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	$7.8x10^{-9}$	$1.7x10^{-9}$	$4.7x10^{-10}$	$2.8x10^{-7}$
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.

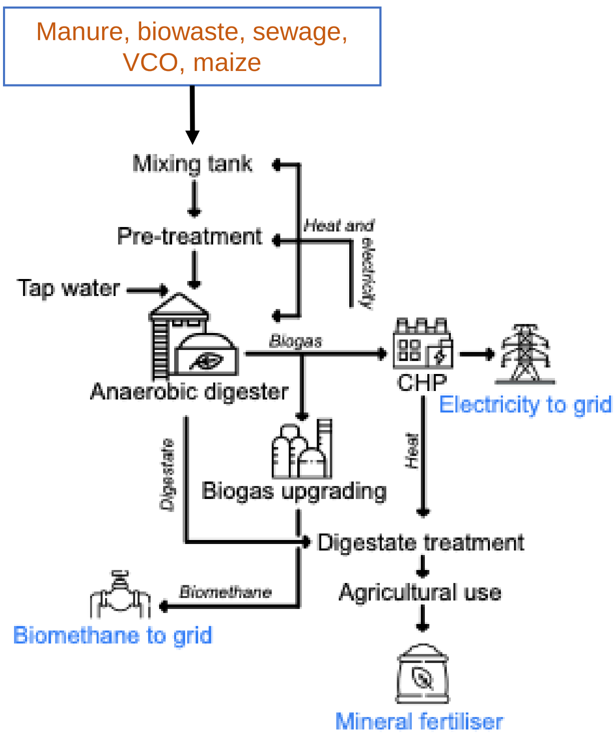

Figure S1 Biomethane and biogas supply chain representation in LCA model adopted from Bakkaloglu et. al.[20]

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 ($kg\ CO_{2-eq}/MJ$)	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 $4x10^{-4}$ 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.

References

1. Thyø, K.A. and H. Wenzel, *Life cycle assessment of biogas from maize silage and from manure: for transport and for heat and power production under displacement of natural gas based heat works and marginal electricity in northern Germany.* 2007.
2. Pour, F.H. and Y.T. Makkawi, *A review of post-consumption food waste management and its potentials for biofuel production.* Energy Reports, 2021. **7**: p. 7759-7784.
3. Ouadi, M., et al., *Food and market waste–a pathway to sustainable fuels and waste valorization.* Energy & Fuels, 2019. **33**(10): p. 9843-9850.
4. Opatokun, S.A., et al., *Characterization of food waste and its digestate as feedstock for thermochemical processing.* Energy & Fuels, 2016. **30**(3): p. 1589-1597.
5. Lümmen, N. and E.V. Røstbø, *Biowaste to hydrogen or Fischer-Tropsch fuels by gasification–A Gibbs energy minimisation study for finding carbon capture potential and fossil carbon displacement on the road.* Energy, 2020. **211**: p. 118996.
6. Demirbaş, A., *Calculation of higher heating values of biomass fuels.* Fuel, 1997. **76**(5): p. 431-434.
7. Boumanchar, I., et al., *Municipal solid waste higher heating value prediction from ultimate analysis using multiple regression and genetic programming techniques.* Waste Management & Research, 2019. **37**(6): p. 578-589.
8. Tillman, D., *Combustion characteristics of lignite and coal: the dominant solid fossil fuels.* The Combustion of Solid Fuels and Wastes, 1991. **378**.
9. Xu, P., Y. Jin, and Y. Cheng, *Thermodynamic analysis of the gasification of municipal solid waste.* Engineering, 2017. **3**(3): p. 416-422.
10. Meraz, L., et al., *A thermochemical concept-based equation to estimate waste combustion enthalpy from elemental composition ☆.* Fuel, 2003. **82**(12): p. 1499-1507.
11. Ostojski, A., *Elementary analysis and energetic potential of the municipal sewage sludges from the Gdańsk and Kościerzyna WWTPs.* 2018.
12. Demirbas, A., *Prediction of higher heating values for vegetable oils and animal fats from proximate analysis data.* Energy Sources, Part A, 2009. **31**(14): p. 1264-1270.
13. AHDB. *Feed value of maize silage and maize grain*. 2023; Available from: https://ahdb.org.uk/knowledge-library/feed-value-maize-silage-maize-grain.
14. GRUBOR, M., et al., *MISCANTHUS AND MAIZE STALK AS SOURCE FOR GREEN ENERGY PRODUCTION.* ACTUAL TASKS ON AGRICULTURAL ENGINEERING, 2021: p. 455.
15. LPELC. *What are typical values for the higher heating value of manure scraped from cattle feedyard surfaces?* 2019; Available from: https://lpelc.org/what-are-typical-values-for-the-higher-heating-value-of-manure-scraped-from-cattle-feedyard-surfaces/.
16. Callejón-Ferre, A., et al., *Greenhouse crop residues: Energy potential and models for the prediction of their higher heating value.* Renewable and sustainable energy reviews, 2011. **15**(2): p. 948-955.
17. Ecoinvent, *Ecoinvent Database v3.8*. 2021: Zurich and Lausanne, Switzerland.
18. Franjo, C.F., et al., *Calorific value of municipal solid waste.* Environmental Technology, 1992. **13**(11): p. 1085-1089.
19. Magrinho, A. and V. Semiao, *Estimation of residual MSW heating value as a function of waste component recycling.* Waste management, 2008. **28**(12): p. 2675-2683.
20. Bakkaloglu, S., J. Cooper, and A. Hawkes, *Life cycle environmental impact assessment of methane emissions from the biowaste management strategy of the United Kingdom: Towards net zero emissions.* Journal of Cleaner Production, 2022. **376**: p. 134229.
21. Slorach, P.C., et al., *Assessing the economic and environmental sustainability of household food waste management in the UK: Current situation and future scenarios.* Science of The Total Environment, 2020. **710**: p. 135580.

22. Angeli, J.B., et al., *Anaerobic digestion and integration at urban scale: feedback and comparative case study.* Energy, Sustainability and Society, 2018. **8**(1): p. 1-23.
23. Rigby, H. and S. Smith, *New markets for digestate from anaerobic digestion.* WRAP Report: ISS001-001, 2011.
24. Slorach, P.C., et al., *Environmental sustainability of anaerobic digestion of household food waste.* Journal of environmental management, 2019. **236**: p. 798-814.
25. WRAP, *Field experiements for quality digestate and compost in agriculture*. 2016.
26. Bakkaloglu, S., J. Cooper, and A. Hawkes, *Methane emissions along biomethane and biogas supply chains are underestimated.* One Earth, 2022. **5**(6): p. 724-736.
27. Walling, E. and C. Vaneeckhaute, *Greenhouse gas emissions from inorganic and organic fertilizer production and use: A review of emission factors and their variability.* Journal of Environmental Management, 2020. **276**: p. 111211.
28. Zhu, Z., et al., *Ammonia and greenhouse gas emissions from co-composting of dead hens with manure as affected by forced aeration rate.* Transactions of the ASABE, 2014. **57**(1): p. 211-217.
29. Ahn, H.K., et al., *Pile mixing increases greenhouse gas emissions during composting of dairy manure.* Bioresource Technology, 2011. **102**(3): p. 2904-2909.
30. Hao, X., C. Chang, and F.J. Larney, *Carbon, nitrogen balances and greenhouse gas emission during cattle feedlot manure composting.* Journal of Environmental Quality, 2004. **33**(1): p. 37-44.
31. Jeong, S., et al., *Field measurement of greenhouse gas emissions from biological treatment facilities of food waste in Republic of Korea.* Waste Management & Research, 2019. **37**(5): p. 452-460.
32. Hellebrand, H., *Emission of nitrous oxide and other trace gases during composting of grass and green waste.* Journal of Agricultural Engineering Research, 1998. **69**(4): p. 365-375.
33. Boldrin, A., et al., *Composting and compost utilization: accounting of greenhouse gases and global warming contributions.* Waste Management & Research, 2009. **27**(8): p. 800-812.
34. Deportes, I., et al., *Programme de recherche de l'Ademe sur les emissions atmospheriques du compostage.* Connaissances acquises et synthese bibliographique (in French). ADEME (Agence de l'Environnement et de la Maîtrise de l'Energie), 2012.
35. Lou, X., *A mathematical estimation of the impact of landfilling, composting and anaerobic digestion on greenhouse gas emissions–the total emissions accountability mode*. 2008, Honours Thesis, Murdoch University.
36. Lou, X. and J. Nair, *The impact of landfilling and composting on greenhouse gas emissions–a review.* Bioresource technology, 2009. **100**(16): p. 3792-3798.
37. Jakobsen, S.T., *Aerobic decomposition of organic wastes I. Stoichiometric calculation of air change.* Resources, conservation and recycling, 1994. **12**(3-4): p. 165-175.
38. IPCC, *2006 IPCC guidelines for national greenhouse gas inventories, Chapter 4: Biological Treatment of Solid Waste.* 2006.
39. IPCC, *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, J.S. P.R. Shukla, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.), Editor. 2022.
40. Kabir, M.R. and A. Kumar, *Development of net energy ratio and emission factor for biohydrogen production pathways.* Bioresource technology, 2011. **102**(19): p. 8972-8985.

41. Ozbilen, A., I. Dincer, and M.A. Rosen, *A comparative life cycle analysis of hydrogen production via thermochemical water splitting using a Cu–Cl cycle.* International Journal of Hydrogen Energy, 2011. **36**(17): p. 11321-11327.
42. Khila, Z., et al., *Thermo-environmental life cycle assessment of hydrogen production by autothermal reforming of bioethanol.* Energy for Sustainable Development, 2017. **37**: p. 66-78.
43. Siddiqui, O. and I. Dincer, *A well to pump life cycle environmental impact assessment of some hydrogen production routes.* International journal of hydrogen energy, 2019. **44**(12): p. 5773-5786.
44. Bhandari, R., C.A. Trudewind, and P. Zapp, *Life cycle assessment of hydrogen production via electrolysis–a review.* Journal of cleaner production, 2014. **85**: p. 151-163.
45. Kolb, S., et al., *Renewable hydrogen imports for the German energy transition–A comparative life cycle assessment.* Journal of Cleaner Production, 2022. **373**: p. 133289.
46. Ozawa, A., et al., *Assessing uncertainties of Well-to-Tank greenhouse gas emissions from hydrogen supply chains.* Sustainability, 2017. **9**(7): p. 1101.
47. Cetinkaya, E., I. Dincer, and G. Naterer, *Life cycle assessment of various hydrogen production methods.* International journal of hydrogen energy, 2012. **37**(3): p. 2071-2080.
48. Hermesmann, M. and T. Müller, *Green, turquoise, blue, or grey? Environmentally friendly hydrogen production in transforming energy systems.* Progress in Energy and Combustion Science, 2022. **90**: p. 100996.
49. Salkuyeh, Y.K., B.A. Saville, and H.L. MacLean, *Techno-economic analysis and life cycle assessment of hydrogen production from natural gas using current and emerging technologies.* International Journal of hydrogen energy, 2017. **42**(30): p. 18894-18909.
50. Oni, A., et al., *Comparative assessment of blue hydrogen from steam methane reforming, autothermal reforming, and natural gas decomposition technologies for natural gas-producing regions.* Energy Conversion and Management, 2022. **254**: p. 115245.
51. Bauer, C., et al., *On the climate impacts of blue hydrogen production.* Sustainable Energy & Fuels, 2022. **6**(1): p. 66-75.
52. Mehmeti, A., et al., *Life cycle assessment and water footprint of hydrogen production methods: from conventional to emerging technologies.* Environments, 2018. **5**(2): p. 24.
53. Spath, P.L. and M.K. Mann, *Life cycle assessment of hydrogen production via natural gas steam reforming*. 2000, National Renewable Energy Lab.(NREL), Golden, CO (United States).
54. Elgowainy, A., J. Han, and H. Zhu, *Updates to parameters of hydrogen production pathways in GREET.* Systems Assessment Group, Energy Systems Group, Argonne National Laboratory, 2013.
55. Li, Z., et al., *Coal-derived methanol for hydrogen vehicles in China: energy, environment, and economic analysis for distributed reforming.* Chemical Engineering Research and Design, 2010. **88**(1): p. 73-80.
56. Verma, A. and A. Kumar, *Life cycle assessment of hydrogen production from underground coal gasification.* Applied Energy, 2015. **147**: p. 556-568.
57. Incer-Valverde, J., et al., *"Colors" of hydrogen: Definitions and carbon intensity.* Energy Conversion and Management, 2023. **291**: p. 117294.
58. Karaca, A.E., I. Dincer, and J. Gu, *Life cycle assessment study on nuclear based sustainable hydrogen production options.* International Journal of Hydrogen Energy, 2020. **45**(41): p. 22148-22159.

59. Cooper, J., et al., *Hydrogen emissions from the hydrogen value chain-emissions profile and impact to global warming.* Science of The Total Environment, 2022. **830**: p. 154624.
60. Al-Breiki, M. and Y. Bicer, *Comparative life cycle assessment of sustainable energy carriers including production, storage, overseas transport and utilization.* Journal of Cleaner Production, 2021. **279**: p. 123481.