Dieter Deublein and
Angelika Steinhauser

Biogas from Waste and Renewable Resources

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Dieter Deublein and Angelika Steinhauser

Biogas from Waste and Renewable Resources

An Introduction

Second, Revised and Expanded Edition

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Contents

Biogas from Waste and Renewable Resources. 2nd Ed., D. Deublein and A. Steinhauser

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Preface

Rising crude oil prices force us to think more about alternative energies. Among different technologies, solar energy is considered most effective even with regard to the environmental protection of plants. Visionaries think that biomass will probably convert solar energy best and will substitute all fossil energy resources in future.

In recent decades, many companies have rigged many biogas plants worldwide. A lot of experience was gained, leading to continuous process optimization of anaerobic fermentation and the development of new and more efficient applications. Overall, the basic knowledge of biogas production, the microorganisms involved, and the biochemical processes was widely extended.

This knowledge and the new ideas have now been put together as a basis to lead and initiate discussions. Since the technological solutions of technical problems in the field of anaerobic digestion of waste water, sewage sludge, and agricultural products are starting slowly to drift apart, without any valid reason, this book is meant to present a consolidation of knowledge in the different fields, so that learning can be leveraged more easily and applications can be harmonized.

The book comprises detailed descriptions of all the process steps to be followed during biogas production, from the preparation of a suitable substrate to the use of biogas, the end product. Each individual stage is assessed and discussed in detail, taking the different aspects such as application and potential into account. Biological, chemical, and engineering processes are detailed in the same way as apparatus, automatic control, energy, and safety engineering. With the help of this book, both tyros and experts should be able to learn or refresh their knowledge, due to its concentrated form with a simple and clear structure and many illustrations. The book can also be used as a reference book, given its many tables and large index. It is strongly recommended for planners and operators of biogas plants as it gives good advice to maximize the potential of the plant.

Originally I collected data and information about biogas plants just out of curiosity. I wanted to know all the details in order to teach my students at the University of Applied Sciences in Munich comprehensively. For about 5 years I surfed the Internet, screened and read many books, patents, and magazines and also approached many companies and manufacturers of plant components who kindly shared their knowledge with me. Mrs. Dipl.-Ing. Angelika Steinhauser assisted

Biogas from Waste and Renewable Resources. 2nd Ed., D. Deublein and A. Steinhauser

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me in writing this book. The first impulse to publish all the knowledge in this book was been clearly given by Mr. Dipl.-Ing. Steffen Steinhauser. We, the authors, thank him cordially for this. We also thank Dr. F. Weinreich of Wiley-VCH Verlag GmbH & Co KGaA for supporting this idea. Last, but not least, I would like to thank my wife and my son. Without their continuous motivation and very active support, this book would never have been finished.

Preface to the Second Edition

Only a few years ago, energy made of biogas was still only an idea, which started slowly to be implemented in a few countries, mainly in Asia and Central Europe. In the past 2 years, however, it has become a topic which is talked about worldwide. All over the world small biogas plants are starting up and food producers and large agricultural companies have started to produce energy from waste.

Research has shifted and is now largely focusing on the biology. New microorganisms have been identified which are effective in methanogenic ecosystems. Extensive analyses were carried out particularly to understand specific methanogenic ecosystems such as those found in the intestinal tract of termites able to decompose cellulose. Further, it was questioned whether indeed the methanogenic microorganisms are solely critical. Instead, the protists on which the methanogens kind of ride may be critical. Given the complexity of this topic, a whole new chapter, “Methanogenic Ecosystems,” was added which presents the current knowledge in that area.

Within the last few years, many process technologies mentioned in the first edition have been approved. Not all were pursued and these are not included in this second edition.

Further, this second edition is enhanced by the results of new studies which were conducted at the biogas institute of Prof. Dr.-Ing. Deublein.

It now also provides an overview of laboratory analyses conducted in the laboratories of the plant owners to optimize the biogas yield and of additives preferred in industry. This knowledge is of great importance as biogas plants today are often large plants providing megawatts of power which are fed into the existing natural gas networks. For those plants it is critical that the biology always works at its optimum and that the biogas yield is as high as possible, which can be influenced by various additives such as enzymes and trace minerals.

One of the chapters, originally covering the relevant laws and regulations in Germany, was shortened without cutting any of the questionnaires, which should be followed to provide sufficient safety of biogas plants.

The authors

Symbols and Abbreviations

α	Plate inclination	
$(\alpha_{BR})_a$	Heat transfer coefficient at the wall outside the bioreactor	$W\,m^{-2}\,K^{-1}$
$(\alpha_{BR})_i$	Heat transfer coefficient at the wall inside the bioreactor	$W\,m^{-2}\,K^{-1}$
$(\alpha_H)_a$	Heat transfer coefficient at the wall outside the heating pipe	$W\,m^{-2}\,K^{-1}$
$(\alpha_H)_i$	Heat transfer coefficient at the wall inside the heating pipe	$W\,m^{-2}\,K^{-1}$
$\Delta\vartheta_{BH}$	Average temperature difference between heating medium and substrate	°C
$\Delta\vartheta_{BR}$	Maximum temperature difference between substrate and the outside of the reactor	°C
$\Delta\vartheta_H$	Temperature difference between inlet and outlet of the heating medium to the bioreactor	°C
$\Delta\vartheta_{SU}$	Maximum temperature difference between substrate inside and outside of the reactor	°C
ΔP_{VP}	Pressure head of the preparation tank pump	bar
ΔT_E, ΔT_A	Differences in absolute temperatures	K
$\Delta G'_f$	Gibbs free energy	$kJ\,mol^{-1}$
ε	Porosity	%
ε_{FS}	Porosity of Siran	%
η_{el}	Efficiency to produce electrical energy	%
η_K	Efficiency of the compressor	%
η_{th}	Efficiency to produce heat	%

Biogas from Waste and Renewable Resources. 2nd Ed., D. Deublein and A. Steinhauser

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η_{VP}	Efficiency of the preparation tank pump	%
Θ	Sludge age	d
ϑ_{HA}	Temperature of the heating medium at the outlet	°C
ϑ_{HE}	Temperature of the heating medium at the inlet	°C
ϑ_S	Dewpoint temperature	°C
ϑ	Temperature	°C
ϑ_A	Lowest ambient temperature	°C
ϑ_{BR}	Temperature of the substrate in the bioreactor	°C
λ	Air : fuel ratio for stoichiometrically equivalent air : fuel ratio $\lambda = 1$	–
λ_{BR}	Heat transmission coefficient of the insulation of the bioreactor	$W\,m^{-1}\,K^{-1}$
ρ_{MK}	Grinding ball density	$kg\,m^{-3}$
ρ^*	Relative density	$kg\,Nm^{-3}$
ρ_{BG}^*	Normal biogas density	$kg\,Nm^{-3}$
ρ_{FS}	Density of Siran	$g\,cm^{-3}$
ρ_G	Density of substrate	$kg\ m^{-3}$
ρ_S	Densitiy of co-ferment	$kg\,m^{-3}$
ρ_w	Density of heating medium	$kg\,m^{-3}$
$(P_{BRR})_{tot}$	Total power consumption of the agitators	kW
$(P_{SC})_{tot}$	Total power consumption of the co-ferment conveyors	kW
A	Area for cultivation of energy plants	m^2
A_{BR}	Surface of the bioreactor, where heat is lost	m^2
A_{COD}	Degree of decomposition determined by the COD value	–
A_D	Total available area	ha
A_{Dtechn}	Technically usable area	ha
A_M	Cultivation area for maize	ha
A_S	Degree of decomposition determined by oxygen demand value	–
AT_4	Breathing activity	$mg\,O_2\,g_{DM}^{-1}$
B	Disintegration intensity	$kJ\,kg^{-1}$
B_A	Bioreactor area load	$kg_{DM}\,m^{-2}\,d^{-1}$
B_{BR}	Average bioreactor volume load	$kg_{DM}\,m^{-3}\,d^{-1}$

bn	billion	
BOD_5	Difference in oxygen concentration (day 1 vs. day 5)	$mg\,O_2\,l^{-1}$
B_R	Bioreactor volume load	$kg_{DM}\,m^{-3}\,d^{-1}$ or $kg_{COD}\,m^{-3}\,d^{-1}$
B_{RoDMSB}	Organic sludge load	$kg\,kg^{-1}\,d^{-1}$
B_{RS}	Total sludge load	$kg_{COD}\,kg_{DM}{}^{-1}\,d^{-1}$
B_S	Breadth	m
c_0	Concentration of organics in the substrate	$kg_{COD}\,m^{-3}$
C_1, C_2	Constants	
COD	Chemical oxygen demand	
COD	COD value	$mg\,O_2\,l^{-1}$
COD_0	COD value of untreated sample	$mg\,O_2\,l^{-1}$
COD_{max}	Maximum COD value	$mg\,O_2\,l^{-1}$
C_S	Biomass concentration in excess sludge	$kg_{COD}\,m^{-3}$
c_{SU}	Specific heat capacity of the substrate	$kJ\,kg^{-1}\,K^{-1}$
c_w	Specific heat capacity of the heating medium	$kJ\,kg^{-1}\,K^{-1}$
D	Net income from fertilizer	US$ a^{-1}
D_{BR}	Diameter of bioreactor	m
D_{BRl}	Diameter of discharge pipe	m
D_{BRR}	Outer diameter of agitator	m
D_D	Decanter diameter	m
D_E	Diameter of residue storage tank	m
d_{FS}	Pore diameter of Siran	m
D_{HR}	Diameter of heating pipe	m
D_{IN}	German industrial norm	–
D_L	Diameter of aeration pipe	m
DM	Dry matter	% or $g\,l^{-1}$
DM_{BR}	Flow rate of dry matter into the bioreactor	$kg_{DM}\,d^{-1}$
d_{MK}	Grinding ball diameter	m
$DM_{R,e}$	Dry matter in outflow of sludge bed reactor	$g\,l^{-1}$
D_{PT}	Diameter of preparation tank	m
D_W	Diameter of windings of heating pipe	m
E	Nominal capacity of electrical power of the CHP	kW
E_{Eel}	Electrical power consumption of the plant	kW
E_{el}	Capacity of the plant to deliver electrical energy	kW

E_M	Yield of CH_4 per biomass	$kmol\,CH_4\,kg^{-1}$
$E_{OILspec}$	Specific energy per volume of ignition oil	$kWh\,l^{-1}$
E_R	Theoretical yield	$Mg_{DM}\,ha^{-1}\,a^{-1}$
E_{Rmax}	Maximum theoretical yield	$Mg_{DM}\,ha^{-1}\,a^{-1}$
E_S	Solar energy	kW
E_{spec}	Specific biogas energy	$kW\,m^{-3}$
E_{th}	Capacity of the plant to deliver heat	kW
E_{tot}	Total energy	kW
f_{VBR}	Factor to increase the bioreactor volume	–
f_{VE}	Factor to increase the residue storage tank	–
f_{VPT}	Factor to increase the preparation tank	–
G	Net income from current	$US\$\,a^{-1}$
GB_{21}	Gas formation within 21 days	$nl\,kg_{DM}^{-1}$
GVE	Animal unit	–
h_1, h_2, h_3, h_4, h_5	Specific enthalpies at different stages of the process	$kJ\,kg^{-1}$
H_{BP}	Filling height for pellet sludge	m
H_{BR}	Bioreactor height	m
H_{BS}	Height of the gas/solid separator	m
H_E	Height of the residue storage tank	m
$H_{O,N}$, $H_{U,N}$	Calorific value	$kWh\,m^{-3}$
H_{PT}	Height of the preparation tank	m
H_S	Height of silo	m
IN	Inhabitant	
I_{SV}	Sludge volume index	$Mg\,l^{-1}$
K, K_1, K_2	Total investment costs	US$
KA	Plant investment costs without CHP	US$
KA_{spec}	Specific investment costs for the biogas plant per unit volume of the bioreactor	$US\$\,m^{-3}$
KB	Investment costs for concrete works	US$
k_{BR}	*k*-Factor of the bioreactor wall with insulation	$W\,m^{-2}\,K^{-1}$
KB_{spec}	Specific price for sold current	$US\$\,kWh^{-1}$
K_{CHP}	Investment costs for the CHP	US$
k_H	*k*-Factor of the heating pipes	$W\,m^{-2}\,K^{-1}$
KK	Amortization per year for the CHP	$US\$\,a^{-1}$

KK_{spec}	Specific investment costs for CHP per unit capacity of electrical energy	US$ kW^{-1}
K_{OIL}	Cost for ignition oil	US$ a^{-1}
$K_{OILspec}$	Specific cost for ignition oil	US$ l^{-1}
KP	Local overhead costs	US$ a^{-1}
KP_{spec}	Specific local overhead costs	US$ h^{-1}
KR	Costs for cultivation of renewable resources	US$ a^{-1}
KR_{spec}	Specific costs for cultivation of renewable resources	US$ $ha^{-1}\,a^{-1}$
KS	Costs for power consumption	US$ a^{-1}
KS_{spec}	Specific costs for power consumption	US$ kWh^{-1}
KT	Investment costs for technical equipment	US$
KV	Insurance costs	US$ a^{-1}
KW	Costs for heat losses	US$
KW_{spec}	Specific price for sold heat	US$ kWh^{-1}
KX	Maintenance costs for the concrete work	US$ a^{-1}
KY	Maintenance costs of technical equipment	US$ a^{-1}
KZ	Maintenance costs of the CHP	US$ a^{-1}
L_D	Decanter length	m
L_{HR}	Length of the heating pipe	m
L_S	Length of the silo	m
m^*	Flow of gas to the compressor	$m^3\,h^{-1}$
$\dot{M}_{BR}$	Produced flow of biogas	$Mg\,d^{-1}$
M_E	Molecular weight	$kg\,kmol^{-1}$
$\dot{M}_G, \dot{M}_{G1}, \dot{M}_{G2}$	Flow rate of substrate	$Mg\,d^{-1}$
$\dot{M}_{oil}$	Flow rate of ignition oil	$Mg\,d^{-1}$
$\dot{M}_S$	Flow rate of co-ferments	$Mg\,a^{-1}$
Mio	Million	
N	Normal	
n_{BRR}	Revolutions of an agitator	rpm
Ne_{BRR}	Newton number of an agitator	
n.s.	Not specified	
oDM	Organic dry matter	kg_{COD} or kg_{DM}
$oDM_{R,e}$	oDM in the outflow of a sludge bed reactor	$g\,l^{-1}$
O_{FSspec}	Specific surface area of Siran	$m^2\,m^{-3}$
O_{spec}	Specific surface area	$m^2\,m^{-3}$
OUR	Oxygen uptake rate	$mg\,l^{-1}\,min^{-1}$
OUR_0	Oxygen uptake rate of untreated substrate	$mg\,l^{-1}\,min^{-1}$

p_1	Biogas pressure before compressing	bar
p_2	Biogas pressure after compressing	bar
P_A	Power consumption of compressor	kW
P_{BRR}	Power consumption of agitator	kW
PE	Population equivalent	
P_{econ}	Economic potential	$kWh\,a^{-1}$
$\overline{P}_{econ}$	Specific economic potential	$kWh\,ha^{-1}\,a^{-1}$
P_K	Power consumption of the air compressor	kW
p_{K1}	Pressure before compressor	bar
p_{K2}	Pressure after compressor	bar
P_{SC}	Power consumption of a co-ferment conveyor	kW
P_{techn}	Technical potential	$kWh\,a^{-1}$
$\overline{P}_{techn}$	Specific technical potential	$kWh\,ha^{-1}\,a^{-1}$
P_{theor}	Theoretical potential	$kWh\,a^{-1}$
$\overline{P}_{theor}$	Specific theoretical potential	$kWh\,ha^{-1}\,a^{-1}$
P_{VP}	Power consumption of the pumps	kW
Q_{BR}	Heat loss of the bioreactor	kW
Q_{SU}	Required energy to heat the substrate	kW
Q_V	Total heat loss	kW
R_{CH_4}	Special gas constant for CH_4	$kJ\,kg^{-1}\,K^{-1}$
S	Overlapping	mm
s_{BR}	Thickness of the insulation of the bioreactor	m
T	Absolute temperature of the gas to be compressed	K
t	Residence time	d
t_B	Annual amortization for concrete works	$US\$\,a^{-1}$
t_{BR}	Residence time in the bioreactor	d
t_{BRl}	Time for discharging the reactor content	h
t_{BRR}	Time of operation of an agitator	$min\,h^{-1}$
t_E	Residence time in the residue storage tank	d
t_K	Time of amortization for the CHP	a
TLV	Treshold limit value = PEL, permissible exposure limit	

t_{min}	Minimum tolerable theoretical residence time	h
TOC	Total organic carbon	
TOC	Total organic carbon in the substrate	$mg\,l^{-1}$
*TOC**	Total organic carbon in the residue	% DM
t_P	Time of local work	h
T_{PT}	Residence time in the preparation tank	d
t_s	Annual operation time	$h\,a^{-1}$
t_{SC}	Running time of a co-ferment conveyor	$h\,d^{-1}$
t_T	Annual amortization for technical equipment	$US\$\,a^{-1}$
t_{TS}	Residence time in the activated sludge tank	d
v_A	Velocity of the upstream	$m\,h^{-1}$
V_{BR}	Bioreactor volume	m^3
v_{BRl}	Velocity in the discharge pipe	$m\,s^{-1}$
V_E	Volume of residue storage tank	m^3
v_F	Velocity of gas in gas pipes	$m\,s^{-1}$
v_G	Velocity of inflow	$m\,h^{-1}$
V_G^*	Inflow rate	$m^3\,d^{-1}$
V_{GS}	Volume of the gas holder	m^3
v_H	Velocity of the heating medium in the pipe	$m\,s^{-1}$
V_K	Volume of compressor pressure vessel	m^3
v_L	Velocity of air in aeration pipe	$m\,s^{-1}$
V_{PT}	Volume of the preparation tank	m^3
V_S	Silo volume	m^3
v_u	Rotational velocity of the agitator system	$m\,s^{-1}$
v_W	Velocity of the substrate in heat exchanger pipes	$m\,s^{-1}$
$\dot{V}_{BR}$	Produced flow of biogas	$m^3\,d^{-1}$
$\dot{V}_E$	Feedback from the residue storage tank to the bioreactor	$m^3\,d^{-1}$
$\dot{V}_K$	Compressor throughput	$Nm^3\,h^{-1}$
$\dot{V}_L$	Volume rate of air in the aeration pipe	$Nm^3\,h^{-1}$
$\dot{V}_S$	Volumetric flow of excess sludge	$m^3\,d^{-1}$
$\dot{V}_{SC}$	Volume flow of co-ferment in the conveyor	$m^3\,h^{-1}$

$\dot{V}_{Oil}$	Volume rate of ignition oil	$m^3\,d^{-1}$
$\dot{V}_{VP}$	Flow rate of the preparation tank pump	$m^3\,h^{-1}$
$\dot{V}_{w}$	Flow rate of heating medium in the pipe	$m^3\,h^{-1}$
W	Net income from heat	$US\$\,a^{-1}$
w_G	Gas velocity in empty reactor	$Nm^3\,m^{-2}\,s^{-1}$
W_O, $W_{O,N}$, $W_{U,N}$	Wobbe index, upper Wobbe index, lower Wobbe index	$kWh\,m^{-3}$
w_s	Area load	$m^3\,m^{-2}\,h^{-1}$
w_t	Specific work of the compressor	$kJ\,kg^{-1}$
X	Biomass concentration in the reactor	$kg_{DM}\,m^{-3}$
x_B	Fraction of the investment costs without CHP for concrete works	–
x_T	Fraction of the investment costs without CHP for technical equipment	–
γ_B	Specific maintenance costs of the concrete work	$US\$\,a^{-1}$
γ_{CHP}	Specific maintenance costs for CHP	$US\$\,a^{-1}$
γ_T	Specific maintenance costs of technical equipment	$US\$\,a^{-1}$
Z	Fraction of liquefied methane	–
Z	Insurance rate	$US\$\,a^{-1}$
Z_R	Interest rate	$US\$\,a^{-1}$

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Abschlussbericht Projekt 4: Verbesserter Abbau von Klärschlämmen durch Zellaufschluss der DFG-Forschergruppe “Biologische Prozesse mit dispersen Feststoffen” – DFG	Figure 27.7a and b
Abschlussbericht Projekt 4: Verbesserter Abbau von Klärschlämmen durch Zellaufschluss der DFG-Forschergruppe “Biologische Prozesse mit dispersen Feststoffen”, Germany	Figure 39.16
AgriKomp GmbH	Figure 19.1(e)
AgriKomp GmbH	Figure 27.2c
AgriKomp GmbH	Figure 29.2
AgriKomp GmbH	Figure 31.4
Awite Bioenergie GmbH	Figure 24.1
BAG-Budissa-Agroservice GmbH	Figure 26.1
Bekon-Energy GmbH	Figure 41.1
Bioferm GmbH	Figure 43.1f
Burkhard Meiners, AgroEnergien	Figure 29.3
Cenotec GmbH, Greven	Figure 16.6(c)
Cenotec GmbH, Greven	Figure 31.5a and b
Cenotec GmbH, Greven	Figure 43.1a, b, d
Coop, Switzerland (www.coop.ch)	Figure 16.6(a)
Daad Saffarini, Associate Professor, University of Wisconsin-Milwaukee, Department of Biological Sciences	Figure 13.5
Dr. W. Schmidt, Zuchtleiter Inland der KWS SAAT AG	Figure 3.7a
Dr.-Ing. St. Battenberg, Dissertation, Carola-Wilhelmina University, Braunschweig, 2000	Figure 13.4d
Filox Filtertechnik GmbH	Figure 21.1(b)
Flottweg GmbH	Figure 21.1(c)
“Four-in-One” Biogas System in Northern China	Figure 5.3 a–d

Biogas from Waste and Renewable Resources. 2nd Ed., D. Deublein and A. Steinhauser

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Gerardo P. Baron	Figure 16.6(e)
Hexis AG, Winterthur, Switzerland	Figure 48.14
Holger Döbert, Radolfzell	Figure 8.3
home.landtag.nrw.de/mdl/reiner.priggen/Lathen-AbholungausgegorenesMaterial.jpg	Figure 29.1
ICA Japan (www.icajapan.org)	Figure 5.3g
ifm-geomar	Figure 7.7
Ishii iron works Ltd	Figure 43.1e
Klein Abwasser- und Schlammtechnik GmbH	Figure 21.1(a)
Kompogas AG	Figure 48.1b
Landratsamt Freising (www.kreis-fs.de)	Figure 43.2
Max-Planck-Institut für Züchtungsforschung	Figure 3.7b
MDE Dezentrale Energiesysteme GmbH	Figure 48.1e
MTU-CFC GmbH	Figure 48.1d
Pondus-Verfahren GmbH	Figure 11.22b
Protego Report No. 27/2003	Figure 24.4
RECK-Technik GmbH & Co. KG	Figure 11.22a
Ritter Apparatebau GmbH	Figure 15.5
Schmack Biogas AG	Figure 27.2e
Schmack Biogas AG, Schwandorf	Figure 16.6(b)
Scientific Engineering Centre "Biomass," Kiev	Figure 5.3h
Sicherheitsregeln für landwirtschaftliche Biogasanlagen der landwirtschaftlichen Berufsgenossenschaften Ausgabe 2002	Figure 14.2
Siemens AG	Figure 48.1c
St. Battenberg, Dissertation, Carola-Wilhelmina University, Braunschweig, 2000; available at www-public.tu-bs.de	Figure 39.15
Stetter & R. Rachel, Universität Regensburg	Figure 13.4b, c
SUMA GmbH	Figure 19.1(d)
SunTechnics	Figure 5.3f
Thoeni Industriebetriebe GmbH, Austria	Figure 16.6(d)
Turbec SpA	Figure 48.1f
U.T.S. Umwelttechnik Süd GmbH	Figure 27.2d
Vorspann-Technik GmbH & Co. KG	Figure 16.3(d) and (e)
VTA Engineering und Umwelttechnik GmbH	Figure 48.1g
WELtec BioPower GmbH	Figure 19.1(a)
www.mvm.uni-karlsruhe.de	Figure 3.7c
www.solarenergie.co.za	Figure 5.3e