0.03
total	**8.07**	**8.08**	**8.07**	**8.08**
process loss	44.6	44.6	44.6	44.6
exported electricity savings	316.1	289.4	316.1	289.4
exported heat savings	196.1	196.1	188.3	188.3
total emissions	52.7	64.8	52.7	64.8
emission savings (total)	652.4	625.7	644.5	617.8
emissions balance (electricity)	263.4	224.5	263.4	224.5
balance (elec + heat)	459.5	420.6	451.7	412.8

Table 28. emission balances for electricity production

(tonne CO_{2eq} $tonne^{-1}$ waste)	MS2e	MC2e	TS2e	TS2e	MS10e	MC10e	TS10e	TS10e
total emissions	0.021	0.026	0.021	0.026	0.020	0.024	0.020	0.024
emission savings (total)	0.261	0.250	0.258	0.247	0.262	0.251	0.260	0.249
emissions balance (electricity)	0.105	0.090	0.105	0.090	0.107	0.091	0.107	0.091
(electricity + heat)	0.184	0.168	0.181	0.165	0.186	0.171	0.184	0.169

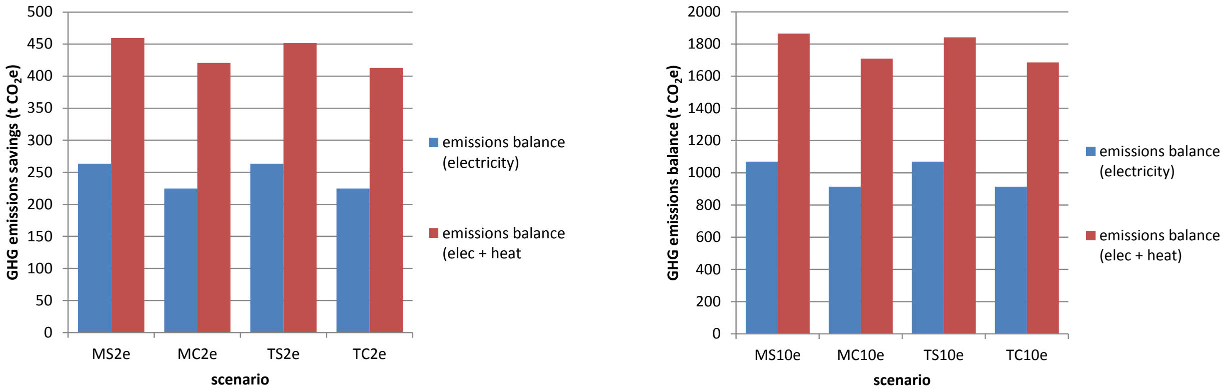


Figure 6. Potential emissions savings from electricity production scenarios

The emissions balances for biogas upgrading and compression options are shown in Table 29. As with the scenarios for electricity production, there is little difference on a per tonne waste basis between the scales of operation. The major difference is between the simple and complex scenarios, and is a result of the higher electricity demand in the complex scenario leading to reduced biogas availability for upgrading. Including the heat export reduces the difference between the simple and complex options, as the increased size of the CHP allows greater potential for heat to be exported.

Table 29. emission balances for biogas upgrading

(tonne CO_{2eq})	MS2u	MC2u	TS2u	TC2u	MS10u	MC10u	TS10u	TC10u
total emissions	54.4	66.5	54.4	66.5	197.4	245.8	197.4	245.8
emission savings (total)	447.3	409.1	439.5	401.2	1799.6	1646.6	1776.4	1623.5
emissions balance								
(biomethane)	358	283	358	283	1451	1152	1451	1152
(biomethane + heat)	393	343	385	335	1602	1401	1579	1378
(tonne CO_{2eq} $tonne^{-1}$ waste)								
total emissions	0.022	0.027	0.022	0.027	0.020	0.025	0.020	0.025
emission savings (total)	0.179	0.164	0.176	0.160	0.180	0.165	0.178	0.162
emissions balance								
(biomethane)	0.143	0.113	0.143	0.113	0.145	0.115	0.145	0.115
(biomethane + heat)	0.157	0.137	0.154	0.134	0.160	0.140	0.158	0.138

5.5 Use of modelling tool to investigate effects of loading rate on energy balance

As an example of its potential applications, the modelling tool was used to investigate the effect of changing the loading rate and feedstock quantities at mesophilic and thermophilic temperatures.

The energy balance for mesophilic systems is slightly higher than for the equivalent thermophilic, for example at 1.98 GJ $tonne^{-1}$ waste compared to 1.90 GJ $tonne^{-1}$ waste for the simple configuration with electricity production and 10,000 tonnes waste input (Table 25). As the amount of waste is the same, this is a result of the increased heat requirement from the feedstock and digester. Increasing the specified loading rate reduces the size of the digester required, thus reducing the heat needed per tonne of waste input. The effect of increasing the loading rate from 4 kg VS m^3 day^{-1} up to 8 on the energy balance per tonne of waste is shown in Figure 7 (m = mesophilic, t = thermophilic).

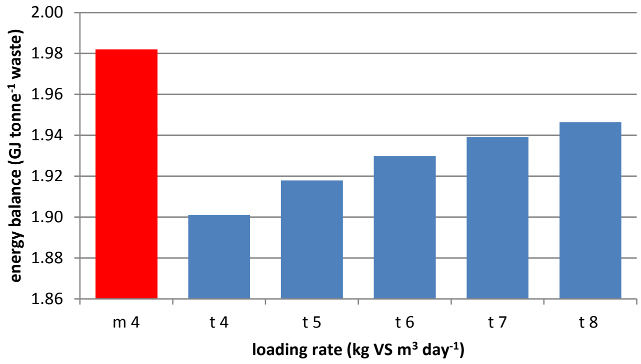


Figure 7. Effect of loading rate on overall energy balance

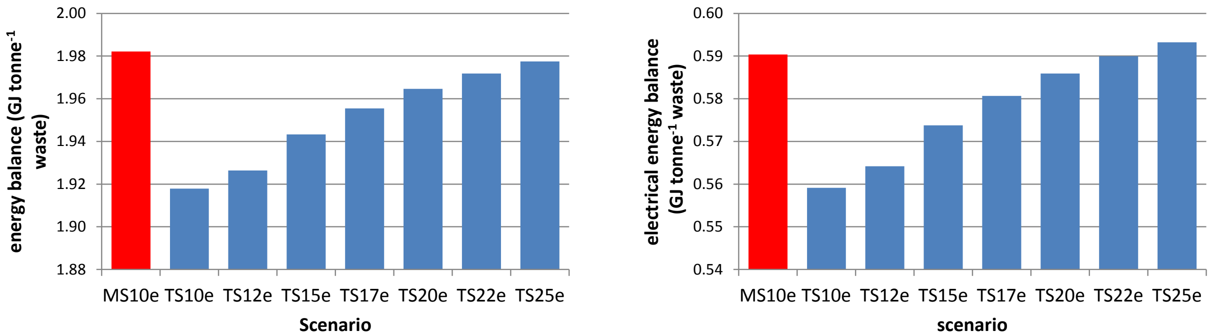
As the loading rate increases the energy balance per tonne of waste approaches that of the mesophilic system, but increasing the loading rate does not reduce the heat required to raise the temperature of the feedstock: this remains the same, depending only on ambient temperature and amount of waste. The degree to which the loading rate can be increased is also limited by the metabolic capacity of the digestion process.

An alternative approach to increase the specific efficiency would be to maintain the digester size and increase the amount of feedstock – thus also increasing the loading rate. An example of this approach to changing loading rates is outlined in Table 30. For this example the digester capacity is maintained at 1664 m^3 and the system assumed is a simple one (M is mesophilic, T thermophilic, MS10e and TS10e are the same as the scenarios above).

Table 30. Maintaining digester capacity, increasing amount of feedstock

Example	MS10e	TS10e	TS12e	TS15e	TS17e	TS20e	TS22e	TS25e
feedstock (10^3 tonnes $year^{-1}$)	10	10	12.5	15	17.5	20	22.5	25
loading rate (kg VS m^{-3} day^{-1})	4	4	5	6	7	8	9	10

The effect of increasing the amount of feedstock on the overall energy balance is shown in Figure 8a, and on the electrical energy only balance in Figure 8b.



(a) Overall energy balance

(b) Electrical output only energy balance

Figure 8. Overall and electrical energy balances for varying load scenarios

By increasing the amount of feedstock material and the rate of processing (by increasing the loading rate) it is possible for the thermophilic process to achieve similar energy balances per tonne of waste to the mesophilic.

The effect on emissions of changing the loading rate in the thermophilic digesters with the same amount of feedstock material is shown in Figure 9, and the effect on the emissions balance of changing the amount of feedstock but maintaining digester capacity is shown in Figure 10. Changing the loading rate has little effect on emissions, as the amount of energy and fertiliser produced is related to feedstock volume and so remains constant. In all cases, use of the heat as a fossil fuel replacement is required to offset the emissions produced.

While the example considered is relatively trivial, it illustrates the use of the modelling tool in exploring the energy and GHG emission implications of a change in operating conditions.

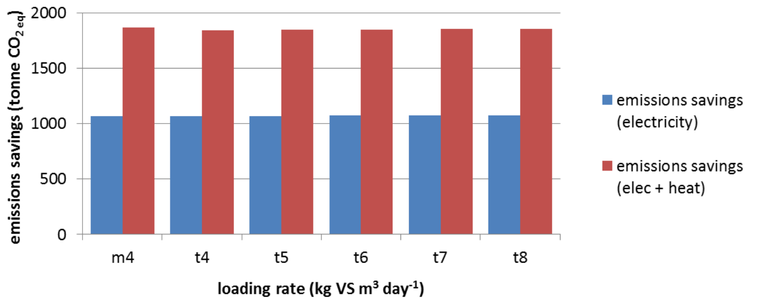


Figure 9. Effect of varying loading rate on emissions balances

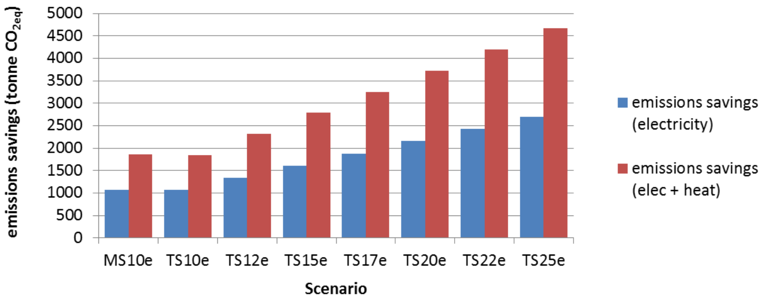


Figure 10. Effect of varying feedstock amount on emissions balances

5.6 Conclusions from scenario modelling

The results of the modelling confirmed that all of the scenarios considered showed a positive energy balance. Thermophilic and complex systems had a slightly lower net energy yield in all cases, and larger systems (higher waste input) had a marginally higher yield than smaller ones, but the differences were not large, due to the relatively high energy inputs available from the produced biogas in comparison with embodied and parasitic requirements in all cases. The main issue was the existence or otherwise of a use for the exportable heat. If the heat can be fully utilised then electricity production shows a marginally higher net energy output; if not then gas upgrading is the more effective option in terms of maximising utilisation of the available energy. GH emission savings are better for upgraded biomethane than CHP electricity production alone but less if the heat generated can be exported as a fossil fuel derived replacement. The values from the anaerobic digestion scenarios with 2,500 tonnes year^{-1} of waste input were taken forward for inclusion in the overall energy balance calculations in section 6.

6 Overall energy and GHG balances from waste to field

The AD model was used to estimate energy and emissions for digestate utilisation based on the values obtained in deliverable D6.2 (VALORGAS, 2013c). The results were combined with output from collections modelling in section 2 to establish overall balances for energy and emissions for the complete system of waste collection, processing and use of digester outputs, as shown in Figure 11.

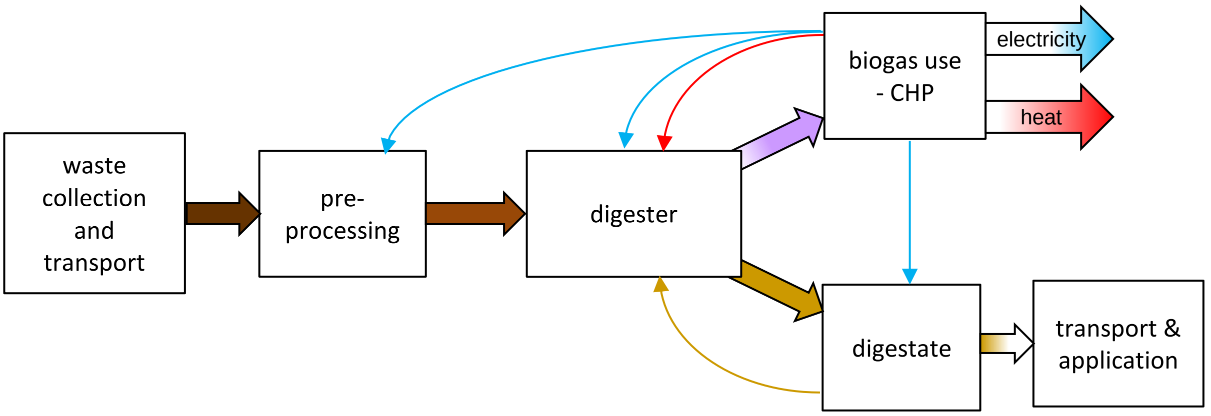


Figure 11. Schematic of overall food waste collection, digestion, gas and digestate utilisation system

6.1 Energy and emissions in digestate transport and utilisation

Energy and emissions factors used for digestate and mineral fertiliser application are shown in Table 31. For the purposes of this study, the farm was assumed to be 30 km away from the site of the digester, with digestate transported to the farm by lorry.

The area required for digestate application is defined by the maximum application rate, which was set at 170 kg N ha^{-1} based on limits for Nitrate Vulnerable Zones (NVZ) in the EU Nitrates directive (91/676/EEC). The nutrient composition of the digestate is based on that of the digester feedstock (section 3.1), but the nutrients become more concentrated during the digestion process as the amount of digestate produced is smaller than the original amount of feedstock. The nutrient content of the digestate reported by the model is 9.9 g N kg^{-1} FM, 3.7 g P_2O_5 kg^{-1} FM and 4.9 g K_2O kg^{-1} FM.

Table 31. Energy and emissions in digestate transport and application

	diesel use	emissions (CO_2eq)	embodied energy
mineral fertiliser application	2.9 l ha^{-1} (a)	7.78 kg ha^{-1} (b)	8.5 MJ ha^{-1} (c)
digestate transport	2.07 MJ $tonne^{-1}$ km^{-1} (d)	0.155 kg $tonne^{-1}$ km^{-1} (b)	36.27 GJ $year^{-1}$ (d)
whole digestate/liquor application	3.8 l ha^{-1} (a)	10.2 kg ha^{-1} (b)	42.8 MJ ha^{-1} (c)
fibre fraction application	9.5 l ha^{-1} (c)	25.5 kg ha^{-1} (b)	47 MJ ha^{-1} (c)

(a) VALORGAS (2013c), (b) 0.075 kg CO_2e MJ^{-1} diesel (AEA, 2010), (c) Salter (2011) (d) Section 2

When applied to a field the digestate was assumed to replace fossil fuel based mineral nitrogen fertiliser which would require 42.9 MJ kg^{-1} to produce and deliver to site with an emission value of 6.81 kg CO_{2eq} kg^{-1} N (Mortimer et al., 2010). For the purposes of the current study energy and GHG emissions savings were based on N fertiliser substitution only, as this is the most significant component in terms of fossil fuel replacement and was used as the limiting factor for land application.

6.2 Overall balances

The energy and emission balances presented in this section are based on 2,500 tonnes year^{-1} of waste incurring an additional collection energy of 1500 GJ year^{-1} and 70 tonnes CO_{2eq} year^{-1}, as derived in section 2. This is combined with the results of the scenarios for 2,500 tonnes of waste input from section 5. The resulting whole system scenarios are summarised in Table 32, where M and T represent mesophilic and thermophilic, S and C simple and complex, and e and u electricity production and gas upgrading options, as before.

Table 32. Whole system scenarios

	WMSe / WMSu	WMCe / WMCu	WTSe / WTSu	WTCe / WTCu
collection	yes (including transport from waste transfer station)			
pretreatment	no	yes	no	yes
digestion	mesophilic	mesophilic	thermophilic	thermophilic
digestate treatment	simple (none)	complex (separation, composting)	simple (none)	complex (separation, composting)
digestate application	single	separate fibre and liquor applications	single	separate fibre and liquor applications

In all cases the 2030 tonnes of digestate produced is enough to provide the nitrogen requirement for 118 ha of crop. In the simple case this is just transported and applied. In the complex case it is separated and the fibre fraction is composted, leading to a further reduction in mass; both fractions are then returned to land in separate applications. The energy requirements for transport and application in this case are shown in Table 33.

The digestate is assumed to replace 20,060 kg of fossil fuel based nitrogen which would require 860 GJ to produce and deliver with an emission value of 136.6 tonnes CO_{2eq} kg^{-1}.

Table 33. Digestate transport and application

	amount (tonnes)	transport (GJ)	transport (tonne CO_{2eq})	application (GJ)	application (tonne CO_{2eq})	embodied energy (GJ)
simple	2030	126.1	9.44	16.1	1.20	41.3
complex - liquor	1441	89.5	6.70	16.1	1.20	41.3
complex - fibre	294.5	18.2	1.37	40.1	3.01	41.3

6.2.1 Energy balances

The results for production of electricity/biomethane only, electricity/biomethane and heat, electricity/biomethane and fertiliser replacement, and electricity/biomethane, heat and fertiliser are shown in Table 34 and Figure 12. In each of the scenarios considered production of electricity only would lead to a negative energy balance (more energy consumed in collection, processing and transport than is available for export as electricity). In these cases, however, export of between 10 and 33% of the available heat would be sufficient to reach a neutral balance. In the complex scenarios, production of electricity and fertiliser also shows a slight negative balance. The balances for biomethane production are positive in all cases. As before, increased complexity or digestion temperature reduces the overall energy balance; while if all of the heat can be utilised production of electricity gives a marginally higher balance than gas upgrading for biomethane under the conditions assumed.

Separation of digestate into liquid and solid fractions incurs higher energy costs for processing, transport and application, despite the mass reduction in the solid component. This may partly reflect the fact that in food waste digestion the solids breakdown is high, and the residual mass reduction in composting is relatively small. Digestate separation may, however, be necessary for certain application techniques to be used.

Table 34. Whole system energy results based on 2500 tonnes waste year^{-1}

(GJ)	WMSe	WMCe	WTSe	WTCe	WMSu	WMCu	WTSu	WTCu
collection inc. embodied	1500	1500	1500	1500	1500	1500	1500	1500
digestion inc. embodied	1131	1507	1269	1644	1695	2154	1832	2314
digestate transport & application inc. embodied	184	247	184	247	184	247	184	247
exported electricity / biomethane	2518	2305	2518	2305	5509	4674	5509	4674
exported heat	3434	3434	3296	3296	619	1044	481	906
mineral N fertiliser replaced	860	860	860	860	860	860	860	860
Total energy balance	3997	3345	3721	3070	3609	2677	3334	2379

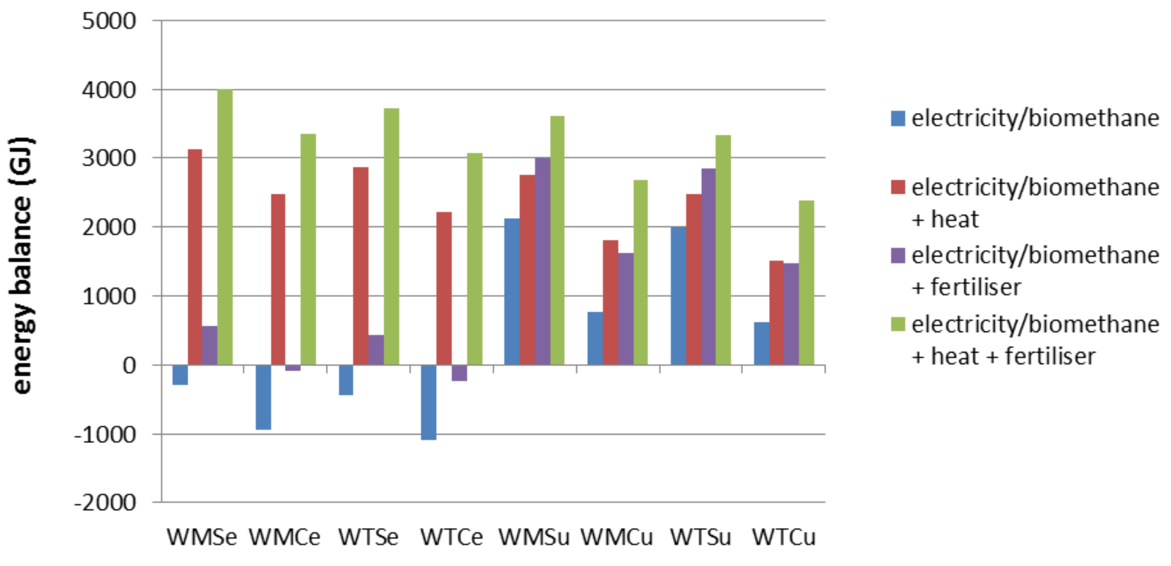


Figure 12. Whole system energy balances.

6.2.2 GHG emissions

The results for GHG emissions are shown in Table 35. In all cases the emissions saved through replacement of electricity, heat and mineral fertiliser are greater than those created by the collection of the waste, construction and operation of the digester, digestate use and from combustion of the biogas in the CHP unit. Effectively this means that the process may have a value in terms of GHG abatement, even without net energy production: if other disposal routes such as landfill may lead to uncontrolled methane losses the benefit will be correspondingly higher.

Process losses of biogas (losses in the digestion plant before combustion) make up 31% of the emissions and their reduction would make the scenarios even more beneficial in terms of emissions savings. The relative emissions savings resulting from the replacement of electricity, heat and fertilisers produced from fossil fuels are shown in Figure 13.

Table 35. Whole system GHG emissions

(tonnes CO_2eq)	WMSe	WMCe	WTSe	WTCe	WMSu	WMCu	WTSu	WTCu
collection inc. embodied	70	70	70	70	70	70	70	70
digestion inc. embodied	52.7	64.8	52.7	64.8	54.4	66.5	54.4	68.1
digestate transport & application inc. embodied	9.64	12.28	9.64	12.28	9.64	12.28	9.64	12.28
process losses	44.6	44.6	44.6	44.6	44.6	44.6	44.6	44.6
replaced grid-produced electricity / diesel fuel	316.1	289.4	316.1	289.4	412	349.5	412	349.5
replaced fossil fuel based heat	196.1	196.1	188.3	188.3	35.3	59.6	27.5	51.7
replaced mineral N fertiliser	140.2	140.2	140.2	140.2	140.2	140.2	140.2	140.2
Total emissions savings	475.5	434.0	467.7	426.2	408.9	355.9	401.1	346.4

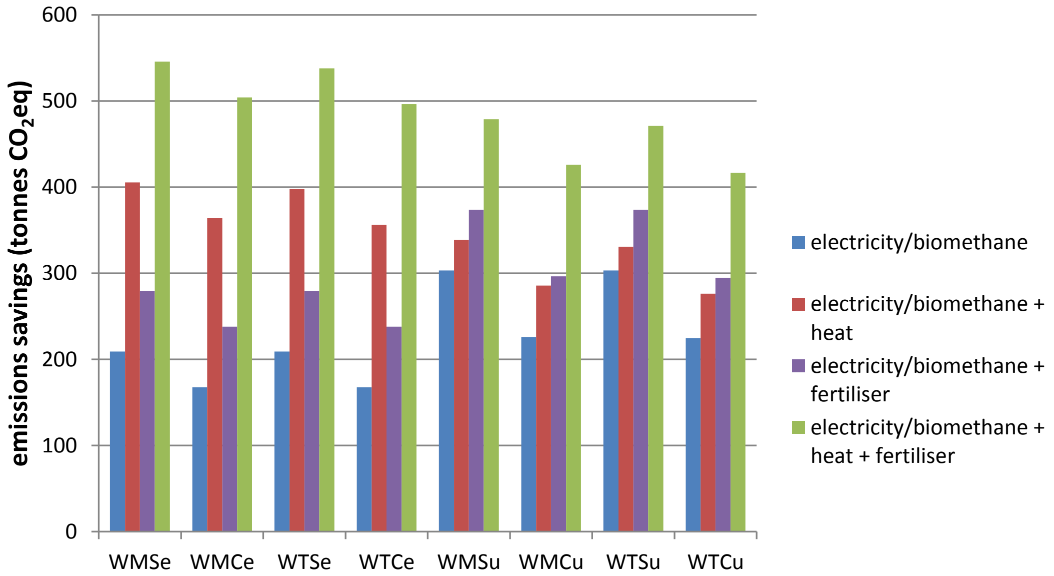


Figure 13. Whole system emissions savings

Mineral fertiliser replacement makes up between 28 and 40% of the net savings in GHG emissions (Figure 14). The emission savings in the case of the complex digester processes are lower, due to the extra processing of waste input and digestate output for production of the same amount of fertiliser; so fertiliser replacement makes up a larger part of the savings in these cases. There is little difference between thermophilic and mesophilic operation in these scenarios.

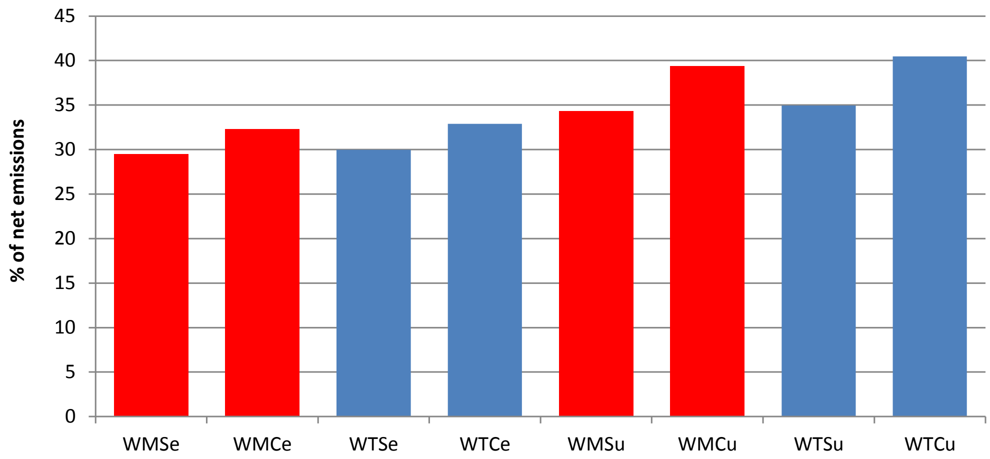


Figure 14. Mineral fertiliser replacement as % of net GHG emission savings

6.2.3 Operation without digestate re-use

In some cases it is not possible to return the digestate to land, for example due to local farming practice; soil or hydrological conditions; regulatory requirements; or unacceptable levels of contamination. The digestate therefore cannot be credited as a mineral fertiliser replacement in the energy and emissions balances. In this situation it is assumed that the digestate is separated into solid and liquid fractions (complex case) and the liquid fraction is treated to an acceptable standard for recycling or discharge to sewer at an assumed energy cost of 48 MJ tonne^{-1} liquor (VALORGAS, 2012a). The fibre fraction of the digestate is assumed to be transported 30 km to a landfill site for disposal, with no further processing requirements.

The energy input and outputs for these scenarios are shown in Table 36, and the emission balances in Table 37. These only apply to the complex digestion scenarios; in the simple scenarios the digestate receives no post-treatment. It can be seen that the total energy balance, while lower than with digestate utilisation, is still positive. Figure 15 shows the comparative energy and emission balances for the whole systems with either application of the liquor and fibre fractions of the digestate to field, or separation and treatment and disposal of the two fractions.

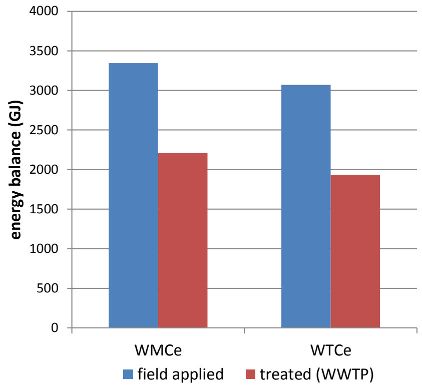
Table 36. Input and output energy for separated digestate without utilisation

(GJ)	WMCe no digestate use	WTCe no digestate use
collection (including embodied)	1500	1500
digestion (including embodied)	1743	1881
digestate transport & application (inc embodied)	49.3	49.3
exported electricity	2068	2068
exported heat	3434	3296
mineral N fertiliser replaced	0	0
Total energy balance	2210	1934

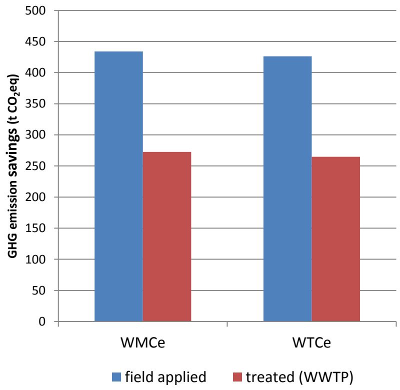
Table 37. Emission balances for separated digestate without utilisation

(tonne CO_2eq)	WMCe no digestate use	WTCe no digestate use
collection inc. embodied	70	70
digestion inc. embodied	64.8	64.8
digestate transport & application (inc. embodied)	3.68	3.68
process losses	44.6	44.6
replaced grid produced electricity	259.6	259.6
replaced fossil fuel based heat	196.1	188.3

mineral N fertiliser replaced	0	0
Total emissions savings	272.6	264.8



(a) energy balances



(b) emission savings

Figure 15. Energy and emission balances

Treating the liquor rather than using it as a nutrient source for crop production reduces the energy balance by 25% (through increased use in the plant reducing the exportable electricity fraction) and the emissions savings by 30% through reduced electricity for export and non-substitution of fossil fuel based fertiliser.

6.3 Discussion and conclusions for whole system assessment

In almost all of the cases considered in this section the net energy production is positive, i.e. the energy derived from the collection, transport and anaerobic digestion of food waste including pre and post-processing and utilisation of the digestate and energy products is greater than the fossil fuel derived energy consumed. The only exceptions to this are where the biogas is used to produce electricity via CHP with no potential to export the heat. This is due to the relatively low energy conversion efficiency for electricity (35%), and can be compensated for by the use of approximately 30% of the heat generated. All of the scenarios involving upgrading of biogas to methane show a positive energy balance, indicating this is a rational means of valorisation especially for small-scale distributed sources of waste.

In all cases considered there is a net savings in terms of GHG emissions through replacement of fossil fuel generated energy. This is to be expected, as relatively small amounts of fossil fuel energy are being consumed compared to the amount of energy generated as electricity, heat or biomethane.

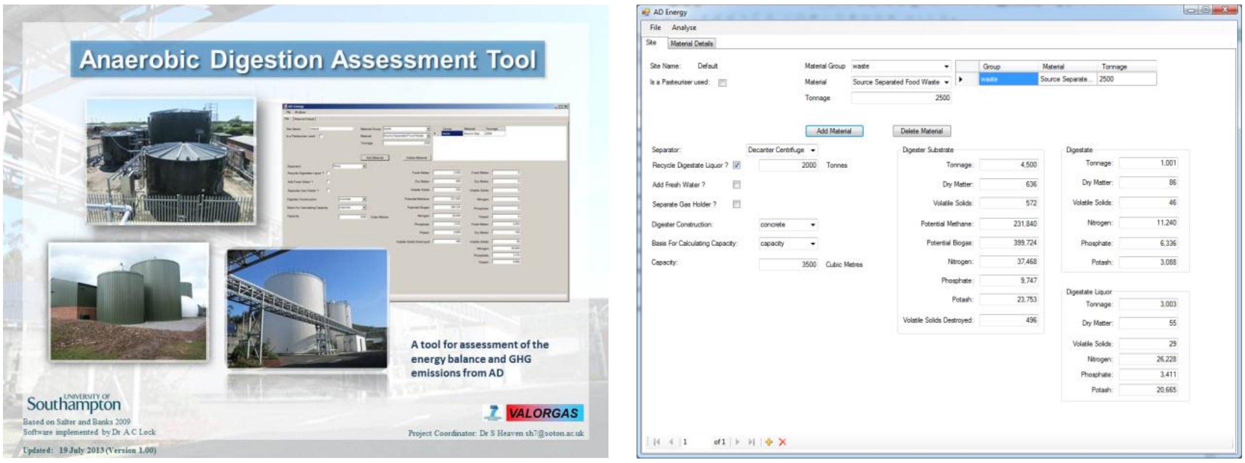
The current scenarios considered small-scale plants with an input of 2,500 tonnes year^{-1} of source segregated domestic food waste. Larger schemes processing more waste may show energy balances that are slightly higher, due to minor increases in efficiency with scale. Further modelling would be needed, however, to consider the effect of any increase in the transport distances required for collection and transfer of the extra waste to a single, centralised digester compared to a distributed digester system (see deliverable D2.5, VALORGAS 2012).

As noted in section 2, energy and emissions in collection and transport depend on a wide range of factors, including ones such as population density and terrain that are specific to the location and cannot easily be 'optimised'. The indications from the current whole system assessment, however, are that the energy potential of food waste as a feedstock for anaerobic digestion is sufficient to give positive energy and GHG emissions balance in any of a variety of typical scenarios. The value of the modelling approach is that it allows assessment of the consequences of choosing options such as mesophilic or thermophilic temperatures, and simple or complex operation with or without export of heat and utilisation of digestate as a fertiliser replacement.

The VALORGAS project is funded under the EU FP7 Energy programme and its main focus is thus on food waste as a substrate for energy production. As noted in the EC's Communication on biowaste management (COM(2010)235), however, appropriate treatment of organic wastes can contribute to meeting other environmental objectives, and often offers one of the most cost-effective solutions. Fertiliser substitution provides an example of this, and is the reason that nutrients were included in the assessment carried out for the VALORGAS project. Nutrients from the soil are incorporated into crops, which are used either directly for human consumption or as feed for livestock: in either case a proportion is exported from the farm. Wastes are generated along the food supply chain, and if the nutrients in these are not captured and returned to the fields then they must be must be replaced from finite resources and/or through the use of fossil fuels. Collection, treatment and application of digestate is a means of returning the nutrients and completing the cycle, and is thus of value in its own right provided that the resulting energy requirements and GHG emissions are lower than those produced from the use of fossil fuels.

6.4 AD assessment tool

As part of the VALORGAS project, the modelling tool has also been encoded as a C# program to facilitate rapid testing of multiple scenarios. When used as a companion software package to the WasteCAT tool, this allows modelling of a very wide range of waste collection and anaerobic digestion scenarios. Figure 16 shows some screenshots from the Anaerobic Digestion Assessment Tool, while tables showing the main user-specified inputs, default values and constants are presented in Appendix 1. The software version of the model is embargoed from general release until January 2014 to allow beta testing by 'external' users (i.e. users not directly involved in creation of the tool); but together with the original tool as described in Salter (2013) it forms an important component in the project's exploitation strategy (deliverable D1.8, VALORGAS 2013d).



(a) Cover page

(b) Screenshot of opening screen

Figure 16. AD assessment modelling tool

As with the WasteCAT model, the outputs from the WasteAD modelling tool can be used to estimate economic costs and payback periods. In the earliest planning stages of the project, however, a deliberate decision was taken not to include this as an output or deliverable: VALORGAS is a pan-European project and it is clear that amongst the member states (or even the project partner countries) there are too many different tariffs, subsidies, local regulations and variations in exchange rate etc to make cost-based outputs useful or reliable. The tool has therefore been specifically developed to present the results in terms of readily quantifiable components such as energy, GHG emissions and nutrients, and thus to provide a robust and durable basis for both economic and life cycle assessment. Examples of how modelling tools of this type can be used for these purposes, and even as a basis for the estimation of marginal abatement costs of GHG emissions, are given e.g. in Jain et al. (2012) and Jain (2013).

7 Conclusions

The model makes it possible to examine a range of scenarios for the same waste inputs, in order to determine which option may provide the most energy or GHG efficient system. Modelling based on literature and reported values gave similar results to those for both of the full-scale plants monitored in the VALORGAs project, indicating the modelling tool is robust and reliable.

The majority of the typical scenarios considered showed positive energy and GHG emissions balances. Scenarios based on electricity production alone without utilisation of heat or digestate are likely to be energy negative. Collection systems operating in very sparsely populated areas with large transport distances may also show reduced or even negative energy balances, while digesters with larger throughput may benefit from improved efficiency. Systems based on production of biomethane showed a positive balance under all the conditions considered, providing further justification for the focus on small-scale gas upgrading and utilisation within the current project. The work reported here focusses mainly on the energy balance, as this is the main goal of the VALORGAS project; but the approaches adopted can be used to support decisions based on a wide range of factors in terms of cost, resources and environmental impact. The output from scenario modelling is not a single answer that will be correct in all cases: the optimum solution for a given scheme is dependent on its specific features, and in practice selection will be strongly influenced by cost and acceptability. The combined modelling tools provide a means of exploring the consequences of different choices in terms of energy, GHG emissions and nutrient, and thus offer support to the decision-making process.

In conclusion it appears that valorisation of food waste to biogas is an effective means of both energy production and environmental benefit. The current work has delivered two tools that can be used in conjunction to make a rational assessment of the energy and environmental benefits of alternative schemes.

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Appendix 1: User manual for spreadsheet version of AD modelling tool

THEME ENERGY.2009.3.2.2
Valorisation of food waste to biogas
Grant agreement no. 241334

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]

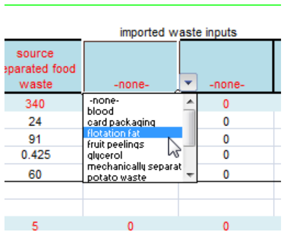
Bio-energy and Organic Research Group
Faculty of Engineering & the Environment
University of Southampton

Introduction

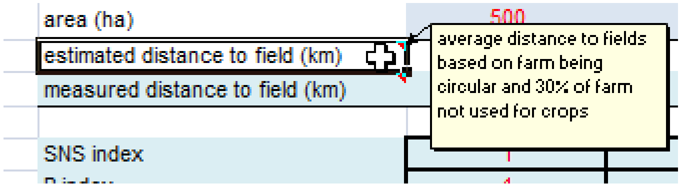
The various aspects of the energy tool have been combined into a spreadsheet based tool in order to allow for the calculation of potential energy balances and emissions using a waste based AD system. The tool enables the user to get a 'snap shot' view based on a single year but with the flexibility to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

User inputs are indicated in the tool by red text

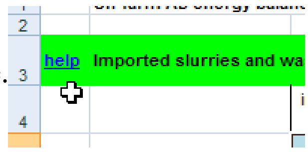
or drop down lists (red text, blue background and thick border).



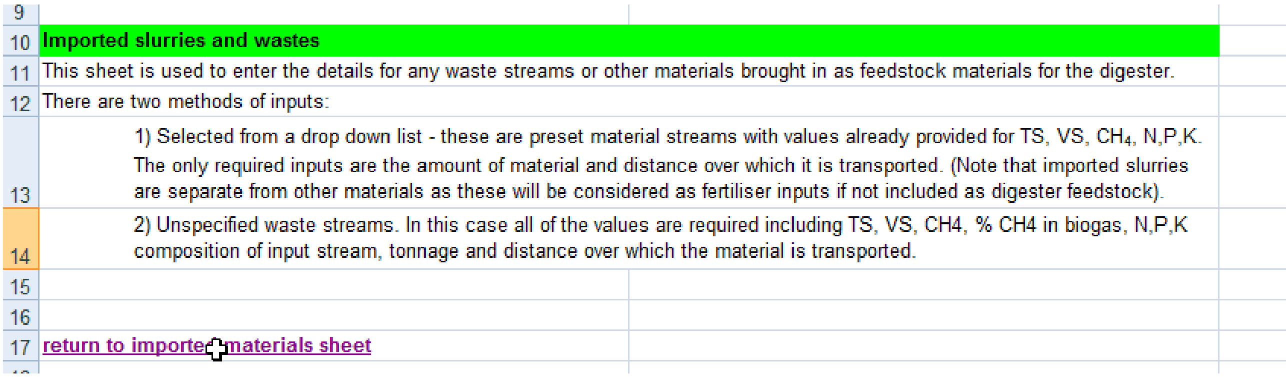
Some cells have a small red triangle in the top right corner. Placing the mouse pointer over the cell will cause a comment box to appear proving some help regarding the information in that row.



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



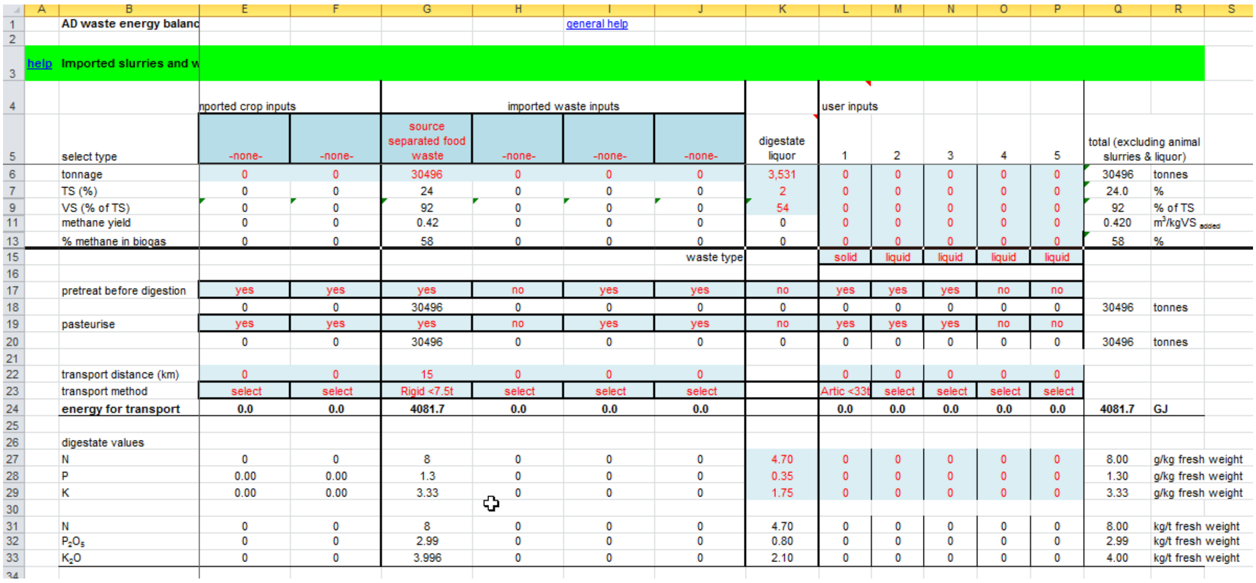
Clicking on the relevant 'return' link from this page returns the user to the selected input sheet.



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

Imported materials

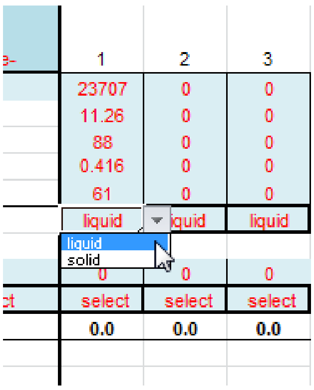
A number of specified import streams including wastes can be entered (Figure 1). Selection can be made from a range of animal slurries including cattle pigs and poultry. Once selected the only other inputs required are the amount and the distance. A range of preselected crop and other waste streams are 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
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.

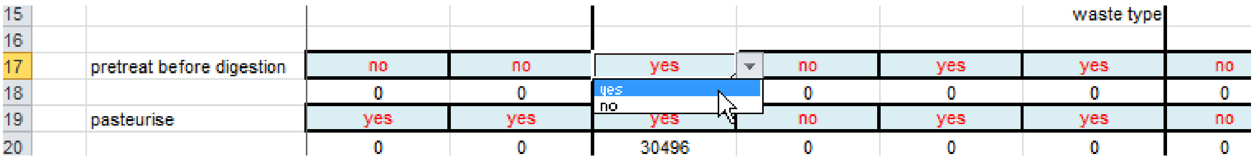


Figure 3: pre-treatment

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

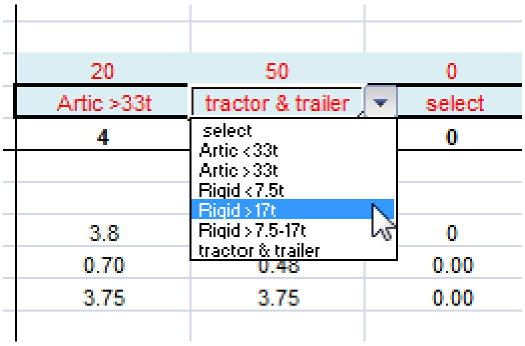
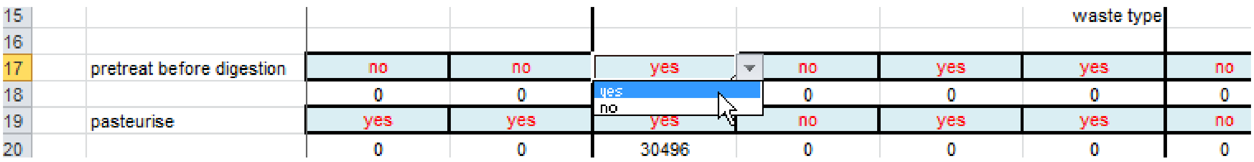


Figure 4: Selecting transport type

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.

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.


waste type
pretreat before digestion
pasteurise
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

The digesters

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

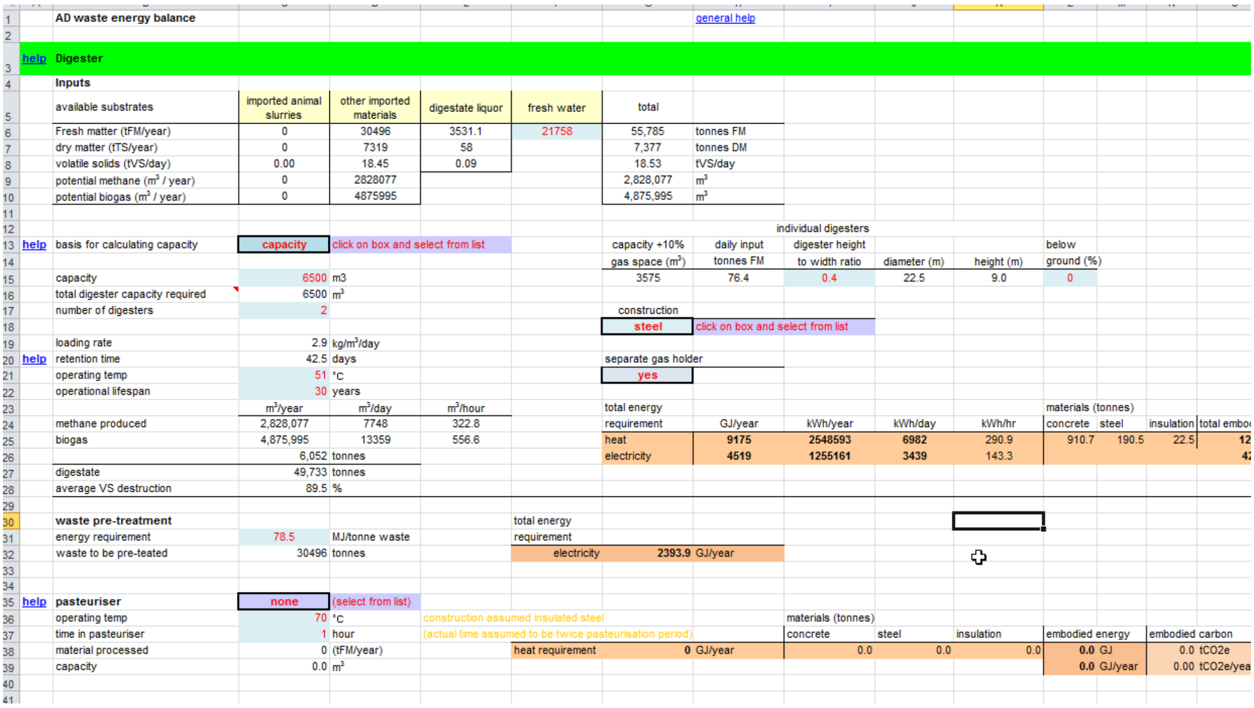


Figure 5: Digester capacity and energy requirements

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.

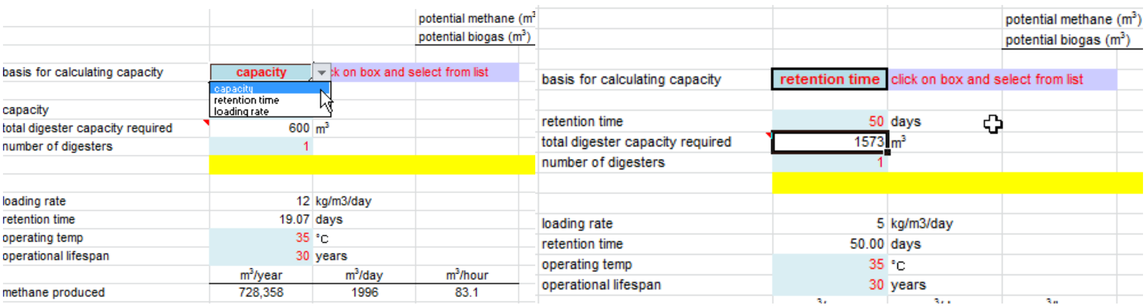


Figure 6: Selection of capacity criteria

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.

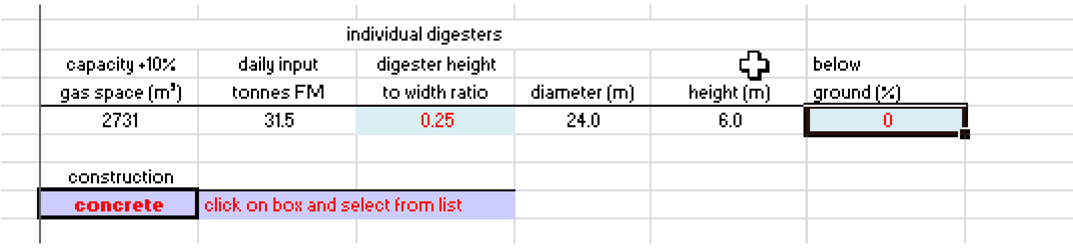


Figure 7: inputs for digester dimensions

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.

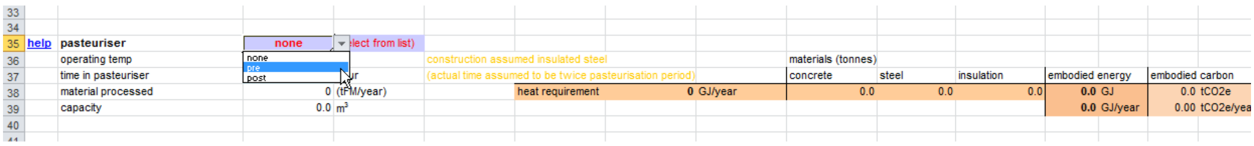


Figure 8: Pasteurisation

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.

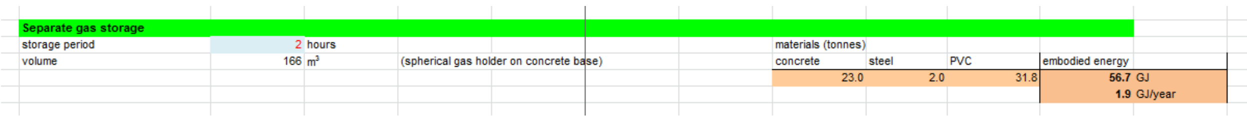


Figure 9: Biogas storage

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	m³	(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									

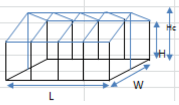


Figure 12: ABPR building

Digestate

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

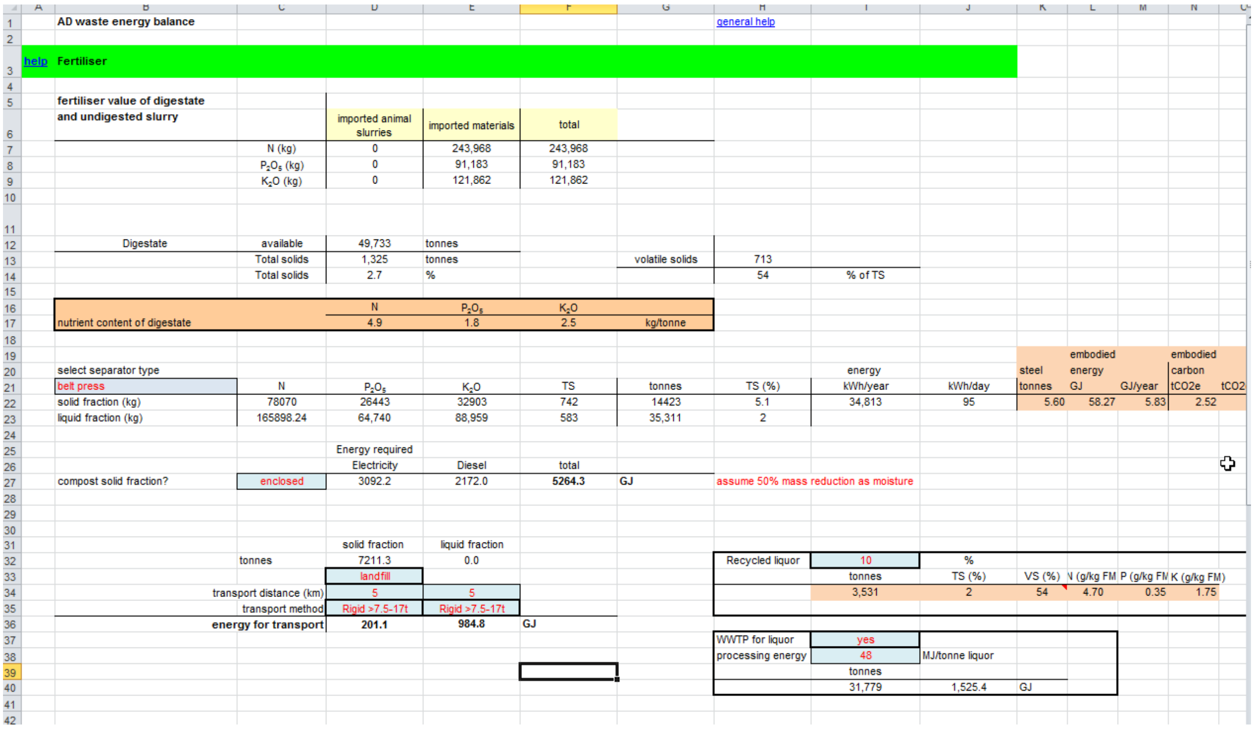


Figure 13: Digestate output

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.

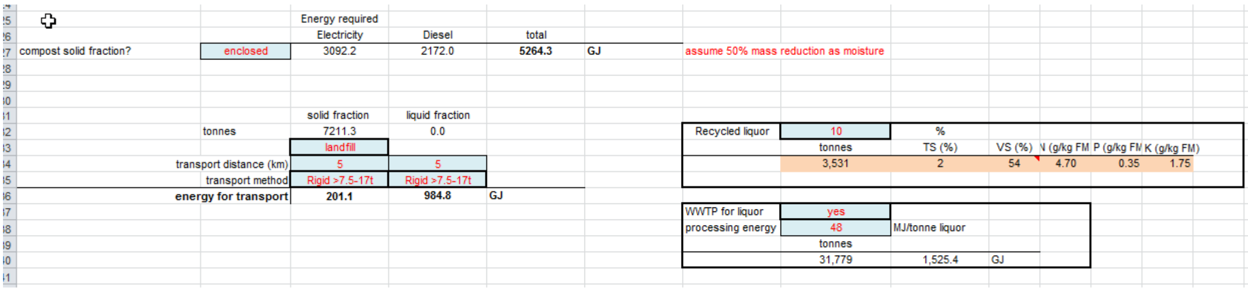


Figure 14. digestate treatment options

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.

1		AD waste energy balance				general help						
2												
3	help	Biogas use										
4		Biogas produced	4875995	m^3								
5		process losses	1	%								
6		Biogas available	4827235	m^3								
7		methane available	2799796	m^3								
8												
9		on-site biogas use	CHP	(select from list)								
10		upgrade	none									
11												
12		methane lost in upgrading	2	%								
13		exported biogas	0	m^3								
14		upgraded CH4	0	m^3	0.0	m3/h						
15												
16		Electricity										
17		CHP electrical efficiency	35	%								
18		CHP electricity produced	35,101	GJ		number of CHP units installed		1				
19			9,751,071	kWh			output per unit	1175	kW			
20		load factor	8,300	hours/year								
21		total CHP electrical capacity	1,175	kW								
22		lifespan of CHP	15	years								
23								CHP embodied energy per unit			total	
24		electricity for pre-processing	2393.9	GJ	1255161	kWh			concrete (GJ)	steel (GJ)	for all units	
25		electricty for digester	4518.5	GJ					25.31	322.7	348.0	GJ
26		electricity for digestate processing	6915.0	GJ							23.2	GJ/year
27		electricity for upgrade & compression	0.0	GJ	0	kWh						
28		electricty requirement total	11433.5	GJ	3176009	kWh						
29		grid supplied electricty	0	GJ	0	kWh						
30												
31		Heat										
32												
33		CHP/boiler heat efficiency	50	%					0.85			
34		CHP/boiler heat produced	50,144	GJ								
35			13,930,101	kWh					none			
36												
37		heat required for digester	1,372	GJ								
38		heat required for pasteuriser	6,713	GJ								
39		heat available for export	42,059.7	GJ	heat utilisation	100	%	this is heat replacing fossil fuels				
40			9,581,193	kWh	heat used	9,581,193	kWh					
41		imported energy for heat	0	GJ								
42		heat energy source	natural gas									
43		volume required	0	m3								

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).

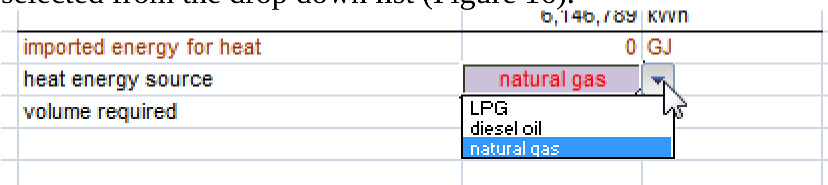


Figure 16: Heat energy sources

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.

5	Upgrading										
6											
7	Electricity for upgrading biogas	1.08	MJ/m^3 biogas		average	1.08	Upgrading embodied energy per unit			stainless	total
8	Electricity for compression of upgraded methane	1.08	MJ/m^3 upgraded		average	1.08		concrete (GJ)	steel (GJ)	steel (GJ)	for all units
9								0.0	0.0	0.0	0.0 GJ
0											0.0 GJ/year
1											

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.

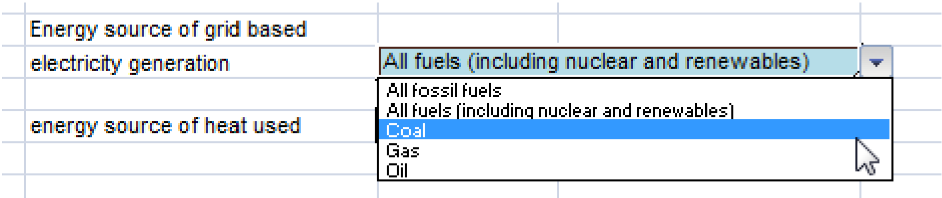


Figure 19: Sources for electricity generation

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 2: 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	$MJ tonne^{-1} km^{-1}$	$L tonne^{-1} km^{-1}$
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 * ($\pi*0.005^2$) * 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.