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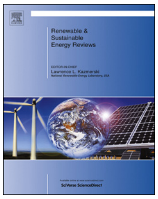

Renewable energy from biogas with reduced carbon dioxide footprint: Implications of applying different plant configurations and operating pressures

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ABSTRACT

Renewable energy from biogas has the potential to decarbonise energy systems. For example, biomethane derived from raw biogas may partially displace fossil fuels in the transportation sector. The implemented renewable energy actually decarbonises energy systems only if its life cycle CO_2 footprint is lower than that of displaced conventional technologies, which is sometimes uncertain. Therefore, this study has been undertaken to review and synthesise knowledge available in the academic literature on the CO_2 footprint of renewable energy from biogas. The typical life cycle CO_2 footprint of biogas reported in literature is between 50 and 450 kgCO_2/MW h_{el}. The review analyses three phases associated with biogas: (i) biomass production, (ii) biomass-to-biogas conversion, and (iii) biogas end use. It is found that remarkable CO_2 footprint reduction can be achieved by innovating the biomass-to-biogas phase through limiting the amount of CO_2 liberated to biogas. The mechanism for reducing CO_2 footprint is proposed and suitable solutions are discussed and evaluated. The literature review is followed by a case study that improves the practical understanding of CO_2 footprint reduction potentials. In the case study anaerobic digestion (AD) and pressurised anaerobic digestion (PAD) are compared in terms of their biomethane, power and heat generations, and CO_2 emissions. Six plant configurations involving AD, biogas upgrading and combined heat and power (CHP) generation are modelled and simulated. The results show that due to the methane enrichment in biogas (94% CH_4 at the self-sustained digester pressure of 5 MPa) CO_2 footprint is reduced. It is revealed that PAD based biogas plants may generate high purity biomethane with the extremely low direct CO_2 footprint of about 13 kgCO_2/MW h_f which contrasts with conventional CHP systems achieving about direct CO_2 footprint of 700 kgCO_2/MW h_{el}. The study also explores the fundamentals of PAD which is one of emerging biogas technologies.

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1. Introduction

Clean and efficiently harvested renewable energy has potentials to reduce CO_2 footprint of energy systems. In developed societies energy demands are however so high that renewables with limited supply potential such as bioenergy, geothermal or hydro will be able to meet only a small proportion of future global energy demands. The largest contribution will have to therefore come from wind, ocean and solar sources. But wind, ocean and solar projects have limited lifetimes and if applied globally might consume a remarkable share of construction materials. Such renewables may therefore from one hand reduce CO_2 footprint of the energy sector but from other hand they may increase CO_2 footprint of the industrial sector, where the production of these construction materials creates additional CO_2 emissions. Therefore, the utilisation of wind, ocean and solar energies need to be carefully monitored and their life cycle CO_2 footprint including the large industries behind needs to be analysed at increasing penetration depths. Meanwhile economically feasible techniques minimising life cycle CO_2 footprint of all available renewable options such as biogas (comprising 35% CO_2) [1] needs to be developed and employed.

Abbreviations: AD, anaerobic digestion; CBM, compressed biomethane; CHP, combined heat and power; CLM, cattle liquid manure; FM, fresh matter; LBM, liquefied biomethane; LCA, life cycle assessment; LCFA, long chain fatty acids; MCFC, molten carbonate fuel cell; MS, maize silage; OLR, organic loading rate; PAD, pressurised anaerobic digestion; SCFA, short chain fatty acids; SOC, soil organic carbon; TFEC, total final energy consumption

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Nomenclature

ADF	acid detergent fibre, %m of TS
ADL	acid detergent lignin, %m of TS
C_i	concentration of component *i* in a digester, kgCOD/m^3
$C_{IN,i}$	concentration of component *i* in feedstock, kgCOD/m^3
CF_{mix}	CO$_2$ footprint of electricity in the national energy mix, kgCO$_2$/MW h$_{el}$
CF_{el}	CO$_2$ footprint of electricity, kgCO$_2$/MW h$_{el}$
CF_f	CO$_2$ footprint of biomethane, kgCO$_2$/MW h$_f$
COD	chemical oxygen demand, kgO$_2$/m^{3}FM
d	density of biomass, (=1000 kg/m^3)
DL_{VS}	degradation level of volatile solids, %
$E_{mix}^{upgrading}$	electricity required for upgrading provided by external sources, MW h$_{el}$/yr
F_{IN}	flow rate of feedstocks to AD digester, m^3/day
F_{OUT}	outlet flow from digester, m^3/day
f_ch	fraction of carbohydrates, kgCOD/kgCOD
f_dg	fraction of digestible cellulose/hemicellulose, -
f_lip_LCFA	fraction of LCFA in lipids=0.95
f_ine	fraction of particulate inerts (mostly lignin), kgCOD/kgCOD
f_lip	fraction of lipids, kgCOD/kgCOD
f_pr	fraction of proteins, kgCOD/kgCOD
G^{CO2}	CO$_2$ emissions, kgCO$_2$/yr
${G_{el}}^{CO2}$	CO$_2$ emissions from electricity, kgCO$_2$/yr
G_f^{CO2}	CO$_2$ emissions from biomethane, kgCO$_2$/yr
H_i	Henry's law constant for volatile component *i*, kgCOD/(m^{3}Pa)
HRT	hydraulic retention time, day
${I_{upgrading}}^E$	decay rate constant for the group *j* of microbes, 1/day
k_j^{dec}	decay rate constant for the group *j* of microbes, 1/day
k_k^{react}	rate constant of bioreaction *k*, 1/day
k_La	gas-liquid mass transfer coefficient, 1/day
M	amount of CO$_2$ emitted from combustion of CH$_4$, CO$_2$ density, =1.96 kgCO$_2$/Nm^3
$MDecay_j$	growth rate of the *j*-th group of microbes, kgCOD-product/(m^{3}day)
$MGrowth_j$	growth rate of the *j*-th group of microbes, kgCOD-product/(m^{3}day)
N_i	rate of gas transfer of component *i* to the gaseous phase, kgCOD/(m^{3}day)
NCV	net calorific value of biomethane, =0.00994 MW h/Nm^3, 35.8 MJ/Nm^3
NDF	neutral detergent fibre, %m of TS
NfE	nitrogen free extracts, %m of TS
OXD	oxygen demand of total solids, kgO$_2$/kgTS
p	pressure, Pa
P_{el}	electrical power, MW h$_{el}$/yr
P_{th}	thermal power, MW h$_{th}$/yr
Q_b	amount of produced biogas, m^3/yr or m^3/day
Q_{bN}	amount of produced biogas in normal conditions N m^3/yr or N m^3/day
Q_f	amount of produced biomethane, N m^3/yr or N m^3/day
R_k	kinetic rate of reaction *k*, kgCOD/(m^{3}day)
S_i	concentration of component *i* dissolved in the liquid phase, kgCOD/m^3 or kmol/m^3
T	temperature, K
t	time, day
TRF	total raw fibre, %m of TS
TRL	total raw lipid, %m of TS
TRP	total raw protein, %m of TS
TS	total solids, %m
V	digester volume, m^3
V_w	working volume of a digester, m^3
VS	volatile solids, %m of TS
X_j^{ret}	concentration of retained microbes from group *j*, kgCODproduct/m^3
x_{CH4}	volumetric CH$_4$ fraction in biogas, -
X_c	complex particulates, kgCOD/m^3
X_j	concentration of microbes from group *j*, kgCODproduct/m^3
Y_j	yield of biomass of microbes from group *j* on uptake of substrate *i*,kgCOD product/kgCOD substrate
η_{el}	electrical efficiency of CHP, %
η_{th}	thermal efficiency of CHP, %
$\rho_{i,j}^{uptake}$	rate of uptake by microbes *j* a substrate *i*, kgCOD substrate/(m^{3}day)
$\nu_{i,k}$	stoichiometric coefficient for component *i* in reaction *k*, -

indexes

b	biogas
bn	biogas under normal conditions
ch	carbohydrates
CO_2	carbon dioxide (CO$_2$)
d	digester (#1 or #2)
dg	digestible cellulose/hemicellulose
E	energy
el	electricity
f	fuel, biomethane
fa	fatty acid
IN	inlet, feedstock
i	chemical component *i*, e.g. EAN-elemental anions, OH-OH$^-$, HCO3-HCO$_3$$^-$, ACI-acetate ions, PROI-propionate ions, BUI-butyrate ions, VAI-valerate ions, H-H$^+$, CAT-cations, NH4-NH$_4$$^+$
j	microbial group *j*
k	reaction *k*
lip	lipids
mix	mixture
NR	number of reactions
OUT	outlet
pi	particulate inerts (mostly lignin)
pr	proteins
th	thermal

Research on CO$_2$ footprint of renewable energy from biogas is particularly relevant today since from one hand state-of-the-art biogas based CHP systems have lower CO$_2$ footprint than fossil fuel based counterparts, but from the other hand these options may have higher CO$_2$ footprint than some other bioenergies such as wood pellets based CHPs [2]. This calls into question the role of renewable energy from biogas in providing low-carbon energy with state-of-the-art technologies. The problem will be more important in near future when the CO$_2$ footprint of national energy mix drops. Under low CO$_2$ footprint of the national energy mix there will be greater competition between renewable energy options and life cycle CO$_2$ footprint might be one of essential selection parameters.

In a broader context renewable energy at its realistic penetration depths may not be sufficient to significantly limit CO$_2$

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