Supplementary Materials

Potential for biomethanisation of CO_2 from anaerobic digestion of organic wastes in the UK'

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S1. Assessment of performance data for CO_2 biomethanisation of organic feedstocks

Tables S1-S4 summarise the available data on CO_2 biomethanisation of organic feedstocks by feedstock type. The following nomenclature and definitions were used to obtain these values, which may therefore differ slightly in some cases from those reported in the original paper. The significance of some parameters is discussed briefly below.

Nomenclature: NB parameters are listed in the order in which they appear in Tables S1-S4

Acronym	*Definition*	*Unit*
OLR	Organic loading rate, expressed as the mass of VS or COD added per unit of digester working volume per unit time	g VS L^{-1} day^{-1} or g COD L^{-1} day^{-1}
HRT	Hydraulic retention time, as reported or calculated from digester working volume divided by the daily volume of feed added	days
H_2 input	Volume of H_2 added per unit of digester working volume per unit time	L H_2 L^{-1} day^{-1}
CO_2 input *	Volume of exogenous CO_2 added, per unit of digester working volume per unit time.	L CO_2 L^{-1} day^{-1}
SMP	Specific methane production, defined as the volume of CH_4 produced from both anaerobic degradation of organic material and CO_2 biomethanisation (including from exogenous CO_2 where applicable), per unit of organic feed added	L CH_4 g^{-1} VS or L CH_4 g^{-1} COD
SMP_{org} *	Volume of CH_4 produced from anaerobic degradation of organic material per unit of organic feed added. Values taken either from a digester without H_2 addition operating in parallel with the experimental digester(s), or from a baseline period with no H_2 addition: these conditions are defined as control conditions.	L CH_4 g^{-1} VS or L CH_4 g^{-1} COD
SMP_{H2}	Volume of CH_4 assumed to be produced from exogenous H_2 via CO_2 biomethanisation, per unit of organic feed added. Taken as the difference between *SMP* and *SMP_{org}*.	L CH_4 g^{-1} VS or L CH_4 g^{-1} COD
SMP_{inc}	Proportional increase in methane production that is attributed to CO_2 biomethanisation, equal to *SMP_{H2}* divided by *SMP_{org}*.	%
VMP	Volumetric methane production, defined as the volume of CH_4 produced from both anaerobic degradation of organic material and CO_2 biomethanisation (including from exogenous CO_2 where applicable), per unit of digester working volume per unit time	L CH_4 L^{-1} day^{-1}

VMP_{org} *	Volume of CH_4 produced from anaerobic degradation of organic material, per unit of digester working volume per unit time, with values taken under control conditions as defined for *SMP_{org}*.	L CH_4 L^{-1} day^{-1}
MER	Methane Evolution Rate, the volume of CH_4 assumed to be produced from CO_2 biomethanisation via exogenous H_2 addition, per unit of digester working volume per unit time. Taken as the difference between *VMP* and *VMP_{org}*.	L CH_4 L^{-1} day^{-1}
VCO_2 *	Volume of CO_2 produced, from both anaerobic degradation of organic material and CO_2 biomethanisation (including exogenous CO_2 where applicable), per unit of digester working volume per unit time.	L CH_4 L^{-1} day^{-1}
VCO_{2org} *	Volume of CO_2 produced from anaerobic degradation of organic material, per unit of digester working volume per unit time, with values taken from control conditions as defined for *SMP_{org}*.	L CH_4 L^{-1} day^{-1}
CRR *	CO_2 Removal Rate, the volume of CO_2 assumed to be removed via CO_2 biomethanisation, per unit of digester working volume per unit time. Taken as the difference between *VCO_2* and *VCO_{2org}*.	L CO_2 L^{-1} day^{-1}
VGP *	Total volume of output gas, including H_2, per unit of digester working volume per unit time.	L L^{-1} day^{-1}
VBP *	Sum of *VMP* and *VCO_2*	L biogas L^{-1} day^{-1}
VBP_{org} *	Sum of *VMP* and *VCO_{2org}*	L biogas L^{-1} day^{-1}
CH_4, CO_2, H_2	Concentrations of CH_4, CO_2 and H_2, respectively, in the output gas on a volumetric basis	%
pH	pH value of digestate	-
H_2/CO_2	Ratio of H_2 added to experimental digester and CO_2 production of control, taken as *H_2 input/VCO_{2org}* for the relevant conditions.	-
H_2 output *	Volume of H_2 leaving in gaseous form, per unit of digester working volume per unit time. Reported or calculated from output gas volume and concentration.	L H_2 L^{-1} day^{-1}
H_2 trans	Volume of H_2 successfully transferred from gaseous phase into the digester, per unit of digester working volume per unit time. Taken as (*H_2 input* - *H_2 output*)	L H_2 L^{-1} day^{-1}
E	H_2 transfer efficiency, the proportion of H_2 successfully transferred from the gaseous phase into the digester, equal to *H_2 trans/H_2 input*	%
Exp MER, Exp CRR *	Theoretical expected values for *MER* and *CRR* equal to the amount of H_2 transferred divided by 4, i.e. *H_2 trans*/4, based on stoichiometry.	L CH_4 L^{-1} day^{-1}, L CO_2 L^{-1} day^{-1}

** Not shown in Table S1-S4*

The *H_2/CO_2* ratio compares the H_2 input with the amount of CO_2 produced by the control, and thus provides an indication of the proportion of endogenous CO_2 that could be converted. This ratio is used as a control parameter in some studies (e.g. [23, 31, 45, 68, 75, 76], and is sometimes reported instead of H_2 input. Experimental work at ratios below 4 may not give the maximum achievable biogas methane content, as in principle there is insufficient H_2 for stoichiometric conversion of the available CO_2.

The H_2 transfer efficiency *E* indicates the proportion of H_2 added that is transferred and utilised in some way, rather than passing straight out of the digester in the output gas: it thus provides an indicator of effective utilisation of exogenous H_2. This is an important consideration given both the energy required for H_2 production, and the fact that it represents a resource for which competing applications may exist.

In addition to the parameters shown above, a number of ratios were considered as they provide some insight on process and performance. The ratio *MER*/*Exp MER* indicates the proportion of the H_2 transferred that is being utilised for something other than CH_4 production. Observed values in Tables S1-S4 can be placed in 3 groups: where the value is < 1, some of the transferred H_2 is being diverted to products other than methane, such as biomass growth or volatile fatty acid (VFA) production (e.g. [41]). Values close to 1 indicate an effective process from the viewpoint of biogas upgrading (e.g. [11, 28]). Values > 1 may indicate non-steady-state operation e.g. with methane produced from consumption of previously accumulated VFA (e.g. [61]); or from enhanced degradation of organic substrate, as discussed below and in the main text.

The ratios H_2 *trans*/*MER* and H_2 *trans*/*CRR* are closely related to *MER*/*Exp MER* and *MER*/*Exp CRR*, respectively, and provide another indication of how much H_2 is being combined with CO_2 to produce CH_4. The reaction stoichimetry from Equation 1 in the main text suggests a value of 4, but in practice both ratios can diverge from this. Based on theoretical pathway analysis, around 5% of H_2 is used in microbial biomass production (Thauer, 2012). The value of H_2 *trans*/*MER* rises when H_2 is used for other purposes. The behaviour of H_2 *trans*/*CRR* is more complicated, as it depends on the nature of products other than CH_4. If, for example, acetic acid is produced according to the equation 2 CO_2 + 4 H_2 = CH_3COOH + $2H_2O$, the stoichiometric ratio between H_2 and CO_2 is 2. If microbial biomass is assumed to have an empirical formula of $C_5H_7NO_2$, the anabolic reaction is 5 CO_2 + 10 H_2 + NH_4^+ = $C_5H_7NO_2$ + 8 H_2O + H^+ and the ratio of H_2 to CO_2 is again 2. In each case carbon is diverted away from CH_4 production and the ratio H_2 *trans*/*CRR* falls. In addition *CRR* is calculated from VCO_2 and VCO_{2org} and depends upon gaseous CO_2 concentrations; but on biomethanisation of headspace CO_2 a proportion of the CO_2 dissolved in the digestate will be released, which may increase the value of H_2 *trans*/*CRR*. More detailed calculations and mass balances of this type are provided by several authors (e.g. [6, 26, 77]).

The ratio *MER*/VCO_{2org} is a measure of how much of the CO_2 produced in the control without H_2 addition has theoretically been converted in an experimental digester. As noted in the main text, in several cases the value is greater than 1, which would imply more than 100% conversion if the available CO_2 has not changed. This may reflect an increase in underlying VMP_{org}, or in VCO_2 if there is sufficient H_2 for conversion, or both. The ratio *VBP*/VBP_{org} indicates whether VBP appears to have changed as a result of CO_2 biomethanisation, and is also greater than 1 in some cases. In some of these cases, the experimental design was sequential, relying on a previous baseline for control values (e.g., [21, 22, 24, 27, 33, 57, 61, 66]), and the increase in *VBP* could therefore possibly reflect changes in feedstock properties and/or acclimatisation over time; however the same phenomenon is also seen in studies with a parallel control (e.g., [29, 43, 45, 47, 68, 74]).

The ratio *CRR*/*Exp CRR* should be above 1 when there is microbial biomass or acetic acid production, and below 1 if biogas production from the organic substrate increases during CO_2 biomethanisation. A value of *MER*/*CRR* close to 1 suggests that the majority of CO_2 removed is being converted to CH_4. This ratio is generally expected to be < 1 as some carbon will be converted into biomass, but could increase when CO_2 biomethanisation causes dissolved CO_2 to come out of solution.

All comparisons between values and ratios presented in Tables S1-S4 should be regarded with caution, as they come from studies carried out under different conditions and are based on simplifying assumptions; but these parameters nevertheless provide some useful and intriguing insights indicating where further research may be needed. Data used for these tables is available at http://doi.org/10.5258/SOTON/D2241, and the authors welcome any comments and corrections.

Table S1 Performance data for CO_2 biomethanisation of livestock manures (for notes on Tables see Table S4)

	Ref	Substrate	Temp oC	Reactor	Total vol L	Working vol L	Mixing	Gas recirc	Injector	Exp'tl design	Varied	Note
Livestock manures		**Manures**										
Luo et al., 2012a	1	CM	55	CSTR	4.5	3.5	Mechanical	No	Ceramic	Parallel	With/without H2	-
												-
Bassani et al., 2015	21	CM	35	2-stage CSTR	n/r	1.5 and 2	Magnetic	No	Diffuser	Sequential	Temp - meso and thermo	Control period
												-
			55									Control period
												-
Treu et al., 2018	22	CM	55	2-stage CSTR	n/r	1.5 and 2	Stirred	No	Diffuser	Sequential	H2 addition	Control period
												Initial value
												After 2 years
Wahid and Horn, 2021a	23	CM	55	2-stage CSTR	10 and 10	6 and 6	Impeller	Yes	Diffuser	Sequential	Mixing and gas recirc	-
												Highest SMP etc
Lebranchu et al., 2020	24	CM	40	CSTR	142	100	Helical	No	Silicone tube	Sequential	H2 addition	Control period
												Best performance
												-
Zhu et al., 2019a	25	PM	55	CSTR	n/r	11.2	Mechanical	No	Distributor	Sequential	Mixing, sodium formate	Control period
												Continuous mixing
												Continuous mixing, HCOONa
Zhu et al., 2019b	26	PM	35	CSTR	n/r	11.2	Mechanical	No	Distributor	Sequential	Temperature and mixing	Meso - intermittent mixing
												Meso - intermittent mixing
												Meso - continuous mixing
			55									Thermo - intermittent mixing
												Thermo - continuous mixing
Zhu et al., 2020	27	PM	35	CSTR	n/r	11.6	Mechanical	No	Distributor	Sequential	H2 addition and mixing	Control period
												Low H2/CO2
												Intermittent mix
Luo et al., 2013a	29	CM + whey	55	CSTR	1	0.6	Magnetic	No	Column/ceramic	Parallel	Diffuser and mixing speed	150 rpm, column
												150 rpm, column
												300 rpm, ceramic
												300 rpm, ceramic
												150 rpm, ceramic
												150 rpm, ceramic
Luo and Angelidaki, 2013b	30	CM + whey	55	CSTR	1	0.6	Magnetic	No	HFM	Parallel	H2 addition	Control reactor
												Best performance
Wahid and Horn, 2021b	31	CM + whey	55	2-stage CSTR	10 and 10	6 and 6	Impeller	Yes	Diffuser	Sequential	Stirring, CM/W ratio, Feed freq	CM/W 9, 80 rpm, daily feed
												CM/W 9, 80 rpm, daily feed
Khan et al., 2022	33	CM + veg waste	37	2-stage	2.5 (total)	2 (total)	None/gas recirc	Yes	Sparger	Sequential	H2 and gas recirc rates	No recirc
												No recirc
												With recirc
												With recirc

Table S1 ctd Performance data for CO_2 biomethanisation of livestock manures (for notes on Tables see Table S4)

Ref	Case	OLR	HRT	H_2 input	SMP	SMP_{H2}	SMPinc	VMP	MER	CH4	CO2	H2	pH	*CRR*	*H2/*	*H2 trans/*	*MER/*	*CRR/*	*MER/*	*MER/*	*VBP/*	*H2 trans/*	*H2 trans/*
		g VS/L-day	days	L/L-day	L/g VS	L/g VS	%	L/L-day	L/L-day	%	%	%			*CO2*	*input*	*Exp MER*	*Exp CRR*	*CRR*	*VCO2org*	*VBPorg*	*MER*	*CRR*
1	No H2	6.2	14.6		0.060			0.37		62.0	38.0		8.00										
	With H2			0.69	0.073	0.013	22%	0.45	0.08	65.0	15.0	20.0	8.30	0.12	3.00	0.80	0.60	0.91	0.65	0.36	0.93	6.7	4.4
21	No H2	0.6	25 and 33		0.111			0.07		69.7	30.3		7.73										
	With H2			0.19	0.168	0.057	51%	0.10	0.03	88.9	8.8	2.3	8.17	0.02	6.74	0.99	0.72	0.39	1.83	1.19	1.16	5.6	10.2
	No H2	1	15 and 20		0.249			0.25		67.1	32.9		7.89										
	With H2			0.51	0.359	0.110	44%	0.36	0.11	85.1	6.6	8.3	8.49	0.09	4.21	0.94	0.94	0.78	1.20	0.93	1.05	4.3	5.1
22	No H2	1.0	15 and 20		0.262			0.26		66.9	33.1		7.90										
	With H2			0.51	0.376	0.114	44%	0.37	0.11	86.5	6.6	6.9	8.49	0.10	4.00	0.94	0.48	0.42	1.13	0.88	1.11	4.3	4.8
	With H2			0.51	0.500	0.238	91%	0.34	0.09	98.7	0.9	0.4	8.71	0.12	4.00	0.99	0.34	0.50	0.68	0.66	0.82	6.0	4.1
23	No H2	3.1	15 and 20		0.217			0.67		62.2	37.8		7.86										
	With H2			1.66	0.411	0.194	90%	0.90	0.23	40.3	11.9	47.7	8.41	-0.03	4.00	0.36	2.56	-0.37	-6.87	0.57	1.08	6.6	-17.8
24	No H2	3.85	28		0.186			0.72		57.4	42.4		7.45										
	With H2			0.45	0.221	0.035	19%	0.85	0.14	68.3	31.6	0.0	7.70	0.14	0.84	0.97	1.25	1.25	1.00	0.26	1.00	3.2	3.2
	With H2+CO2			0.60	0.236	0.050	27%	0.91	0.19	67.5	32.5	0.0	7.80	0.09	1.04	1.00	1.26	0.61	2.07	0.36	1.08	3.2	6.5
25	No H2	2	25		0.222			0.44		66.0	34.0		7.63										
	With H2			0.95	0.253	0.031	13%	0.51	0.02	46.9	14.7	38.4	7.73	0.07	4.15	0.56	2.18	0.53	0.86	0.27	0.99	8.7	7.6
	With H2			0.95	0.292	0.069	27%	0.58	0.03	54.8	11.5	33.7	7.85	0.11	4.15	0.62	1.07	0.72	1.31	0.61	1.05	4.3	5.6
26	No H2	2	25		0.197			0.10		62.0	38.0		7.36										
	With H2	2		0.13	0.200	0.003	2%	0.10	0.00	59.8	32.2	8.0	7.40	0.03	0.55	0.60	3.35	1.30	0.23	0.02	0.97	13.4	3.1
	With H2	2		0.64	0.210	0.013	5%	0.11	0.01	39.1	16.8	44.1	7.59	0.06	2.66	0.26	1.63	1.45	0.42	0.11	0.94	6.5	2.8
	No H2	2			0.222	0.025	12%	0.11	0.01	66.0	34.0		7.63										
	With H2	2		0.66	0.245	0.048	20%	0.12	0.02	68.3	19.3	12.4	7.77	0.09	2.89	0.86	3.11	0.63	0.51	0.20	0.93	12.4	6.3
27	No H2	2	25		0.189			0.39		62.0	38.0		7.36										
	With H2			0.19	0.200	0.011	6%	0.42	0.03	55.8	30.0	14.2	7.42	0.01	0.78	0.43	0.66	0.65	2.33	0.13	1.04	2.6	6.2
	With H2			0.89	0.245	0.055	29%	0.51	0.12	32.5	16.7	50.8	7.63	-0.02	3.74	0.11	0.20	-0.97	-5.06	0.50	1.25	0.8	-4.1
29	No H2	1.67	15		0.287			0.48		55.0	45.0	0.0	7.28										
	With H2			1.70	0.452	0.166	58%	0.76	0.28	53.0	13.0	34.0	7.74	0.21	4.32	0.71	0.91	0.69	1.33	0.70	1.08	4.4	5.8
	No H2	1.67	15		0.299			0.50		56.0	44.0	0.0	7.33										
	With H2			1.70	0.501	0.202	67%	0.84	0.34	68.0	8.8	23.2	7.84	0.29	4.32	0.83	0.96	0.81	1.19	0.86	1.06	4.2	5.0
	No H2	1.67	15		0.295			0.49		56.7	43.3	0.0	7.31										
	With H2			1.70	0.529	0.234	79%	0.89	0.39	75.0	6.6	18.4	7.89	0.30	4.50	0.87	1.05	0.81	1.30	1.03	1.10	3.8	4.9
30	No H2	1.67	15		0.288			0.48		55.4	44.6		7.30										
	With H2			1.76	0.516	0.265	92%	0.86	0.38	96.1	3.9	0.0	8.31	0.35	4.56	1.00	1.00	0.80	1.26	1.15	1.03	4.0	5.0
31	No H2	4.13	20		0.144			0.59		59.1	40.9		7.94										
	With H2			1.44	0.165	0.031	23%	0.68	0.13	38.7	19.1	42.2	7.95	0.07	3.54	0.48	0.52	0.41	1.28	0.22	1.02	7.7	9.8
33	No H2	3.5	10		0.300			1.05		73	27		7.20										
	With H2	3.5	10	1.60	0.500	0.200	67%	1.75	0.7	63	5	31.6	7.00	0.24	4.12	0.45	3.89	1.31	2.96	1.80	1.36	1.0	3.0
	No H2	3.5	10		0.425			1.49		76	24		7.30										
	With H2	3.5	10	1.60	0.897	0.472	157%	3.14	1.652	96	1	3.1	7.20	0.44	3.41	0.94	4.41	1.17	3.77	3.52	3.52	0.9	3.4

Table S2 Performance data for CO_2 biomethanisation of crops and agro-wastes (for notes on Tables see Table S4)

	Ref	Substrate	Temp oC	Reactor	Total vol L	Working vol L	Mixing	Gas recirc	Injector	Exp'tl design	Varied	Note
Crops and agro-wastes												
Voelklein et al., 2019	42	Grass silage	55	CSTR	9.5	n/r	Mechanical	Yes	Low capacity diffuser	Sequential	Diffuser type	Control period
												Low capacity diffuser
									Ceramic diffuser			Control period
												Ceramic diffuser
Illi et al., 2021	43	Maize silage + sugar beet silage effluent	37	Anaerobic filter	130	95	Pump	Yes?	Venturi	Parallel	H2 ratio	Control reactor
												H2/CO2 = 2
												H2/CO2 = 4
Schönberg and Busch, 2012	44	Maize silage hydrolysate	55	2-stage	n/r	200 + 145 (exptl)	Percolation	No?	Injector	Parallel	Hydrolysis conditions	Hydrolysis at 55 oC
												-
												Hydrolysis at 60 oC
												-
												Hydrolysis at 60 oC
												-
Agneessens et al., 2017	45	Mixed agrowaste digestate	38	CSTR	2	0.3	Stirred	No	Headspace - pulsed	Parallel	H2/CO2 ratio	Control reactor
												H2/CO2 = 6
Agneessens et al., 2018	47	Mixed agrowaste digestate	38	CSTR	1.4	0.3	Stirred	No	Headspace - pulsed	Parallel	OLR and H2 addition	OLR 2
												>25% CO2, OLR 2, inj 1
												OLR 2
												<7% CO2, OLR 2, inj 10

Table S2 ctd Performance data for CO_2 biomethanisation of crops and agro-wastes (for notes on Tables see Table S4)

Ref	**Case**	**OLR**	**HRT**	**H_2 input**	**SMP**	**SMP_{H2}**	**SMPinc**	**VMP**	**MER**	**CH4**	**CO2**	**H2**	**pH**	*CRR*	*H2/*	*H2 trans/*	*MER/*	*CRR/*	*MER/*	*MER/*	*VBP/*	*H2 trans/*	*H2 trans/*
		g VS/L-day	days	L/L-day	L/g VS	L/g VS	%	L/L-day	L/L-day	%	%	%			*CO2*	*input*	*Exp MER*	*Exp CRR*	*CRR*	*VCO2org*	*VBPorg*	*MER*	*CRR*
42	No H2	4.0	46		0.388			1.53		54.8	45.2	0.0	7.81										
	With H2			5.05	0.461	0.073	19%	1.82	0.29	32.1	11.4	56.5	7.97	0.62	4.00	0.37	0.63	1.33	0.47	0.23	0.88	6.4	1.2
	No H2				0.382			1.51		53.2	46.8		7.89										
	With H2			5.29	0.640	0.258	68%	2.52	0.99	60.3	5.1	34.6	8.37	1.12	3.98	0.73	1.05	1.16	0.91	0.76	0.96	3.8	2.7
43	No H2	2.92	17		0.310			0.91		66.1	27.9		7.91										
	With H2	3.00	17	0.75	0.350	0.040	13%	1.05	0.14	62.7	18.4	11.0	8.17	0.07	1.95	0.76	0.99	0.53	1.87	0.36	1.05	4.0	7.6
	With H2	3.53	16	1.51	0.350	0.040	13%	1.20	0.29	56.7	12.0	27.0	8.55	0.13	3.94	0.62	1.23	0.55	2.25	0.76	1.12	3.2	7.3
44	No H2	1.02	22		0.28			0.29	n/a	norm	norm	n/r	n/r										
	With H2	1.12	22	2.67	0.31	0.025	9%	0.34	n/a	norm	norm	n/r	n/r	-0.02	n/r	n/r	0.08	n/r	n/r	0.17	n/r	n/r	n/r
	No H2	0.89	24		0.31			0.27	n/a	norm	norm	n/r	n/r										
	With H2	1.01	24	4.57	0.31	0.007	2%	0.32	n/a	norm	norm	n/r	n/r	0.04	n/r	n/r	0.04	n/r	n/r	0.11	n/r	n/r	n/r
	No H2	1.27	46		0.38			0.49	n/a	norm	norm	n/r	n/r										
	With H2	1.39	46	10.95	0.41	0.022	8%	0.56	n/a	norm	norm	n/r	n/r	-0.03	n/r	n/r	0.03	n/r	n/r	0.15	n/r	n/r	n/r
45	No H2	0.77	20		0.293			0.23		59.4	40.7	n/a	7.91										
	With H2	0.77	20	0.93	0.571	0.214	73%	0.44	0.21	100.0	0.0	n/a	7.91	0.15	6.00	1.01	0.94	0.68	1.39	1.39	1.16	4.2	5.8
47	No H2	2.0	20		0.129			0.26		56.0	44.0	n/a	7.92										
	With H2	2.0	20	1.30	0.230	0.102	79%	0.46	0.20	94.0	6.0	n/a	7.92	0.17	6.42	1.00	0.62	3.61	1.17	1.00	1.07	6.4	7.5
	No H2	2.0	20		0.077			0.15		55.0	45.0	n/a	8.35										
	With H2	2.0	20	1.30	0.145	0.068	89%	0.29	0.14	83.0	17.0	n/a	8.34	0.07	10.32	1.00	0.42	6.32	2.05	1.08	1.25	9.5	19.5

Table S3 Performance data for CO_2 biomethanisation of food wastes (for notes on Tables see Table S4)

	Ref	Substrate	Temp oC	Reactor	Total vol L	Working vol L	Mixing	Gas recirc	Injector	Exp'tl design	Varied	Note
Food wastes												
Tao et al., 2020	12	Commercial and industrial FW	37	CSTR	3	2	Impeller	Yes	Bubble	Sequential	H2, exogenous CO2 + H2	Additional data provided by authors
Zhang (pers com 2022)	53	Source separated domestic FW	37	CSTR	5	4	Mechanical	Yes	Bubble	Parallel	with/without H2	Pers. com. -
Kim et al., 2021	54	FW	37	CSTR	3.7	3	Mechanical	No	Sparger	Sequential	H2 and pressure	1 bar 5 bar 5 bar
Yang et al., 2020	55	FW	37 55	CSTR	5	4	Mechanical	No	Aeration basket	Sequential	Syngas injection rate	Meso - Thermo -
Thapa et al., 2021	57	Thermally-treated FW digestate	37	Trickling filter	n/r	1.1	Liquid recirc	Yes	Headspace	Sequential	H2 and recirc rate	- Lowest H2% Highest SMP
Treu et al., 2019	61	Whey	37	CSTR	n/r	1.5	Magnetic	Yes	Ceramic	Sequential	Temperature + feedstock	with buffer -
Fontana et al., 2018a	62	cheese whey permeate + powder	55	CSTR	n/r	3	Magnetic	Yes	Ceramic membrane	Sequential	H2 addition	- -
Lovato et al., 2017	63	Whey + CM	55	CSTR	1.8	1.2	tbc	tbc	tbc	Sequential	with/without H2	- -
Treu et al., 2019	61	Whey + CM	54	CSTR	n/r	1.5	Magnetic	Yes	Ceramic	Sequential	Temperature + feedstock	- -
Bassani et al., 2016	65	Potato-starch wastewater	55	UASB	n/r	1.4	Liquid recirc	No	Separate chamber	Parallel	Liquid recirc + injection	Rashig - Ceramic with gas recirc -
Deschamps et al., 2021	66	Ethanol distillery wastewater	37	AnMBR	?	148 calc	Liquid recirc	No	Tubular ceramic	Sequential	H2 addition	Control period -
Tao et al., 2019	67	Synthetic organic feed	37	CSTR	1	0.5	Impeller	Yes	Bubble	Parallel	OLR and additional CO2	Average of duplicates Average of duplicates Average of duplicates Average of duplicates Average of duplicates Average of duplicates Average of duplicates Average of duplicates Average of duplicates Average of duplicates
Tao et al., 2020	12	Synthetic organic feed	37	CSTR	1	0.5	Impeller	Yes	Bubble	Parallel	TAN concentration	TAN 2 g N/L TAN 2 g N/L TAN 3 g N/L TAN 3 g N/L
Wahid et al., 2019	68	Glucose	37	CSTR	0.5	0.39	Shaker	No	Headspace	Parallel	H2 addition	- -
Jing et al., 2017	70	Glucose	37	UASB	1.2	1	Upflow	Yes	Microporous diffuser	Parallel	CO flow rate and recirculation	CO not H2 CO not H2

Table S3 ctd Performance data for CO_2 biomethanisation of food wastes (for notes on Tables see Table S4)

Ref	Case	OLR	HRT	H_2 input	SMP	SMP_{H2}	SMPinc	VMP	MER	CH4	CO2	H2	pH	*CRR*	*H2/*	*H2 trans/*	*MER/*	*CRR/*	*MER/*	*MER/*	*VBP/*	*H2 trans/*	*H2 trans/*
		g VS/L-day	days	L/L-day	L/g VS	L/g VS	%	L/L-day	L/L-day	%	%	%			*CO2*	*input*	*Exp MER*	*Exp CRR*	*CRR*	*VCO2org*	*VBPorg*	*MER*	*CRR*
12	No H2	4.14	25		0.561			2.32		65.5	34.2	0.0	8.11										
	With H2	4.14	25	3.70	0.776	0.215	38%	3.21	0.89	90.4	9.1	0.0	8.52	0.89	3.05	1.00	0.96	0.96	1.04	0.74	1.00	4.0	4.2
	With H2 and CO2	4.14	25	10.90	1.215	0.654	84%	5.03	2.71	89.3	9.9	0.0	8.51	2.66	4.26	1.00	0.99	0.97	1.03	0.52	1.58	4.0	4.1
53	No H2	3	81		0.446			1.32		61.8	36.3		8.07										
	With H2	3	81	2.42	0.719	0.272	61%	1.94	0.62	74.4	17.9	9.6	8.14	0.31	3.12	0.90	1.15	0.57	2.03	1.16	1.06	3.5	7.1
54	No H2	2.67	75		0.280			0.75		52.4	47.0		7.50										
	No H2	2.67	75		0.260			0.68		74.0	25.5		7.20										
	With H2	2.67	75	0.54	0.280	0.020	8%	0.85	0.17	90.6	7.5	0.8	7.80	0.16	2.35	0.99	1.28	1.19	1.07	0.74	0.99	3.1	3.3
55	No syngas	3.5	20		0.321			1.13		62.2	37.8		7.12										
	With syngas	3.5	20	1.33	0.422	0.101	31%	1.49	0.36	61.1	37.0	2.0	7.19	0.21	n/a	0.96	1.12	0.67	1.67	0.52	1.31	n/a	n/a
	No syngas	3.5	20		0.384			1.35		63.5	36.5		7.22										
	With syngas	3.5	20	1.33	0.509	0.125	33%	1.79	0.44	64.0	35.8	0.2	7.22	0.31	n/a	1.00	1.34	0.95	1.41	0.57	1.31	n/a	n/a
57	No H2	1.88	10		0.239			0.45		48.7	51.4	0.0	7.82										
	With H2	1.88	10	1.40	0.415	0.176	73%	0.78	0.33	71.4	22.8	5.8	7.98	0.26	2.75	0.96	0.99	0.78	1.27	0.65	1.14	4.1	5.2
	With H2	1.88	10	1.50	0.452	0.213	89%	0.85	0.40	68.2	16.7	15.1	8.02	0.31	2.94	0.87	1.22	0.95	1.29	0.78	1.29	3.3	4.2
61	No H2	2.2	25		0.288			0.63		58.6	41.4		6.88										
	With H2	2.2	25	0.90	0.434	0.146	51%	0.96	0.32	56.5	25.0	18.6	7.59	0.03	2.00	0.65	2.20	0.18	12.28	0.76	1.27	1.8	22.3
62	No H2	2.4	15		0.110			0.26		44.6	55.4		n/r										
	With H2	2.4	15	0.82	0.142	0.032	29%	0.34	0.08	51.6	23.0	25.4	n/r	0.18	2.49	0.79	0.39	0.89	0.44	0.23	0.83	8.4	3.7
63	No H2	3.71	15		0.244			0.90		65.6	34.4		7.74										
	With H2	3.71	15	0.80	0.283	0.039	16%	1.05	0.14	72.7	22.2	5.1	7.92	0.15	1.69	0.91	0.80	0.85	0.94	0.31	0.99	5.0	4.7
61	No H2	2.2	15		0.412			0.91		68.2	31.8		7.76										
	With H2	2.2	15	0.84	0.444	0.032	8%	0.98	0.07	73.2	21.6	5.1	8.03	0.13	2.00	0.92	0.36	0.69	0.53	0.25	0.95	11.0	5.8
65	No H2	3.73	5		0.329			1.23		60.9	39.1		7.60										
	With H2	3.73	5	2.64	0.401	0.072	18%	1.50	0.27	44.9	18.5	36.6	7.90	0.17	3.35	0.54	0.76	0.48	1.58	0.34	1.05	5.2	8.3
	No H2	3.73	5	`	0.311			1.16		61.1	38.9		7.64										
	With H2	3.73	5	2.14	0.366	0.055	15%	1.37	0.20	66.4	20.5	13.0	7.83	0.32	2.90	0.87	0.44	0.68	0.64	0.28	0.94	9.2	5.9
66	No H2	3.5	3.5		0.297			1.04		74.7	25.3		7.30										
	With H2	4.4	4.4	1.88	0.389	0.092	31%	1.71	0.40	97.9	1.4	0.7	7.90	0.42	5.33	0.99	0.87	0.90	0.97	1.15	1.26	4.6	4.5
67	OLR 2 no H2	2	15		0.289			0.58		49.9	47.3		7.14										
	OLR 2 with H2	2	15	2.10	0.532	0.244	84%	1.06	0.52	92.5	4.2	0.3	7.87	0.50	3.84	1.00	0.93	0.95	0.98	0.89	0.99	4.0	4.2
	OLR 2 with H2+CO2	2	15	6.20	0.963	0.674	234%	1.93	1.55	89.1	4.4	0.0	7.84	1.55	3.76	1.00	0.87	1.00	0.87	0.82	1.80	4.6	4.0
	OLR 3 no H2	3	15		0.288			0.86		50.1	47.3		7.35										
	OLR 3 with H2	3	15	2.90	0.493	0.205	71%	1.48	0.72	92.3	4.3	1.0	7.96	0.75	3.55	0.99	0.85	1.04	0.82	0.75	0.92	4.0	3.9
	OLR 3 with H2+CO2	3	15	9.12	0.918	0.630	219%	2.75	2.28	88.0	4.9	0.0	7.75	2.30	3.71	1.00	0.83	1.01	0.82	0.77	1.73	4.8	4.0
	OLR 4 no H2	4	15		0.290			1.16		49.9	47.7		7.39										
	OLR 4 with H2	4	15	4.43	0.562	0.272	94%	2.25	1.11	91.4	5.5	0.0	8.16	0.97	3.99	1.00	0.98	0.88	1.11	0.98	1.05	4.0	4.5
	OLR 5 no H2	5	15		0.278			1.39		48.6	48.9		7.38										
	OLR 5 with H2	5	15	4.20	0.451	0.174	63%	2.26	0.97	72.0	15.3	10.7	7.77	0.92	3.01	0.92	0.90	0.95	0.95	0.62	0.98	4.0	4.2
12	No H2	3	15		0.295			0.89		54.3	45.3	0.0	7.67										
	with H2	3	15	2.40	0.462	0.166	56%	1.39	0.50	88.6	10.7	0.0	8.23	0.57	3.25	1.00	0.83	0.95	0.88	0.68	0.96	4.8	4.2
	No H2	3	15		0.242			0.73		54.5	45.1	0.0	7.81										
	with H2	3	15	1.60	0.374	0.131	54%	1.12	0.39	80.5	18.6	0.0	8.17	0.34	2.66	1.00	0.98	0.86	1.15	0.65	1.04	4.1	4.7
68	No H2	0.07	21		0.35			0.00		66.7	33.3		7.07										
	With H2			0.06	0.57	0.222	63%	0.04	0.02	94.5	3.1	2.5	7.64	0.01	4.61	0.98	1.12	0.79	1.42	1.26	1.13	3.6	5.1
70	No CO	5	3		0.312			1.56		74.2	24.5		7.67										
	With CO	5	3	n/a	0.536	0.225	72%	2.68	1.12	36.7	55.3	5.1	7.28	n/a	n/a	0.93	0.97	n/a	n/a	2.18	3.24	n/a	n/a

Table S4 Performance data for CO_2 biomethanisation of sewage sludges

	Ref	Substrate	Temp	Reactor	Total vol	Working vol	Mixing	Gas recirc	Injector	Exp'tl design	Varied	Note
			oC		L	L						
Sewage sludge												
Alfaro et al., 2019	74	Mixed SS	35	CSTR	27.8	20	Pump	Yes	HFM	Parallel	gas recirculation rate	Low gas recirc
												-
												Intermediate gas recirc
												-
												High gas recirc
												-
Tao et al., 2020	12	Mixed SS	37	CSTR	3	2	Mechanical	Yes	Bubble	Sequential	with/without H2	Additional data
												provided by authors
Zhang (pers com 2022)	53	Mixed SS	37	CSTR	3	2	Mechanical	Yes	Bubble	Sequential	with H2 and H2 + CO2	Pers. com.
												-
												-
Corbellini et al., 2019	75	Mixed SS	35	CSTR	2.4	1	Magnetic	No	Syringe	Parallel	H2 addition	-
												-
												-
Corbellini et al., 2021	76	Mixed SS	36.7	CSTR	16	11	Mechanical	No	Tube	Sequential	H2 addition	Control period
												H2/CO2 4
												H2/CO2 6
												H2/CO2 7
Diaz et al., 2020	77	Mixed SS	35	CSTR	48	35	Recirc + static mixer	No	n/r	Sequential	Pressure and H2 addition	200 kPa
												300 kPa
Luo et al., 2013c	78	Mixed SS	55	CSTR	0.6	0.4	Magnetic	No	HFM	Parallel	CO addition	Control reactor
												Highest SMP without residual CO
												Control reactor
												Highest SMP
Wang et al., 2013	79	Mixed SS	37	CSTR	3	2	Mechanical	No	HFM	Sequential	with/without SCOG and pH control	Control period
												No pH control
												pH controlled to <8

Table S4 ctd Performance data for CO_2 biomethanisation of sewage sludges

Ref	Case	OLR g VS/L-day	HRT days	H_2 input L/L-day	SMP L/g VS	SMP_{H2} L/g VS	SMPinc %	VMP L/L-day	MER L/L-day	CH4 %	CO2 %	H2 %	pH	*CRR*	*H2/ CO2*	*H2 trans/ input*	*MER/ Exp MER*	*CRR/ Exp CRR*	*MER/ CRR*	*MER/ VCO2org*	*VBP/ VBPorg*	*H2 trans/ MER*	*H2 trans/ CRR*
74	No H2	1.3	20		0.338			0.44		65.8	34.1	0.0	7.41										
	With H2		20	0.87	0.415	0.077	23%	0.54	0.10	51.1	12.4	36.5	7.28	0.10	3.95	56%	0.72	0.72	1.00	0.44	1.00	4.8	4.8
	No H2	1.5	20		0.213			0.32		68.0	32.0	0.0	7.42										
	With H2		20	0.87	0.313	0.100	47%	0.47	0.15	70.9	11.4	17.7	7.80	0.07	3.95	86%	0.69	0.32	2.14	1.00	1.17	5.0	10.7
	No H2	1.8	20		0.211			0.38		67.1	32.9	0.0	7.41										
	With H2		20	0.87	0.300	0.089	42%	0.54	0.16	73.1	19.7	7.2	8.09	0.03	3.95	94%	0.68	0.13	5.33	0.87	1.23	5.1	27.2
12	No H2	3.64	15		0.309			1.12		60.1	39.4	0.0	7.32										
	With H2	3.64	15	2.70	0.437	0.129	42%	1.59	0.47	90.5	8.2	0.0	7.94	0.59	3.67	100%	0.69	0.88	0.79	0.64	0.94	5.8	4.6
53	No H2	3	20.4		0.214			0.63		65.4	36.1		7.56										
	With H2	3	25.6	1.12	0.351	0.138	64%	1.05	0.43	85.0	15.3	0.0	7.96	0.16	3.24	100%	1.53	0.56	2.75	1.24	1.28	2.6	7.2
	with H2 + CO2	3	25.9	7.65	1.001	0.787	224%	3.00	2.38	65.0	16.9	17.1	7.76	1.61	22.14	94%	1.33	0.90	1.48	0.99	3.91	3.0	4.4
75	No H2	1	15		0.162			0.167		71.3	28.6		7.00										
	With H2	1	15	0.13	0.194	0.032	20%	0.195	0.03	77.2	22.8	0.0	7.30	0.01	1.99	100%	0.86	0.28	3.08	12.80	1.08	4.7	14.4
	With H2	1	15	0.12	0.194	0.032	20%	0.195	0.03	77.0	22.3	0.0	7.20	0.01	1.85	100%	0.90	0.34	2.66	13.48	1.08	4.4	11.8
76	No H2	1.3	22		0.194			0.252		75.6	24.4		7.4										
	With H2	1.4	22	0.37	0.224	0.043	23%	0.314	0.08	81.0	14.2	4.8	7.4	2%	5.10	95%	0.90	0.19	4.68	1.09	1.20	4.4	20.8
	With H2	1.5	22	0.33	0.218	0.036	20%	0.327	0.09	83.5	13.4	3.1	7.4	2%	4.61	96%	1.14	0.24	4.69	1.27	1.23	3.5	16.4
	With H2	1.5	22	0.37	0.203	0.022	12%	0.305	0.07	86.3	7.6	6.0	7.4	4%	5.11	94%	0.80	0.52	1.54	0.96	1.08	5.0	7.7
77	With H2	0.92	20	0.45	0.332	0.000	0%	0.31	0.00	69.4	15.2	15.4	6.60		n/a	85%							
	With H2	1.2	20	0.64	0.418	0.110	30%	0.50	0.13	92.9	6.3	0.8	7.00	n/r	n/a	99%	0.83	n/r	n/r	n/a	n/a	4.8	n/r
78	No CO	3.35	10		0.201			0.67		62.1	36.6		7.24										
	With CO		10	n/a	0.541	0.339	169%	1.81	1.14	29.8	68.9	0.0	7.03	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	No CO	3.35	10	n/a	0.187			0.63		61.0	38.3		7.29										
	With CO		10	n/a	0.595	0.407	217%	1.99	1.36	19.2	44.5	35.2	7.17	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
79	No SCOG	1.08	10		0.256			0.28		64.4	34.2	1.4	7.00										
	With SCOG		10	0.65	0.404	0.148	58%	0.44	0.16	89.9	9.1	1.0	7.50	0.15	0.10	100%	1.02	0.70	1.55	1.08	1.13	n/a	n/a
	With SCOG		10	1.44	0.604	0.200	78%	0.65	0.22	98.8	0.3	0.9	8.00	0.35	0.15	100%	0.96	0.40	2.59	2.55	1.54	n/a	n/a

Notes for Tables S1-S4:

AnMBR	Anaerobic membrane bioreactor	n/r	Not reported
CM	Cattle manure or slurry	PM	Pig manure
CSTR	Continuous stirred tank reactor	SCOG	Simulated coke-oven gas
FW	Food waste	SS	Sewage sludge
HFM	Hollow Fibre Membrane	UASB	Upflow anaerobic sludge blanket reactor

S2. Sources of Anaerobic Digestion Feedstock and Generation Data

Note that some sources in the main text and in link below may refer to data for a particular year. These are generally part of a regular (i.e. monthly, quarterly, yearly) series of data for which an internet search can provide the most recent details.

Other energy-based initiatives exist (for example, Contracts for Difference (CfD) and Smart Export Guarantee (SEG)) but, although anaerobic digestion (AD) could technically access these, in practice AD operators have not taken up the option.

S2.1 GENERATION DATA

S2.1.1. Generation Data from UK Government Sources

a. **Renewables Obligation (RO).** The RO was a 20-year index-linked incentive available between 2002-2017 to AD operators who wished to generate electricity for use on site or feeding into the national grid by using biogas in a combined heat and power plant (CHP). Data on generation is available from the Ofgem portal:
https://renewablesandchp.ofgem.gov.uk/Public/ReportManager.aspx?ReportVisibility=1&ReportCategory=0
A list of accredited generating stations can be derived under the RO, filtering by technology group AD, although this excludes AD stations from technology group '50kW DNC or less'.

Because Renewables Obligation Certificates (ROCs) show generation for all stations under a technology group, a better approach is to use ROCs. 'Fuelled' is the technology group and 'AD' the generation type. There was no FIT in Northern Ireland, so those (usually smaller) plants which might have accessed the Feed-In Tariff (FIT) instead operated under the RO.

At an individual technology level, RO generation capacity can sometimes be overstated, possibly because the site has an overall installed capacity derived from several technologies. This is particularly the case with a few very large plants which use AD combined with other technologies. The installed capacity (or even the average installed capacity for all generators) therefore cannot be reliably used to calculate load factors.

ROCs have a unique ROCs accreditation number. Other useful data includes the number of certificates and MWh per certificate because some sites get different ROCs, e.g. Factors of .5555, .25, .333., .5, .52 and 1. Both fields are needed to calculate generation associated with the ROC. Certificate status is necessary, as revoked ones could indicate an error, but Issued, Redeemed and Retired ones can be used. Issue date is important in order to determine if station is still generating, at least under this scheme. ROC data can change because although the 'year' runs from April to March, the data is subject to change up to the following 1st of November which is the legislative deadline for the calculation and distribution of the buyout.

b. **Feed-In Tariff (FIT)** –The FIT was a 20-year index linked incentive available to small-scale (<5 MWe) AD operators who wished to generate electricity through a CHP.

Ofgem data for FIT AD generators is available from:
https://www.ofgem.gov.uk/publications/feed-tariff-installation-report-31-march-2021

From three large spreadsheets, the Non-Domestic AD tariff can be extracted. There is no unique identifying code in the public data: coding is likely to be based on the Meter Point Administration

Number (MPAN), of which only first two characters are shown to the public. The most useful information is the generator's Total Installed Capacity (TIC). Further data includes the first half of a post code and location data, including Government Office Region, Local Authority and Lower/Middle Layer Super Output Area which are typically census data region codes.

Ofgem Load Factors (LF) can be applied to the TIC in order to estimate the generation of a particular site. These LF are updated yearly and, for the year 20-21 have a weighted mean of 61.4%, whereas the year before were 75.3% for AD. LF's are different from the DUKES data which calculates a load factor for sewage sludge digestion of 49.6% and AD of 61.7%

It is possible to find actual generation data for some of the generators, but not all of them. The link in the REF data explains this approach. Unlike solar, load factors for AD sites can vary considerably from each other.

The FIT annual report and accompanying dataset report the number of installations and TIC >50kW and < 50kW. (https://www.ofgem.gov.uk/publications/feed-tariff-fit-annual-report-2020-21)

Monthly central feed-in tariff register statistics provide a list, broken down by month of the number of accredited plants and TIC: https://www.gov.uk/government/statistical-data-sets/monthly-central-feed-in-tariff-register-statistics

c. **Renewable Heat Incentive (RHI)**. The RHI (2011-21) was a 20-year index-linked incentive designed to encourage biogas combustion for heat, as well as for biomethane production, usually going to the gas grid.

The reports and data here: https://www.ofgem.gov.uk/environmental-and-social-schemes/non-domestic-renewable-heat-incentive-rhi/contacts-guidance-and-resources/public-reports-and-data-ndrhi. Monthly data are produced (where the March monthly data acts as annual data – tables beginning with S). Heat is divided into biogas and biomethane. A 'small number' of unspecified generators are included in the biogas figures are not using AD, so these figures should be treated with caution.

Table 1.5 does, however, show cumulative generation from Nov 11 to Dec xx, so it is possible to extract biomethane generation by subtracting successive reports over the time frame required. Tables which show generation by region include redacted figures if there are only a small number of generators, so only a total number of accredited stations can be derived.

Capacity is not quoted for biomethane plants because plants do not fall within the official definition of capacity. Table 1.5 uses an unspecified CV to quote a GWh generation figure.

RO and FIT generation was compared with DUKES electricity generation and differences were minor, likely due to factors such as rounding and timing differences. DUKES generation for biomethane injection was 64% greater than the RHI generation which could potentially be due to the inclusion of Renewable Transport Fuel Certificates which would not be included in RHI data, as well as other timing and rounding factors.

d. **Renewable Transport Fuel Obligation (RTFO)**. The RTFO is a market-based incentive which requires obligated suppliers of fuel to have a proportion of renewable fuel in the mix, evidenced by Renewable Transport Fuel Certificates (RTFCs). It came into force in 2008 but for many years had relatively little take-up by AD operators because funding for an AD plant could not be raised on the potential income at the existing - and fluctuating - market price, which also had no floor (i.e.

minimum) value. However, later flexibility within policy, coupled with growing numbers of biomethane vehicles and refuelling infrastructure has meant strong growth in this sector in recent years. The latest Green Gas Support Scheme is flexible enough to allow operators to choose between using gas for the purposes of biomethane injection or transport fuel. Injection into the grid occurs for both purposes – it is simply the end use which differs.

Data are available here: https://www.gov.uk/government/statistics/renewable-fuel-statistics-2021-third-provisional-report. The DUKES methodology states that RTFO data is included, but it is not specifically split out of the AD figures; the differences between the RHI biomethane generation figures and the DUKES biomethane figures are sufficiently large for the reasonable assumption to be made that the RTFO figures are included in the DUKES biomethane data (see DUKES data below for further discussion).

e. **Digest of UK Energy Statistics (DUKES) Data**. DUKES uses a vast array of data sources to provide a comprehensive overview of energy sources and use within the UK.

DUKES data is available here:
https://www.gov.uk/government/statistics/digest-of-uk-energy-statistics-dukes-2021. For the purposes of obtaining data on AD, the detailed chapter 6 information on renewables is useful: https://www.gov.uk/government/statistics/renewable-sources-of-energy-chapter-6-digest-of-united-kingdom-energy-statistics-dukes

Detailed data can be obtained from tables 6.4 and 6.6, as well as the methodology:
https://www.gov.uk/government/publications/renewable-energy-statistics-data-sources-and-methodologies .

Sources for data that are relevant to AD include
Ofgem renewables and CHP https://renewablesandchp.ofgem.gov.uk
FIT https://www.gov.uk/government/statistical-data-sets/monthly-central-feed-in-tariff-register-statistics
RHI https://rhi.ofgem.gov.uk/Public/Login.aspx?id=1
CHP https://www.gov.uk/government/collections/combined-heat-and-power-statistics
Microgeneration ROO-FIT
https://data.gov.uk/dataset/microgeneration_certification_scheme_and_roofit_statistics
NNFCC list of operational AD sites http://www.biogas-info.co.uk/resources/biogas-map
WRAP list of operational AD sites http://www.wrap.org.uk/content/operational-ad-sites
RTFO https://www.gov.uk/government/collections/biofuels-statistics
Whilst the methodology gives a good general description of data sources, it is not clear exactly what data is used from each source and how it is derived.

Calorific values are in the methodology and here:
https://www.gov.uk/government/statistics/dukes-calorific-values. Rather incorrectly, DUKES describe biomethane to grid as 'biogas grid injection'. Additionally, the methodology uses a net calorific value (NCV) of 19-24 for 'biogas (anaerobic digestion – farm/food)' but does not specify assumptions for the NCV of biomethane.

The DUKES methodology description specifically states the following: "Biogas grid injection: Some AD is injected into the main GB gas network. In the renewables energy balance, this is considered a statistical transfer of biogas from renewables to natural gas. This is sourced from RHI data." This implies that RTFO data is not used; however, DUKES overall data sources do include RTFO data so it is unclear where the proportion of biomethane destined for road transport is included; as stated above, it would appear to possibly be included within RHI figures.

S2.1.2. Generation data from non-governmental sources

In addition to the NNFCC data mentioned above, there are at least two further reliable and regularly updated sources for AD plant generation data.

a. **Anaerobic Digestion Bioresources Association (ADBA) –** A comprehensive database that is regularly updated is provided to members. Sources are not stated, but are derived from public information, e.g. planning information, Ofgem, and press releases. A subset of the data is publicly available at https://adbioresources.org/resources/ad-plant-map.

b. **Renewable Energy Foundation (REF) –** The Renewable Energy Foundation provides a comprehensive list of renewable generators, FIT generators and renewable electricity totals from which AD generation can be extracted. Data are available here:
https://www.ref.org.uk/energy-data
The data are derived from publicly available information, with sources described here:
https://www.ref.org.uk/energy-data/notes-on-renewable-generation-data

Notes on data derivation: With regards to electricity generation from AD, in order of precedence, the REF use RO data (ROCs), then Renewable Energy Guarantees of Origins (REGOs) and then Climate Change Levy Exemption Certificates (LECs). REGOs, for example, can be downloaded from Ofgem, but they appear to cover both ROC and FIT generation so have to be referenced back to the generation lists, although this is particularly difficult for FIT generators who are only publicly identified by the first part of the post code. A proportion of FIT generators do not seem to claim REGOS, so for these REF generation data is estimated from the Total Installed Capacity (TIC) named in the FIT Register, using the technology load factor being derived from generators for which they do have data. Further information on their methodology is available here:
https://www.ref.org.uk/energy-data/notes-on-small-scale-green-generators

S2.2 FEEDSTOCK DATA

a. **GENERAL –** Some AD plants have different sustainability reporting requirements, depending upon which incentive scheme they operate under, the size of the AD plant and, possibly, when they joined the scheme, e.g. sustainability criteria applied to new FIT (known by Ofgem as ROO-FIT) accredited after 1 May 17.

Feedstock sustainability is evidenced through the submission of a Fuel Measurement and Sampling Questionnaire (FMS). This also applies to RO stations, RHI, GGSS and RTFC's, but all differ slightly in their interpretations of wastes, products, co-products and by-products. Thereafter quarterly sustainability declarations are submitted (usually, though there are exceptions, see links below).

FIT sustainability info here:
https://www.ofgem.gov.uk/fuelling-and-sustainability-fit-anaerobic-digestion-installations
and ROC sustainability info here:
https://www.ofgem.gov.uk/environmental-and-social-schemes/renewables-obligation-ro/applicants/biomass-sustainability

b. **RO feedstock data**- The issuance of a ROC for a station with a TIC > 1MWe is predicated on them putting in their quarterly feedstock sustainability data (they have an additional independent yearly audit); the issuance of a ROC between 50kWe and 1MWe is not predicated on Ofgem receiving feedstock data. Stations with a TIC < 50kWe (as well as some others under conditions not quite specified in the data) can report amalgamated feedstock data once a year, so some assumptions are made.

The sustainability dataset for the RO can be downloaded here:
https://www.ofgem.gov.uk/publications/biomass-sustainability-dataset-2019-20
and is the data which underlies the annual report
https://www.ofgem.gov.uk/publications/renewables-obligation-ro-annual-report-2019-20

This list is split into two: Land Use and GHG which is for stations over 1MW and Profiling Data which includes everyone. AD (fuel type) has to be filtered out from biomass, energy crop, gasification, pyrolysis, etc. The fuel name can be anything from 'Anaerobic Digestion' to 'AD-Straw' to 'AD-CU-13' to 'Maize Silage'. In other words, there is no consistent categorisation: someone may call something 'biogas derived from sugar beet', others 'beet', others 'sugar beet pulp'. Indeed, for most feedstocks the fuel name is sufficient; however, in the fuel name 'Anaerobic Digestion', it is necessary to go to the 'consignment' field to get further detail. Nevertheless, there are still some coded fields. The data is by quantity of biogas not by tonnage of feedstock.

c. **Department of Energy, Food & Rural Affairs (Defra) data.**

Defra holds data on the area of crops grown for bioenergy, which is available from:
https://www.gov.uk/government/statistics/area-of-crops-grown-for-bioenergy-in-england-and-the-uk-2008-2019

Table G reflects DUKES data, and only shows biodiesel and bioethanol for transport fuels and not biomethane. Currently data only go to 2019 and this report was prepared using 2020 data.

Data for AD can be found here:
https://www.gov.uk/government/statistics/area-of-crops-grown-for-bioenergy-in-england-and-the-uk-2008-2020/section-3-anaerobic-digestion

The dataset which underlies this web page is available here:
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1039249/nonfood-dataset-9dec21.ods

References
For numbered references in tables and text, see main article

Additional References
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