A Comparative Study of Biomethane and Biogas with Natural Gas and Hydrogen Alternatives

THE SUPPLEMENTARY INFORMATION

Semra Bakkaloglu[1], Adam Hawkes[1]

[1]Department of Chemical Engineering, Imperial College London, SW7 2AZ, UK

Table S1. The detailed list of LCA models

Biogas and biomethane generation routes	
a) CHP generation from biogas – heat and electricity credit	
1	Biogas generation from manure for CHP generation
2	Biogas generation from biowaste for CHP generation
3	Biogas generation from sewage for CHP generation
4	Biogas generation from used vegetable oil for CHP generation
5	Biogas generation from maize silage for CHP generation[a]
b) Biomethane generation	
6	Biomethane generation from manure with amine washing upgrade
7	Biomethane generation from manure with PSA upgrade
8	Biomethane generation from manure with membrane upgrade
9	Biomethane generation from biowaste with amine washing
10	Biomethane generation from biowaste with PSA
11	Biomethane generation from biowaste with membrane
12	Biomethane generation from sewage with amine washing
13	Biomethane generation from sewage with PSA
14	Biomethane generation from sewage with membrane
15	Biomethane generation from used vegetable cooking oil with amine washing
16	Biomethane generation from used vegetable cooking oil with PSA
17	Biomethane generation from used vegetable cooking oil with membrane
18	Biomethane generation from maize silage[a]
c) Biomethane generation from wood biomass gasification for biomethane generation	
19	Fluidized bed for Switzerland (CH)
20	Fluidized bed for Rest of the World (RoW)
21	Fixed bed for Switzerland
22	Fixed bed for Rest of the World

Notes: [a] The maize silage LCA model data is adopted from [1]. CHP: combined heat and power

Table S2. The energy content (higher heating value) of different feedstocks

Type of feedstock	MJ/ kg	References
Food waste	15.7 - 23.3	[2-4]
Biowaste	9.0 - 17.1	[5-7]
Garden waste	9.3 - 19.5	[7-10]
Sewage	9.48 - 17.5	[11]
Vegetable oils	37.3 - 40.5	[12]
Maize silage	9.5 - 16.2	[13, 14]
Manure	4.7 - 11.6	[15]
Energy crops	12.6 -17.0	[16]
Biowaste, kitchen and garden waste	4.3 - 11.7	[17]
Dry woody biomass	17 – 25	[6]
Mixed waste	17.5 – 22.4	[7, 18, 19]

Table S3 Inventory data for the biodegradable waste treatment via anaerobic digestion [17, 20-24]

Parameter	Unit	Manure	Biowaste	Sewage	VCO
Biogas generated	Nm^3/ kg waste	0.021	0.15	0.013	0.98
Electricity consumed	MJ/kg waste	0.016	3.6	0.012	0.56
Heat consumed	MJ/ kg waste	0.094	1	0.051	3.4
Chemical factory	number of units	7.8×10^{-9}	1.7×10^{-9}	4.7×10^{-10}	2.8×10^{-7}
Inorganic chemical consumed	g/ kg waste			0.07	
Emissions to air					
Carbon dioxide	kg/ kg waste	0.0019	0.21	0.0012	0.015
Ammonia	g/ kg waste	0.047	3.37		
Hydrogen sulphide	mg/ kg waste	1.12	89.6		
Nitrous oxide	mg/ kg waste		7		
Dinitrogen monoxide	g/ kg waste	0.007			
NMVOC	mg/ kg waste		45		
Water consumption	kg/ kg waste		0.23		
Digestate amount	kg/kg waste	0.97	0.62	-	0.015
Displaced mineral fertiliser					
Nitrogen fertiliser, as N [25]	Equiv. % of the mass of N in digestate	40	50	-	50
Phosphate (P_2O_5) [24]	Equiv. % of the mass of P in digestate	100	100	-	100
Potassium fertiliser, as K_2O[24]	Equiv. % of the mass of N in digestate	100	100	-	100
Digestate dry solid (DS) fraction [23]	%	4.9	4.5		4.5
Total N in digestate [23]	% of DS	16.1	15		15
Total P in digestate [23]	% of DS	0.9	0.7		0.7
Total K in digestate [23]	% of DS	3.2	4.7		4.7

Functional unit is 1 kg of biodegradable waste. Methane emission ranges are given in Table S6.

Table S4 Inventory data for the CHP unit [17]

Parameter	Unit	Value
Electricity generated	MJ/ m^3 biogas	8.41
Heat generated	MJ/m^3 biogas	12
Emissions to air		
Methane (CHP units)	g/ m^3 biogas	0.5
Carbon dioxide (CHP)	kg/ m^3 biogas	0.75
Carbon monoxide	g/ m^3 biogas	1.1
Nitrogen oxides	g/ m^3 biogas	0.34
Sulphur dioxide	g/ m^3 biogas	0.57
NMVOC	mg/ m^3 biogas	45.5
Nitrous oxide	mg/ m^3 biogas	0.007

Table S5 Inventory data for the biogas upgrading systems [17, 20]

Parameter	Unit	Amine	PSA	Membrane
Biogas entered	m^3/ Nm^3 biomethane	1.56	1.54	1.54
Electricity consumed	MJ/ Nm^3 biomethane	0.42	0.69	2.07
Heat consumed	MJ/ Nm^3 biomethane	3.85		
Chemical factory	number of units	$5.5x10^{-11}$	$5.4x10^{-11}$	$5.4x10^{-11}$
Charcoal consumed	g/ Nm^3 biomethane	0.7	0.004	
Steel consumed	g/ Nm^3 biomethane			0.10
Lubricating oil consumed	g/ Nm^3 biomethane		0.15	0.11
Light fuel oil consumed	mg/ Nm^3 biomethane	2.79		
Monoethanolamine consumed	g/ Nm^3 biomethane	0.12		
Sodium chloride consumed	g/ Nm^3 biomethane	0.09		
Silicone consumed	g/ Nm^3 biomethane	0.36		
Tab water consumed	mg / Nm^3 biomethane	75.8		
Activated carbon	g/ Nm^3 biomethane			2.14
Organic chemical	g/ Nm^3 biomethane	0.03		
Compressed air	m^3/ Nm^3 biomethane	0.0015		
Share of methane in biomethane	%	>96	>96	>96
Emissions				
Carbon dioxide	kg/ Nm^3 biomethane	1.03	0.98	0.99
Hydrogen sulphide	mg/ Nm^3 biomethane	9.8	6.7	9.9
Nitrogen	kg/ Nm^3 biomethane	0.06	0.05	0.05
Sulphur dioxide	g/ Nm^3 biomethane	0.55	0.007	0.007
Waste heat	MJ/ Nm^3 biomethane	4.15	1.28	1.28

Table S6. Average methane emissions for each stage and each feedstock as % of produced gas (based on[26])

Feedstock type	Feedstock stage	AD stage	Upgrading/ Amine washing	Upgrading/ PSA	Upgrading/ Membrane	Digestate stage
Manure	1% (0.5-3.1)	2.8% (0.38-9.9)	0.4% (0.4-2)	0.9% (0.23-6)	0.4% (0.33-0.52)	3.3% (0.6-14.8)
Biowaste	1% (0.95-3.1)	3.0% (0.38-9.9)	1.4% (0.75-2)	0.2% (0.1-6)	0.52% (0.33-0.52)	3.3% (0.6-14.8)
Sewage	1% (0.1-3.1)	1.0% (0.55-9.9)	1.4% (0.75-2)	2.5% (1.75-6)	0.52% (0.33-0.52)	N/A
VCO	1% (0.003-3.1)	2% (0.001-5.5)	1.5% (0.2-4.8)	2.5% (1.75-5.3)	0.52% (0.33-0.52)	3.3% (0.001-14.8)
Maize	0.05% (0.003-3.1)	1% (0.001-5.5)		1% (0.2-4.8)		2% (0.001-14.8)

Notes: Parentheses show the range of emissions. LCA based on sewage feedstock does not consider to digestate production[17]. The density of methane is taken as 0.72 kg/m3. Due to the lack of specific data for VCO and maize, we applied a range of CH4 emissions based on existing literature.

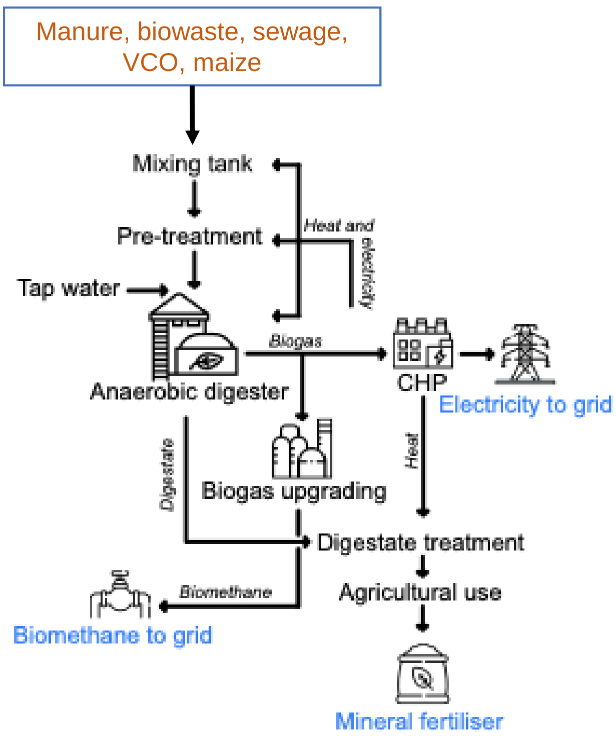

Figure S1 Biomethane and biogas supply chain representation in LCA model adopted from Bakkaloglu et. al.[20]

Table S7. Feedstock emission factors for compost production [27]

Waste type	Emission factor (kg CO_2-eq./tonne of waste), including CO_2	References
Hen carcasses and manure	45-82	[28]
Dairy manure	145-173	[29]
Cattle manure	400	[30]
Food waste		[31]
Grass and green waste	380	[32]
Garden and biowaste	46-942	[33]
Biowaste	173-1873	[34]
Sludge	89-298	[34]
Livestock waste	475-2307	[34]
Mixed waste		[35, 36]
General	323	[37]
Dry mixed waste[a]		[38]
Wet mixed waste[a]		[38]

Notes: [a]The Global Warming Potential (GWP) of CH_4 is considered to be 28 to be consistent with IPCC AR6 impact category, and the GWP of N_2O is considered to be 273 based on [39].

Table S8. Hydrogen generation LCAs

System Boundary	Production method	GHG intensities (kg $CO_{2\text{-eq}}$/ MJ)	References
Well to tank (Feedstock to hydrogen transportation)	Biomass gasification	0.0085 – 0.057 (3)	[40, 41]
Cradle to gate[1]	Bioethanol ATR	0.051	[42]
Cradle to gate[1]	Green Hydrogen: Electrolysis- with renewable energy (wind, solar and biomass)	0.005–0.035 (30)	[40, 41, 43-48]
Well to tank	Blue Hydrogen: natural gas SMR+CCS, ATR+CCS, syngas chemical looping+CCS and chemical looping+CCS	0.004 – 0.085 (14)	[49-51]
Well to tank	Grey Hydrogen: natural gas SMR and ATR, methanol with SMR; syngas chemical looping and chemical looping	0.013 – 0.13 (16)	[43, 47-50, 52-55]
Well to tank (cradle to grave)	Black Hydrogen: coal gasification	0.079 – 0.25 (8)	[43, 47, 52, 55-57]
Cradle to gate[1]	Turquoise Hydrogen: methane pyrolysis (thermal splitting of methane)	0.0099 – 0.051 (9)	[42, 48]
Cradle to gate[1]	Pink Hydrogen: electrolysis with nuclear power	0.0029 – 0.0141 (8)	[41, 58]

Notes: ATR: Autothermal reforming; CCS: Carbon capture and storage; SMR: Steam methane reforming; Parenthesis shows the data number. The transformation storage and distribution (TSD) emissions are considered in these LCA studies. The end use emissions are not included. The energy content of hydrogen is assumed to be 141.9 MJ per kg H_2. The parentheses indicate the number of datasets.[1] The conducted LCA covers the entire product life cycle from resource extraction to the factory gate, also known as "cradle-to-gate." Stages beyond this point, like hydrogen transport and storage, along with their environmental effects, are independent of the hydrogen production method used. Therefore, including these stages in the assessment wouldn't substantially alter the study's overall findings[48], as hydrogen emissions from its supply chain changes range from 4×10^{-4} to 1 g CO_2/MJ_{HHV}[59] which is negligible.

Table S9. Low carbon hydrogen generation electrolysis LCA results

System Boundary	Production method	Functional unit	LCE (kg CO_{2-eq})	References
Well to tank	Wind	kg H_2	1.2	[46]
Cradle to gate	Canada/wind to Germany	kg H_2	1.505	[45]
Cradle to gate	Chile/wind to Germany	kg H_2	2.457	[45]
Cradle to gate	Germany wind /domestic	kg H_2	1.989	[45]
Cradle to gate	Canada/wind to Germany	kg H_2	1.505	[45]
Cradle to gate	Chile/wind to Germany	kg H_2	2.457	[45]
Cradle to gate	Germany wind /domestic	kg H_2	1.989	[45]
Cradle to gate	Canada/wind to Germany	kg H_2	0.99	[45]
Cradle to gate	Chile/wind to Germany	kg H_2	0.852	[45]
Cradle to gate	Chile/solar to Germany	kg H_2	2.466	[45]
Cradle to gate	Canada/wind to Germany	kg H_2	0.794	[45]
Cradle to gate	Chile/wind to Germany	kg H_2	0.711	[45]
Cradle to gate	Germany wind /domestic	kg H_2	1.553	[45]
Cradle to gate	Chile/solar to Germany	kg H_2	1.953	[45]
Cradle to gate	Marrakesh/ solar to Germany	kg H_2	2.708	[45]

Al-Breiki and Bicer[60] study's system boundary includes raw materials extraction, feedstock transportation, liquefied energy carrier production, storage and transportation. Utilisation is excluded. Kolb et al. [45]'s cradle to gate study covers the emissions from electrolysis, storage, shipping, regasification and compression stages. This study both consider import and domestic hydrogen production. The energy content of hydrogen is assumed to be 141.9 MJ per kg H_2. We considered the UK low carbon hydrogen standard, which requires meeting a GHG emissions intensity of 20 g CO_{2-eq}/MJ_{LHV} and rearranged the data according to that standard. The Lower Heating Value of hydrogen is assumed to be 120 MJ per kg H_2.

Table S10. Each GHG emissions from various biogas and biomethane LCA (TSD stage excluded) per kg treated waste

Biogas and biomethane generation routes		Emissions, g			kg CO_{2-eq}
a) CHP generation from biogas – heat and electricity credit		CO_2	CH_4	N_2O	GWP_{20}
1	Biogas generation from manure for CHP generation	-11.7	0.2 – 3.8	-0.06	0.03 – 0.33
2	Biogas generation from biowaste for CHP generation	-31.7	1.8 – 19.5	-0.07	0.33 – 1.58
3	Biogas generation from sewage for CHP generation	1.5	0.7 – 21.0	0.10	0.08 – 1.76
4	Biogas generation from used VCO for CHP generation	98.6	1.9 – 122.2	0.02	1.35 – 11.28
5	Biogas generation from maize silage for CHP generation	-47.3	8.7 – 90.6	-0.3	0.14 – 6.89
b) Biomethane generation from AD		CO_2	CH_4	N_2O	GWP_{20}
6	Biomethane generation from manure with amine upgrade	-5.6	0.3 – 3.8	-0.06	0.02 – 0.30
7	Biomethane generation from manure with PSA upgrade	-11.2	0.3 – 4.4	-0.06	0.01 – 0.35
8	Biomethane generation from manure with membrane upgrade	-9.8	0.3 – 3.9	-0.06	0.02 – 0.31
9	Biomethane generation from biowaste with amine washing	11.7	2.4 – 19.5	-0.07	0.23 – 1.64
10	Biomethane generation from biowaste with PSA	-28.5	1.7 – 18.5	-0.07	0.13 – 1.52
11	Biomethane generation from biowaste with membrane	-18.6	2.0 – 21.4	-0.07	0.17 – 1.76
12	Biomethane generation from sewage with amine washing	5.2	0.7 – 21.1	0.04	0.07 – 1.76
13	Biomethane generation from sewage with PSA	1.8	0.7 – 21.0	0.04	0.07 – 1.74
14	Biomethane generation from sewage with membrane	2.6	0.7 – 21.0	0.03	0.07 – 1.74
15	Biomethane generation from used VCO with amine washing	382	2.9 – 144.0	0.01	0.50 – 12.13
16	Biomethane generation from used VCO with PSA	119	9.4 – 145.9	0.01	0.75 – 12.01
17	Biomethane generation from used VCO with membrane	184	3.1 – 148.6	0.01	0.30 – 12.30
18	Biomethane generation from maize silage	17.3	0.9 – 93.5	-0.28	0.16 – 7.80
c) Wood chips biomass gasification to generate biomethane		CO_2	CH_4	N_2O	GWP_{20}
19	Fluidized bed for Switzerland (CH)	139	-1.6	0.07	-1.88
20	Fluidized bed for Rest of the World (RoW)	742	0.27	0.08	-1.04
21	Fixed bed for Switzerland	102	-1.7	0.07	-1.88
22	Fixed bed for Rest of the World	711	0.19	0.08	-1.11

Notes: CH_4 emissions are based on emission range given in Table S4. NG: natural gas, VCO: vegetable cooking oil. [a] Emissions are calculated based on the amount of produced biomethane per m^3.

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