

Contents lists available at [ScienceDirect](http://ScienceDirect.com)

# Waste Management

journal homepage: [www.elsevier.com/locate/wasman](http://www.elsevier.com/locate/wasman)

## Energy balance, greenhouse gas emissions, and profitability of thermobarical pretreatment of cattle waste in anaerobic digestion



Jörn Budde<sup>a,\*</sup>, Annette Prochnow<sup>a,b</sup>, Matthias Plöchl<sup>a</sup>, Teresa Suárez Quiñones<sup>a</sup>, Monika Heiermann<sup>a</sup>

<sup>a</sup> Leibniz-Institute for Agricultural Engineering Potsdam-Bornim, Max-Eyth-Allee 100, 14469 Potsdam, Germany

<sup>b</sup> Humboldt-University of Berlin, Faculty of Life Sciences, Invalidenstrasse 42, 10115 Berlin, Germany

### ARTICLE INFO

#### Article history:

Received 8 July 2015

Revised 1 December 2015

Accepted 5 December 2015

Available online 18 December 2015

#### Keywords:

Assessment

Lignocellulosic feedstock

Maize

Methane yield

GHG mitigation

LCA

### ABSTRACT

In this study modeled full scale application of thermobarical hydrolysis of less degradable feedstock for biomethanation was assessed in terms of energy balance, greenhouse gas emissions, and economy. Data were provided whether the substitution of maize silage as feedstock for biogas production by pretreated cattle wastes is beneficial in full-scale application or not.

A model device for thermobarical treatment has been suggested for and theoretically integrated in a biogas plant. The assessment considered the replacement of maize silage as feedstock with liquid and/or solid cattle waste (feces, litter, and feed residues from animal husbandry of high-performance dairy cattle, dry cows, and heifers). The integration of thermobarical pretreatment is beneficial for raw material with high contents of organic dry matter and ligno-cellulose: Solid cattle waste revealed very short payback times, e.g. 9 months for energy, 3 months for greenhouse gases, and 3 years 3 months for economic amortization, whereas, in contrast, liquid cattle waste did not perform positive replacement effects in this analysis.

© 2015 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

### 1. Introduction

Anaerobic digestion is a mature and proven technology providing a versatile renewable energy carrier (Browne and Murphy, 2013). The growing number of biogas installations and the rising

*Abbreviations:* AHO, annual hours of operation; ADO, annual days of operation; P1, biogas plant 1; P2, biogas plant 2; CO<sub>2</sub>-eq., carbon dioxide equivalent; CMC, carbon dioxide mitigation costs; CHP, combined heat and power plant; constr., construction; C, costs; m<sup>3</sup>, cubic meter; d, days; °C, degree celsius;  $\rho$ , density; dig, digestate; \$, dollar; DM, dry matter; ECAM, Economic amortization mass; ECAP, Economic amortization period;  $\eta$ , efficiency; el, electric; E, Energy; EPBM, Energy payback mass; EPBT, Energy payback time; €, Euro; ct, Euro-cent; FS, feedstock; FM, fresh matter; g, grams; GHG, Greenhouse gas; GPBM, greenhouse gas payback mass; GPBT, greenhouse gas payback time; h, hours; in, input; K, Kelvin; kg, kilograms; kJ, kilojoules; km, kilometers; kW, kilowatts; kWh, kilowatt hours; LCA, life-cycle assessment; LCM, liquid cattle manure; l, liters; LHV, lower heating value; MT, maintenance; MS, maize silage; m, mass; Mg, megagrams; P<sub>MC</sub>, methanation capacity; l<sub>N</sub>, norm liters; OM, organic matter; out, output; %, percent; P[n]Y[n]M, period in years and months; P, power; s, seconds; T<sub>set-point</sub>, set-point temperature; SCM, solid cattle manure; SLCM, solid and liquid cattle manure; c<sub>p</sub>, specific heat capacity; spr, spreading; T, temperature; th, thermal; TBH, thermobarical hydrolysis; V, volume; WL, wheel loader; a, years; Y, yield.

\* Corresponding author. Tel.: +49 331 5699 315. fax: +49 331 5699 849.

E-mail address: [jbudde@atb-potsdam.de](mailto:jbudde@atb-potsdam.de) (J. Budde).

<http://dx.doi.org/10.1016/j.wasman.2015.12.003>

0956-053X/© 2015 The Authors. Published by Elsevier Ltd.

This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

demand for higher methane output have led to an increasing request for effective feedstock and hence for a shift from liquid animal waste to solid energy crops and residue from agricultural production (Plöchl et al., 2009). Therefore, the biogas sector is not only encouraged to deploy new and untapped biomass resources (Zhang et al., 2013), but also to use advanced and innovative technologies to improve biogas production and process efficiency, as well as to increase cost effectiveness (Appels et al., 2008; Ward et al., 2008).

Solid manure from livestock represents a huge still unexploited potential as feedstock for conversion processes. More than 30 million tons of solid animal manure accrued in Germany in 2009 (Schultheiß et al., 2010). However, it contains considerable amounts of straw, which is almost indigestible under usual conditions of anaerobic digestion (Grabber, 2005). Furthermore, lignocellulosic feedstock tends to float and agglomerate to an almost irreversible floating layer in the digester. Therefore, the complex structure of straw requires proper pretreatment enabling efficient fragmentation of the less digestible material.

Previous studies comparing different methods such as mechanical, thermal, chemical and/or biochemical pretreatment have identified thermobarical pretreatment (also called liquid hot water or thermal pressure treatment) as an appropriate method for breaking down fibrous, high-molecular substances into their

constituents, thus making them available for a more rapid and extensive anaerobic digestion resulting in higher methane yields (Budde et al., 2008; Carlsson et al., 2012; Hendriks and Zeeman, 2009; Schumacher, 2008; Weiß and Brückner, 2008). Nevertheless, unsuitable pretreatment conditions can result in decreased methane yields due to formation of inhibitors and non-digestible substances. In principle, high temperatures and related saturated water vapor pressures (range 140–250 °C and 3.6–39.7 bar) are used to hydrolyze high-molecular substances (i.e. lignin, cellulose, hemicellulose) and thus anticipate the biological step. Budde et al. (2014) demonstrated in extensive lab-scale experiments that thermobarical treatment significantly enhances the methane yield of dairy cattle waste. Thermobarical treatment temperatures in these lab-scale experiments were 140–220 °C in 20 K steps for a 5-min duration. Methane yields could be increased by up to 58% at a treatment temperature of 180 °C. At 220 °C, the abundance of inhibitors and other non-digestible substances led to lower methane yields than those obtained from untreated material.

Recently, few studies have been published dealing with pretreatment of biomasses and residues derived from agriculture for subsequent biomethanation in full-scale application (Cano et al., 2014; Elbeshbishy et al., 2011; Mönch-Tegeder et al., 2014; Shafiei et al., 2013). The authors investigated the impact of mechanical pretreatment using a cross flow grinder on horse manure, steam explosion on wheat straw and cow manure, and ultrasonication on hog manure. Results were given in changes in energy or methane output in any case and often economic data are given whereas changes in on-farm procedures, e.g. waste handling, spreading procedures, or transportation of biomasses were disregarded.

Thermobarical pretreatment is to be considered as a variant with moderate electric and high thermal power consumption, hence appropriate for biogas plants with attached combined heat and power plant (CHP) as often available in agricultural context. Low to moderate installation and maintenance costs and no hazardous risk but a strong effect on biomethanation are further advantages of this pretreatment option. As no pumps or comminution are needed it is highly appropriate for common agricultural biomasses and residues.

The implementation of this technology should preferably take place in existing biogas plants (Menardo et al., 2011), mostly equipped with continuous stirred tank reactors as digester (Weiland, 2008). However, pretreatment of various feedstocks challenge sustainable production in terms of greenhouse gas (GHG) mitigation, efficient energy conversion, or profitability (European Commission, 2010). The GHG emissions of biogas production are mainly determined by the type of feedstock and its origin (Fritsche, 2007; Seeberg-Elverfeldt, 2010). Nothing yet is published about the energy balance, the GHG emissions or the profitability of thermobarical hydrolysis (TBH).

The objective of this paper is to assess the feasibility of TBH in a modeled full-scale application, considering balances of energy and GHG as well as profitability. A thermobarical hydrolysis device is therefore theoretically integrated in an already existing biogas plant. The exhaust gas from a combined heat and power plant (as part of the biogas plant) is used for provision of thermal energy. Feedstocks (solid and liquid cattle manures and mixtures of these from two origins) were pretreated at conditions of 140–180 °C and associated saturated water vapor pressures (3.6–10.0 bar). The assessment considers the entire changes caused by that integration, e.g. production and operation of the device, changes in feedstocks and feedstocks composition, changed storage conditions, and changes in plant operation.

## 2. Material and methods

### 2.1. System boundaries, scenarios and functional unit

Full scale application of thermobarical pretreatment is assessed in terms of energy efficiency and greenhouse gas emissions as well as economic performance. The assessment of GHG emissions follows an attributional life cycle assessment (LCA) approach according to ISO 14044 (2006). The explicit assessment method used here is explained in detail in the following sections. Input data derived by other studies were either given directly in the text or presented in Table 1. The sources of the respective data are given for each value separately and values are introduced in their genuine units. All calculations were presented explicitly and applied to spread sheet analysis for computation. In the following, boundaries necessary to perform this assessment are set up for the system before and after implementation of a TBH.

The system before the implementation of TBH is shown in Fig. 1a (Budde, 2015). In this case maize silage is delivered to a plant site as biogas plant feedstock. The feeding to the biogas plant is accomplished by a wheel loader. Liquid cattle manure (LCM) from stable is stored for an intermediate period (several hours up to several days) and then pumped to the biogas plant. Solid cattle manure (SCM) from cattle breeding and digestate from biogas plant are stored for up to several months until they are spread on the field as fertilizer. The heat of combined heat and power generation from biogas is partly used for maintaining mesophilic conditions in the digester. Electricity, as the most valuable product, is sold. The plant presented here is exemplarily for the majority of biogas plants in Germany. Among 63 biogas plants analyzed all over Germany approximately 95% are using maize silage (FNR, 2010). LCM is used by 60% but only 22% are using SCM as well and only at a share of 2 mass-percent whereas LCM accounts for 24% (w/w). Approximately 90% of these plants are equipped with digesters for wet fermentation (continuous stirred tank reactors) and only 10% with digesters enabling utilization of SCM without pretreatment, so called dry fermentation. The majority of plants (33%) are using 250 kW<sub>el</sub> CHPs, 17% 300 kW<sub>el</sub> CHPs, and 25% 500 kW<sub>el</sub> CHPs. It is assumed that the feeding and spreading procedures used in this model are current practice in biogas plants of that size.

Fig. 1b displays the alteration of the system by a retrofit of a TBH device. The alterations are regarded in scenarios named after the types of cattle wastes (see Section 2.3) and are further distinguished by the treatment temperature ( $T = 140, 160, 180$  °C) or lack of treatment respectively (Table 2):

- SCM: Pretreatment of solid cattle manure.
- LCM: Pretreatment of liquid cattle manure.
- SLCM: Pretreatment of a mixture of solid and liquid cattle manure.

The following process alterations due to changes in feedstock and TBH treatment are regarded:

- Changes resulting from substitution of maize silage.
- Changes in the feeding process (on-site process).
- Parameters of decomposition of the different feedstock for GHG balance.
- Changes in manure and digestate spreading procedure (off-site process).

Energy equivalent shares of maize silage are substituted by a fixed volume of one of the three feedstocks. Thus a unit volume of LCM, SCM or SLCM substitutes different gravimetric shares of

**Table 1**  
General input-data.

General data		Reference
Density of methane at 0 °C	0.72 kg m <sup>-3</sup>	VDI (1991)
Lower heating value of methane	50.01 MJ kg <sup>-1</sup>	Beitz and Grote (1997)
Molar mass of methane	16 g mol <sup>-1</sup>	
Molar mass of carbon dioxide	44 g mol <sup>-1</sup>	
Specific heat capacity of water	4.20 kJ kg <sup>-1</sup> K <sup>-1</sup>	VDI (1991)
Electricity costs	11.00 ct kW h <sub>el</sub> <sup>-1</sup>	Own assumption
Federal electricity-mix production costs	5.80 ct kW h <sub>el</sub> <sup>-1</sup>	Stenuil and Raab (2010)
Emissions from federal electricity-mix	0.611 kg CO <sub>2</sub> -eq. kW h <sub>el</sub> <sup>-1</sup>	Vogt (2008)
<i>Combined heat and power plant – nominal data</i>		
Nominal electric power	330 kW	GE Jenbacher GmbH and Co OHG (2006)
Nominal thermal power	400 kW	
Electric efficiency	0.387	
Thermal efficiency	0.469	
<i>Combined heat and power plant – exhaust gas</i>		
Mass flow	1878 kg h <sup>-1</sup>	GE Jenbacher GmbH and Co OHG (2006)
Specific heat capacity	1.125 kJ kg <sup>-1</sup> K <sup>-1</sup>	Unpublished engineering report
Input temperature	500 °C	
Output temperature	230 °C	
Thermal power	158.46 kW	
<i>Thermobarical hydrolysis device – components masses</i>		
Dosing feeder	4500 kg	Unpublished engineering report
Vessel	3500 kg	
Stirring device	1000 kg	
Thermal-oil facility	4000 kg	
Associated heat exchangers	1000 kg	
<i>Thermobarical hydrolysis device – energy for construction</i>		
Stainless steel provision	24.3 kW h kg <sup>-1</sup>	Ecoinvent (2007); cumulative energy demand
Drawing of tubes	1.3 kW h kg <sup>-1</sup>	
Rolling of sheets	3.1 kW h kg <sup>-1</sup>	
<i>Thermobarical hydrolysis device – emissions from construction</i>		
Stainless steel provision	5.7123 kg CO <sub>2</sub> -eq. kg <sup>-1</sup>	Ecoinvent (2007); CML 2001 GWP 20a
Drawing of tubes	0.39233 kg CO <sub>2</sub> -eq. kg <sup>-1</sup>	
Rolling of sheets	0.39272 kg CO <sub>2</sub> -eq. kg <sup>-1</sup>	

maize silage. LCM and SCM are pretreated by TBH and then fed to the biogas plant. LCM and SCM exceeding the daily load of the TBH device are not regarded in this analysis and remain in the usual process chain. The SCM is loaded by a wheel loader and LCM pumped through pipes to the TBH vessel. Thermobarical pretreatment is driven by heat from CHP.

Scenarios SCM and LCM considered feedstock from two different biogas plant sites (P1 and P2) and therefore differing feedstock compositions (Budde et al., 2014). Scenario SLCM was based on a mixture of solid and liquid cattle manure from biogas plant 1 only as feedstock. The utilization of untreated SCM was not regarded in the scenarios SCM and SLCM due to lesser digestibility and the risk of formation of floating layers.

Environmental assessment in this study, based on methodology described in ISO 14044 (ISO 14044, 2006), focuses on energy efficiency and GHG emissions and comprises

- feedstock supply,
- transport of feedstock on an agricultural biogas plant site,
- storage of waste from dairy cattle farming (solid and liquid cattle manure) and of digestate from biogas process,
- thermobarical pretreatment of solid and liquid cattle waste and its mixture,
- their conversion to electricity and heat via biomethanation and combined heat and power plant,
- manure spreading with or without pretreatment and biomethanation.

All parameters are related to (theoretical) electricity output, the main product of the overall process with the functional unit 1 kW h<sub>el</sub> as it allows the comparison with other bioenergy and

non-renewable energy systems and pretreatment options related to them (Cherubini and Strømman, 2011). The electricity output as functional unit is directly linked to the depletion of non-renewable energy resources.

The values related to time period are given as per year. An integration over the year is necessary as the amount in terms of fresh matter (FM) pretreated per year is a fixed value but the methanation capacity is influenced by the respective methane yield and by the organic matter (OM) content of feedstock.

Although the parameterization in per Mg implies that a size independent scaling would be possible – disregarding the fact that the amount of feedstock that can be treated in a given biogas plant is limited – values are also given in per Mg FM, thus allowing to compare this study with other studies giving mass related values only.

## 2.2. Principle construction and operational design of a full-scale thermobarical device and its retrofit to an existing biogas plant

The schematic flow chart of the thermobarical device and its integration into the biogas plant is shown in Fig. 2. The TBH device is linked to the CHP via a thermal-oil circuit. Regarding feeding of the biogas plant, it is interposed in the pipeline of liquid cattle waste transport from stable to biogas plant. If liquid waste is unavailable, a recirculation pipeline from/to digester is to be retrofitted.

The main components of this TBH device are a dosing feeder, a high temperature/high pressure vessel and a stirring device. The production of these components is assumed to be comparable to the rolling of stainless steel sheet. The thermal-oil facilities and the associated heat exchanger consisting mainly of stainless steel

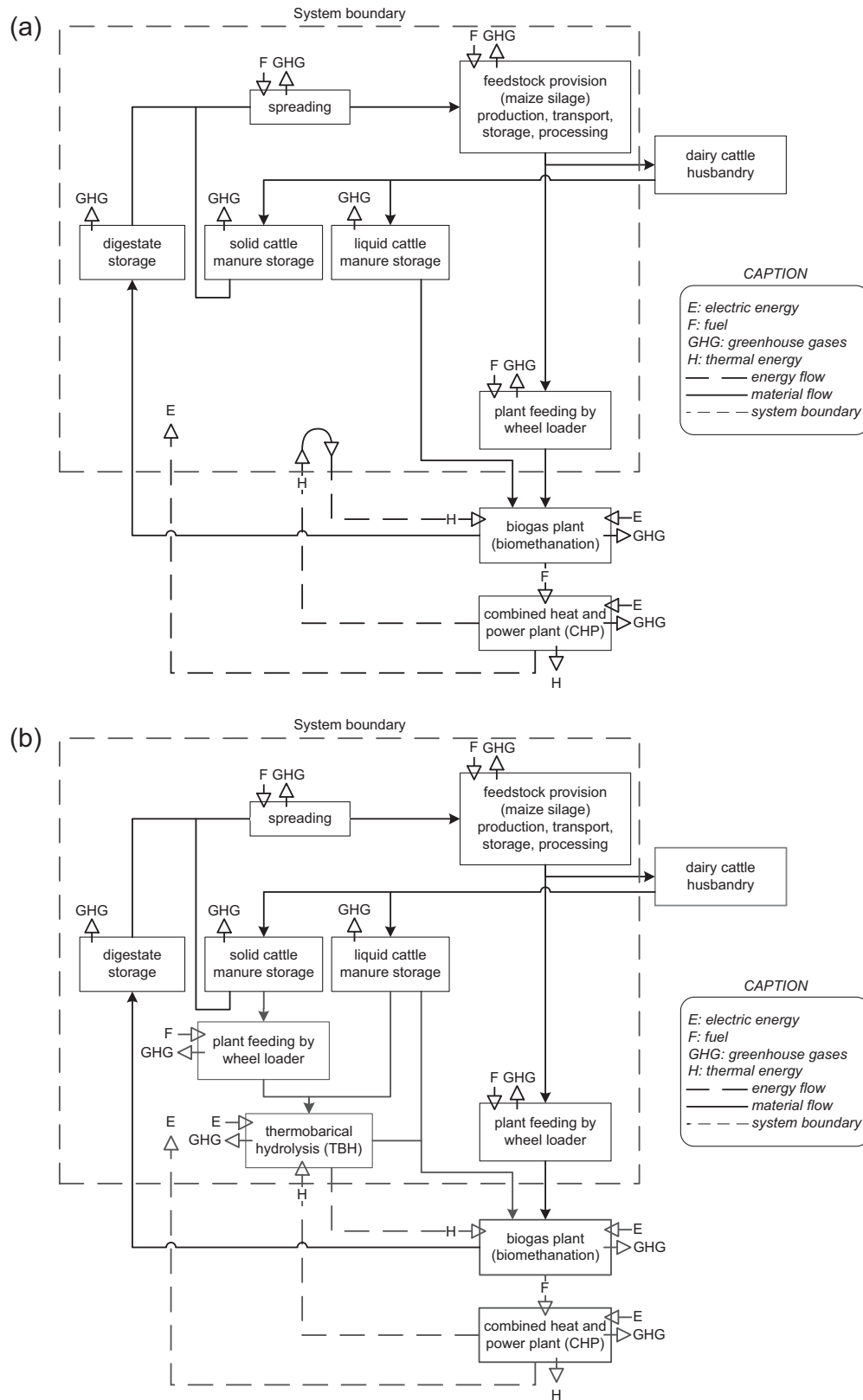


Fig. 1. Flow scheme of mass, energy, and fuel and GHG emissions of (a) the reference system before and (b) the modified system after implementation of a TBH device.

tubes are assumed to be comparable to cold drawn tubes. The masses of the respective components are summarized in Table 1. The entire facility is designed for a lifetime of 20 years.

Heat uncoupled from CHP exhaust gas is transported to the TBH device vessel via a thermal-oil circuit by a thermal-oil pump with a nominal electric power of 4.0 kW<sub>el</sub>. The actual consumption of

**Table 2**

Overview of the different scenarios in terms of raw material and pretreatment temperature.

Raw material	Pretreatment set-point temperature (°C)			
	w/o	140	160	180
P1-LCM	X	X	X	X
P1-SCM		X	X	X
P1-SLCM		X	X	X
P2-LCM	X	X	X	X
P2-SCM		X	X	X

LCM – Liquid cattle manure; P1 – Plant 1; P2 – Plant 2; SCM – Solid cattle manure; SLCM – Solid and liquid cattle manure; w/o – without pretreatment.

electricity depends on the running hours of the consumer loads. The amount of heat available depends on CHP power and the resulting temperature and mass flow of exhaust gas. To control the heat input into the feedstock, the vessel inlet and outlet temperatures of the thermal-oil are measured, as well as the temperature of the feedstock and the inner-vessel pressure. The heat-flow is controlled by using a bypass to the exhaust gas heat exchanger.

The solid feedstock is brought to a receiver tank of 12 m<sup>3</sup> once a day where it can be mixed with liquid feedstock. A feedstock volume of 3 m<sup>3</sup> is delivered four times per day from the receiver tank to the vessel where the pretreatment takes place. Charging can be realized by a dosing feeder, equipped with a scale for measuring the amount of feedstock. The pipe between dosing feeder and vessel is blocked by a valve during pretreatment. Different mixing elements are possible, but to avoid clogging it is recommended that a mixing stirrer agitating near the vessel inside wall should be installed. Stirring power is approximately 1 kW<sub>el</sub> Mg<sup>-1</sup> substrate at the beginning, and decreases with increasing temperature and ongoing hydrolysis to 0.3 kW<sub>el</sub> Mg<sup>-1</sup> substrate for temperatures above 100 °C (unpublished engineering report).

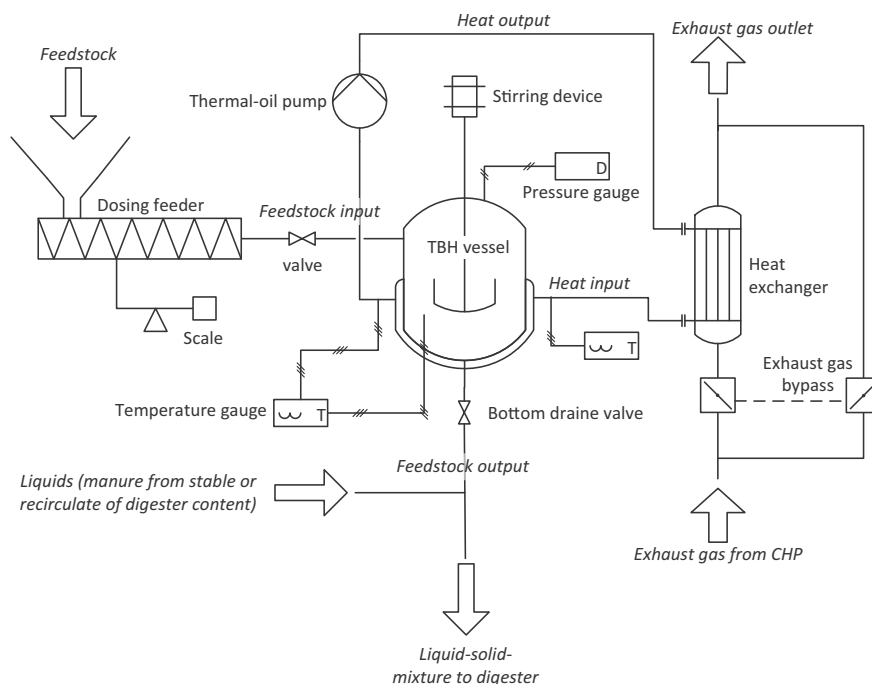
The time for heating up feedstock to 100 °C is estimated to be 1.61 h, and 3.22 h for reaching set-point hydrolysis temperature. This period of 4.83 h is used for all designated set-point temperatures. The electric mixing power for SCM is then calculated to be

1.0 kW<sub>el</sub>. For further calculations it is assumed that the power for mixing LCM and SLCM equals that of SCM (unpublished engineering report).

After pretreatment the heated feedstock is released through a bottom drain valve using the water vapor pressure inside the vessel as driving force. Simultaneously liquid feedstock is pumped through a pipeline that is linked to the outlet pipe. The mixtures of both treated feedstock and liquid feedstock are then delivered to the digester of the biogas plant.

### 2.3. Feedstock

The main characteristics of the feedstock are displayed in Table 3 (for full characteristics see Budde et al. (2014)). SCM used for dry cows and heifers consisted of less straw in the case of P1 than SCM from P2. Although LCMs of P1 and P2 show differences, they both include parts of the litter and feed residues fallen through the slatted floor of high-performance dairy cattle. Methane yields of raw materials as well as alteration in methane yields due to pretreatment are gained from lab-scale experiments (Budde et al., 2014). The farm-based raw materials have been treated in a 600 ml stainless steel reactor of company Parr Instruments at temperatures of 140–220 °C and related saturated water vapor pressure (3.6–23.2 bar) in 20 K steps for a 5-min duration at set-point temperature. A detailed description of the methods applied in lab-scale is given in Budde et al. (2014). Calculations of methane yields refer to a fresh matter base, as the daily amount of feedstock to be pretreated is limited by the TBH device vessel-volume. The fresh matter volume flow to be pretreated is 12 m<sup>3</sup> d<sup>-1</sup> for any feedstock. Mass flows were calculated using (bulk) densities of 1000 kg m<sup>-3</sup> for LCM and 800 kg m<sup>-3</sup> for SCM (Rühlmann, 2000). The density of SLCM was set to 1000 kg m<sup>-3</sup>, assuming that the spaces in the solid cattle manure are completely filled with liquid. The fresh matter mass fraction of SCM in SLCM is 0.327. The resulting mass flows of the different feedstocks are 0.1389 kg FM s<sup>-1</sup> in the case of LCM and SCLM and 0.1111 kg FM s<sup>-1</sup> in the case of SCM. The annual average temperature of fresh solid and liquid cattle manure is set to 15 °C.



**Fig. 2.** TBH facility. Schematic flow chart of the entire TBH facility (simplified) including the heat uncoupling from CHP and the feeding device (based on DIN EN ISO 10628).

**Table 3**  
Parameters of untreated and treated feedstock (from Budde et al., 2014) and number of wheel loader trips.

Raw material	Set-point temperature (°C)	Average methane yield <sup>a</sup> Y <sub>30</sub> (l <sub>N</sub> kg <sup>-1</sup> OM)	ODM (% FM)	OM	Mass fraction of methane from SCM in methane from SLCM	Fresh matter related methane yield of		Volume flow of		Number of wheel loader trips <sup>b</sup> (trips d <sup>-1</sup> )
						LCM	SCM	MS	SCM	
						(l <sub>N</sub> kg <sup>-1</sup> FM)		(m <sup>3</sup> d <sup>-1</sup> )		
P1-LCM	Untreated	203.37	6.37	7.17	–	–	–	–	–	–
P1-LCM	140	305.80	6.37	7.17	–	7.3	0.0	3.3	0.0	–4
P1-LCM	160	310.57	6.37	7.17	–	7.7	0.0	3.4	0.0	–4
P1-LCM	180	234.72	6.37	7.17	–	2.2	0.0	1.0	0.0	–1
P1-SCM	Untreated	167.53	15.00	15.67	–	–	–	–	–	–
P1-SCM	140	186.09	15.00	15.67	–	0.0	29.2	10.4	12.0	1
P1-SCM	160	187.38	15.00	15.67	–	0.0	29.4	10.5	12.0	1
P1-SCM	180	216.41	15.00	15.67	–	0.0	33.9	12.1	12.0	–1
P1-SLCM	Untreated	225.66	7.36	8.09	0.467	–	–	–	–	–
P1-SLCM	140	296.08	7.36	8.09	0.393	4.8	9.4	2.5	4.5	2
P1-SLCM	160	291.08	7.36	8.09	0.391	4.6	9.2	2.5	4.5	2
P1-SLCM	180	289.37	7.36	8.09	0.495	2.1	11.6	2.0	4.5	3
P2-LCM	Untreated	224.76	5.41	6.05	–	–	–	–	–	–
P2-LCM	140	258.77	5.41	6.05	–	2.1	0.0	0.9	0.0	–1
P2-LCM	160	261.67	5.41	6.05	–	2.2	0.0	1.0	0.0	–1
P2-LCM	180	245.28	5.41	6.05	–	1.2	0.0	0.6	0.0	–1
P2-SCM	Untreated	161.69	16.34	16.92	–	–	–	–	–	–
P2-SCM	140	231.58	16.34	16.92	–	0.0	39.2	14.0	12.0	–2
P2-SCM	160	255.35	16.34	16.92	–	0.0	43.2	15.4	12.0	–4
P2-SCM	180	176.64	16.34	16.92	–	0.0	29.9	10.6	12.0	1

LCM – Liquid cattle manure; MS – Maize silage; ODM – Organic dry matter; OM – Organic matter (sum of ODM and volatile organic acids); P1 – Plant 1; P2 – Plant 2; SCM – Solid cattle manure; SLCM – Solid and liquid cattle manure; Y<sub>30</sub> – Methane yields from lab-scale experiments.

<sup>a</sup> Mean of three replicates (LCM and SLCM from plant 1 were not tested in repetition).

<sup>b</sup> Number of wheel loader trips needed for transport of the respective feedstock (LCM, SCM, or SLCM) minus number of wheel loader trips necessary to transport substituted maize silage.

Maize silage is chosen as reference feedstock. It is the most frequent crop feedstock in anaerobic digestion in Germany today due to its high methane yield per hectare (DBFZ, 2010). Characteristics of maize silage are a bulk density of 300 kg m<sup>3</sup> (Köppen, 2002) and a fresh matter methane yield of 90 l<sub>N</sub> kg<sup>-1</sup> FM (calculated according to data from KTBL; KTBL, 2010a).

#### 2.4. Full-scale biogas plant

A modular design has been projected to ensure wide-range applicability of the TBH. It allows a retrofit to almost all kinds of existing biogas plants. Therefore, the effect of thermobarical pretreatment is calculated without considering the particular biogas process in detail.

All calculations assume that the heat necessary to maintain mesophilic temperatures ( $T_{\text{dig}} = 40\text{ °C}$ ) is provided either directly from CHP to digester and/or via TBH. Heat losses during pretreatment in comparison to losses in the heating system of the biogas plant digester are not regarded. It is assumed that hydraulic retention time is not considerably decreased and viscosity not changed by the additional feedstock per day necessary to provide the same mass flow of methane (compared to maize silage). Reduction in volume of feedstock due to biomethanation is not considered. A possible change in feedstock degradation or degradability and stirring power is not regarded.

A wheel loader with a shovel-volume of 1 m<sup>3</sup> is used for transport of solid feedstock to the feeding device of the biogas plant or the receiver tank of the TBH device. It is assumed that the distance between the storage location and the feeding device is 300 m, that the distance is covered with an average speed of 20 km h<sup>-1</sup> and that both charging and discharging are done within 15 s. One charging process lasts 2.3 min under these assumptions.

LCM – also if used without pretreatment in biogas plant – does not require transport by wheel loader. But it could save an extra amount of maize silage if pretreatment enhances the fresh matter

related methane yield. It could therefore save wheel loader trips that would otherwise have been necessary for transporting maize silage equivalent to the additional methane yield. SCM has a lower fresh matter related methane yield than maize silage, but a higher bulk density. Hence maize silage substitution changes the number of trips of the wheel loader necessary to provide the same amount of methane after biomethanation of SCM. In the case of the SLCM, the necessary extra trips and the saved trips corresponding to the respective mass fractions of LCM and SCM in SLCM are calculated. The fresh matter volume-flow of feedstock and maize silage substituted and the numbers of additional or reduced wheel loader trips per day are shown in Table 3. They are calculated according to

$$\dot{V}_{\text{FM,MS}} = \dot{V}_{\text{FS}} \cdot \frac{Y_{\text{CH}_4,\text{FM,FS}} \cdot \rho_{\text{FS}}}{Y_{\text{CH}_4,\text{FM,MS}} \cdot \rho_{\text{MS}}} \quad (1)$$

The nomenclature for this and all following equations is presented in Table 4.

Heat is the main energy needed for TBH. It is provided by a combined heat and power plant. The CHP used for these calculations is a 330 kW<sub>el</sub> biogas-otto-engine (for further data see Table 1).

The maximal set-point temperature  $T_{\text{set-point}}$  for TBH process is 180 °C. The temperature of uncoupled heat needs to be considerably higher to obtain a heat-flow that allows feedstock to be heated in a reasonable time. Therefore, the exhaust gas output temperature is set to 230 °C. The thermal power available for the TBH process is calculated to be 158 kJ s<sup>-1</sup> from the characteristics of the exhaust gas of the CHP in the example. It is assumed that CHP (and biogas plant) are in full operational state for ADO = 350 days or AHO = 8400 h per year respectively, for all following calculations (FNR, 2010).

#### 2.5. Energy balance

The energy balance considers the energy needed for construction materials  $E_{\text{constr}}$  as well as the electricity input (energy per

**Table 4**  
Nomenclature for symbols in equations in the order of their appearance.

Equation number	Parameter	Nomenclature
1	$\dot{V}_{FM,MS}$	Fresh matter volume-flow of maize silage substituted ( $m^3 d^{-1}$ )
	$\dot{V}_{FS}$	Fresh matter volume flow of feedstock ( $m^3 d^{-1}$ )
	$Y_{CH_4,FM,FS}$	Methane yield of feedstock on a fresh matter basis ( $l_N CH_4 kg^{-1} FM$ )
	$Y_{CH_4,FM,MS}$	Methane yield of maize silage on a fresh matter basis ( $l_N CH_4 kg^{-1} FM$ )
	$\rho_{FS}$	Bulk density of feedstock ( $kg m^{-3}$ )
2	$\rho_{MS}$	Bulk density of maize silage ( $kg m^{-3}$ )
	$P_{th,FS}$	Thermal input to feedstock for reaching set-point temperature ( $kW h a^{-1}$ )
	$\dot{m}_{FS}$	Mass flow of the respective feedstock ( $kg FM s^{-1}$ )
	$c_{p,H_2O}$	(temperature-independent) specific heat capacity of water ( $kJ kg^{-1} K^{-1}$ )
	$T_{set-point}$	Set-point temperature of the pretreatment ( $^{\circ}C$ )
3	$T_{FS}$	Feedstock temperature ( $^{\circ}C$ )
	AHO	Annual hours of operation ( $h a^{-1}$ )
	$e_{th,FS}$	Thermal input to feedstock for reaching set-point temperature ( $kW h Mg^{-1} FM$ )
4	$c_{p,H_2O}$	(temperature-independent) specific heat capacity of water ( $kJ kg^{-1} K^{-1}$ )
	$T_{set-point}$	Set-point temperature of the pretreatment ( $^{\circ}C$ )
	$T_{FS}$	Feedstock temperature ( $^{\circ}C$ )
	$e_{th,process}$	Thermal input serving as process energy for the biogas plant ( $kW h a^{-1}$ )
5	$\dot{m}_{FS}$	Mass flow of the respective feedstock ( $kg FM s^{-1}$ )
	$c_{p,H_2O}$	(temperature-independent) specific heat capacity of water ( $kJ kg^{-1} K^{-1}$ )
	$T_{set-point}$	Set-point temperature of the pretreatment ( $^{\circ}C$ )
	$T_{dig}$	Temperature of digester content ( $^{\circ}C$ )
	AHO	Annual hours of operation ( $h a^{-1}$ )
6	$e_{th,process}$	Thermal input serving as process energy for the biogas plant ( $kW h Mg^{-1} FM$ )
	$c_{p,H_2O}$	(temperature-independent) specific heat capacity of water ( $kJ kg^{-1} K^{-1}$ )
	$T_{set-point}$	Set-point temperature of the pretreatment ( $^{\circ}C$ )
	$T_{dig}$	Temperature of digester content ( $^{\circ}C$ )
7	$Y_{CH_4,FM,LCM}$	Methane yield of LCM assigned to the TBH on a fresh matter basis ( $l_N CH_4 kg^{-1} FM$ )
	$W_{OM,LCM}$	Mass fraction of organic matter in fresh matter of LCM
	$Y_{30,LCM,T}$	Methane yield of LCM pretreated at the respective temperature $T$ ( $l_N kg^{-1} OM$ )
	$Y_{30,LCM,w/o}$	Methane yield of untreated LCM ( $l_N kg^{-1} OM$ )
8	$Y_{CH_4,FM,SCM}$	Methane yield of SCM on a fresh matter basis ( $l_N CH_4 kg^{-1} FM$ )
	$W_{OM,SCM}$	Mass fraction of organic matter to fresh matter of SCM
	$Y_{30,SCM,T}$	Methane yield of SCM pretreated at the respective temperature $T$ ( $l_N kg^{-1} OM$ )
9	$W_{CH_4,FM,SCM,T}$	Ratio of methane from SCM to methane from LCM within SLCM at the different pretreatment temperatures $T$
	$W_{FM,SCM}$	Fresh matter mass fraction of SCM in SLCM
	$Y_{30,SCM,T}$	Methane yield of SCM pretreated at the respective temperature $T$ ( $l_N kg^{-1} OM$ )
	$W_{OM,SCM}$	Mass fraction of organic matter to fresh matter of SCM
	$Y_{30,LCM,T}$	Methane yield of LCM pretreated at the respective temperature $T$ ( $l_N kg^{-1} OM$ )
	$W_{OM,LCM}$	Mass fraction of organic matter in fresh matter of LCM
	$Y_{CH_4,FM,(S)LCM,T}$	Methane from LCM within SLCM ( $l_N kg^{-1} FM$ )
10	$W_{CH_4,FM,SCM,T}$	Weighted ratio of the respective methane yields of feedstock pretreated at the respective temperature $T$
	$W_{CH_4,FM,SCM,w/o}$	Weighted ratio of the respective methane yields of untreated feedstock
	$Y_{30,SLCM,T}$	Methane yield of SLCM ( $l_N kg^{-1} OM$ )
	$Y_{30,SLCM,w/o}$	Methane yield of untreated SLCM ( $l_N kg^{-1} OM$ )
	$W_{OM,SLCM}$	Mass fraction of organic matter in fresh matter of SLCM
11	$Y_{CH_4,FM,S(L)CM,T}$	Methane from SCM within SLCM ( $l_N kg^{-1} FM$ )
	$W_{CH_4,FM,SCM,T}$	Weighted ratio of the respective methane yields of feedstock pretreated at the respective temperature $T$
	$Y_{30,SLCM,T}$	Methane yield of SLCM ( $l_N kg^{-1} OM$ )
	$W_{OM,SLCM}$	Mass fraction of organic matter in fresh matter of SLCM
12	$P_{MC}$	Methanation capacity ( $kW h a^{-1}$ )
	$Y_{CH_4,FM,FS}$	Methane yield of feedstock on a fresh matter basis ( $l_N CH_4 kg^{-1} FM$ )
	$\rho_{CH_4}$	Density of methane ( $kg m^{-3}$ )
	$LHV_{CH_4}$	Lower heating value of methane ( $MJ kg^{-1}$ )
	$\dot{m}_{FS}$	Mass flow of the respective feedstock ( $kg FM s^{-1}$ )
13	AHO	Annual hours of operation ( $h a^{-1}$ )
	EPBT	Energy payback time (P[n]Y[n]M)
	$E_{constr}$	Energy needed for construction materials ( $kW h$ )
	$P_{el,out}$	Electric energy output ( $kW h a^{-1}$ )
14	$P_{el,in}$	Electricity input for operation of the TBH device ( $kW h a^{-1}$ )
	EPBM	Energy payback mass ( $Mg FM$ )
	$E_{constr}$	Energy needed for construction materials ( $kW h$ )
	$e_{el,out}$	Electric energy output ( $kW h Mg^{-1} FM$ )
15	$e_{el,in}$	Electricity input for operation of the TBH device ( $kW h Mg^{-1} FM$ )
	$GHG_{net}$	Net GHG balance ( $kg CO_2\text{-eq. } kW h_{el}^{-1}$ )
	$GHG_{constr}$	Emissions from TBH construction ( $kg CO_2\text{-eq. } kW h_{el}^{-1}$ )
	$GHG_{el,in}$	Emissions from TBH operation, ( $kg CO_2\text{-eq. } kW h_{el}^{-1}$ )
16	$\delta GHG_{SCM}$	Emissions from SCM storage ( $kg CO_2\text{-eq. } kW h_{el}^{-1}$ )

Table 4 (continued)

Equation number	Parameter	Nomenclature	
15	$\delta\text{GHG}_{\text{MS}}$	Emissions from maize supply (kg CO <sub>2</sub> -eq. kW h <sub>el</sub> <sup>-1</sup> )	
	$\text{GHG}_{\text{net}}^{\ddagger}$	Net GHG balance (kg CO <sub>2</sub> -eq. Mg <sup>-1</sup> FM)	
	$\text{GHG}_{\text{constr}}^{\ddagger}$	Emissions from TBH construction (kg CO <sub>2</sub> -eq. Mg <sup>-1</sup> FM)	
	$\text{GHG}_{\text{el.in}}^{\ddagger}$	Emissions from TBH operation, (kg CO <sub>2</sub> -eq. Mg <sup>-1</sup> FM)	
	$\delta\text{GHG}_{\text{SCM}}^{\ddagger}$	Emissions from SCM storage (kg CO <sub>2</sub> -eq. Mg <sup>-1</sup> FM)	
16	$\delta\text{GHG}_{\text{MS}}^{\ddagger}$	Emissions from maize supply (kg CO <sub>2</sub> -eq. Mg <sup>-1</sup> FM)	
	$\text{GHG}_{\text{el.in}}$	Emissions from TBH operation, (kg CO <sub>2</sub> -eq. kW h <sub>el</sub> <sup>-1</sup> )	
	$P_{\text{el.in}}$	Electricity input for operation of the TBH device (kW h a <sup>-1</sup> )	
	$\text{GHG}_{\text{grid}}$	Emissions balance of grid electricity (kg CO <sub>2</sub> -eq. kW h <sub>el</sub> <sup>-1</sup> )	
	$P_{\text{el.out}}$	Electric energy output (kW h a <sup>-1</sup> )	
17	$\text{GHG}_{\text{el.in}}^{\ddagger}$	Emissions from TBH operation, (kg CO <sub>2</sub> -eq. Mg <sup>-1</sup> FM)	
	$e_{\text{el.in}}$	Electricity input for operation of the TBH device (kW h Mg <sup>-1</sup> FM)	
	$\text{GHG}_{\text{grid}}$	Emissions balance of grid electricity (kg CO <sub>2</sub> -eq. kW h <sub>el</sub> <sup>-1</sup> )	
18	$\delta\text{GHG}_{\text{SCM}}$	Emissions from SCM storage (kg CO <sub>2</sub> -eq. kW h <sub>el</sub> <sup>-1</sup> )	
	$M_{\text{CO}_2}$	Molar mass of CO <sub>2</sub> (g mol <sup>-1</sup> )	
	$\dot{m}_{\text{CH}_4,\text{SCM}}$	Mass flow of methane attained from SCM (kg s <sup>-1</sup> )	
	$M_{\text{CH}_4}$	Molar mass of CH <sub>4</sub> (g mol <sup>-1</sup> )	
	$P_{\text{el.out}}$	Electric energy output (kW h a <sup>-1</sup> )	
19	$\delta\text{GHG}_{\text{SCM}}^{\ddagger}$	Emissions from SCM storage (kg CO <sub>2</sub> -eq. Mg <sup>-1</sup> FM)	
	$M_{\text{CO}_2}$	Molar mass of CO <sub>2</sub> (g mol <sup>-1</sup> )	
	$M_{\text{CH}_4}$	Molar mass of CH <sub>4</sub> (g mol <sup>-1</sup> )	
	$Y_{\text{CH}_4,\text{FM},\text{SCM}}$	Methane yield of SCM on a fresh matter basis (l <sub>N</sub> CH <sub>4</sub> kg <sup>-1</sup> FM)	
	$\rho_{\text{CH}_4}$	Density of methane (kg m <sup>-3</sup> )	
20	$\delta C_{\text{MS}}^{\ddagger}$	Costs of electricity production using maize silage (€ Mg <sup>-1</sup> FM)	
	$\delta C_{\text{MS}}$	Costs of electricity production using maize silage (ct kW h <sub>el</sub> <sup>-1</sup> )	
	$e_{\text{el.out}}$	Electric energy output (kW h Mg <sup>-1</sup> FM)	
21	Profit	Profit (ct kW h <sub>el</sub> <sup>-1</sup> )	
	$C_{\text{constr}}$	Costs of purchasing the TBH device (ct kW h <sub>el</sub> <sup>-1</sup> )	
	$C_{\text{el.in}}$	Costs of electricity consumption of the TBH device (ct kW h <sub>el</sub> <sup>-1</sup> )	
	$C_{\text{MT}}$	Costs of maintaining the TBH device (ct kW h <sub>el</sub> <sup>-1</sup> )	
	$\delta C_{\text{WL}}$	Costs of wheel loader employment (ct kW h <sub>el</sub> <sup>-1</sup> )	
	$\delta C_{\text{spreading}}$	Costs of changes in spreading-procedure (ct kW h <sub>el</sub> <sup>-1</sup> )	
	$\delta C_{\text{el.out}}$	Revenues from a bonus within German feed-in tariff structure of electricity sales (ct kW h <sub>el</sub> <sup>-1</sup> )	
	$\delta C_{\text{MS}}$	Costs of electricity production using maize silage (ct kW h <sub>el</sub> <sup>-1</sup> )	
22	Profit <sup>†</sup>	Profit (€ Mg <sup>-1</sup> FM)	
	$C_{\text{constr}}^{\ddagger}$	Costs of purchasing the TBH device (€ Mg <sup>-1</sup> FM)	
	$C_{\text{el.in}}^{\ddagger}$	Costs of electricity consumption of the TBH device (€ Mg <sup>-1</sup> FM)	
	$C_{\text{MT}}^{\ddagger}$	Costs of maintaining the TBH device (€ Mg <sup>-1</sup> FM)	
	$\delta C_{\text{WL}}^{\ddagger}$	Costs of wheel loader employment (€ Mg <sup>-1</sup> FM)	
	$\delta C_{\text{spreading}}^{\ddagger}$	Costs of changes in spreading-procedure (€ Mg <sup>-1</sup> FM)	
	$\delta C_{\text{el.out}}^{\ddagger}$	Revenues from a bonus within German feed-in tariff structure of electricity sales (€ Mg <sup>-1</sup> FM)	
	$\delta C_{\text{MS}}^{\ddagger}$	Costs of electricity production using maize silage (€ Mg <sup>-1</sup> FM)	
	23	$\delta C_{\text{spr,dig,FS}}$	Costs of spreading digestate from the respective feedstock (ct kW h <sub>el</sub> <sup>-1</sup> )
$\dot{V}_{\text{FM,FS}}$		Fresh matter volume flow of the respective feedstock (m <sup>3</sup> d <sup>-1</sup> )	
$\rho_{\text{FS}}$		Bulk density of feedstock (kg m <sup>-3</sup> )	
$\rho_{\text{dig}}$		Density of digestate (kg m <sup>-3</sup> )	
$C_{\text{spr,V}}$		Costs of transport and spreading of LCM or digestate (€ m <sup>-3</sup> )	
ADO		Annual days of operation (d a <sup>-1</sup> )	
$P_{\text{el.out}}$		Electric energy output (kW h a <sup>-1</sup> )	
24		$\delta C_{\text{spr,dig,FS}}^{\ddagger}$	Costs of spreading digestate from the respective feedstock (€ Mg <sup>-1</sup> FM)
	$\dot{V}_{\text{FM,FS}}$	Fresh matter volume flow of the respective feedstock (m <sup>3</sup> d <sup>-1</sup> )	
	$\rho_{\text{FS}}$	Bulk density of feedstock (kg m <sup>-3</sup> )	
	$\rho_{\text{dig}}$	Density of digestate (kg m <sup>-3</sup> )	
	$C_{\text{spr,V}}$	Costs of transport and spreading of LCM or digestate (ct m <sup>-3</sup> )	
	$\dot{m}_{\text{FS}}$	Mass flow of the respective feedstock (kg FM s <sup>-1</sup> )	
	25	$\delta C_{\text{spr,SCM,w/o}}$	Costs of spreading untreated SCM (€ kW h <sub>el</sub> <sup>-1</sup> )
		$\dot{V}_{\text{FM,SCM}}$	Fresh matter volume flow of SCM (m <sup>3</sup> d <sup>-1</sup> )
$\rho_{\text{SCM}}$		Bulk density of SCM (kg m <sup>-3</sup> )	
$C_{\text{spr,m}}$		Costs of transport and spreading of SCM (€ Mg <sup>-1</sup> )	
ADO		Annual days of operation (d a <sup>-1</sup> )	
$P_{\text{el.out}}$		Electric energy output (kW h a <sup>-1</sup> )	
26	$\delta C_{\text{spr,SCM,w/o}}^{\ddagger}$	Costs of spreading untreated SCM (€ Mg <sup>-1</sup> FM)	
	$C_{\text{spr,m}}$	Costs of transport and spreading of SCM (ct Mg <sup>-1</sup> )	
27	$\delta C_{\text{spreading}}$	Costs of changes in spreading-procedure (ct kW h <sub>el</sub> <sup>-1</sup> )	

(continued on next page)



Table 4 (continued)

Equation number	Parameter	Nomenclature
28	$\delta C_{\text{spr,SCM,w/o}}^{\dagger}$	Costs of spreading untreated SCM (ct kW h <sub>el</sub> <sup>-1</sup> )
	$\delta C_{\text{spr,dig,SCM}}^{\dagger}$	Costs of spreading digestate from SCM (ct kW h <sub>el</sub> <sup>-1</sup> )
	$\delta C_{\text{spr,dig,MS}}^{\dagger}$	Costs of spreading digestate from maize silage (ct kW h <sub>el</sub> <sup>-1</sup> )
	$\delta C_{\text{spreading}}^{\dagger}$	Costs of changes in spreading-procedure (€ Mg <sup>-1</sup> FM)
	$\delta C_{\text{spr,SCM,w/o}}^{\dagger}$	Costs of spreading untreated SCM (€ Mg <sup>-1</sup> FM)
29	$\delta C_{\text{spr,dig,SCM}}^{\dagger}$	Costs of spreading digestate from SCM (€ Mg <sup>-1</sup> FM)
	$\delta C_{\text{spr,dig,MS}}^{\dagger}$	Costs of spreading digestate from maize silage (€ Mg <sup>-1</sup> FM)
	$\delta C_{\text{el,out}}^{\dagger}$	Revenues from a bonus within German feed-in tariff structure of electricity sales (€ Mg <sup>-1</sup> FM)
	$e_{\text{el,out}}$	Electric energy output (kW h Mg <sup>-1</sup> FM)
30	ECAP	Economic amortization period (P[n]Y[n]M)
	Investment	Investment (€)
	Profit	Profit (€ a <sup>-1</sup> )
	Depreciation	Depreciation (€ a <sup>-1</sup> )
31	Interest	Interest rate (€ a <sup>-1</sup> )
	ECAM	Economic amortization mass (t FM)
	ECAP	Economic amortization period (P[n]Y[n]M)
	$\dot{m}_{\text{FS}}$	Mass flow of the respective feedstock (kg FM s <sup>-1</sup> )
32	ADO	Annual days of operation (d a <sup>-1</sup> )
	CMC	CO <sub>2</sub> mitigation costs (€ Mg <sup>-1</sup> CO <sub>2</sub> -eq.)
	$C_{\text{EP,TBH}}$	Electricity production costs (€ kW h <sub>el</sub> <sup>-1</sup> )
	$C_{\text{EP,grid}}$	Grid electricity-mix production costs (€ kW h <sub>el</sub> <sup>-1</sup> )
	$\text{GHG}_{\text{grid}}$	Emissions balance of grid electricity (kg CO <sub>2</sub> -eq. kW h <sub>el</sub> <sup>-1</sup> )
$\text{GHG}_{\text{net}}$	Net GHG balance (kg CO <sub>2</sub> -eq. kW h <sub>el</sub> <sup>-1</sup> )	

time or per mass) for operation of the TBH device  $P_{\text{el,in}}$  or  $e_{\text{el,in}}$  and compares these inputs with the energy output, electric ( $P_{\text{el,out}}$  or  $e_{\text{el,out}}$ ) as well as thermal ( $P_{\text{th,out}}$  or  $e_{\text{th,out}}$ ), attained from pretreated feedstock via methane. Furthermore, the heat balance of heating up feedstock through TBH ( $P_{\text{th,FS}}$  or  $e_{\text{th,FS}}$ ) and heat transfer into digester ( $P_{\text{th,process}}$  or  $e_{\text{th,process}}$ ) is presented, as well as savings from energy needed for maize supply ( $\delta P_{\text{MS}}$  or  $\delta e_{\text{MS}}$ ). The energy payback time or payback mass (EPBT or EPBM) is calculated in order to assess the energy efficiency.

The respective energy input for employment of agricultural machines for TBH device or biogas plant feeding and manure or digestate spreading was neglected. Calculation revealed values lying in most cases below 0.91% of the entire energy input or output of the system, and never more than 2.45%.

The energy for construction and provision of raw material  $E_{\text{constr}}$  in kW h has to be taken into consideration as part of an energy converting facility. The total energy demand for provision of stainless steel and for construction of a TBH device  $E_{\text{constr}}$  is calculated as 374,600 kW h. Dependent on the lifetime of the TBH facility and on feedstock density the mass related values  $e_{\text{constr}}$  are either 4.5 or 5.6 kW h Mg<sup>-1</sup> FM.

The electricity demand  $P_{\text{el,in}}$  or  $e_{\text{el,in}}$  of the largest consumer loads of the TBH device, the stirrer and the thermal-oil pump, adds up to 42,000 kW h<sub>el</sub> a<sup>-1</sup> or dependent on feedstock density either 10 or 12.5 kW h<sub>el</sub> Mg<sup>-1</sup> FM.

In idealized calculation, thermal energy necessary to heat feedstock is affected by feedstock temperature  $T_{\text{FS}}$ , set-point temperature of the pretreatment  $T_{\text{set-point}}$ , and the density of the feedstock (the specific heat capacity of water and the volume flow of respective feedstock are assumed to be fixed values). The thermal input to feedstock  $P_{\text{th,FS}}$  in kW h a<sup>-1</sup> for reaching set-point temperature during thermobarical hydrolysis is

$$P_{\text{th,FS}} = \dot{m}_{\text{FS}} \cdot c_{p,\text{H}_2\text{O}} \cdot (T_{\text{set-point}} - T_{\text{FS}}) \cdot \text{AHO} \quad (2)$$

Related to fresh matter the thermal input  $e_{\text{th,FS}}$  in kW h Mg<sup>-1</sup> FM is calculated according to

$$e_{\text{th,FS}} = c_{p,\text{H}_2\text{O}} \cdot (T_{\text{set-point}} - T_{\text{FS}}) \cdot 3.6^{-1} \quad (3)$$

After thermobarical hydrolysis, the heated feedstock is discharged into the biogas plant. It is assumed that there is no loss in thermal energy during transport of feedstock from the TBH device to the biogas plant. The heat input into the downstream biogas plant is determined by the temperature difference between feedstock ( $T_{\text{FS}}$ ) and digester content ( $T_{\text{dig}}$ ) and the mass flow of the respective feedstock. The thermal energy input  $P_{\text{th,process}}$ , given in kW h a<sup>-1</sup> or  $e_{\text{th,process}}$ , given in kW h Mg<sup>-1</sup> FM, serves as process energy for the biogas plant: pretreatment and heating of feedstock contribute positive energy to the system while the untreated variants make a negative contribution. Process energy in kW h a<sup>-1</sup> is calculated

$$P_{\text{th,process}} = \dot{m}_{\text{FS}} \cdot c_{p,\text{H}_2\text{O}} \cdot (T_{\text{set-point}} - T_{\text{dig}}) \cdot \text{AHO} \quad (4)$$

Related to fresh matter the process energy in kW h Mg<sup>-1</sup> FM is calculated according to

$$e_{\text{th,process}} = c_{p,\text{H}_2\text{O}} \cdot (T_{\text{set-point}} - T_{\text{dig}}) \cdot 3.6^{-1} \quad (5)$$

In the case of no treatment, the term  $T_{\text{set-point}}$  is to be replaced by  $T_{\text{FS}}$ . The required heating of 'cold' untreated feedstock to mesophilic digester temperatures of 40 °C leads to losses of 122,500 kW h<sub>th</sub> a<sup>-1</sup> in the case of LCM and SLCM and 98,000 kW h<sub>th</sub> a<sup>-1</sup> in the case of SCM. When related to fresh matter, it is 29.2 kW h<sub>th</sub> Mg<sup>-1</sup> FM in any case.

It is assumed that the methane achievable from the respective feedstock in biogas plant equals the methane yield determined in lab-scale experiments.

The processing of LCM as well as the methane attainable from untreated LCM are assigned to the biogas plant, as it is assumed that LCM is used or can be used in continuous stirred tank reactors without any pretreatment.

$$Y_{\text{CH}_4,\text{FM,LCM}} = w_{\text{OM,LCM}} \cdot (Y_{30,\text{LCM,T}} - Y_{30,\text{LCM,w/o}}) \quad (6)$$

The methane available from SCM is completely allotted to the TBH, as it is not suitable for utilization in conventional continuous stirred tank reactors without pretreatment.

$$Y_{CH_4,FM,SCM} = W_{OM,SCM} \cdot Y_{30,SCM,T} \quad (7)$$

The shares of methane from LCM and SCM within SLCM have to be related to the respective feedstock. It is expected, that the difference in methane yield of the respective feedstock – SCM or LCM – due to pretreatment corresponds with that in the mixture of both – SLCM. The ratio of methane from SCM to methane from LCM within SLCM at the different pretreatment temperatures  $T$  is then calculated according to

$$W_{CH_4,FM,SCM,T} = W_{FM,SCM} \cdot \frac{Y_{30,SCM,T} \cdot W_{OM,SCM}}{Y_{30,LCM,T} \cdot W_{OM,LCM}} \cdot \left( W_{FM,SCM} \cdot \frac{Y_{30,SCM,T} \cdot W_{OM,SCM}}{Y_{30,LCM,T} \cdot W_{OM,LCM}} + (1 - W_{FM,SCM}) \right)^{-1} \quad (8)$$

The methane from LCM within SLCM  $Y_{CH_4,FM,(S)LCM,T}$  in  $l_N \cdot kg^{-1}$  FM is

$$Y_{CH_4,FM,(S)LCM} = [(1 - W_{CH_4,FM,SCM,T}) \cdot Y_{30,SLCM,T} - (1 - W_{CH_4,FM,SCM,w/o}) \cdot Y_{30,SLCM,w/o}] \cdot W_{OM,SLCM} \quad (9)$$

The methane attainable from SCM within SLCM is

$$Y_{CH_4,FM,S(L)CM} = W_{CH_4,FM,SCM,T} \cdot Y_{30,SLCM,T} \cdot W_{OM,SLCM} \quad (10)$$

Table 3 shows the values of untreated LCM and SCM of biogas plant 1 allowing this calculation.

The methanation capacity  $P_{MC}$  in  $kW h a^{-1}$  is calculated from the respective methane yields (Table 5)

$$P_{MC} = Y_{CH_4,FM,FS} \cdot \rho_{CH_4} \cdot LHV_{CH_4} \cdot \dot{m}_{FS} \cdot AHO \quad (11)$$

The methane is converted to electricity and heat by the CHP. The term  $P_{el,out}$  or  $e_{el,out}$  is the electricity in  $kW h_{el} a^{-1}$  or  $kW h_{el} Mg^{-1}$  FM achieved from the respective feedstock (Table 5).

The thermal output  $P_{th,out}$  or  $e_{th,out}$  in  $kW h_{th} a^{-1}$  or  $kW h_{th} Mg^{-1}$  FM is calculated by the thermal efficiency  $\eta_{th}$  of the CHP (Table 1).

The energy saved by substitution of maize silage ( $\delta P_{MS}$ ), needed for the entire supply chain of maize silage, is in any case  $0.162 kW h kW h_{el}^{-1}$  (Isermeyer et al., 2007). The values related ( $\delta e_{MS}$ ) to fresh matter are displayed in Table 5.

The energy payback time or payback mass respectively is the time or FM mass needed for providing just as much net energy as is needed for construction of the power generation plant regarded. Assuming that only electric energy is used for production and processing of steel and semi-finished products, as is usual in modern steel plants, the energy payback time in (P[n]Y[n]M) adds up to

$$EPBT = \frac{E_{constr}}{P_{el,out} - P_{el,in}} \quad (12)$$

The energetic payback mass in Mg FM is calculated according to

$$EPBM = \frac{E_{constr}}{e_{el,out} - e_{el,in}} \quad (13)$$

## 2.6. Greenhouse gas balance

The net GHG balance  $GHG_{net}$  in  $kg CO_2\text{-eq. per } kW h_{el}$  or per Mg fresh mass (symbols indicated by a superscript double plus are related to fresh matter) results from emissions from TBH construction  $GHG_{constr}$  and operation  $GHG_{el,in}$ , saved emissions from SCM storage  $\delta GHG_{SCM}$ , and saved emissions from maize supply  $\delta GHG_{MS}$  (Table 6):

$$GHG_{net} = GHG_{constr} + GHG_{el,in} + \delta GHG_{SCM} + \delta GHG_{MS} \quad (14)$$

Related to fresh matter the net emissions  $GHG_{net}^{\ddagger}$  are calculated according to

$$GHG_{net}^{\ddagger} = GHG_{constr}^{\ddagger} + GHG_{el,in}^{\ddagger} + \delta GHG_{SCM}^{\ddagger} + \delta GHG_{MS}^{\ddagger} \quad (15)$$

The GHG payback time or payback mass (GPBT or GPBM) is the time or fresh matter needed for saving the same amount of GHG that accrued during construction of, in this case, the TBH device ( $GHG_{constr}$  or  $GHG_{constr}^{\ddagger}$ ).

It is assumed that the emissions which result from wheel loader employment for feedstock processing and from the entire process chain of spreading the agricultural manures can be neglected. Calculations revealed values below 0.88% in most cases and never more than 2.27%. Possible emission savings from avoiding LCM storage in open liquid manure storage facilities are assigned completely to the biogas plant and not considered here. It is further assumed that thermobarical pretreatment releases feedstock constituents which, without pretreatment, would not have contributed to methane emissions during storage of untreated LCM because of their lower degradability.

Emissions from TBH construction  $GHG_{constr}$  or  $GHG_{constr}^{\ddagger}$  are calculated based on parameters of semi-finished products, as explained for the energy input. The emissions sum up to 85,468  $kg CO_2\text{-eq.}$ , whereby the masses of raw materials and the emissions from provision as shown in Table 1 are taken into consideration.

One has to consider the emissions balance of grid electricity  $GHG_{grid}$  or  $GHG_{grid}^{\ddagger}$ , as under German conditions, due to the difference in purchase prices of electricity and the granted feed-in tariff for electricity from biomass it is advantageous to use electric energy from the grid for the internal processes of a biogas plant (Table 1). Related to the electric energy produced the emissions  $GHG_{el,in}$  in  $kg CO_2\text{-eq. per } kW h_{el}$  are calculated according to

$$GHG_{el,in} = \frac{P_{el,in}}{P_{el,out}} \cdot GHG_{grid} \quad (16)$$

Related to fresh matter the emissions  $GHG_{el,in}^{\ddagger}$  in  $kg CO_2\text{-eq. per } Mg$  FM are calculated according to

$$GHG_{el,in}^{\ddagger} = e_{el,in} \cdot GHG_{grid} \quad (17)$$

SCM is usually stored in heaps on a concrete surface. During storage the carbon within the SCM is aerobically reduced to  $CO_2$  by microorganisms. It is expected that otherwise all carbon in  $CH_4$  that is composed by microorganisms during anaerobic digestion would have led to  $CO_2$  emissions. Therefore the emissions due to utilization of SCM are calculated according to

$$\delta GHG_{SCM} = - \frac{M_{CO_2}}{M_{CH_4}} \cdot \frac{\dot{m}_{CH_4,SCM}}{P_{el,out}} \cdot 31.536 \cdot 10^6 \quad (18)$$

Related to fresh matter these emissions are calculated according to

$$\delta GHG_{SCM}^{\ddagger} = - \frac{M_{CO_2}}{M_{CH_4}} \cdot Y_{CH_4,FM,SCM} \cdot \rho_{CH_4} \quad (19)$$

The emissions of  $CH_4$  and  $N_2O$  during rotting process are disregarded.

In the case of SLCM only the emissions from SCM are taken into account.

The emissions from cultivation, harvest, transport and ensiling of maize silage from whole crop  $GHG_{MS}$  are set to  $0.144 kg CO_2\text{-eq. } kW h_{el}^{-1}$  (Isermeyer et al., 2007). It is further assumed that 25% of the ensiled maize used is grown on former grassland. This land use change causes emissions of  $0.0695 kg CO_2\text{-eq. } kW h_{el}^{-1}$  (Isermeyer et al., 2007; Meyer-Aurich et al., 2012). Thus the use of maize silage results in total emissions of  $0.2135 kg CO_2\text{-eq. } kW h_{el}^{-1}$ . The values related to fresh matter are displayed in Table 6.

The GPBT or GPBM respectively is the period or the fresh matter of the respective feedstock needed to save the same amount of emissions deriving from constructing the TBH device.

**Table 5**  
Energetic assessment including energy payback time.

Raw material	Set-point temperature (°C)	$P_{constr}$	$P_{el,in}$	$P_{th,FS}$	$P_{th,process}$	$P_{MC}$		$P_{el,out}$		$P_{th,out}$	$\delta P_{MS}$	EPBT
						LCM	SCM	LCM	SCM			
						(kW h a <sup>-1</sup> )						(P[n]Y [n]M)
P1-LCM	140	18,730	42,000	612,500	490,000	308,498	–	119,389	–	144,685	19,341	P4Y10M
P1-LCM	160	18,730	42,000	710,500	588,000	322,857	–	124,945	–	151,420	20,241	P4Y6M
P1-LCM	180	18,730	42,000	808,500	686,000	94,436	–	36,547	–	44,290	5,921	–
P1-SCM	140	18,730	42,000	490,000	392,000	–	980,265	–	379,362	459,744	61,457	P1Y1M
P1-SCM	160	18,730	42,000	568,400	470,400	–	987,062	–	381,993	462,932	61,883	P1Y1M
P1-SCM	180	18,730	42,000	646,800	548,800	–	1,139,986	–	441,175	534,654	71,470	P11M
P1-SLCM	140	18,730	42,000	612,500	490,000	202,105	394,995	78,214	152,863	280,040	37,435	P2Y
P1-SLCM	160	18,730	42,000	710,500	588,000	193,797	386,303	74,999	149,499	272,067	36,369	P2Y1M
P1-SLCM	180	18,730	42,000	808,500	686,000	87,794	486,492	33,976	188,273	269,340	36,004	P2Y1M
P2-LCM	140	18,730	42,000	612,500	490,000	86,406	–	33,439	–	40,524	5,417	–
P2-LCM	160	18,730	42,000	710,500	588,000	93,778	–	36,292	–	43,982	5,879	–
P2-LCM	180	18,730	42,000	808,500	686,000	52,138	–	20,177	–	24,453	3,269	–
P2-SCM	140	18,730	42,000	490,000	392,000	–	1,316,902	–	509,641	617,627	82,562	P10M
P2-SCM	160	18,730	42,000	568,400	470,400	–	1,452,106	–	561,965	681,038	91,038	P9M
P2-SCM	180	18,730	42,000	646,800	548,800	–	1,004,477	–	388,733	471,100	62,975	P1Y1M
		$e_{constr}$	$e_{el,in}$	$e_{th,FS}$	$e_{th,process}$	$e_{MC}$		$e_{el,out}$		$e_{th,out}$	$\delta e_{MS}$	EPBM
						(kW h Mg <sup>-1</sup> FM)						(Mg FM)
P1-LCM	140	4.5	10.0	145.8	116.7	73.5	–	28.4	–	34.4	4.6	20,330
P1-LCM	160	4.5	10.0	169.2	140.0	76.9	–	29.7	–	36.1	4.8	18,968
P1-LCM	180	4.5	10.0	192.5	163.3	22.5	–	8.7	–	10.5	1.4	–
P1-SCM	140	5.6	12.5	145.8	116.7	–	291.7	–	112.9	136.8	18.3	3731
P1-SCM	160	5.6	12.5	169.2	140.0	–	293.8	–	113.7	137.8	18.4	3702
P1-SCM	180	5.6	12.5	192.5	163.3	–	339.3	–	131.3	159.1	21.3	3153
P1-SLCM	140	4.5	10.0	145.8	116.7	48.1	94.0	18.6	36.4	66.7	8.9	8321
P1-SLCM	160	4.5	10.0	169.2	140.0	46.1	92.0	17.9	35.6	64.8	8.7	8621
P1-SLCM	180	4.5	10.0	192.5	163.3	20.9	115.8	8.1	44.8	64.1	8.6	8729
P2-LCM	140	4.5	10.0	145.8	116.7	20.6	–	8.0	–	9.6	1.3	–
P2-LCM	160	4.5	10.0	169.2	140.0	22.3	–	8.6	–	10.5	1.4	–
P2-LCM	180	4.5	10.0	192.5	163.3	12.4	–	4.8	–	5.8	0.8	–
P2-SCM	140	5.6	12.5	145.8	116.7	–	391.9	–	151.7	183.8	24.6	2691
P2-SCM	160	5.6	12.5	169.2	140.0	–	432.2	–	167.3	202.7	27.1	2421
P2-SCM	180	5.6	12.5	192.5	163.3	–	299.0	–	115.7	140.2	18.7	3630

$e_{constr}$  – Energy for construction of thermobarical hydrolysis device;  $e_{el,in}$  – Electricity consumption of thermobarical hydrolysis device;  $e_{el,out}$  – Electric energy attainable from the respective feedstock;  $e_{MC}$  – Methanation capacity; EPBT – Energy payback time; EPBM – Energy payback mass;  $e_{th,FS}$  – Thermal power necessary for heating feedstock;  $e_{th,out}$  – Thermal energy attainable from the respective feedstock;  $e_{th,process}$  – Thermal energy flow from feedstock to biogas plant; LCM – Liquid cattle manure; P1 – Plant 1; P2 – Plant 2;  $P_{constr}$  – Energy for construction of thermobarical hydrolysis device;  $P_{el,in}$  – Electricity consumption of thermobarical hydrolysis device;  $P_{el,out}$  – Electric energy attainable from the respective feedstock;  $P_{MC}$  – Methanation capacity;  $P_{th,FS}$  – Thermal power necessary for heating feedstock;  $P_{th,out}$  – Thermal energy attainable from the respective feedstock;  $P_{th,process}$  – Thermal energy flow from feedstock to biogas plant; SCM – Solid cattle manure; SLCM – Solid and liquid cattle manure.

## 2.7. Profitability

The assessment of the economic performance of TBH is based on profitability, amortization period and CO<sub>2</sub> mitigation costs (CMC).

Costs arise from purchasing ( $C_{constr}$  or  $C_{constr}^{\ddagger}$ ) and operating ( $C_{el,in}$  or  $C_{el,in}^{\ddagger}$  and  $C_{MT}$  or  $C_{MT}^{\ddagger}$ ) the TBH device. Changes in wheel loader employment  $\delta C_{WL}$  or  $\delta C_{WL}^{\ddagger}$  can save as well as cause costs, whereas changes in spreading-procedure  $\delta C_{spreading}$  or  $\delta C_{spreading}^{\ddagger}$  save costs in any case. Revenues in this analysis result from a bonus within the German feed-in tariff structure for electricity sales  $\delta C_{el,out}$  or  $\delta C_{el,out}^{\ddagger}$ . The agricultural wastes used instead of maize silage are assumed to be available free of charge. All energy related cost factors related to TBH are balanced to a base of 10.06 ct kW h<sub>el</sub><sup>-1</sup>, derived from the costs of electricity production using maize silage  $\delta C_{MS}$  considering an average price of 35 € per ton of fresh maize silage (Bönewitz, 2007). Related to fresh matter the costs in € Mg<sup>-1</sup> FM of electricity production using maize silage are calculated according to

$$\delta C_{MS}^{\ddagger} = \delta C_{MS} \cdot e_{el,out} \quad (20)$$

Hence, profit in ct kW h<sub>el</sub><sup>-1</sup> or in € Mg<sup>-1</sup> FM is obtained as

$$\text{Profit} = C_{constr} + C_{el,in} + C_{MT} + \delta C_{WL} + \delta C_{spreading} + \delta C_{el,out} + \delta C_{MS} \quad (21)$$

$$\text{Profit}^{\ddagger} = C_{constr}^{\ddagger} + C_{el,in}^{\ddagger} + C_{MT}^{\ddagger} + \delta C_{WL}^{\ddagger} + \delta C_{spreading}^{\ddagger} + \delta C_{el,out}^{\ddagger} + \delta C_{MS}^{\ddagger} \quad (22)$$

Investment for TBH is estimated to 250,000 € (unpublished engineering report). Fixed costs of 17,500 € a<sup>-1</sup> comprise depreciation (life time 20 years, operation time 8400 h a<sup>-1</sup>) and interest (at a rate of 4%). Variable costs include electric energy consumption  $C_{el,in}$  or  $C_{el,in}^{\ddagger}$  (4620 € a<sup>-1</sup>, own calculation), repair and maintenance  $C_{MT}$  or  $C_{MT}^{\ddagger}$  (4200 € a<sup>-1</sup>; KTBL, 2010b) and labor costs from wheel loader employment.

Changes in costs due to alteration in feedstock comprise costs of wheel loader and spreading. Investment of the wheel loader is 73,000 €. Fixed costs include depreciation (lifetime 10.3 years), interest (at a rate of 4%), taxes and insurance (50 € a<sup>-1</sup>). Variable costs comprise diesel fuel (0.7 € l<sup>-1</sup>; 6.5 l h<sup>-1</sup>), lubricants (2 € l<sup>-1</sup>; 0.065 l h<sup>-1</sup>), repair and maintenance (1.41 € h<sup>-1</sup>). The costs of common labor are 13 € h<sup>-1</sup> (Hanff et al., 2010; KTBL, 2010b). These cost items are summed up to 36.73 cent per minute of wheel loader employment. Specific costs in cent per kW h<sub>el</sub> or in € per Mg FM are calculated depending on the volume of the respective feedstock to be transported for substitution of maize silage and the electric energy attainable or the FM mass flow of the respective feedstock.

**Table 6**  
Greenhouse gas emissions and greenhouse gas payback time.

Raw material	Set-point temperature (°C)	GHG <sub>constr</sub>	GHG <sub>el,in</sub>	δGHG <sub>SCM</sub>	δGHG <sub>MS</sub>	GHG <sub>net</sub>	GHG <sub>net</sub>	GPBT
		(kg CO <sub>2</sub> -eq. kW h <sub>el</sub> <sup>-1</sup> )					(kg CO <sub>2</sub> -eq. a <sup>-1</sup> )	
P1-LCM	140	0.0358	0.215	–	–0.2135	0.037	4446	–
P1-LCM	160	0.0342	0.205	–	–0.2135	0.026	3260	–
P1-LCM	180	0.1169	0.702	–	–0.2135	0.606	22,133	–
P1-SCM	140	0.0113	0.068	–0.512	–0.2135	–0.646	–245,112	P4M
P1-SCM	160	0.0112	0.067	–0.512	–0.2135	–0.647	–247,019	P4M
P1-SCM	180	0.0097	0.058	–0.512	–0.2135	–0.657	–289,928	P4M
P1-SLCM	140	0.0185	0.111	–0.271	–0.2135	–0.355	–81,954	P1Y1M
P1-SLCM	160	0.0190	0.114	–0.273	–0.2135	–0.353	–79,173	P1Y1M
P1-SLCM	180	0.0192	0.115	–0.347	–0.2135	–0.425	–94,560	P11M
P2-LCM	140	0.1278	0.767	–	–0.2135	0.682	22,796	–
P2-LCM	160	0.1178	0.707	–	–0.2135	0.611	22,187	–
P2-LCM	180	0.2118	1.272	–	–0.2135	1.270	25,628	–
P2-SCM	140	0.0084	0.050	–0.512	–0.2135	–0.666	–339,568	P3M
P2-SCM	160	0.0076	0.046	–0.512	–0.2135	–0.672	–377,504	P3M
P2-SCM	180	0.0110	0.066	–0.512	–0.2135	–0.648	–251,906	P4M

		GHG <sub>constr</sub> <sup>‡</sup>	GHG <sub>el,in</sub> <sup>‡</sup>	δGHG <sub>SCM</sub> <sup>‡</sup>	δGHG <sub>MS</sub> <sup>‡</sup>	GHG <sub>net</sub> <sup>‡</sup>	GPBM
		(kg CO <sub>2</sub> -eq. Mg <sup>-1</sup> FM)					
P1-LCM	140	1.0	6.1	–	–6.1	1.1	–
P1-LCM	160	1.0	6.1	–	–6.4	0.8	–
P1-LCM	180	1.0	6.1	–	–1.9	5.3	–
P1-SCM	140	1.3	7.6	–57.8	–24.1	–73.0	1172
P1-SCM	160	1.3	7.6	–58.2	–24.3	–73.5	1163
P1-SCM	180	1.3	7.6	–67.2	–28.0	–86.3	991
P1-SLCM	140	1.0	6.1	–18.6	–11.7	–23.2	3678
P1-SLCM	160	1.0	6.1	–18.2	–11.4	–22.5	3800
P1-SLCM	180	1.0	6.1	–22.9	–11.3	–27.1	3154
P2-LCM	140	1.0	6.1	–	–1.7	5.4	–
P2-LCM	160	1.0	6.1	–	–1.8	5.3	–
P2-LCM	180	1.0	6.1	–	–1.0	6.1	–
P2-SCM	140	1.3	7.6	–77.6	–32.4	–101.1	846
P2-SCM	160	1.3	7.6	–85.6	–35.7	–112.4	761
P2-SCM	180	1.3	7.6	–59.2	–24.7	–75.0	1140

GHG<sub>constr</sub> and GHG<sub>constr</sub><sup>‡</sup> – Emissions from construction of thermobarical hydrolysis device; GHG<sub>el,in</sub> and GHG<sub>el,in</sub><sup>‡</sup> – Emissions from electricity consumption of thermobarical hydrolysis; δGHG<sub>SCM</sub> and δGHG<sub>SCM</sub><sup>‡</sup> – Emissions from storing LCM; δGHG<sub>MS</sub> and δGHG<sub>MS</sub><sup>‡</sup> – Emissions from substitution of maize silage; GHG<sub>net</sub> and GHG<sub>net</sub><sup>‡</sup> – Sum of all emissions; GPBT – Greenhouse gas payback time; GPBM – Greenhouse gas payback mass; LCM – Liquid cattle manure; P1 – Plant 1; P2 – Plant 2; SCM – Solid cattle manure; SLCM – Solid and liquid cattle manure.

The agricultural wastes would have led to costs for transport and spreading if not used for biomethanation. Costs that arise from transport and spreading of LCM or digestate sum up to C<sub>spr,V</sub> = 6.21 € per m<sup>3</sup>. Costs C<sub>spr,m</sub> of 8.46 € Mg<sup>-1</sup> SCM result from transport and spreading of SCM (Hanff et al., 2010; Schindler, 2009; own calculation). Those costs are decreased by the saved spreading of digestate from feedstock to be substituted, in our case maize silage. The bulk densities of feedstock before biomethanation are ρ<sub>SCM</sub> = 800 kg m<sup>-3</sup> in the case of SCM and ρ<sub>MS</sub> = 300 kg m<sup>-3</sup> in the case of maize silage. After biomethanation the density of digestate ρ<sub>dig</sub> is 1000 kg m<sup>-3</sup> in any case. The costs in ct kW h<sub>el</sub><sup>-1</sup> arising from spreading digestate are

$$\delta C_{spr,dig,FS} = \frac{\dot{V}_{FM,FS} \cdot \frac{\rho_{FS}}{\rho_{dig}} \cdot C_{spr,V} \cdot ADO}{P_{el,out}} \cdot 100 \quad (23)$$

Related to fresh matter the costs in € Mg<sup>-1</sup> FM arising from spreading digestate are calculated according to

$$\delta C_{spr,dig,FS}^{\ddagger} = \frac{\dot{V}_{FM,FS} \cdot \frac{\rho_{FS}}{\rho_{dig}} \cdot C_{spr,V}}{\dot{m}_{FS}} \cdot 8640^{-1} \quad (24)$$

As mentioned above, any processing of LCM is assigned to the biogas plant. As a result of increased methane yields through TBH, a concordant share of digestate from maize silage is replaced.

The saved spreading of SCM reduces costs, but the higher amount of digestate arising from SCM compared to digestate from maize

silage causes additional costs for spreading. The costs in ct kW h<sub>el</sub><sup>-1</sup> from spreading untreated SCM are calculated according to

$$\delta C_{spr,SCM,w/o} = \frac{\dot{V}_{FM,SCM} \cdot \rho_{SCM} \cdot C_{spr,m} \cdot ADO}{P_{el,out}} \cdot 1000^{-1} \quad (25)$$

Related to fresh matter the costs in € Mg<sup>-1</sup> FM from spreading untreated SCM

$$C_{spr,SCM,w/o}^{\ddagger} = C_{spr,m} \quad (26)$$

Costs in ct kW h<sub>el</sub><sup>-1</sup> or in € Mg<sup>-1</sup> FM of spreading SLCM are compartmentalized according to its volumetric fractions.

The overall costs in ct kW h<sub>el</sub><sup>-1</sup> for any feedstock sum up to

$$\delta C_{spreading} = -\delta C_{spr,SCM,w/o} + \delta C_{spr,dig,SCM} - \delta C_{spr,dig,MS} \quad (27)$$

Related to fresh matter the overall costs in € Mg<sup>-1</sup> FM for spreading are calculated according to

$$\delta C_{spreading}^{\ddagger} = -\delta C_{spr,SCM,w/o}^{\ddagger} + \delta C_{spr,dig,SCM}^{\ddagger} - \delta C_{spr,dig,MS}^{\ddagger} \quad (28)$$

Main income from biogas production is determined by feeding electricity into the grid with a given feed-in tariff. Despite a new Renewable Energy Sources Act that came into force in 2014, the following calculations are in accordance with the Renewable Energy Sources Act of 2012 (German Government, 2012a) as the TBH device – designed as modular concept – is aimed for retrofitting already existing biogas plants. The basic feed-in tariff for electricity generated from biomass amounts to 12.3 ct kW h<sub>el</sub><sup>-1</sup>. If only

renewable resources such as energy crops are used, an additional 6.0 ct kW h<sub>el</sub><sup>-1</sup> can be obtained. Another 2.0 ct kW h<sub>el</sub><sup>-1</sup> can be attained if animal waste or other agricultural residues are used. These 2 cents are calculated with fixed methane yields for SCM of 53 l<sub>N</sub> kg<sup>-1</sup> FM and for LCM of 17 l<sub>N</sub> kg<sup>-1</sup> FM (German Government, 2012b). These additional 2 ct kW h<sub>el</sub><sup>-1</sup> are perpetuated in the new Renewable Energy Sources Act of 2014 (German Government, 2014) and calculated with the same fixed methane yields named above. As the basic fee is allotted to the biogas plant, only the additional fee for using agricultural wastes can be charged to the TBH, thus it is calculated by the shared contribution of feedstock constituents to generated electricity. The fee attainable is set at a fixed 2 cent per kW h<sub>el</sub>. Related to fresh matter mass the fee attainable in € Mg<sup>-1</sup> FM is calculated according to

$$\delta C_{el,out}^{\dagger} = 0.02 \text{€} \cdot \text{kW h}_{el}^{-1} \cdot e_{el,out} \quad (29)$$

The economic amortization period (ECAP) or amortization mass (ECAM) is the time in years and months (P[n]Y[n]M) or FM mass in Mg pretreated until investment for the entire TBH facility and all running expenditures – except for depreciation and interest rate – is paid back. In order to assess ECAP or ECAM, total investment is divided by profit. Depreciation and interest rate (in sum 17,500 € a<sup>-1</sup>) are added to profit as C<sub>TBH</sub>, as part of profit already contains investment for such a TBH device in the form of depreciation and interest rate

$$ECAP = \frac{\text{Investment}}{\text{Profit} + \text{Depreciation} + \text{Interest}} \quad (30)$$

$$ECAM = ECAP \cdot \dot{m}_{FS} \cdot ADO \cdot 86.4 \quad (31)$$

The CO<sub>2</sub> mitigation costs in € per Mg of CO<sub>2</sub>-eq. (in addition to that of the downstream biogas plant) are deduced from the electricity production costs C<sub>EP,TBH</sub> (Profit without δC<sub>MS</sub>) compared to the grid electricity-mix production costs C<sub>EP,grid</sub> (Table 1; Öko-Institut, 1998; Stenull and Raab, 2010).

$$CMC = \frac{C_{EP,TBH} - C_{EP,grid}}{GHG_{grid} - GHG_{net}} \cdot 1000 \quad (32)$$

## 2.8. Sensitivity analysis

Sensitivity analyses are performed by alternating the following input parameters by ±50%:

- stirring power exemplary both for changes in demand of electric energy of TBH and as parameter influenced by feedstock viscosity,
- investment for displaying changes in fixed costs,
- organic matter content of feedstock as example for changes in feedstock composition and for presenting the impact of changes of organic loading rate on the model output.

The output parameters chosen are:

- GHG as a parameter sensitive to changes in feedstock parameters and energy demand of the device but not influenced by changes of economical parameters,
- CMC as it is displaying the environmental impact and the costs occurring if using TBH in combination with an agricultural biogas plant as mitigation strategy,
- ECAP as it is sensitive to all input parameters that lead to changes in economic viability but disregards the environmental impact.

## 3. Results and discussion

### 3.1. Energy balance of thermobarical pretreatment

The energy input for TBH construction is 18,730 kW h<sub>el</sub> a<sup>-1</sup> (Table 5; Budde, 2015) and accounts for between 2.15% and 3.40% of the overall energy demand (thermal as well as electric). The operation of the TBH demands much more energy, electric as well as thermal. The annual electric energy demand amounts to 42,000 kW h<sub>el</sub> a<sup>-1</sup> and is needed for stirring and the thermal-oil pump, independently of the kind of feedstock. Related to fresh mass values are either 10 or 12.5 kW h<sub>el</sub> Mg<sup>-1</sup> FM depending on feedstock bulk density of 1000 or 800 kg m<sup>-3</sup> respectively. The electric energy demand presented here is comparable to values reported by Mönch-Tegeeder et al. (2014) who needed 11.3 kW h<sub>el</sub> Mg<sup>-1</sup> FM for mechanically pretreating horse manure in full-scale application and by Elbeshbishy et al. (2011) who calculated 13 kW h<sub>el</sub> Mg<sup>-1</sup> FM for ultrasonic pretreatment. It accounts for between 4.83% and 7.63% of the total energy demand of the TBH device. Thermal energy input required for achieving the treatment temperature also depends on the kind of feedstock, expressed in different densities. It ranges from 490,000 to 808,500 kW h<sub>th</sub> a<sup>-1</sup> or 145.8 to 192.5 kW h<sub>th</sub> Mg<sup>-1</sup> FM, accounting for roughly 90% of the overall energy demand. Between 392,000 and 686,000 kW h<sub>th</sub> a<sup>-1</sup> or 116.7 to 163.3 kW h<sub>th</sub> Mg<sup>-1</sup> FM of this energy are available as process energy to maintain mesophilic conditions in the digester. The difference in energy values of TBH heat input and output to digester is caused by the different temperatures of feedstock before TBH treatment and substrate in the digester (15–40 °C). Consequently, the thermal energy actually required for hydrolysis is negligible.

The energy output of the TBH treatment of the different feedstocks is expressed as methanation capacity and is therefore independent of the overall conversion route of the methane. It can be divided into electric and thermal output, as well as losses if particular CHP is considered as conversion. The methanation capacity depends on feedstock and methane attainable as a consequence of differences in pretreatment. In general it can be stated that SCM from plant 2 pretreated at 160 °C displays best and LCM from plant 2 pretreated at 180 °C always shows lowest output. Values for methanation capacity range from 52,138 to 1,452,106 kW h a<sup>-1</sup>. Considering a model CHP (Table 1), an electric energy output of 20,177–561,965 kW h<sub>el</sub> a<sup>-1</sup> can be achieved. Thus, TBH-treated feedstock would contribute 0.7 to 20.3% of the electric output of the CHP. The thermal output of the CHP from pretreated feedstock ranges from 24,453 to 681,038 kW h<sub>th</sub> a<sup>-1</sup>. A (surplus) energy output from 4.8 to 167.3 kW h<sub>el</sub> Mg<sup>-1</sup> FM and 5.8–202.7 kW h<sub>th</sub> Mg<sup>-1</sup> FM can be gained via the conversion route methane – CHP. Thus, the electricity input for thermobarical treatment accounts for 7% of the electricity output in best case and 208% in worst case.

An increase in uncoupled thermal energy from CHP is possible by cooling down the exhaust gas to 180 °C, as during the first period of heat-up the heat input into feedstock is limited by the available thermal power. Above a feedstock temperature of approximately 110 °C, the heat input into feedstock is limited by the heat transfer that is lower than the thermal power available. It should be possible to considerably enhance the thermal power used by operating two devices time off-set in parallel during this second period. Thus, the share of alternative feedstock can be significantly enhanced.

The electric energy possibly gained depends on feedstock and changes in digestibility as well as on the organic matter (OM (in % FM)) of feedstock. Feedstock with high OM and hence higher FM-related methane yield is preferred as the fixed vessel volume

limits the fresh matter volume to be pretreated per batch. In the case of P1-LCM pretreated at 180 °C and all variants of P2-LCM, the electricity consumption is higher than the electricity produced. But compared with alternative pretreatment methods the electric energy consumption is very low: e.g. an extruder sized for the same mass flow will need approximately 20 kW<sub>el</sub> and will cause much higher costs for maintenance and spare parts (Weiß and Brückner, 2008).

From an energetic point of view, it is possible to obtain more thermal energy from pretreated feedstock than is necessary for pretreatment, e.g. P2-SCM pretreated at 140 and 160 °C deliver 617,627 and 681,038 kW h<sub>th</sub> a<sup>-1</sup>, but need only 490,000 and 568,400 kW h<sub>th</sub> a<sup>-1</sup> respectively. From the exergetic point of view, the balance may be inverted. Only 96.3 kW (24.1% of nominal thermal power) are transferred to feedstock through TBH from 158 kW thermal power (that is 39.5% of the nominal thermal power of the CHP) uncoupled from CHP exhaust gas.

Substituting maize silage as biogas feedstock can save between 3269 and 91,038 kW h a<sup>-1</sup>, thus enhancing the “fuel” output ( $P_{MC}$ ) by 6.3% in any case.

The lowest energy payback time is 9 months for P2-SCM pretreated at 160 °C. For LCM it is possible to reach an EPBT of 4 years 6 months (P1-LCM, 160 °C) although only the extra amount of methane is included in the calculation. Compared with other renewable energy converting facilities, the EPBT of TBH can be very short. Wind turbines for example need 3–6 months, photovoltaic cells 2–5 years to feed in the electricity needed for construction (Lübbert, 2007). Related to fresh mass (EPBM) 2,421 (P2-SCM, 160 °C) to 20,330 Mg FM (P1-LCM, 140 °C) are to be pretreated in order to achieve the same amount of energy that was spent for construction of the TBH device. The annual volumetric throughput of 4200 m<sup>3</sup> FM equals 3360 or 4200 Mg FM, depending on bulk density. The energy payback time or mass in total is at least that of the biogas plant as the TBH device is only a pretreating unit attached to a biogas plant (including the CHP) that is the actual renewable energy converting facility.

### 3.2. Greenhouse gas emissions balance of thermobarical pretreatment

Thermobarical hydrolysis can save a considerable amount of greenhouse gases of up to 0.672 kg CO<sub>2</sub>-eq. kW h<sub>el</sub><sup>-1</sup> or 377,504 kg CO<sub>2</sub>-eq. per year (best case P2-SCM, 160 °C) (Table 6). LCM does not save GHG emissions but emits from 0.026 to a maximum of 1.270 kg CO<sub>2</sub>-eq. kW h<sub>el</sub><sup>-1</sup>.

The emissions from construction and operation of a TBH device related to electric energy output are affected by the fresh matter related methane yields of respective feedstock while the absolute emissions are independent of feedstock and treatment temperatures. The emissions from construction are 0.0076 (P2-SCM, 160 °C) to 0.2118 kg CO<sub>2</sub>-eq. kW h<sub>el</sub><sup>-1</sup> (P2-LCM, 180 °C), accounting for 14% of all emissions (without regarding emissions mitigated) in any case. The complementary 86% of emissions arise from grid electricity used for operation of the device and amount to 0.046 (P2-SCM, 160 °C) to 1.272 kg CO<sub>2</sub>-eq. kW h<sub>el</sub><sup>-1</sup> (P2-LCM, 180 °C).

The mitigation potential of using SCM is 0.512 kg CO<sub>2</sub>-eq. kW h<sub>el</sub><sup>-1</sup> in any case, as both the saved CO<sub>2</sub> emissions and the electricity generated are directly dependent on methane production. It accounts for 71% of the overall mitigations. The mitigation potential of SLCM derives from the share of SCM and is between 0.271 and 0.347 kg CO<sub>2</sub>-eq. kW h<sub>el</sub><sup>-1</sup>, accounting for between 56% and 62%. Although significant emissions of CH<sub>4</sub> and N<sub>2</sub>O during the rotting process are to be expected they were not regarded here. These emissions depend strongly on the kind of SCM and the actual storing conditions. It is unknown how farmers are handling the material although best practice suggests to regularly turning the material for keeping aerobic conditions and by this preventing emissions that

occur only under anaerobic storing conditions. A rough calculation revealed that approximately 200 kg CO<sub>2</sub>-eq. Mg<sup>-1</sup> FM (17 g C m<sup>-3</sup> FM d<sup>-1</sup> as methane and 0.411 g N m<sup>-3</sup> FM d<sup>-1</sup> as nitrous oxide) (Sneath et al., 2006) can be avoided within an assumed storing period of 180 days. These emissions are more than doubling the direct emissions of CO<sub>2</sub>. Thus, integrating the avoided emissions from other greenhouse gases than CO<sub>2</sub> in this model will lead to a further considerable reduction of net emissions.

LCM does not mitigate GHG emissions, as it is assumed that thermobarical pretreatment releases feedstock constituents that – without pretreatment – would not have contributed to methane emissions during storage of untreated LCM because of their lower degradability.

When maize silage is substituted, further GHG emissions of 0.2135 kg CO<sub>2</sub>-eq. kW h<sub>el</sub><sup>-1</sup> can be avoided. These include the entire supply chain as well as direct land use changes. This avoidance contributes to the overall mitigation by 100% in the case of LCM, 29% in the case of SCM, and 38–44% in the case of SLCM. The differences in relative mitigation are mainly attributable to the differences in SCM storage and their emission mitigation.

The net emissions of TBH treatment can be as low as 7% of the total mitigated emissions (P2-SCM, 160 °C), or exceed them by 695% (P2-LCM, 180 °C). SCM and SLCM save emissions in any case. The highest value of emissions is 11% of mitigated emissions for SCM and 27% for SLCM. LCM always emits more GHG than are mitigated. The relative values range from 112% to 695%.

The differences between the various scenarios become even more obvious if mitigation effect per year is considered. The values range from –377,504 (P2-SCM, 160 °C) to 25,628 kg CO<sub>2</sub>-eq. a<sup>-1</sup> (P2-LCM, 180 °C). For example, P1-SLCM and P2-SCM both treated at 160 °C differ in energy-related GHG emissions from –0.353 kg CO<sub>2</sub>-eq. kW h<sub>el</sub><sup>-1</sup> to –0.672 kg CO<sub>2</sub>-eq. kW h<sub>el</sub><sup>-1</sup>, while the annual emissions vary more than 4-fold with values of –79,173 kg CO<sub>2</sub>-eq. a<sup>-1</sup> and –377,504 kg CO<sub>2</sub>-eq. a<sup>-1</sup> respectively. The difference in energy related emissions is mainly caused by mitigation potential of the various feedstocks while the time-related value is further amplified by the much higher fresh matter related methane yield of SCM compared with SLCM or LCM.

Treatment temperature further controls the mitigation potential. Appropriate treatment can lead to 50% higher avoided GHG emissions per year, e.g. SCM from P2 pretreated at 160 °C with a daily input of 12 m<sup>3</sup> saves 377,504 CO<sub>2</sub>-eq. per year, whereas when pretreated at 180 °C, with even a higher methane yield than the untreated SCM, it saves only 251,906 kg CO<sub>2</sub>-eq. a<sup>-1</sup>. In most cases, 160 °C is the optimal pretreatment temperature.

The net GHG emissions described above directly influence the greenhouse gas payback time. The GPBT of a TBH device using SCM is very short, between 3 and 4 months. Pretreating SLCM leads to a GPBT of between 11 and 13 months. LCM does not have any GPBT because emissions always exceed mitigation. Related to fresh mass a substantial amount of between 22.5 and 112.4 kg CO<sub>2</sub>-eq. Mg<sup>-1</sup> FM can be omitted by implementing a TBH device in an already existing biogas plant. The GPBM ranges from 761 (P2-SCM, 160 °C) to 3800 Mg FM (P1-SLCM, 160 °C).

### 3.3. Profitability and mitigation costs of thermobarical pretreatment

The annual profits range from 3763 € a<sup>-1</sup> for P1-SLCM (180 °C) to 60,253 € a<sup>-1</sup> for P2-SCM (160 °C) whereas LCM generates losses of up to 23,199 € a<sup>-1</sup> (Table 7).

Depreciation and capital costs for the TBH device are responsible for two thirds of the overall costs and range from 3.11 (P2-SCM, 160 °C) to 86.73 ct kW h<sub>el</sub><sup>-1</sup> (P2-LCM, 180 °C). Each, costs of electricity consumption and costs of maintenance and spare parts, account for a sixth of the overall costs, ranging from 0.75 (C<sub>MT</sub>; P2-SCM, 160 °C) to 22.90 ct kW h<sub>el</sub><sup>-1</sup> (C<sub>el,in</sub>; P2-LCM, 180 °C).

**Table 7**  
Economic assessment including economic amortization period and CO<sub>2</sub> mitigation costs.

Raw material	Set-point temperature (°C)	C <sub>constr</sub>	C <sub>el,in</sub>	C <sub>MT</sub>	δC <sub>WL</sub>	δC <sub>spreading</sub>	δC <sub>el,out</sub>	δC <sub>MS</sub>	Profit	Profit	ECAP	CMC
		(ct kW h <sub>el</sub> <sup>-1</sup> )								(€ a <sup>-1</sup> )	(P[n]Y[n]M)	(€ Mg <sup>-1</sup> CO <sub>2</sub> -eq.)
P1-LCM	140	14.66	3.87	3.52	-0.99	-1.80	-2.00	-10.06	-7.19	-8584	P28Y	200
P1-LCM	160	14.01	3.70	3.36	-0.95	-1.77	-2.00	-10.06	-6.28	-7848	P25Y11M	180
P1-LCM	180	47.88	12.64	11.49	-0.81	-1.78	-2.00	-10.06	-57.36	-20,964	-	114,151
P1-SCM	140	4.61	1.22	1.11	0.08	-3.78	-2.00	-10.06	8.83	33,488	P4Y11M	-36
P1-SCM	160	4.58	1.21	1.10	0.08	-3.77	-2.00	-10.06	8.87	33,870	P4Y10M	-37
P1-SCM	180	3.97	1.05	0.95	-0.07	-3.50	-2.00	-10.06	9.67	42,644	P4Y2M	-43
P1-SLCM	140	7.57	2.00	1.82	0.26	-1.94	-2.00	-10.06	2.36	5450	P10Y11M	20
P1-SLCM	160	7.80	2.06	1.87	0.26	-2.00	-2.00	-10.06	2.07	4656	P11Y3M	23
P1-SLCM	180	7.87	2.08	1.89	0.40	-1.87	-2.00	-10.06	1.69	3763	P11Y9M	25
P2-LCM	140	52.33	13.82	12.56	-0.88	-1.75	-2.00	-10.06	-64.01	-21,404	-	-
P2-LCM	160	48.22	12.73	11.57	-0.81	-1.80	-2.00	-10.06	-57.85	-20,994	-	-
P2-LCM	180	86.73	22.90	20.82	-1.47	-1.94	-2.00	-10.06	-114.98	-23,199	-	-
P2-SCM	140	3.43	0.91	0.82	-0.12	-3.27	-2.00	-10.06	10.29	52,438	P3Y7M	-47
P2-SCM	160	3.11	0.82	0.75	-0.21	-3.13	-2.00	-10.06	10.72	60,253	P3Y3M	-50
P2-SCM	180	4.50	1.19	1.08	0.08	-3.72	-2.00	-10.06	8.94	34,748	P4Y9M	-37
		C <sub>constr</sub> <sup>‡</sup>	C <sub>el,in</sub> <sup>‡</sup>	C <sub>MT</sub> <sup>‡</sup>	δC <sub>WL</sub> <sup>‡</sup>	δC <sub>spreading</sub> <sup>‡</sup>	δC <sub>el,out</sub> <sup>‡</sup>	δC <sub>MS</sub> <sup>‡</sup>	Profit <sup>‡</sup>		ECAM	
		(€ Mg <sup>-1</sup> FM)									(Mg FM)	
P1-LCM	140	4.17	1.10	1.00	-0.28	-0.51	-0.57	-2.86	-2.04		117,764	
P1-LCM	160	4.17	1.10	1.00	-0.28	-0.53	-0.59	-2.99	-1.87		108,790	
P1-LCM	180	4.17	1.10	1.00	-0.07	-0.16	-0.17	-0.88	-4.99		-	
P1-SCM	140	5.21	1.38	1.25	0.09	-4.27	-2.26	-11.36	9.97		16,475	
P1-SCM	160	5.21	1.38	1.25	0.09	-4.29	-2.27	-11.44	10.08		16,352	
P1-SCM	180	5.21	1.38	1.25	-0.09	-4.60	-2.63	-13.21	12.69		13,966	
P1-SLCM	140	4.17	1.10	1.00	0.14	-1.07	-1.10	-5.54	1.30		45,751	
P1-SLCM	160	4.17	1.10	1.00	0.14	-1.07	-1.07	-5.38	1.11		47,390	
P1-SLCM	180	4.17	1.10	1.00	0.21	-0.99	-1.06	-5.32	0.90		49,381	
P2-LCM	140	4.17	1.10	1.00	-0.07	-0.14	-0.16	-0.80	-5.10		-	
P2-LCM	160	4.17	1.10	1.00	-0.07	-0.16	-0.17	-0.87	-5.00		-	
P2-LCM	180	4.17	1.10	1.00	-0.07	-0.09	-0.10	-0.48	-5.52		-	
P2-SCM	140	5.21	1.38	1.25	-0.18	-4.97	-3.03	-15.26	15.61		12,011	
P2-SCM	160	5.21	1.38	1.25	-0.35	-5.24	-3.35	-16.83	17.93		10,803	
P2-SCM	180	5.21	1.38	1.25	0.09	-4.31	-2.31	-11.64	10.34		16,077	

C<sub>constr</sub> and C<sub>constr</sub><sup>‡</sup> – Costs of construction of thermobarical hydrolysis device; C<sub>el,in</sub> and C<sub>el,in</sub><sup>‡</sup> – Costs of electricity consumption of thermobarical hydrolysis device; δC<sub>el,out</sub> and δC<sub>el,out</sub><sup>‡</sup> – Costs of selling electricity; CMC – CO<sub>2</sub> mitigation costs; δC<sub>MS</sub> and δC<sub>MS</sub><sup>‡</sup> – Costs of maize silage; C<sub>MT</sub> and C<sub>MT</sub><sup>‡</sup> – Costs of maintenance of thermobarical hydrolysis device; δC<sub>spreading</sub> and δC<sub>spreading</sub><sup>‡</sup> – Costs of spreading manure or digestate; δC<sub>WL</sub> and δC<sub>WL</sub><sup>‡</sup> – Costs of feedstock transport by wheel loader; ECAP – Economic amortization period; ECAM – Economic amortization mass; LCM – Liquid cattle manure; P1 – Plant 1; P2 – Plant 2; SCM – Solid cattle manure; SLCM – Solid and liquid cattle manure.

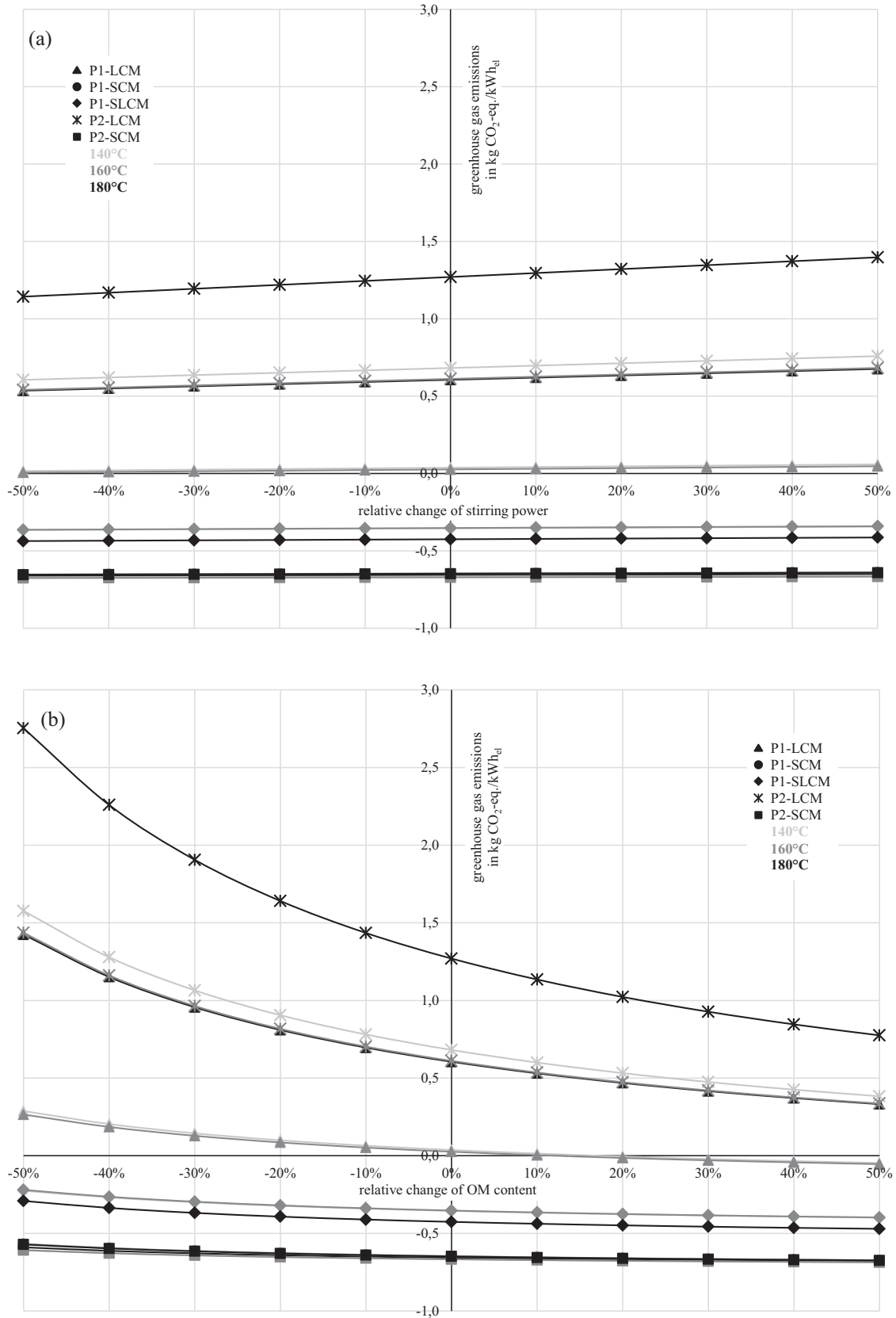
Additional wheel loader employment compared with the reference scenario costs up to 0.40 ct kW h<sub>el</sub><sup>-1</sup> (P1-SLCM, 180 °C). These costs have a 1–3% share in the overall costs. Up to 1.47 ct kW h<sub>el</sub><sup>-1</sup> (P2-LCM, 180 °C) can be saved if wheel loader employment can be decreased, thus contributing 9% to the revenues.

The electricity production costs can be reduced by a maximum of 3.78 ct kW h<sub>el</sub><sup>-1</sup> (P1-SCM, 140 °C) by changing the spreading procedure from solid manure to liquid digestate. The reduction in costs following substitution by LCM is up to 1.94 ct kW h<sub>el</sub><sup>-1</sup>. Saved spreading costs amount to 12–13% of the total revenue for LCM, 20–24% for SCM, and 13–14% for SLCM.

Although methane yields of the feedstock examined differ from the statutory values, the fee attainable is fixed at 2 cent per kW h<sub>el</sub> in each case. In general, it can be stated that a methane yield higher than the statutory level is assumed to lower the share of energy crops in total feedstock to achieve the same electric power and therefore increases the fee attainable and consequently the income. This applies for LCM from plant 1 pretreated at 140 and 160 °C only. The income assigned to this bonus contributes 13–14% to the total revenues.

If related to fresh mass, the revenues are between 0.65 (P2-LCM, 180 °C) and 22.42 € Mg<sup>-1</sup> FM (P2-SCM, 160 °C) disregarding additional income from feed-in fees according to the Renewable Energy Sources Act (German Government, 2012a) which range from 0.10 (P2-LCM, 180 °C) to 3.35 € Mg<sup>-1</sup> FM (P2-SCM, 160 °C).

The overall electricity production costs, disregarding saved expenditures for maize silage and additional income due to Renewable Energy Sources Act, range from 1.34 ct kW h<sub>el</sub><sup>-1</sup> (P2-SCM, 160 °C) to 127.04 ct kW h<sub>el</sub><sup>-1</sup> (P2-LCM, 180 °C). These values allow the feedstock regarded to be assessed under differing legal or economic circumstances. They demonstrate that TBH pretreatment is feasible as long as feedstock substituted costs more than 1.34 ct kW h<sub>el</sub><sup>-1</sup>. Considering all possible revenues, the total electricity production costs would be negative and amount to -0.66 ct kW h<sub>el</sub><sup>-1</sup> in the best case (P2-SCM, 160 °C). Related to the targeted electricity production costs of 10.06 ct kW h<sub>el</sub><sup>-1</sup> – that are the costs of maize silage – these overall costs are within a very wide range: between -107% for P2-SCM (160 °C) and 1243% for P2-LCM (180 °C). The LCM variants have a negative profit and are not economically viable. The profits of the other variants range from 1.69 for P1-SLCM (180 °C) to 10.72 ct kW h<sub>el</sub><sup>-1</sup> for P2-SCM (160 °C). Moreover, the energy-related values are here amplified by the methanation capability of the respective feedstock. The annual profits are then between 3763 for P1-SLCM (180 °C) and 60,253 € a<sup>-1</sup> for P2-SCM (160 °C). If related to fresh mass, the total costs amount for 2.24 (P2-SCM 160 °C) to 6.10 € Mg<sup>-1</sup> FM (P2-LCM 180 °C). Cano et al. (2014) presented costs for construction of a steam explosion facility for pretreating, e.g. cow manure from slaughterhouse of 3.33 € Mg<sup>-1</sup> FM, considering a mass flow of 30,000 Mg FM a<sup>-1</sup>. These costs are higher than the construction of



**Fig. 3.** Sensitivity analysis of the influence of changes in (a) stirring power on GHG emissions, (b) OM content on GHG emissions in terms of kg CO<sub>2</sub>-eq. kW h<sup>-1</sup>, (c) OM content on GHG emissions in terms of kg CO<sub>2</sub>-eq. a<sup>-1</sup>, (d) OM content on CO<sub>2</sub> mitigation costs, (e) stirring power on the economic amortization period, (f) OM content on the economic amortization period, and (g) investment on the economic amortization period.



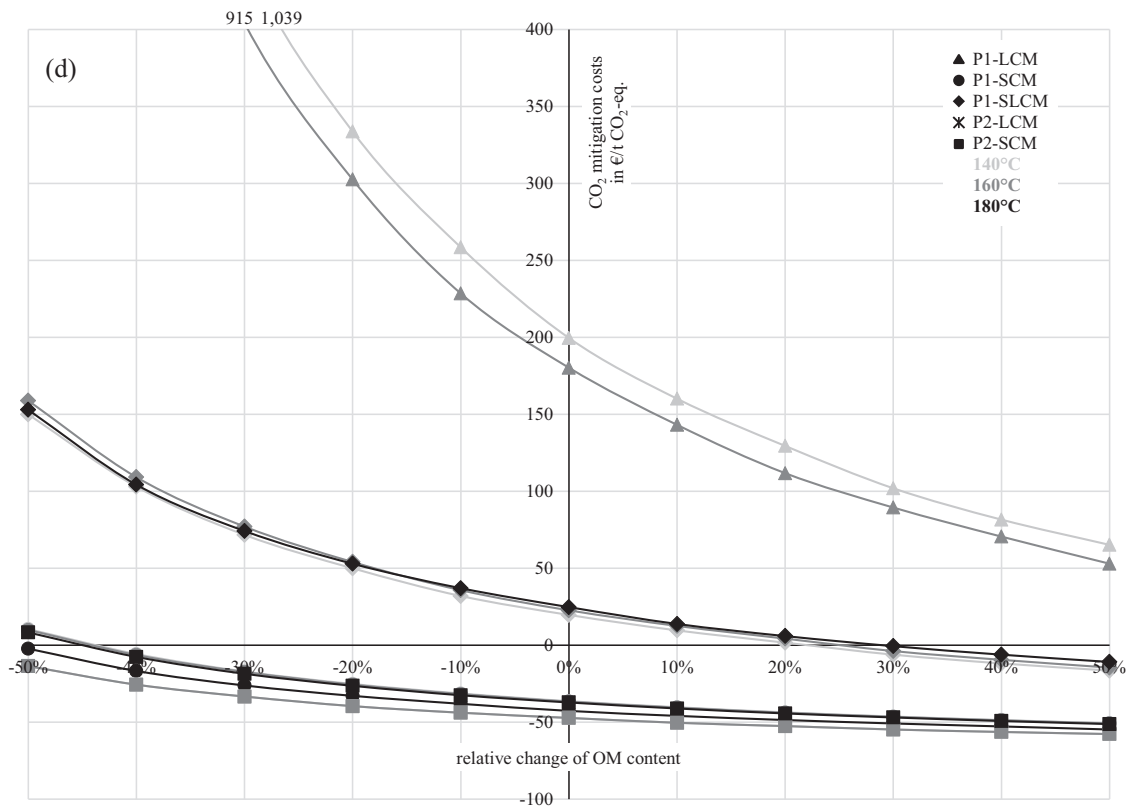
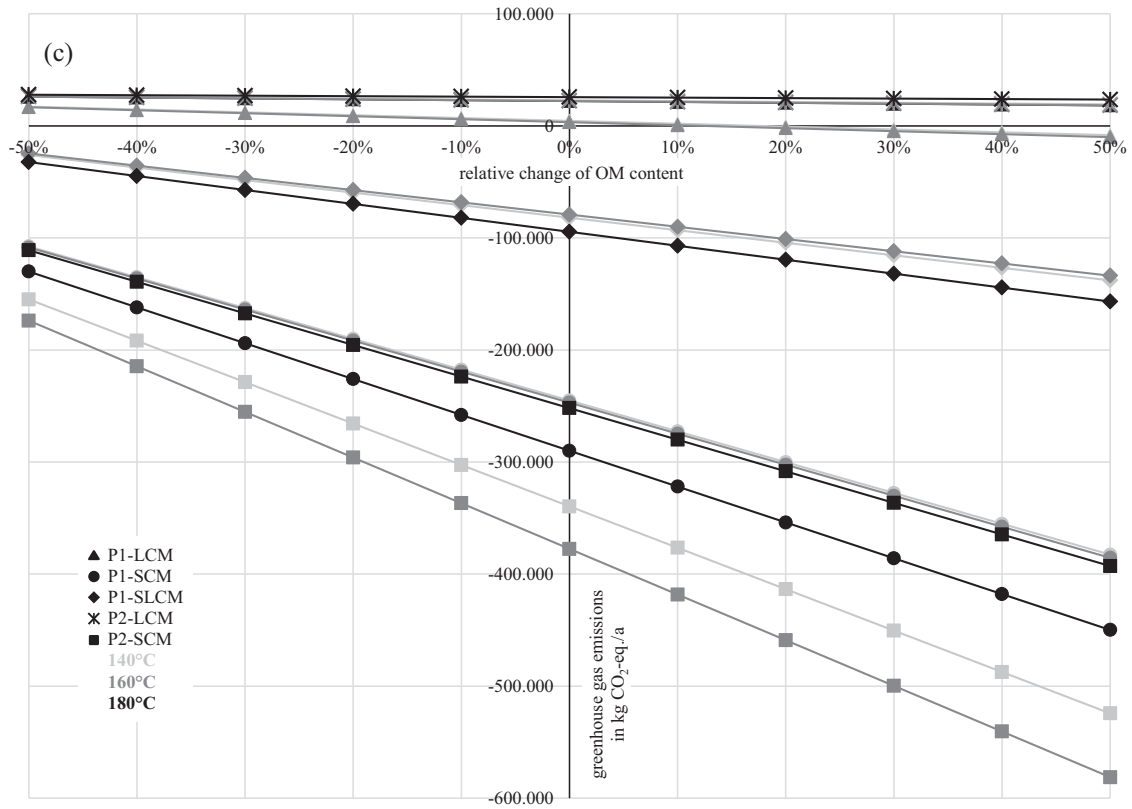


Fig. 3 (continued)

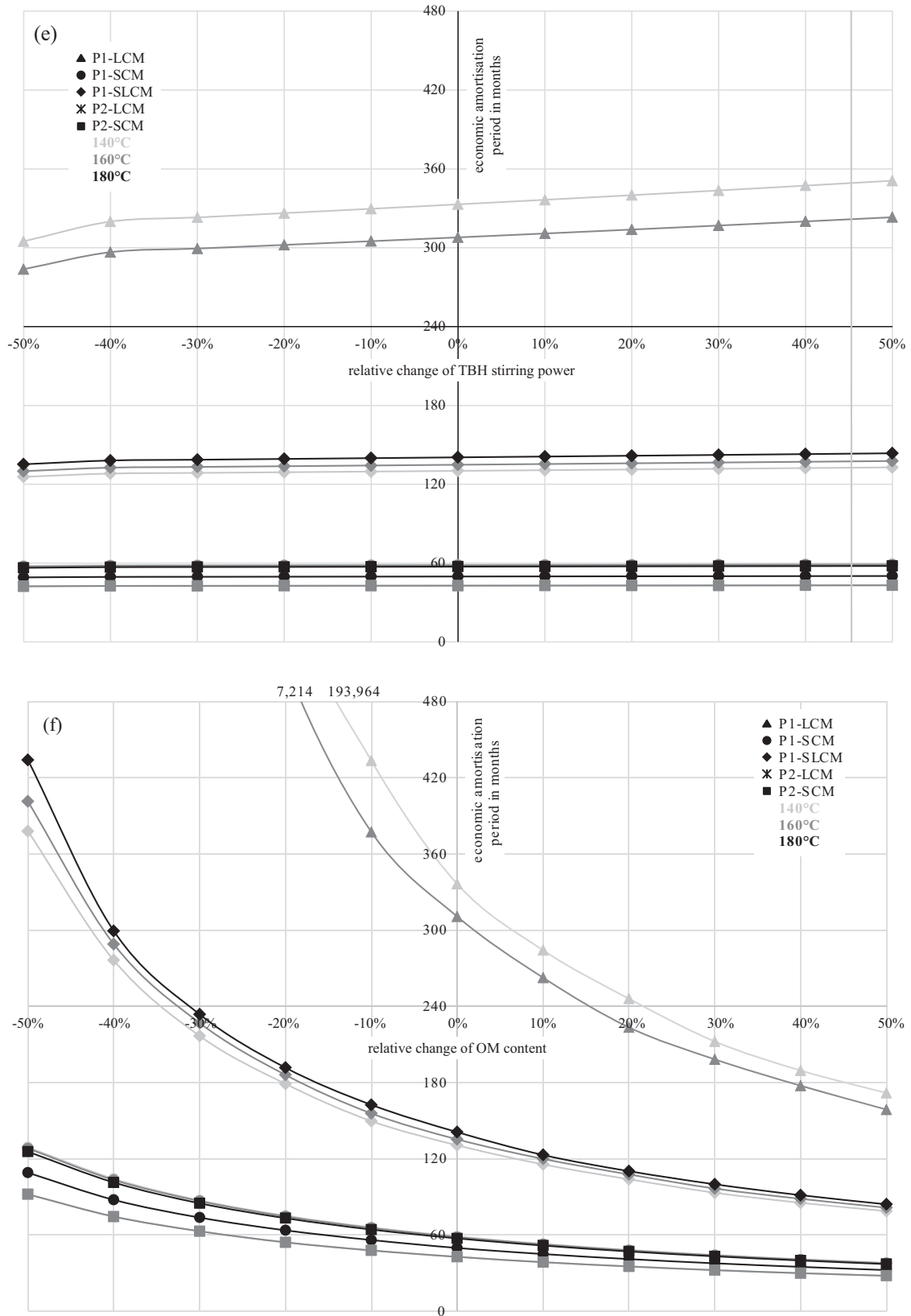


Fig. 3 (continued)

a TBH device – disregarding capital costs and depreciation – that is 2.98 € Mg<sup>-1</sup> FM at a mass flow of 4200 Mg FM a<sup>-1</sup> and although lower at a mass flow of 3360 Mg FM a<sup>-1</sup> (3.72 € Mg<sup>-1</sup> FM) it is assumed that they are higher in any case if regarding the economy of scale.

The ECAP lies between 3 years and 3 months in the best case (P2-SCM; 160 °C) and 28 years in the worst case (P1-LCM; 140 °C). Most feedstocks, but none of the LCM variants, are economically feasible as the device is designed for a service life

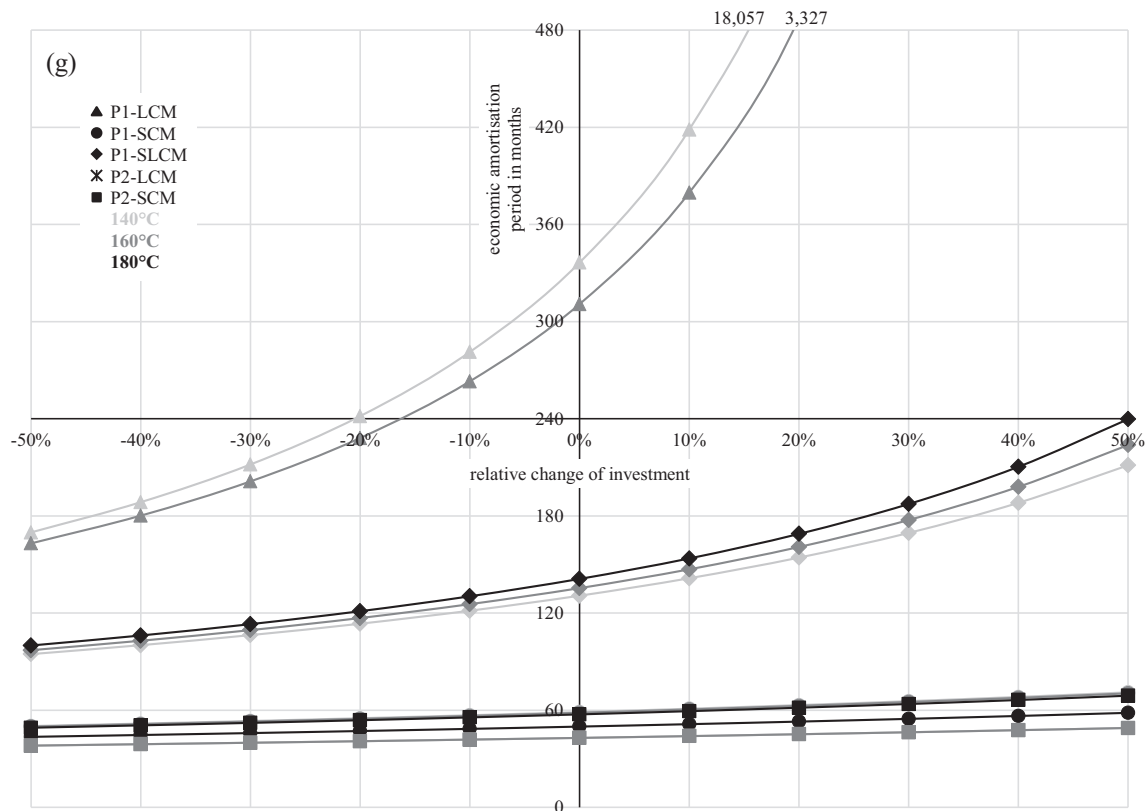


Fig. 3 (continued)

of 20 years. The fresh mass to be pretreated for regaining the entire investment (ECAM) is between 10,803 for P2-SCM (160 °C) and 117,764 Mg FM for P1-LCM (140 °C).

If the additional electricity production costs according to this study are lower than the grid electricity production costs, the additional CO<sub>2</sub> mitigation costs become negative. The CO<sub>2</sub> mitigation costs of the process step regarded would result in  $-50 \text{ € Mg}^{-1} \text{ CO}_2\text{-eq.}$  in the best case, thus reducing the CO<sub>2</sub> mitigation costs of electricity in biogas plant. These costs usually range between  $350 \text{ € Mg}^{-1} \text{ CO}_2\text{-eq.}$  for biogas plants using a substantial share of LCM and  $600 \text{ € Mg}^{-1} \text{ CO}_2\text{-eq.}$  for biogas plants using energy crops only (Scholz et al., 2011).

### 3.4. Sensitivity analysis

Sensitivity analyses were performed to assess the viability of the model against hardly determinable parameters, to justify simplifications and to assess the impact of variations of selected input parameters on representative output parameters.

GHG emissions per unit energy increase with increasing stirring power (Fig. 3a), decrease with increasing organic matter content (Fig. 3b) and are indifferent to changes in investment (not shown here).

The increase in GHG emissions with increasing stirring power is due to the assumption that the electricity derives from the national grid with its fossil and nuclear resources. The alteration of stirring power from  $-50\%$  or  $+50\%$  leads to changes in GHG emissions of maximum  $0.127 \text{ kg CO}_2\text{-eq. kW h}_{\text{el}}^{-1}$  for P2-LCM (180 °C).

OM content of the particular feedstock has a considerably stronger impact on GHG emissions than the changes in stirring power. The alteration of OM content of  $-50\%$  leads to an increase of maximum  $1.484 \text{ kg CO}_2\text{-eq. kW h}_{\text{el}}^{-1}$  (P2-LCM; 180 °C) while the increase in OM content by 50% leads to a decrease of maximum

$0.495 \text{ kg CO}_2\text{-eq. kW h}_{\text{el}}^{-1}$  (P2-LCM; 180 °C). Owing to the increasing amount of maize silage displaced with increasing OM content, the GHG emissions of LCM scenarios decrease. Increasing OM content in SCM scenarios omits surplus emissions from storage and hence decreases the net GHG emissions.

Although the effect of OM content of a particular feedstock is non-linear and almost doubles the GHG emissions per unit energy with a decrease of 50% in the OM content of LCMs, the impact on GHG emission per year is negligible for LCMs (Fig. 3c). On the other hand, the GHG emissions per year from SCM scenarios decrease considerably with increasing OM content of the feedstock. These differences reflect the increasing yield in surplus energy deriving from feedstock with higher OM content like SCMs.

CO<sub>2</sub> mitigation costs are significantly decreased by increasing OM content of feedstock (Fig. 3d) but are almost unaffected by changes in stirring power (not displayed here). Investment is directly influencing linearly the CMCs (not displayed here).

Scenarios with high electricity production costs and high energy related emissions compared to that of grid electricity in base scenario are strongly influenced by changes in OM content. As shown above, increase in OM content reduces the emissions related to electric energy and reduces the costs for producing that electric energy as well. Especially the CMCs of LCM scenarios are therefore significantly decreased by increased OM content. SLCM also shows a sixfold increase with decrease of the OM content of feedstock by 50%. The SCMs are slightly reduced by decrease of OM content and almost unaffected by increase.

Sensitivity analyses for the ECAP display a baseline ( $x$ -axis) at the specified lifetime of the TBH facility of 20 years or 240 months (Fig. 3e–g).

Stirring power only slightly influences the ECAP (Fig. 3e). The maximal change in the ECAP within lifetime of the TBH facility is

from 135 months for the original scenario to 130 months for –50% and to 138 months for +50% stirring power. That is a change of 5.7% only.

In contrast, changes in OM content strongly influence the ECAP (Fig. 3f). The SCMs show an increase of the ECAP of 60 months in average with decreasing OM content by 50% and a decrease of 18 months in average with an increase of the OM content of 50%. In the case of LCM from P1 pretreated at 140 °C, 15 € per year only can be gained for paying off the investment if the OM content is decreased by 50%. That leads to an irrelevantly high ECAP of approximately 16,000 years. On the other hand, however, an increase in OM content by 50% leads to an amortization of investment after 172 months which is within the specified lifetime of the TBH facility.

ECAP of variants with already high profits are more or less unimpaired by changes in investment as it is given for the SCM scenarios (Fig. 3g). In contrast, variants with only low profit are strongly influenced: A surplus in investment of 50% causes a doubling of ECAP for P1-SLCM. Especially for variants with profits above the interest rate and below the repayment rate as for P1-LCM pretreated at 140 and 160 °C prohibitively high values occur here as well: The ECAP for P1-LCM pretreated at 140 °C is 18,057 months (approx. 1500 years) if investment is increased by 50%. In contrast, lowering the investment by 20% will make LCMs economically viable as well.

The performed sensitivity analyses confirm the assumption that the overall results are influenced only marginally by the accuracy of estimating the stirring power.

The energy per time unit attainable from SCMs is high in contrast to the changes in energy related output parameters. In opposition to the SCMs, only slight changes in output parameters occur if related to time for the LCMs as the energy per time unit is low. However, if related to energy there are substantial changes of the overall results.

#### 4. Conclusions

Thermobarical hydrolysis is feasible for many feedstocks such as solid cattle wastes and mixtures of solid and liquid cattle wastes. The additional benefits exceed the additional expenses in terms of energy, greenhouse gas emissions and profitability. Thermobarical hydrolysis treatment of liquid cattle waste does not provide sufficient advantages compared with untreated liquid cattle waste. Therefore substituting maize silage with treated liquid cattle waste is not recommended.

In general, it is preferable to use a feedstock with a high fresh matter related organic matter content and ligno-cellulose that is usually unsuitable for anaerobic digestion without pretreatment. Thermobarical hydrolysis of such material will have short to very short energetic and greenhouse gas payback time and economic amortization period.

#### Acknowledgement

The work underlying this publication was supported by the European Commission FP 6, Contract No TREN/06/FP6EN/S07. 64183/019884.

#### Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.wasman.2015.12.003>.

#### References

- Appels, L., Baeyens, J., Degrève, J., Dewil, R., 2008. Principles and potential of the anaerobic digestion of waste-activated sludge. *Prog. Energy Combust. Sci.* 34, 755–781.
- Beitz, W., Grote, K.-H. (Eds.), 1997. *Dubbel – Taschenbuch für den Maschinenbau*, 19th ed. Springer-Verlag, Berlin.
- Bönnewitz, U., 2007. Silomais für die Biogasanlage – mit welchen Kosten muss man rechnen und zu welchen Preisen kann man verkaufen? INFODIENST 04/07 für Beratung und Schulung der Sächsische Agrarverwaltung 4, 21–27.
- Browne, J.D., Murphy, J.D., 2013. Assessment of the resource associated with biomethane from food waste. *Appl. Energy* 104, 170–177.
- Budde, J., 2015. Improving Digestibility of Cattle Waste by Thermobarical Treatment: Lab-Scale Experiments and Assessment of Full-Scale Model Application, Doctoral thesis at Humboldt University of Berlin. Berlin.
- Budde, J., Suárez Quiñones, T., Plöchl, M., Heiermann, M., 2008. Methods of pre-treatment of less fermentable material and their applicability in anaerobic digestion. In: Proceedings of the International Conference on Agricultural Engineering & Industry Exhibition AgEng2008, 23–25 June 2008. Hersonissos, Paper No. 1130243.
- Budde, J., Heiermann, M., Suárez Quiñones, T., Plöchl, M., 2014. Effects of thermobarical pretreatment of cattle waste as feedstock for anaerobic digestion. *Waste Manage.* 34, 522–529.
- Cano, R., Nielfa, A., Fdz-Polanco, M., 2014. Thermal hydrolysis integration in the anaerobic digestion process of different solid wastes: energy and economic feasibility study. *Bioresour. Technol.* 168, 14–22.
- Carlsson, M., Lagerkvist, A., Morgan-Sagastume, F., 2012. The effects of substrate pre-treatment on anaerobic digestion systems: a review. *Waste Manage.* 32, 1634–1650.
- Cherubini, F., Strømman, A.H., 2011. Life cycle assessment of bioenergy systems: state of the art and future challenges. *Bioresour. Technol.* 102, 437–451.
- DBFZ, 2010. Monitoring zur Wirkung des Erneuerbare-Energien-Gesetzes (EEG) auf die Entwicklung der Stromerzeugung aus Biomasse, Leipzig.
- DIN EN ISO 10628, 1997. Flow Diagrams for Process Plants. Deutsches Institut für Normung, Berlin.
- Ecoinvent V2.01, 2007. Swiss Centre for Life Cycle Inventories. St-Gallen.
- Elbeshbishy, E., Aldin, S., Hafez, H., Nakhla, G., Ray, M., 2011. Impact of ultrasonication of hog manure on anaerobic digestability. *Ultrason. Sonochem.* 18, 164–171.
- European Commission, 2010. Report from the commission to the council and the European parliament on sustainability requirements for the use of solid and gaseous biomass sources in electricity, heating and cooling. Brussels.
- FNR, 2010. Biogas-Messprogramm II, second ed. Fachagentur Nachwachsende Rohstoffe e.V. (FNR), Gülzow.
- Fritsche, U.-R., 2007. Treibhausgasemissionen und Vermeidungskosten der nuklearen, fossilen und erneuerbaren Strombereitstellung – Arbeitspapier <<http://www.oeko.de/oekodoc/318/2007-008-de.pdf>> (accessed 13.03.2013).
- GE Jenbacher GmbH & Co OHG, 2006. Technical Specification JMS 208 GS-B.L Biogas 330kW el. Jenbach.
- German Government, 2012a. Act on Granting Priority to Renewable Energy Sources (Renewable Energy Sources Act – EEG). Berlin.
- German Government, 2012b. Ordinance on the Generation of Electricity from Biomass. Berlin.
- German Government, 2014. Act on the Development of Renewable Energy Sources (Renewable Energy Sources Act – RES Act 2014). Berlin.
- Grabber, J.H., 2005. How do lignin composition, structure, and cross-linking affect degradability? A review of cell wall model studies. *Crop Sci.* 45, 820–831.
- Hanff, H., Neubert, G., Brudel, H., 2010. Datensammlung für die Betriebsplanung und die betriebswirtschaftliche Bewertung landwirtschaftlicher Produktionsverfahren im Land Brandenburg. Schriftenreihe des Landesamtes für Ländliche Entwicklung, Landwirtschaft und Flurneuordnung, Abteilung Landwirtschaft und Gartenbau, Reihe Landwirtschaft 11 (8), 1–131.
- Hendriks, A., Zeeman, G., 2009. Pretreatments to enhance the digestibility of lignocellulosic biomass. *Bioresour. Technol.* 100, 10–18.
- Isermeyer, F., Otte, A., Christen, O., Dabbert, S., Froberg, K., Grabski-Kieron, U., Hartung, J., Heissenhuber, A., Hess, J., Kirschke, D., Schmitz, P.M., Spiller, A., Sundrum, A., Thoroe, C., 2007. Nutzung von Biomasse zur Energiegewinnung. *Zeitschrift für Agrarpolitik und Landwirtschaft* 216, 1–198.
- ISO 14044, 2006. Environmental Management – Life Cycle Assessment – Requirements and Guidelines. International Organization for Standardization (ISO), Geneva.
- Köppen, D., 2002. Entwicklung eines Messverfahrens für die Oberflächendichte von Siliergut, Master thesis at Universität Rostock. Rostock.
- KTBL, 2010a. Gasaubeute in landwirtschaftlichen Biogasanlagen. Darmstadt.
- KTBL, 2010b. Betriebsplanung Landwirtschaft 2010/2011. Darmstadt.
- Lübbert, D., 2007. CO<sub>2</sub>-Bilanzen verschiedener Energieträger im Vergleich – Zur Klimafreundlichkeit von fossilen Energien, Kernenergie und erneuerbaren Energien <[https://thkrouter.dyndns.org/moodle/pluginfile.php/6424/mod\\_resource/content/1/CO2-Bilanzen\\_verschiedener\\_Energietraeger\\_im\\_Vergleich.pdf](https://thkrouter.dyndns.org/moodle/pluginfile.php/6424/mod_resource/content/1/CO2-Bilanzen_verschiedener_Energietraeger_im_Vergleich.pdf)> (accessed 08.12.2015).
- Menardo, S., Balsari, P., Dinuccio, E., Gioelli, F., 2011. Thermal pre-treatment of solid fraction from mechanically-separated raw and digested slurry to increase methane yield. *Bioresour. Technol.* 102, 2026–2032.

- Meyer-Aurich, A., Schattauer, A., Hellebrand, H.J., Klauss, H., Plöchl, M., Berg, W., 2012. Impact of uncertainties on greenhouse gas mitigation potential of biogas production from agricultural resources. *Renew. Energy* 37, 277–284.
- Mönch-Tegeeder, M., Lemmer, A., Oechsner, H., 2014. Enhancement of methane production with horse manure supplement and pretreatment in a full-scale biogas process. *Energy* 73, 523–530.
- Öko-Institut, 1998. CO<sub>2</sub>-Vermeidungskosten: Konzept, Potenziale und Grenze eines Instruments für politische Entscheidungen. Berlin.
- Plöchl, M., Hilse, A., Heiermann, M., Budde, J., Suarez, T., Prochnow, A., 2009. Hydrolytic enzymes improve fluidity of biogas feedstock. *Agricult. Eng. Int.: CIGR EJ.*, 1529 <<http://www.cigrjournal.org/index.php/Ejournal/article/view/1529/1259>> (accessed 13.03.2013).
- Rühlmann, O., 2000. Wirtschaftsdünger effektiv und umweltschonend lagern und einsetzen <[http://www.humusnetzwerk.de/uploads/media/Ruehlmann\\_widue\\_Sachsen\\_2000.pdf](http://www.humusnetzwerk.de/uploads/media/Ruehlmann_widue_Sachsen_2000.pdf)> (accessed 13.03.2013).
- Schindler, M., 2009. Welchen Wert haben Wirtschaftsdünger. *Landwirtschaftliches Wochenblatt* 30, 31–32.
- Scholz, L., Meyer-Aurich, A., Kirschke, D., 2011. Greenhouse gas mitigation potential and mitigation costs of biogas production from agricultural resources. *AgBioForum* 14, 133–141.
- Schultheis, U., Döhler, H., Schwab, M., 2010. Wirtschaftsdünger tierischer Herkunft – jährliche Anfallmengen in der Bundesrepublik Deutschland. *Landtechnik* 5, 354–356.
- Schumacher, B., 2008. Untersuchungen zur Aufbereitung und Umwandlung von Energiepflanzen in Biogas und Bioethanol. Dissertation at Universität Hohenheim, Hohenheim.
- Seeberg-Elverfeldt, C., 2010. Carbon Finance Possibilities for Agriculture, Forestry and Other Land Use Projects in a Smallholder Context. Natural Resources Management and Environment Department Food and Agriculture Organization of the United Nations (FAO), Rome.
- Shafiei, M., Kabir, M.M., Zilouei, H., Sárvári Horváth, I., Karimi, K., 2013. Techno-economical study of biogas production improved by steam explosion pretreatment. *Bioresour. Technol.* 148, 53–60.
- Sneath, R.W., Beline, F., Hilhorst, M.A., Peu, P., 2006. Monitoring GHG from manure stores on organic and conventional dairy farms. *Agr. Ecosyst. Environ.* 112, 122–128.
- Stenull, M., Raab, K., 2010. Beitrag zu Arbeitsgruppe 3 Systemanalyse Teil Klimaschutz/Treibhausgasemissionen <<http://www2.um.baden-wuerttemberg.de/servlet/is/41164/AG3%20Systemanalyse.pdf?command=downloadContent&filename=AG3%20Systemanalyse.pdf>> (accessed 13.03.2013).
- VDI, 1991. VDI-Wärmeatlas: Berechnungsblätter für den Wärmeübergang, 6th ed. Verein Deutscher Ingenieure VDI-Gesellschaft Verfahrenstechnik und Chemieingenieurwesen, Düsseldorf.
- Vogt, R., 2008. Basisdaten zu THG-Bilanzen für Biogas-Prozessketten und Erstellung neuer THG-Bilanzen <[http://www.ifeu.de/oekobilanzen/pdf/THG\\_Bilanzen\\_Bio\\_Erdgas.pdf](http://www.ifeu.de/oekobilanzen/pdf/THG_Bilanzen_Bio_Erdgas.pdf)> (accessed 13.03.2013).
- Ward, A.J., Hobbs, P.J., Holliman, P.J., Jones, D.L., 2008. Optimisation of the anaerobic digestion of agricultural resources. *Bioresour. Technol.* 99, 7928–7940.
- Weiland, P., 2008. Trockenfermentation in der Landwirtschaft: Welche Substrate und Techniken finden Anwendung. Eigenverlag des Forums für Abfallwirtschaft und Altlasten e.V., Dresden, pp. 235–247.
- Weiß D., Brückner C., 2008. Aufarbeitung landwirtschaftlicher Biomasse für den Vergärungsprozess. Schriftenreihe der Sächsischen Landesanstalt für Landwirtschaft. Sächsische Landesanstalt für Landwirtschaft (Ed.). Eigenverlag 19, 1–112.
- Zhang, C., Xiao, G., Peng, L., Su, H., Tan, T., 2013. The anaerobic co-digestion of food waste and cattle manure. *Bioresour. Technol.* 129, 170–176.