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This work has been accepted by the Faculty of Organic Agricultural Sciences of the University of Kassel as a thesis for acquiring the academic degree of Doktor der Agrarwissenschaften (Dr. agr.).

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PREFACE

Within the recent years, the use of agricultural biomass resources for energy production has rapidly increased in Germany. More than one fifth of the arable land was dedicated to energy recovery in 2012, mostly contributing to electricity supply by anaerobic digestion and to fuel provision by biodiesel production. With the share of energy crops increasing, there is a rising debate about the overall ecological and social impact of energy production from agricultural biomass. Concerns about the ecological efficiency in terms of greenhouse gas savings, biodiversity aspects and spatial nutrient surplus are only some of the issues currently discussed.

This book is based on a dissertation that investigated several technical and ecological aspects of a newly developed approach of biomass conversion, the Integrated Generation of Solid Fuel and Biogas from Biomass (IFBB). The overarching motivation of this technical procedure is, firstly, the improvement of the ecological performance of biomass processing by increasing the conversion efficiency and, on the other hand, the ability to convert a wider spectrum of biomass resources in order to enhance the diversity of input materials. Both aspects were addressed in this work by comprehensive life cycle assessment studies and the evaluation of technical parameters when using different types of biomasses.

One of the main messages of this book is that the IFBB technique is particularly favourable when fibre-rich biomasses, such as residual materials from landscape conservation, urban green waste and heterogeneous feedstock from late cut grasslands, are used. All of the biomasses mentioned are frequently not used, but appear in huge amounts every year. It goes without saying that these materials are highly relevant for future energy recovery from biomass, as they do not compete with other purposes like food production or animal nutrition. Thus, this book is an important contribution to the exploitation of further biomass resources, with the potential to ease the conflict we currently observe considering intensive energy cropping.

The underlying data were mainly collected within the European project “PROGRASS - Securing the Conservation of Natura Grassland Habitats With a Distributed Bioenergy Production” (www.prograss.eu), which was carried out from 2009 to 2012 and coordinated by the Department of Grassland Science and Renewable Plant Resources at the University of Kassel. Lutz Bühle was responsible for the technical project management.

It is hoped that this book finds appreciation among those stakeholders who participate in the energy transition and that it makes a significant contribution to a sustainable supply of renewable energy in the future.

Witzenhausen, November 2013 *Prof. Dr. Michael Wachendorf*

ACKNOWLEDGEMENT

This thesis was submitted to the Faculty of Organic Agricultural Sciences of the University of Kassel to fulfil the requirements for the degree Doktor der Agrarwissenschaften (Dr. agr.). This dissertation is based on four papers as first author, which are published by international refereed journals. A list of the original papers including the chapter in which they appear in this dissertation will be given on the next pages. A list of other publications (e.g. contributions to conference proceedings) is given in chapter 12.

First of all, I am deeply grateful to my supervising professor Michael Wachendorf for giving me the opportunity to qualify in different fields of applied science. He frequently and unhesitatingly gave support and guidance in data analysis and scientific writing and was ready to discuss a huge number of issues whenever there was need. Furthermore, it was really enriching for me to work together with him in the planning and network building of new research projects.

I would also like to thank the staff of the Department of Grassland Science and Renewable Plant Resources. My sincere thanks go to Dr. Reinhold Stülpnagel, Dr. Thomas Fricke and Dr. Rüdiger Graß, whose experience in the implementation of experiments was a big help for me. Furthermore, I would like to thank Andrea Gerke, Manfred Ellrich, Wolfgang Funke and Julia Sondermann for all technical assistance and sample processing. Great thanks go to all PhDs of the department for an unforgetable cooperation and a lot of fun within and out of working hours. I am also grateful to all partners of the PROGRASS project in the Vogelsberg, in Estonia and Wales for the fruitful collaboration.

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Thanks to my parents for "hosting" me during hours of paper writing.

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Witzenhausen, November 2013 *Lutz Bühle*

LIST OF PAPERS

Chapter 3: BÜHLE L., REULEIN J., STÜLPNAGEL R., ZERR W. and WACHENDORF M. (2012) Methane yields and digestion dynamics of press fluids from mechanically dehydrated maize silages using different types of digesters. Bioenergy Research, 5, 294-305.

Chapter 4: BÜHLE L., DÜRL G., HENSGEN F., URBAN A. and WACHENDORF M. (2014) Effects of hydrothermal conditioning and mechanical dewatering on ash melting behaviour of solid fuel produced from European semi-natural grasslands. Fuel, 118, 123-129.

Chapter 5: BÜHLE L., STÜLPNAGEL R. and WACHENDORF M. (2011) Comparative life cycle assessment of the integrated generation of solid fuel and biogas from biomass (IFBB) and whole crop digestion (WCD) in Germany. Biomass and Bioenergy, 35, 363-373.

Chapter 6: BÜHLE L., HENSGEN F., DONNISON I., HEINSOO K. and WACHENDORF M. (2012) Life cycle assessment of the integrated generation of solid fuel and biogas from biomass (IFBB) in comparison to different energy recovery, animal-based and non-refining management systems. Bioresource Technology, 111, 230-239.

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ABBREVIATIONS

AST:	Ash softening temperature
BBCH:	Biologische Bundesanstalt Bundessortenamt and chemical industry
BC:	Beef cattle
CF:	Crude fibre
CHP:	Combined heat and power plant
CO:	Composting
COD:	Chemical oxygen demand
CP:	Crude protein
DF:	Dry fermentation
DM:	Dry matter
EE:	Ether extract
FT:	Fermentation time
FM:	Fresh matter
GHG:	Greenhouse gases
HC:	Hay combustion
HHV:	Higher heating value
IFBB:	Integrated generation of solid fuel and biogas from biomass
IFBB-AO:	IFBB-add-on system
IFBB-SA:	IFBB-stand-alone system
LCA:	Life cycle assessment
LHV:	Lower heating value
l_N:	Normal litre
ME:	Metabolisable energy
MU:	Mulching

MY:	Methane yield
NfE:	Nitrogen-free extract
oADF:	Acid detergent fibre
oADL:	Acid detergent lignin
oM:	Organic matter
oNDF:	Neutral detergent fibre
PF:	Press fluid
s.e.:	Standard error
tkm:	tonne-kilometre
VS:	Volatile solids
VFA:	Volatile fatty acids
W:	Water
WCD:	Whole crop digestion
XF:	Crude fibre
XL:	Crude fat
XP:	Crude protein

1 General introduction

Declining availability of fossil energy carriers, growing conflicts of resource scarcity and increasing effects of climate change have entailed strategies to promote renewable energies on the European and national level (Carvalho, 2012; Eskeland et al., 2012). The European Union set the target to achieve an overall contribution of renewables of 20% to the energy consumption in 2020, with differing rates of the member states (EC, 2006). For example, the share of the German's renewables to the final energy comsumption rised from 3.9% in 2000 to 12.5% in 2011, and it should achieve a contribution of 18% in 2020 (BMU, 2012).

Among the different types of renewable resources, the use of biomass is considered to play a major role. Compared to other renewables, the conversion of organic matters into energy allows the supply of different forms of end energy carriers, such as electricity or solid and liquid biofuels for the heat and transport sector (Ericsson and Nilsson, 2006; Faaij, 2006; Flamos et al., 2011). Looking at the situation in Germany, the agricultural area used for the cultivation of renewable resources increased from 0.7 m ha in 2000 to 2.5 m ha in 2012, corresponding to 15% of the total agricultural land (FNR, 2013).

In the recent past, the rapid growth of energy production from agricultural biomass has been increasingly discussed for various effects on environment and society (Fritsche et al., 2010; Buchholz et al., 2009). Energy cropping is dominated by the cultivation of rapeseed for biodiesel production and mainly by maize for biogas production in Germany (FNR, 2013). The cultivation shows often a spatial concentration of bioenergy plants and monotonous crop rotations (Herrmann, 2013), which have a negative impact on the biodiversity level and the landscape value (Fletcher at al., 2011; Dauber et al., 2010). In many cases, energy cropping is associated with an intensification of agricultural production, which might lead to environmental concerns of soil degradation and water pollution (Erb et al., 2012; Love et al., 2011). In certain circumstances, an increased input in crop growing might even lead to a higher release of greenhouse gases compared to the use of fossil energy carriers. This indicates the need of a full cycle analyses of bioenergy systems (Crutzen et al., 2007; Fernando et al., 2010). Due to the high share of area grown by energy crops, a controversial debate has been arisen about the competition on food and forage production (Harvey and Pilgrim, 2011; Murphy et al., 2011).

Against this background, the exploitation of residual and so far unused biomass resources became on focus of political recommendations for further biomass strategies (EEA, 2011; Leopoldina, 2012; Tilman et al., 2009). One of those potential biomass resources are semi-natural grasslands, which have been established under extensive management over years and are characterised by high nature value due to their biodiverse plant composition. In many European regions, changes of the agricultural structure led to decreasing livestock levels in these, often disadvantaged, grassland areas (Isselstein et al., 2005; Rösch et al., 2009). Thus, large amounts of biomass that had served as forage, are not longer used. A regular cut and biomass removal are preconditions of biodiversity conservation (Halada et al., 2011); therefore, alternative options to use this biomass are seeked to ensure the continuation of management.

Aiming to increase the energy efficiency of biomass conversion and to extend the possibilities of input materials, the integrated generation of solid fuel and biogas from biomass (IFBB) was developed (Wachendorf et al., 2009; Graß et al., 2009). The core element of the IFBB process is the hydro-thermal conditioning of the wet conserved biomass and the subsequent mechanical separation into a press cake and a press liquid. After drying and compacting, the press cake is used as a solid fuel for combustion. The press liquid serves as a substrate for anaerobic digestion. The resulting biogas is used by a heat and power plant.

Previous studies on the IFBB showed that the treatment of the biomass allows the exploitation of materials, such as semi-natural grassland biomass, that are not suitable for biogas or combustion systems. By separation of the biomass, the fibrous part with a low methane potential is transferred into the solid for combustion, whereas large parts of the minerals, contributing to the risk of corrosion and slagging, and the easily digestible compounds are transferred into the press liquid. Consequently, combustion characteristics of the solid fuel can be improved compared to the untreated biomass, and, a liquid can be produced with a high methane potential. As the minerals of the press liquid stay in the digestate after anarobic fermentation, the remainder represents a valuable fertiliser with high contents of agriculturally important nutrients (Richter et al., 2009; Richter et al., 2010; Hensgen et al., 2012).

The first part of the thesis (chapter 3 and 4) aimed at the assessment of biological and chemical parameters of press fluid digestion and combustion of the press cake. In contrast to the use of maize in conventional biogas systems, the biogas production from press fluids needs an adapted technology due to the faster biomass degradation and the resulting short retention times. The experiments were designed to get insight in the overall methane potential of press fluid digestion as well as the dynamics of continuous operation using different types of digesters. Considering the combustion properties of the press cake, the ash melting behaviour is one of the most crucial issues when using herbaceous biomass for combustion. Ash deformation characteristics were investigated at an experimental scale and the effect of fuel constituents on the ash melting behaviour was evaluated.

The second part of the thesis (chapter 5 and 6) dealt with a comprehensive analysis of the IFBB system to investigate the overall ecological efficiency. Life cycle assessment (LCA) was conducted for using arable or grassland biomass. The entire process chain from biomass provision to energy supply was calculated considering all input and output quantities of energy and relevant emissions. The main parameters of investigation were the energy efficiency as well as the substitution potentials of fossil energy carriers and the emissions of greenhouse gases.

2 Research objectives

The objectives of this thesis were to investigate biological and chemical parameters of press fluid digestion and press cake combustion as well as the LCA of the IFBB system.

Press fluid digestion was examined by use of fluids from mechanically dehydrated maize silages. Batch tests were conducted to analyse the methane potential and long-term tests using stirrer tank and fixed-bed digesters were conducted to analyse the continuous operation. Determination of the ash melting behaviour of the press cake was done by an experimental procedure to identify the temperatures of characteristic shapes of ash deformation. It was based on silage and press cake samples from 18 European semi-natural grassland sites.

LCA was conducted for a rye and maize double-cropping system comparing the IFBB conversion system to the conventional whole crop digestion (WCD). The performance of the IFBB system was analysed for different temperatures of hydro-thermal conditioning, whereas for the WCD system the degree of waste heat use was varied. Furthermore, LCA was carried out for the IFBB system using semi-natural grassland biomass and in comparison to other options of grassland use, such as energy supply systems or animal-based and non-refining management systems.

The specific objectives of the experiments were

(i) to determine the methane potential and the degree of degradation of press fluids from mechanically dehydrated maize silages and to evaluate the digestion in continuously working stirrer tank and fixed bed digesters

(ii) to determine the ash melting temperature of press cakes from semi-natural grassland biomass in comparison to the untreated biomass and to analyse the effect of fuel constituents on the ash melting behaviour

(iii) to evaluate the IFBB system in terms of the energy efficiency and savings of primary energy and greenhouse gas emissions, when using rye and maize as double-crops and in comparison to WCD

(iv) to evaluate the IFBB system in terms of the energy efficiency and savings of primary energy and greenhouse gas emissions, when using semi-natural grassland biomass and in comparison to dry fermentation, hay combustion, beef cattle husbandry, mulching and composting.

3 Methane yields and digestion dynamics of press fluids from mechanically dehydrated maize silages using different types of digesters

Abstract The mechanical dehydration of ensiled agricultural crops results in two major products: a fibrous press cake and a press fluid containing mainly easily digestible constituents. This study is aimed at the investigation on methane yields and digestion dynamics of the press fluids from maize silages using different types of digesters. Methane yields investigated in batch experiments account for 390-506 l_N CH_4 kg^{-1} volatile solids (VS) with a degree of degradation of the organic matter in the fluid of more than 90%. The investigation of digestion dynamics in a continuously working stirrer tank digester at different levels of retention time and volume load suggests that a stable fermentation of press fluids can only be achieved with retention times of more than 20 days and with volume loads below 2 g VS l^{-1} day^{-1}. In a continuously working fixed bed digester a steady fermentation could be achieved at a retention time of 8 days and a volume load of 3 g VS l^{-1} day^{-1}.

3.1 Introduction

The most common way of using wet conserved energy crops in Germany is the anaerobic digestion of whole crop silage (FNR, 2010). Biogas production from wet biomass proved to be a suitable way of conversion (Lettinga, 2009) and especially the use of maize results in high methane yields due to its comparatively high productivity and digestibility (Amon et al., 2007a). Nevertheless, the low share of waste heat exploitation by using the biogas in combined heat and power plants is still a major problem of biogas plants affecting the total conversion efficiency. Shortage of cost effectiveness and losses during heat transport over long distances are the main reasons leading to a share of approximately 25% of the heat which is used by external consumers (Weiland, 2009).

With the goal to improve the conversion efficiency in bioenergy production, a novel technique (integrated generation of solid fuel and biogas from biomass, IFBB, Figure 3.1) was suggested (Graß et al., 2009; Wachendorf et al., 2009). By means of mechanical dehydration, the silage is separated into a press cake and a press fluid. The solid fraction which shows improved combustion characteristics compared to the undehydrated biomass is available for thermal or chemo-thermal utilisation, while the press fluid serves as substrate for biogas production. The waste heat of biogas combustion is used for drying of the press cake to a storable solid fuel. Due to mainly thermal use of the biomass and extraction of the easily digestible compounds into the fluid for anaerobic digestion, conversion efficiency can be increased in comparison to a whole crop digestion system. Comprehensive life cycle assessment showed that the area-related savings of non-renewable primary energy are significantly higher for IFBB if only small parts of the waste heat can be used in conventional biogas systems (Bühle et al., 2011a).

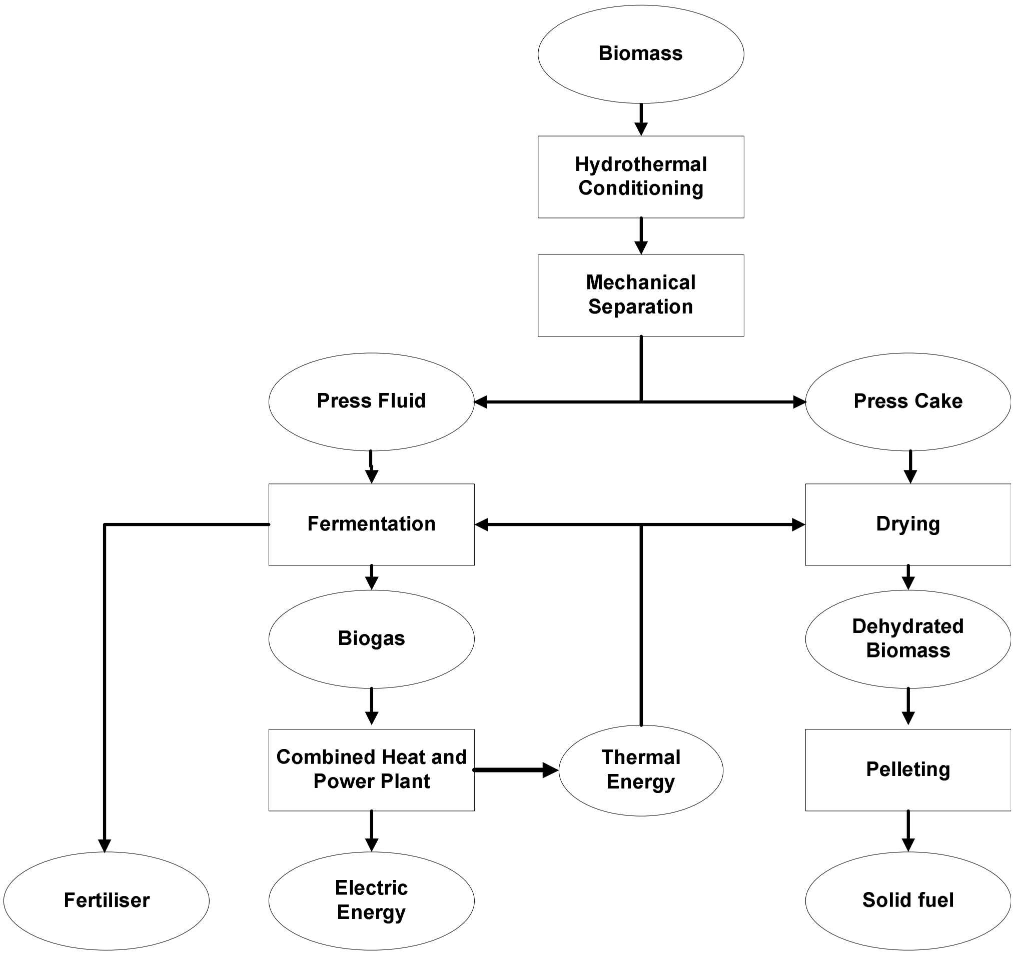

Figure 3.1 Integrated generation of solid fuel and biogas from biomass (IFBB).

Recent investigations showed that by dehydration with a screw press, 66% of dry matter (DM) contained in the whole plant silage of maize is transferred into the press cake, when the silage was treated with water prior to dewatering. Sixty-three percent of the crude ash are extracted from the silage into the fluid (Graß et al., 2009), representing a substantial improvement in fuel quality of the press cake, due to the prevention of corrosion damage and ash melting evoked by e.g. chlorine and potassium during combustion (Obernberger et al., 2006). Reduction of the ash content also leads to an increase of about 10% of the dry-matter-based heating value. About 50% of the nitrogen and sulphur is transferred into the press fluid, leading to reduced concentrations in the fuel and lower discharge of nitrogen oxide and sulphur dioxide (Graß et al., 2009; Greul, 1998). Considering nutrient balance of valuable mineral compounds, 88% of the potassium and

85% of the phosphorus can be redirected as fertilisers by application of the digestates (Graß et al., 2009). Depending on legal conditions, combustion chamber ash can be added to the digestate and increase the return rate of the nutrients. Low fibre contents and high contents of easily degradable matter turns the press fluid into an excellent fermentation substrate for biogas plants (Richter et al., 2009; Richter et al., 2010).

The present study deals with results from a series of digestion tests with press fluids from maize silages processed by the IFBB technique, focussing on the following questions:

1. Which methane yields can be achieved with an anaerobic digestion of the press fluids and what degrees of degradation of the volatile solids (VS) can be obtained using batch digesters?
2. Which patterns of digestion occur over time?
3. How do press fluids perform in continuously working stirrer tank digesters and fixed bed digesters?

3.2 Material and Methods

The digestion of press fluid obtained from maize silages made from a single crop that was harvested at four sequential stages of maturity was assessed in a batch digester system. Maize silage press fluid was also assessed in two types of continuous digester system - a stirrer tank (where the effects of retention time and volume load were determined) and a fixed bed (where the effects of volume load was determined) digester.

3.2.1 Production of silages and press fluids

The maize crop which was grown in a single experiment used for production of the press fluids for the single batch digestion experiment was harvested at four different developmental stages between early milk ripeness (BBCH 81 stage according to the scale of Biologische Bundesanstalt, Bundessortenamt and Chemical industry

(Hess et al., 1997)) and physiological ripeness (BBCH 85; Table 3.1) and ensiled in high-density polyethylene (HDPE) barrels after chopping (one barrel per developmental stage). Chopping of the biomass was carried out using a drum chopper with a resulting chopping length of 5 to 50 mm. Duration of ensiling was at least 28 days. The cylindric and blue coloured HDPE barrels had a volume of 60 l (middle of the barrel x height, 400 x 620 mm) and were sealed gasproof by a low-pressure polyethylene cover with a gasket fixed by a galvanised steel circlip. Biomass yield of maize crops, dry matter (DM) content and the Weende constituents of the silage as well as the mass flow of DM into the press fluid during mechanical dehydration and press fluid yield are shown in Table 3.1. The biomass for the continuous digestion experiments was taken from another maize crop which was harvested at the stage of BBCH 83 by a self-propelled drum chopper on a largescale level. Ensiling took place in a bunker silo. Compacting of the biomass was carried out by a tractor through frequent mechanical compression. Mechanical dehydration of the silage was conducted with a screw press (type Av, Anhydro Ltd., Kassel, Germany). The conical screw had a pitch of 1:7.5 and a rotational speed of 12 rpm. The screen encapsulating the screw had a perforation of 1.5 mm. Sub-samples of the press fluid were stored at -21°C prior to anaerobic digestion. DM content of all sub-samples of the silage, the press cake and the press fluid was determined by oven-drying at 105°C. VS, a term of environmental chemistry, are those solids of the fresh matter that are lost on ignition of the dry matter and determined at 550°C in a muffle furnace. VS equate to the organic matter concentration. In this study, VS includes volatile fatty acids (VFA) and ethanol which were analysed by gas chromatography (Table 3.2) and serves as the basis for calculation of methane yields.

Table 3.1 Biomass yield of maize harvested at different phenological growth stages, dry matter (DM) content, Weende constituents of the silage as well as mass flow of DM into the press fluid during mechanical dehydration and press fluid yield.

Phenological growth stage	**Biomass yield**	**DM**	**Ash**	**CP**	**EE**	**CF**	**NfE**	**Mass flow of DM**	**Press fluid yield**
	(t DM ha^{-1})	(g kg^{-1} FM)	(g kg^{-1} DM)					(%)	(t FM ha^{-1})
BBCH 81	16.4	199	48	63	10	280	600	27.0	4.4
BBCH 82	17.3	250	44	63	16	242	634	30.0	5.2
BBCH 83	19.4	266	44	74	23	219	640	25.0	4.9
BBCH 85	20.4	418	27	72	32	178	691	9.0	1.8

3.2.2 Technical set up and implementation of the digestion tests

Sub-samples of press fluids from each developmental stage were allocated to two different digesters for the batch digestion tests. Sub-samples of press fluids for the two continuous digestion tests were also allocated to two different digesters. Biogas production was determined in accordance with the German standard (VDI, 2004) and based on a method described by Zerr (2006). Fermentation of the press fluids in the batch and both continuous parts of this study took place in gas-proof 20-l low-pressure polyethylene digesters (Speidel, Ofterdingen, Germany; Figure 3.2). The digesters had a diameter of 310 mm and a height of 418 mm. Mixing of the digester content was carried out by means of a u-shaped stirrer attached to a shaft that was run through a central dip tube. The shaft was driven by a 12-V direct current motor fixed to a tripod above the fermenter cap. During fermentation a clock timer was used to make the stirrers turn for 15 min every 2 h. Gas discharge out of the digester passed a gas-proof nozzle screwed into the top of the digester. From the nozzle the gas was channelled into aluminium gas bags (model: TECOBAG; volume, 40 l; Tesseraux, Bürstadt, Germany). The experiments were performed in a mesophile temperature range of 37°C with a fluctuation of ± 1°C continuously adjusted by temperature sensors in water basins.

Table 3.2 Parameters and methods/devices applied to monitor the press fluid and the fermentation process.

Parameter	Method/devices
Dry matter (DM)	DIN EN 12880
Volatile solids (VS)	DIN EN 12880, DIN EN 12879
Weende constituents (Ash, CP, EE, CF, NfE)	Standard procedures (Bassler, 1976)
Volatile fatty acid (VFA)	Gas chromatograph (Varian, type 3400 and Agilent Technologies, type 6890 N, Santa Clara, USA)
pH	pH-electrode (Metrohm, type pH-Meter 654, Filderstadt, Germany)
Chemical oxygen demand (COD)	Bulb test by photometer (Hach Lange, Düsseldorf, Germany)
Acetic acid equivalent	DIN 38414
Biogas volume	Drum type meter (Ritter, type 1/6, Bochum, Germany)
Methane content	Infrared spectrometer (GS Messtechnik, type GS IRM 100, Ratingen, Germany)

3.2.2.1 Batch digestion tests

At the start of the test the digesters were filled with 15 kg fresh matter (FM) of digestate from a biogas plant used as inoculum and with 1.5-2.0 kg FM of press fluid. The relationship between the total amount of VS in the digestate and the total amount of VS in the press fluid was on average 0.23, which is below the value of 0.5 as required by Verein Deutscher Ingenieure (VDI, 2004). Digestion of press fluids from each phenological growth stage was carried out with one replicate. To ensure homogeneity and low residual gas potential the digestate was separated from bigger particles by a screen with a mesh size of 12 x 12 mm. Two digesters filled with pure inoculum served as a control. Methane yields from inoculum digestion were subtracted from the total methane yields of digestion of the mixture of inoculum and press fluid to determine the actual methane yield from press fluid digestion. Altogether, ten digesters were run in this experimental unit (two for each of the four phenological growth stages and two controls). Duration of the experiment was 13 days. Measuring of biogas yield and methane content (devices see Table 3.2) was carried out at days 1, 2, 3, 4, 6, 8, 11 and 13. Towards the final stage the gas yield of two or three sequenced days was combined.

Figure 3.2 Experimental set up of anaerobic digestion tests showing a a 20-l polyethylene batch digester with direct current motor on top for the stirring unit and b a continuously working stirrer tank digester in a water basin with the additional apparatus for removal of digester fluid.

3.2.2.2 Continuous digestion tests using stirrer tank digesters

Stirrer tank digesters used for the continuously working tests were constructed of the same type like the digesters used for batch digestion tests and additionally provided with an inflow for addition of press fluid and removal of digestate as shown in Figure 3.2. Digestate was removed once per day by suction through a tube at a level of about 7 cm above the digester basement before feeding of the press fluid and while permanent stirring to ensure homogeneous extraction. The press fluid was fed three times per day in equal amounts (9 a.m., 12 a.m., 3 p.m). At the start of the continuous tests, digestate from the same large-scale biogas plant as described for the batch tests was used as inoculum. Digesters were operated 90 days at six different levels of retention time (30, 25, 20, 15, 10 and 8 days).

Digestion at each level of retention time was carried out with one replicate. Within each level of retention time, volume load was increased monthly (1 g VS l^{-1} day^{-1} from days 1 to 30, 2 g VS l^{-1} day^{-1} from days 31 to 60, 3 g VS l^{-1} day^{-1} from days 61 to 90). With this a complete replacement of the digester content even with the longest retention time (30 days) was guaranteed. Press fluids were diluted with water to adjust for the amount of digestate to be replaced each day (Table 3.3). Two digesters fed with pure inoculum served as a control and were operated without any addition. Methane yields from inoculum digestion were subtracted from the total methane yields of digestion of the mixture of inoculum and press fluid to determine the actual methane yield from press fluid digestion. The total experimental unit comprised 14 simultaneously operated digesters (two for each of the six retention times and two controls). Gas measuring was carried out daily after the last feeding. Twice per week one sample of each digester was analysed for pH and acetic acid equivalent (Table 3.2). In case of degrading methane production, the analysis was conducted every 2 days.

Table 3.3 Total amount (TA) of substrate added and digestate removed daily from the continuously operated stirrer tank and fixed bed digester and amount of press fluid (PF) and water (W) added daily at different levels of retention time and volume load. Endash "–" imply that VS (volatile solids) concentration of the press fluids was too low to produce the target volume loads at high levels of retention time.

Retention time (d)	**TA** (g digester^{-1})	**Volume load** (g VS l^{-1} d^{-1}) 1		2		3	
		PF	**W**	**PF**	**W**	**PF**	**W**
Continuous digestion tests using stirrer tank digester							
8	1800	188	1612	376	1424	563	1237
10	1440	188	1252	376	1064	563	877
15	960	188	772	376	584	563	397
20	720	188	532	376	344	563	157
25	576	188	388	376	200	563	13
30	480	188	292	376	104	-	-
Continuous digestion tests using fixed bed digester							
		Volume load (g VS l^{-1} d^{-1})					
		1		3		5	
		PF	**W**	**PF**	**W**	**PF**	**W**
8	1643	171	1471	514	1128	857	786

3.2.2.3 Continuous digestion tests using fixed bed digesters

The same type of digesters was used for the continuous tests with fixed bed installed. Inside of the digester grinding fleece (grain size 600; Elefant Schleifmittel GmbH, Wanfried, Germany) was attached around the central stirrer accounting for 50% of the effective digester volume. Three levels of volume load (1, 3 and 5 g VS l^{-1} day^{-1}) were tested over a period of 37 days with a fixed retention time of 8 days (Table 3.3). At the start of the continuous tests, digestate from the same large-scale biogas plant as described for the batch tests was used as inoculum. Digestion at each level of volume load was carried out with one replicate. Two digesters fed with pure inoculum served as a control and were operated without any addition. Methane yields from inoculum digestion were subtracted from the total methane yields of digestion of the mixture of inoculum and press fluid to determine the actual methane yield from press fluid digestion. The total experimental unit comprised eight simultaneously operated digesters (two for each of the three volume loads and two controls). Feeding procedure, gas measuring and analysis of pH and acetic acid equivalent was equal to the tests using stirrer tank digesters.

3.2.3 Measurements for monitoring the fermentation process

The methods and devices applied to monitor the fermentation process are listed in

Table 3.2. Methane volumes that were measured under laboratory room conditions were converted to standard conditions (273.15K; 101,325 Pa; dry gas) and expressed as normal litre (l_N). These methane volumes were referred to the amount of VS in the substrate (norm litre CH_4 per kilogram VS). The VS-based degree of decomposition (η_{VS}), which indicates the decomposition of the organic substance during anaerobic digestion, was determined by relating the mass (*m*) of CH_4 and CO_2 obtained to the mass of VS in the press fluid according to VDI (2004):

$$\eta_{VS} = \frac{m_{CH_4} + m_{CO_2}}{m_{subst.} \cdot VS \cdot 0.93}$$

VS was set at 93%, as it is assumed that about 7% would be decomposed but used for the production of bacterial biomass.

Assuming that 1 g chemical oxygen demand gives an output of 0.32 l CH_4 (reduced by the demand for reproduction of bacteria), chemical oxygen demand (COD)-based degree of decomposition was calculated according to the following equation (VDI, 2004):

$$\eta_{COD} = \frac{V_{CH_4}}{m_{subst.} \cdot COD \cdot 0.32}$$

3.2.4 Statistical analysis

Regression analyses were performed using SigmaPlot 9.0 Software for batch digestion experiments.

3.3 Results

3.3.1 Chemical composition of the press fluids

VS content of press fluids from mechanically dehydrated maize silages used for batch digestion experiments ranged from 67 to 144 g kg^{-1} FM and increased with increasing maturity of the crop (Table 3.4). VFA mainly consisted of acetic acid and covered a small range between 5 and 7 g kg^{-1} FM. Propanoic acid could not be detected. Ethanol as another important volatile component could be found in concentrations between 8 and 11 g kg^{-1} FM. VFA plus ethanol made up 93 to 224 g kg^{-1} VS. Concentrations of lactic acid produced during ensiling range between 16 and 30 g kg^{-1} FM. pH values of 3.9-4.1 indicate an appropriate acidification during ensiling. Corresponding to VS content, chemical oxygen demand was lowest for the press fluid from early stage (112.0 g l^{-1}) and increased to 242.0 g l^{-1} for press fluid from late-harvested maize.

Table 3.4 Contents of volatile solids (VS), acetic acid, lactic acid, ethanol, chemical oxygen demand (COD) and pH value of press fluids from mechanically dehydrated maize silages for batch digestion tests and continuous digestion tests, wet basis (n.d. = not determined).

Press fluid used for batch tests (phenological growth stage)	**VS**	**Acetic acid**	**Lactic acid**	**Ethanol**	**COD**	**pH**
	(g kg^{-1} FM)				(g l^{-1})	(-)
BBCH 81	67	7	18	8	112.0	4.0
BBCH 82	93	6	16	9	140.0	4.1
BBCH 83	107	5	30	5	165.0	3.9
BBCH 85	144	6	18	11	242.0	4.1
Press fluid used for continuous tests	65	6	n.d.	6	96.2	3.9

3.3.2 Batch digestion tests

The cumulative methane production of all press fluids, irrespective of phenological growth stage, was characterised by high yields in the first 3 days of the experiment and a decreasing production in the following days, whereas the total yield at the most advanced growth stages (BBCH 83 and 85) was on average 75 l_N CH_4 kg^{-1} VS lower than that of the early stage-treatment (BBCH 81 and 82; Figure 3.3, Table 3.5). The regression models fitted to the data of the type $y = y_0 + a\ (1-e^{-bx})$ had coefficients of determination between 0.97 and 0.99***. According to these models, 90% of the total methane yield had been generated by day 3.7 (BBCH 81), day 3.4 (BBCH 82), day 3.9 (BBCH 83) and day 5.2 (BBCH 85), respectively. The proportion of methane in the biogas was between 58.1% and 61.5% (*v*/*v*) with a low variability among the growth stages. The VS-based degree of decomposition was between 89.9% and 109.1%, where values of more than 100% indicate analytical or methodological errors. According to the total methane yields, the degree of decomposition declined with increasing maturity of the maize crop. COD-based degree of decomposition decreased as well, but the overall level (77.9-94.6%) was lower compared to the VS based calculation (Table 3.5). Methane yields from the two controls used as inoculum accounted for 1.74 l_N CH_4 kg^{-1} FM after 13 days with a standard error (s.e.) of 0.11 l_N CH_4 kg^{-1} FM, corresponding to 37.7 l_N CH_4 kg^{-1} VS and a s.e. of 2.4 l_N CH_4 kg^{-1} VS.

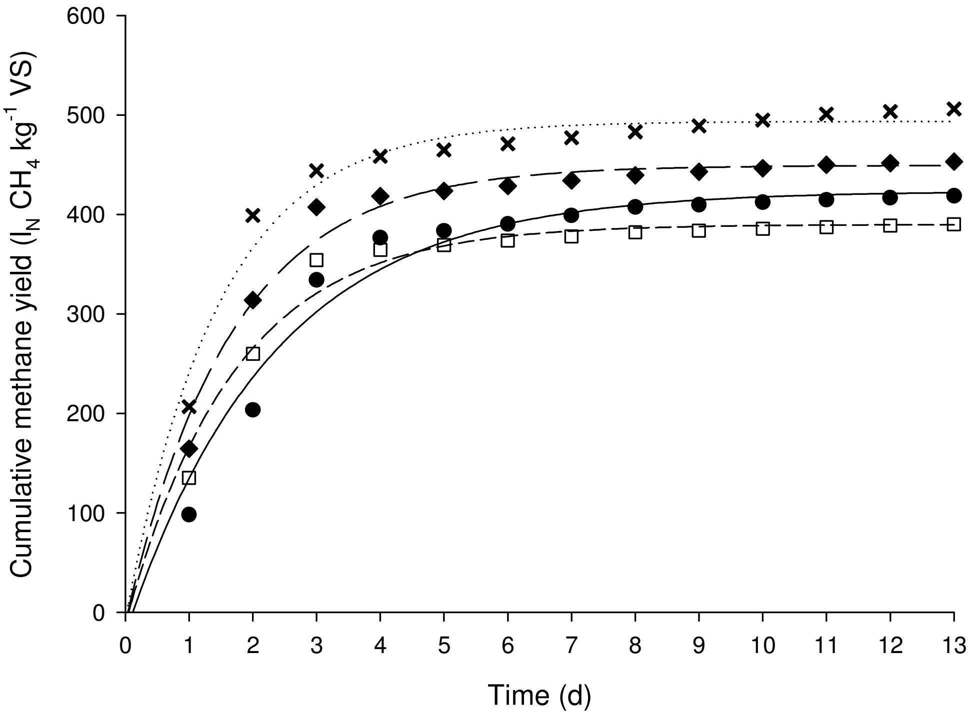

Figure 3.3 Mean values of the cumulative methane yield (MY) from press fluids of mechanically dehydrated maize silages in batch tests with a fermentation time (FT) of 13 days of BBCH 81 (*dotted multiplication sign*), BBCH 82 (*dashed black diamond*), BBCH 83 (*dashed white square*) and BBCH 85 (*dashed black circle*). The equations of the fitted curves are: $MY_{BBCH\ 81}=-504.20+1{,}000.36\ (1-e^{-0.68FT}$; $R^2=0.99^{***})$; $MY_{BBCH\ 82}=-390.67+843.28\ (1-e^{-0.60FT})$, $R^2=0.99^{***}$; $MY_{BBCH\ 83}=-327.65+720.74\ (1-e^{-0.58FT})$, $R^2=0.98^{***}$; $MY_{BBCH\ 85}=-255.66+683.19\ (1-e^{-0.42FT})$, $R^2=0.97^{***}$.

Table 3.5 Mean values of methane yield, methane content and degree of decomposition (based on content of volatile solids and chemical oxygen demand) of maize press fluids in batch digestion experiments.

Phenological growth stage	**Methane yield**	**Methane content**	**Degree of decomposition**	
			η_{VS}	η_{COD}
	(l$_N$ CH_4 kg^{-1} VS)	(% *v*/*v*)	(%)	
BBCH 81	506.2	61.5	109.1	94.6
BBCH 82	453.0	60.1	99.6	94.0
BBCH 83	390.3	58.1	90.7	79.1
BBCH 85	418.7	60.8	89.9	77.9

3.3.3 Continuous digestion tests using stirrer tank digesters

Regarding press fluid digestion with a retention time of 30 and 25 days, daily methane production was variable but overall at a constant level (Figure 3.4). Averaged over the total time of measurement methane yield was 395.5 l_N CH_4 kg^{-1} VS at a retention time of 30 days which was 41.5 l_N CH_4 kg^{-1} VS less than the maximum yield (437 l_N CH_4 kg^{-1} VS), as determined in batch experiments at a degree of decomposition of 98%. At a retention time of 25 days, the averaged methane yield was at a similar level and accounted for 399.3 l_N CH_4 kg^{-1} VS. Concentration of volatile fatty acids (shown as acetic acid equivalents), methane content as well as pH value indicated that press fluid digestion with these retention times was at a steady state at any time. Digestion with a retention time of 30 days with a volume load of 3 g VS l^{-1} day^{-1} could not be tested as the VS concentration in the press fluid was not sufficient to reach higher feeding rate at this level of input volume. Fermentation with a retention time of 20 days reflected a stable fermentation status at only a volume load of 1 g VS l^{-1} day^{-1}. At a volume load of 2 g VS l^{-1} day^{-1} methane production, methane content and pH remained unchanged whereas the content of acetic acid equivalent increased from 0.1 to 0.5 g l^{-1}. Step-up to a volume load of 3 g VS l^{-1} day^{-1} resulted in a pronounced peak in acetic acid equivalent concentration of more than 7 g l^{-1} accompanied by a breakdown of methane production and a rapid decline of methane content and pH value. Digestion at a retention time of 15 days resulted in a cease in fermentation even at a volume load of only 2 g VS l^{-1} day^{-1}. Retention times of 10 and 8 days caused methane production to collapse already after 30 days with a volume load of only 1 g VS l^{-1} d^{-1} always accompanied by a sharp increase in acetic acid equivalent concentration. By trend, malfunctioning methane production was indicated first by the increase of fatty acids, rapidly followed by a simultaneous breakdown of gas production, methane content and pH value.

3.3.4 Continuous digestion tests using fixed bed digesters

Daily methane yields at a volume load of 1 g VS l^{-1} day^{-1} and a constant retention time of 8 days was fluctuating between 312 and 588 l_N CH_4 kg^{-1} VS and was 409 l_N CH_4 kg^{-1} VS on average which is close to the maximum yield (437 l_N CH_4 kg^{-1} VS), as determined in batch digestion experiments (Figure 3.5). Concentrations of acetic acid equivalent averaged at 0.4 g l^{-1} and showed by trend decreasing values. Methane content amounted to 61.8% (*v*/*v*) and pH accounted for 7.3 indicating an unimpeded decomposition.

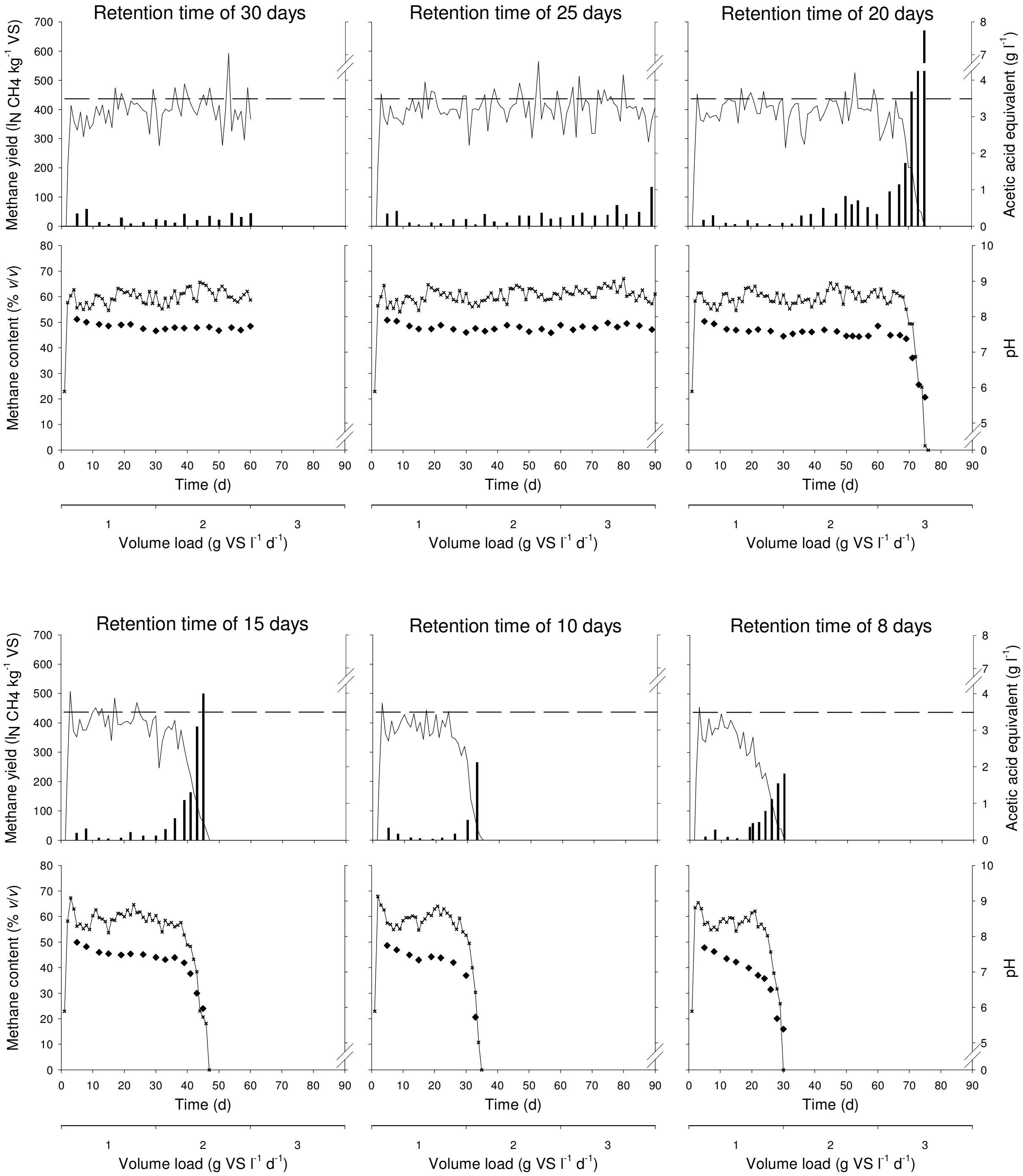

Figure 3.4 Mean values of the methane yield (*line*; s.e.=19 l_N CH_4 kg^{-1} VS), content of acetic acid equivalent (*black bar*; s.e.=0.33 g l^{-1}), methane content (*multiplication sign*; s.e.=1.5% (*v/v*)) and pH (*black diamond*; s.e.=0.10) during digestion of press fluids from mechanically dehydrated maize silages at different levels of retention time and volume load in continuous digestion tests using a stirrer tank digester. The *dashed line* indicates the maximum methane yield which was determined in batch digestion tests at a degree of decomposition of 98%.

At a volume load level of 3 g VS l^{-1} day^{-1}, daily methane production started at a low level and concentration of acetic acid equivalent was in a critical range of more than 3 g l^{-1} within the first 2 weeks. From day 15 on it continuously decreased to 1.5 g l^{-1} while methane yield increased and remained between 307 and 429 l_N CH_4 kg^{-1} VS until day 38. Stabilisation of the digestion was furthermore indicated by rising pH values at the end of the experiment and by an increasing methane content from 53.9 within the first 15 days to 62.0% (*v/v*) averaged for the remaining time. By contrast the digestion at a volume load of 5 g VS l^{-1} day^{-1} showed initially high concentrations of acetic acid equivalent above 9 g l^{-1} which remained on that level over the whole test period. Daily methane yield was permanently in a critical range of less than 200 l_N CH_4 kg^{-1} VS and decreased from day 3 on to final breakdown of gas production at day 25. pH value and the methane content have been falling since the first day of digestion.

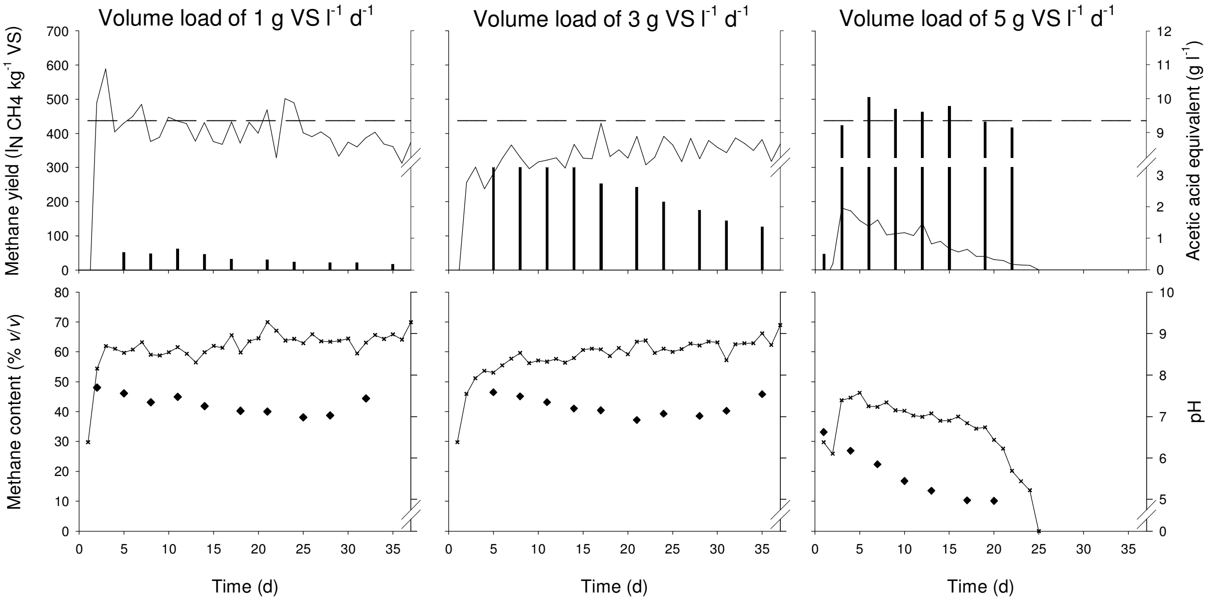

Figure 3.5 Mean values of the methane yield (*line*; s.e.=18 l_N CH_4 kg^{-1} VS), content of acetic acid equivalent (*black bar*; s.e.=0.16 g l^{-1}), methane content (*multiplication sign*; s.e.=0.7% (*v/v*)) and pH (*black diamond*; s.e.=0.04) during digestion of press fluids from mechanically dehydrated maize silages at a retention time of 8 days and different levels of volume load (1, 3 and 5 g VS l^{-1} day^{-1}) in continuous digestion tests using a fixed bed digester. The *dashed line* indicates the maximum methane yield which was determined in batch experiments at a degree of decomposition of 98%.

3.4 Discussion

3.4.1 Chemical composition of press fluids and batch digestion tests

Considering the chemical composition of the press fluids it became apparent that volatile constituents form a significant part of the total VS. VFA concentrations of the maize press fluids plus ethanol accounted for 93-224 g kg^{-1} VS. These values are well above the VFA content of untreated maize silage that range about 100 g VFA kg^{-1} silage VS or below (Fenner and Barnes, 1965; Phipps et al., 2000). This makes clear that it is essential to determine and include the VFA and other volatile substances when characterising press fluids as a reference for methane yields. Even though the data base for press fluids is still very small, analysed DM and VFA content were in good accordance (s.e. = 0.3; R^2 = 0.99**) with the empirical formula VS = 2.22 + 0.96 x $DM_{105°C}$ (Weissbach and Kuhla, 1995), which corrects the organic matter content by drying at 105°C and ashing. Thus, GC determination of VFA possibly can be replaced by calculation, but the database for the regression model needs to be further broadened.

Highest methane yields were achieved by press fluids from early-harvested maize. Differences in yields may result from chemical composition of the crop. Amon et al. (2007b) showed declining VS specific methane yields for whole crop digestion of maize ranging from 312 to 365 l_N CH_4 kg^{-1} VS (milk ripeness) to 268-286 l_N CH_4 kg^{-1} VS (full ripeness). Lower methane yields at a late-maturity stage result from decreased contents of protein, increased concentrations of fibrous constituents (Tolera et al., 1998) and lower digestibility of the starch (Fernandez et al., 2004). Furthermore, pressure and shearing forces during mechanical dehydration may have contributed to the variation in methane yields by differences in mobilisation of soluble and particulate matter. Analyses of the press fluid showed that acetic acid and ethanol had an increased share in the total VS when the maize crop was harvested at an earlier stage. The share of VFA plus ethanol in total VS decreased by trend from 224 g kg^{-1} VS for press fluids from BBCH 81 to 118 g kg^{-1} VS for press fluids from BBCH 85 (cp. Table 3.4). As acetic acid and ethanol are direct pre-products of methane synthesis (Pipyn and Verstraete, 1981), they possibly contribute to enlarged biogas production from press fluids from early harvested maize crops.

The very rapid start of biogas production within the first 4 days of digestion and its early termination after only 2 weeks proofs that the chemical composition of press fluids are completely different from the silage characteristics. Batch digestion of whole crop silages from maize takes more than 4 weeks until the gas production reaches the maximum value (Neureiter et al., 2005; Vindis et al., 2008). Obviously, the share of easily digestible constituents is significantly increased through the process of mechanical dehydration. Due to the very fast fermentation, retention time in continuously working digesters can be reduced in comparison to whole crop fermentation, where hydraulic retention times were reported to be 40-80 days (FNR, 2009).

Degrees of degradation, based on VS content, amounted for more than 90% and also achieved values of more than 100% that indicated analytical or methodological failures. Due to very small deviations between the replicates in the analysis of VS (s.e. = 0.1-2.0 g VS kg^{-1} FM) and gas amounts (s.e. = 9.0-17.5 l_N CH_4 kg^{-1} VS) that are the basis for the calculation of the degree of decomposition, analytical inaccuracy is unlikely. Possibly, the overestimation results from errors associated with the methodological approach applied using the controls. The controls may have greater digestion in the presence of press fluid than digestion of the controls in the absence of press fluid. Furthermore, degrees of decomposition may be overrated due to the fact that parts of the H contained in the methane do not originate from the organic matter of the press fluids but from dissociated H of the digester fluid. Stülpnagel et al. (2008b) showed that the relation between the amounts of H and C in common energy crops does not allow a complete conversion of C into methane. Thus, referring to the mass of organic matter, about 5% has to be added in form of H. Particularly in situations of high degradability of the biomass, these effects can lead to an overestimation of the degree of decomposition. Although further research is necessary to quantify exactly the amount of external sources for biogas production, an over-assessment of about 5% is most likely. Furthermore, the portion of biomass used for bacteria regeneration, given by VDI (2004), may be too high resulting in an increase in the calculated degree of decomposition. Values calculated on the basis of COD were about 10% lower, suggesting that COD seems to be more appropriate to determine VS content, as it necessarily affects all organic compounds compared to drying oven and VFA measuring. Thus, an underestimation of the VS content seems to be possible due to incomplete collection of all volatile compounds, also explaining the high degrees of decomposition based on VS.

3.4.2 Continuous digestion tests

Continuous digestion experiments by use of a stirrer tank digester showed that a steady-state biogas production from press fluids relies on retention times of more than 25 days and low volume loads. It can be assumed that the breakdown of methane production was mainly caused by the loss of bacteria with daily removal of digestate, since the reproduction rate of methane-forming bacteria (Archaea) can extend to more than 10 days, whereas generation time of acetogenic bacteria is only a few days (Ghosh and Pohland, 1974; Kaltschmitt and Hartmann, 2001; Weiland, 2003a). At the beginning of the digestion experiments at retention times of less than 20 days, discharge of bacteria could be compensated by high bacteria concentration of the inoculum. Thinning of the manure-rich digestate used as inoculum with a high buffer capacity (Weiland, 2003b) could have also contributed to increased concentrations of acetic acid equivalent and seemed to be a subsequent inhibitor of methane production. Archaea strongly depends on the pH value which is optimal at 7-7.5 (Kaltschmitt and Hartmann, 2001). High concentrations of VFA are caused by a large supply of immediately digestible substrates resulting in an exponential activity by acetogens leading to a major drop in pH and inhibition of methanogenesis. Furthermore, development of Archaea population is delayed in comparison to acetogenic bacteria and thus also contributes to breakdown of methane production (García-Ochoa et al., 1999). In summary, a common stirrer tank digester did not prove to be a suitable device to produce biogas from press fluids in contrast to the conversion of the untreated whole crop silages. Mechanical dehydration of the silage results in a press fluid with a strongly increased content of easily digestible constituents, leading to rapid degradation of the biomass and the necessity of biogas technologies with reduced bacteria losses.

It is in the field of wastewater treatment, where different techniques have already been developed to keep the bacteria inside the digester even when retention times of only a few hours were possible (Borja et al., 1992; Lettinga et al., 2004). However, high performance digesters with very low retention times of only few hours or days are out of question for the digestion of press fluids, because degradation minimally lasts 8 days. Furthermore, the higher share of solids in the press fluid may constrain the use of an upflow anaerobic sludge blanket reactor due to faster sedimentation or in anaerobic filters that are susceptible to plugging. Thus, adapted carrier materials have to be identified for press fluid digestion.

Improved performance concerning steady-state digestion of the press fluids in comparison to the experiments in a stirrer tank digester could be realised by use of a fixed bed digester where steady fermentation at retention time of 8 days was possible. The use of grinding fleece as carrier material for micro-organism resulted in a reduced wash-out of bacteria. Nevertheless, the stabilising impact of the grinding fleece on digestion seemed to be limited, as indicated by fermentation breakdown at high volume loads of 5 g VS l^{-1} day^{-1}. Possibly the start-up phase which is needed to build up an effective anaerobic biofilm was too short. Michauda et al. (2002) observed decreasing methane yields over 40 days after starting an anaerobic fixed-film reactor before the film was established. Thus, sufficient growth of the biofilm and in particular of the methane-forming bacteria with high doubling times was not possible in this experiment. High volume loads resulting in increased release of fatty acids require well-operating bacteria population. According to Austermann-Haun (1997), the initial starting phase should be carried out at volume load of 2 g VS l^{-1} day^{-1} followed by a stepwise increase.

Further research related to the optimisation of fixed bed digesters for the digestion of press fluids from maize silage have been done in pre-tests with different mineral and synthetic materials for bacterial colonisation. Among these fixed bed materials (quartzous granulate, diatomite, cellular material, fine and raw fleece) diatomite allowed a much more stable anaerobic digestion compared to a stirrer tank digester (Günther, 2007). Nevertheless, further research activities should aim at investigations on more different fixed bed materials and the design of the digester operation.

3.5 Conclusions

Based on the results of this study, the following conclusions can be drawn:

1. Press fluids resulting from mechanical dehydration of maize silage achieved methane yields between 390 and 506 l_N CH_4 kg^{-1} VS. The degree of degradation of VS amounted for more than 90%. Methane yields decreased with increasing crop maturity. Due to the fast and almost complete digestion of the press fluids, they proved to be a very suitable substrate for biogas production.

2. Methane production levelled off soon after a rapid starting phase. About 90% of biomass degradation took place within the first 4 days of fermentation, indicating the need for developing substrate adapted technologies for continuous digestion systems which allow shorter retention times than those in common biogas plants using untreated silages.

3. The significantly accelerated digestion of press fluids in comparison to the fermentation of the untreated maize silage requires adapted technologies for continuously working digesters. Common stirrer tank digesters did not prove to be an adequate design, as there is no carrier material for immobilisation of bacteria available. Steady-state digestion within a stirrer tank digester relies on retention times of more than 20 days and low volume loads of organic matter. Performance of digestion could be improved by an anaerobic filter. The use of grinding fleece as carrier material for biofilm permitted stable fermentation at retention times of 8 days. Breakdown of methane production at volume loads of 5 g VS l^{-1} day^{-1} indicated that further research is necessary to identify more suitable anaerobic filters and operation parameters especially during the start-up phase.

4 Effects of hydrothermal conditioning and mechanical dewatering on ash melting behaviour of solid fuel produced from European semi-natural grasslands

Abstract Biomass from high nature value grasslands is a potential resource for renewable energy production, since its use as forage is declining due to decreasing livestock levels in many European regions. This study investigated silages and the derived press cakes after hydrothermal conditioning and mechanical dewatering from 18 European grassland sites on fuel relevant parameters. Through silage treatment high reductions of the concentration in the fuel of more than 73% of Cl, K and Na were obtained. Experimental investigation of the ash melting behaviour showed an increase of the ash softening temperature (AST) from approximately 1,000°C for the ash from the silage to 1,050°C for the press cake ashes. At the spherical, hemisphere and flow temperature differences between silage and press cake ashes were even bigger and ranged from 63 to 67K. Linear regression models, which were based on the fuel content of K, Ca, Si, Al and Na, were able to predict the AST with high accuracy (R^2 = 0.88-0.89). Models showed that an increasing content of K led to decreasing AST. By contrast, AST was positively influenced by increasing contents of Ca. The effect of Si depended on the content of alkalis and earth alkalis.

4.1 Introduction

Biomass is considered as one of the major sources of future energy supply systems. However, in the recent past, agricultural energy cropping on arable land has been critically discussed for various environmental and social reasons. In many cases, the supply of energy crops is associated with an intensification of agricultural production, which might lead to environmental problems, like soil degradation and water pollution (Erb et al., 2012; Love et al., 2011). Furthermore, energy cropping is expected to have a negative impact on biodiversity and landscape value, due to the spatial concentration of monotonous crop growing (Fletcher at al., 2011; Dauber et al., 2010). Finally, questions arise about the competition on food and forage production (Harvey and Pilgrim, 2011; Murphy et al., 2011). Against this background, the extension of energy recovery from residual biomass, which can be used with less negative impacts, is object of many recommendations for political support strategies (EEA, 2011; Leopoldina, 2012).

This paper addresses a research question of a newly developed approach to exploit unused biomass resources from semi-natural grassland areas that are of particular nature conservation value. Large parts of European high biodiversity grasslands are manmade by low input management over decades, but changes of agricultural structure led to decreasing livestock in these, often disadvantaged, grassland areas (Isselstein et al., 2005). Thus, alternative options to use this biomass are highly welcome to ensure the continuation of regular biomass cut, which is the precondition of biodiversity conservation (Halada et al., 2011).

The integrated generation of solid fuel and biogas from biomass (IFBB) is adapted to the physical and chemical characteristics of grassland biomass that is characterised by a great heterogeneity of chemical constituents and high contents of minerals and nitrogen leading to problems associated with combustion, like ash melting, corrosion and harmful emissions (Wachendorf et al., 2009). By water mashing and subsequent mechanical separation of the wet conserved biomass, large parts of alkalis, chlorine and sulphur are transferred into the liquid that is used for biogas production. This leads to a considerable improvement of the quality of the solid fuel that is also characterised by a slight increase of the heating value compared to the untreated biomass (Richter et al., 2010).

Previous research on the IFBB concept was mainly focused on chemical characterisation of the grassland biomass and the derived fuels after the pressing process and the combustion performance (Hensgen et al., 2012; Bühle et al., 2011b). The study at hand investigated the ash melting behaviour of both grassland fuels and press cakes on an experimental basis using biomasses from 18 European grassland sites. The main goal was to determine the effect of chemical fuel composition on ash melting behaviour, which would allow a simplified fuel assessment in terms of furnace setup and operating conditions. The following questions were addressed:

1. How does chemical fuel and ash composition change by hydrothermal conditioning and dewatering considering parameters relevant for ash melting?
2. Is there an influence of hydrothermal conditioning and dewatering on characteristic temperatures of ash deformation?
3. Can the ash melting temperature be predicted by chemical fuel composition?

4.2 Materials and methods

4.2.1 Biomass feedstock, conservation and processing

The study was based on biomasses from each six grassland sites in Germany, Wales and Estonia (Table 4.1) in the framework of the European project PROGRASS with an average number of 45 plant species per site. The areas are of particular nature conservation value and mostly part of NATURA 2000, which is an ecological network of protected areas in the territory of the European Union. Samples were taken in 2010 with 3 replicates at each site by mowing with a finger bar mower at a stubble height of 5 cm, then they were chopped to a chopping length of 5 cm on average using a drum chopper and directly ensiled in 60-l polyethylene barrels. Harvest mainly took place at beginning of July, which is a typical date to ensure flowering and reproduction of the plant inventory and which is also in accordance with most of the European nature conservations schemes. Processing was conducted after a minimum ensiling duration of six weeks by a mobile IFBB prototype that is installed on a semi trailer and which was operated in the three European grassland regions (Hensgen et al., 2012). The silage was treated by hydrothermal conditioning (circulating percolation with tap water, silage:water ratio of 1:8) at 25°C for 30 min and subsequently dewatered by a conical screw press (type Av, Anhydro Ltd., Kassel, Germany) with a pitch of 1:6 and a sieve with punched holes of 1.5 mm.

4.2.2 Sample preparation, chemical analysis and slagging indices

Dry matter content of both silage and press cake was determined by drying of a subsample at 105°C for 48h. Ash content was measured by ashing at 550°C. Another subsample of about 500 g dry matter was dried at 105°C and was later used for combustion and subsequent analysis of the ash melting behaviour. In addition, another subsample was dried at 60°C for 48h and served for analysis of organic and inorganic compounds.

Silage and press cake were analysed for C, H, and N using an elemental analyser (Vario MAX CHN Elementar Analysensysteme GmbH, Hanau, Germany). Content of O was calculated by difference. Content of K, Na, Mg, Ca, Cl, S and P were determined by X-ray fluorescence analysis. Si, Al and Fe were determined in accordance with DIN EN 15290.

Table 4.1 Origin of silages investigated in this study.

Site		NATURA 2000 habitat type (code)	Date of harvest in 2010	Altitude (m a.s.l)	No. of species	Dominant species
Germany	I	Lowland hay meadow (6510)	07/07	570	54	*Festuca rubra, Agrostis capillaris*
	II	Lowland hay meadow (6510)	05/07	420	62	*Festuca rubra, Agrostis capillaris*
	III	Mountain hay meadow (6520)	06/07	580	77	*Festuca rubra, Sanguisorba officinalis*
	IV	Species-rich Nardus grasslands (6230)	08/07	580	61	*Festuca rubra, Nardus stricta*
	V	Molinia meadow (6410)	20/07	500	68	*Deschampsia cespitosa, Juncus acutiflorus*
	VI	Humid tall herb fringes of watercourses and woodlands (6431)	07/09	380	18	*Scirpus sylvatica, Filipendula ulmaria*
Wales	I	Degraded raised bogs still capable of natural regeneration (7120)	24/08	190	49	*Molinia caerulea, Juncus acutiflorus*
	II	Degraded raised bogs still capable of natural regeneration (7120)	07/10	160	35	*Juncus effusus, Deschampsia cespitosa*
	III	Degraded raised bogs still capable of natural regeneration (7120)	22/09	400	35	*Juncus effusus, Agrostis canina*
	IV	European dry heaths (4030)	09/09	560	25	*Vaccinium myrtillus, Deschampsia cespitosa*
	V	Not classifiable	12/08	300	45	*Pteridium aquilinum, Agrostis capillaris*
	VI	Blanket bogs (7130)	16/09	440	17	*Molinia caerulea, Festuca ovina*
Estonia	I	Northern boreal alluvial meadows (6450)	05/07	40	60	*Alopecurus pratensis, Filipendula ulmaria*
	II	Fennoscandian lowland species-rich dry to mesic grasslands (6270)	07/07	40	23	*Alopecurus pratensis, Deschampsia cespitosa*
	III	Fennoscandian wooded meadows (6530)	07/07	60	63	*Scorzonera humilis, Brachypodium pinnatum*
	IV	Northern boreal alluvial meadows (6450)	05/07	40	34	*Carex disticha, Carex cespitosa*
	V	Fennoscandian lowland species-rich dry to mesic grasslands (6270)	07/07	40	33	*Anthsicus sylvestris,Veronica longifolia*
	VI	Fennoscandian wooded meadows (6530)	06/07	60	47	*Galium boreale, Anthriscus sylvestris*

Although high uncertainties still prevail in predicting ash melting characteristics from chemical properties, in particular with regard to biofuels, a number of studies identified the influence of ash parameters on slagging behaviour. Findings of these investigations led to the development of slagging indices, which frequently showed strong correlations to slagging properties of ashes, particularly for coal and waste incineration residues (Pronobis, 2005; Dunnu et al., 2010; Kim et al., 2010). The most common slagging indices were applied in this study. Index $R_{b/a}$ (formula 1) displays the ratio between the contents of basic *(b)* compounds that lower the ash melting temperature and acidic ones *(a)*, which have an increasing effect. $R_{b/a(+P)}$ (formula 2) has been introduced to account for the lowering effect of P_2O_5 on melting temperature in case of P rich fuels, by adding the P_2O_5 content to the numerator of $R_{b/a}$. $R_{b/a\ x\ Na}$ (formula 3) particularly accounts for the lowering effect of Na by multiplying $R_{b/a}$ by the Na_2O content. The Babcock-index R_S (formula 4) considers the impact of sulphur through the multiplication of $R_{b/a}$ by the S content (% in dry fuel). The slag viscosity index S_R (formula 5) pays special attention to the interaction of Si with Fe and earth alkalis. A further index used in this study was the K/Ca ratio (formula 6). It has been identified to have a strong impact on the melting behaviour when characterising biofuels produced from wood, agricultural crops and organic residues (Öhman et al., 2000). In this study, indices were based on the contents of the corresponding oxides in the fuel. The lower the indices the lower is the risk of slagging, except for formula 5 where it is the other way round.

$$R_{b/a} = \frac{Fe_2O_3 + CaO + MgO + Na_2O + K_2O}{SiO_2 + Al_2O_3} \quad (1)$$

$$R_{b/a(+P)} = \frac{Fe_2O_3 + CaO + MgO + Na_2O + K_2O + P_2O_5}{SiO_2 + Al_2O_3} \quad (2)$$

$$R_{b/a\,x\,Na} = \frac{Fe_2O_3 + CaO + MgO + Na_2O + K_2O}{SiO_2 + Al_2O_3}\ x\ Na_2O \quad (3)$$

$$R_S = \frac{Fe_2O_3 + CaO + MgO + Na_2O + K_2O}{SiO_2 + Al_2O_3}\ x\ S \quad (4)$$

$$S_R = \frac{SiO_2}{SiO_2 + Fe_2O_3 + CaO + MgO}\ x\,100 \quad (5)$$

$$K/Ca = \frac{K_2O}{CaO} \quad (6)$$

4.2.3 Determination of ash melting behaviour

Prior to experimental determination of ash melting behaviour, the dried biomass was combusted at 815°C using a muffle oven. Tests of the ash melting behaviour were conducted on the basis of the DIN 51730 (DIN, 2007) and DIN CEN/TS 15370-1 (DIN, 2006a) standards. The ash was compacted to a cylindrical body with a diameter and height of 10 mm each. A high-temperature kiln was then used to analyse characteristic shapes of the ash while permanent heating of the kiln under oxidising conditions. The ash was heated at a rate of 10°C min^{-1} starting from 550°C. Softening temperature (A), spherical temperature (B), hemisphere temperature (C) and flow temperature (D) were measured with an accuracy of ± 25°C by visual observation.

4.2.4 Statistical analysis

Statistical analyses were done using the Software R (R Core Team, 2012). Analyses of variance (ANOVA) were performed to test for the differences between fuel parameters of the silage and press cake. Normality and homogeneity of variances as preconditions of ANOVA were tested.

Multiple linear regression analyses were performed to test for the effect of chemical constituents on the ash melting behaviour of silages and press cakes. Elemental concentrations were included in the models as main effects, quadratic terms and two fold interactions if their significance was above 5%. With regard to the degrees of freedom, a maximum of 4 elements per model was considered. Multicollinearity was tested by calculation of the variance inflation factor (VIF) and could be ruled out if VIF < 10 (Sachs and Hedderich, 2009). Model development was done according to the rules of hierarchy and marginality (Nelder and Lane, 1995). A term is included in the model if it appears as a part of an interaction or quadratic term (hierarchy). If a term appears as part of a more complex term, the term itself is not tested for significance, because the meaning would be open to misinterpretation (marginality) (Connolly and Wachendorf, 2001). Models were presented graphically. Predictions for significant main effects were presented as one line in the range of highest observed frequency of values. Significant interactions of continuous variables were plotted as three lines, one each for a high, medium and low level of one variable (approximately its mean ± s.d.), while the other variable was varied continuously (Connolly and Wachendorf, 2001).

4.3 Results and Discussion

4.3.1 Chemical fuel and ash composition and slagging indices

Hydrothermal conditioning and subsequent mechanical dewatering of the grassland silage led to considerable changes of the total ash content as well as the chemical composition of the ash (Table 4.2). Considering ultimate analysis, highest reductions by biomass treatment were obtained for Cl and smaller reductions for the total ash, S and N content. Analysis of the minerals (incl. Cl) showed that their contents added up to 88 and 85% of the total ash content of the silage and press cake, respectively, and revealed highest reductions for alkalis K and Na of more than 73%. Above-average reductions were also obtained for P, Mg and Mn of 59, 53 and 53%, respectively. By contrast, there was an increase of Si, Al and Fe content of 9, 10 and 16%, respectively, during silage treatment. These results confirmed findings by Hensgen et al. (2011) on fuel characteristics of similarly treated biomass using residual green cut, as well as values of different types of leached straw and grasses investigated by Dayton et al. (1999).

Percental composition of the ash of silage and press cake is shown in Figure 4.1. Due to the high transfer rates of K and Na into the liquid during silage treatment, the SiO_2 content considerably increased from 32% to almost 50% in the press cake, whereas the percentage of earth alkalis Ca and Mg within the ash remained almost constant.

Based on ultimate and mineral analysis, first conclusions considering the expected ash melting behaviour could be drawn from chemical constituents. The percentage of basic constituents, which increase the risk of slagging at low temperatures, is remarkably reduced in the press cake by 32%, thus, indicating a positive effect of silage treatment on fuel quality. This fact was clearly reflected when considering the slagging indices $R_{b/a}$ and R_S that showed a decline ranging between 57 and 91%. S_R increased through dewatering of the silages, thereby reducing the slagging tendency through the percental increase of Si compared to basic constituents. Also the reduction of the K/Ca ratio suggested an improvement of fuel quality.

Table 4.2 Mean values, standard error and relative change of silage and press cake constituents from 18 European grassland sites and popular slagging indices as well as level of significance of ANOVA.

	Silage		**Press cake**		**Comparison silage vs. press cake**	
	Mean	SE	Mean	SE	Rel. change	Significance
	$g\ kg^{-1}$ (dry basis)		$g\ kg^{-1}$ (dry basis)		%	*P value*
Ultimate analysis						
Ash	67.56	5.02	47.67	4.68	-29.4	$p < 0.01$
C	478.83	3.19	487.15	2.73	1.7	$p = 0.0557$
H	53.31	0.32	56.10	0.32	5.2	$p < 0.001$
N	14.59	0.26	12.08	0.37	-17.2	$p < 0.001$
O	384.08	1.99	395.97	2.28	3.1	$p < 0.001$
S	1.63	0.05	1.04	0.02	-36.5	$p < 0.001$
Cl	3.86	0.43	0.63	0.07	-83.7	$p < 0.001$
Mineral analysis (given as corresponding oxides)						
CaO	9.78	1.07	7.14	0.84	-27.0	$p = 0.0612$
MgO	4.46	0.37	2.09	0.16	-53.1	$p < 0.001$
K_2O	12.04	1.30	3.18	0.45	-73.6	$p < 0.001$
Na_2O	1.68	0.41	0.41	0.08	-75.6	$p < 0.001$
P_2O_5	4.04	0.27	1.66	0.18	-58.9	$p < 0.001$
SiO_2	21.35	2.77	23.30	3.14	9.1	$p = 0.645$
Al_2O_3	0.72	0.27	0.79	0.19	9.7	$p = 0.838$
Fe_2O_3	0.90	0.29	1.04	0.39	16.0	$p = 0.77$
Mn_3O_4	0.73	0.16	0.34	0.06	-53.1	$p < 0.05$
ZnO	0.06	0.01	0.05	0.00	-19.2	$p = 0.117$
Indices						
$R_{b/a}$	1.63	0.20	0.70	0.08	-57.4	$p < 0.001$
$R_{b/a(+P)}$	1.87	0.23	0.78	0.09	-58.5	$p < 0.001$
$R_{b/a\ x\ Na}$	3.29	1.04	0.29	0.08	-91.0	$p < 0.01$
R_S	0.26	0.03	0.07	0.01	-72.7	$p < 0.001$
S_R	56.62	2.72	67.18	2.53	18.6	$p < 0.01$
K_2O/CaO	1.50	0.24	0.50	0.07	-66.4	$p < 0.001$

Slagging indices obtained in this study were well in the range of previous investigations on biofuels, however, the literature on ash melting characteristics of biofuels is still scarce. Masia et al. (2007) reported $R_{b/a}$ values between 0.2 to 9.0 for various types of biomass. Ratios of 4.1 and 2.4 were calculated by Pronobis (2005) and Dunnu et al. (2010), respectively, for wooden biomasses. Although wood can be very heterogeneous, its characteristics can be used as a benchmark due to the widespread applications of burners using wood and the resulting experience of technological performance. Based on literature background, biomass from semi-natural grasslands used in the study at hand, and in particular the derived press cakes, seemed to have chemical characteristics that are promising regarding their use in adapted furnace units. However, it has to be kept in mind, that the slagging indices only give a hint on the probable combustion performance. Furthermore, it must be taken into account that slagging indices were developed for coals based on their mineralogical composition that is strongly different from biomass. Considering biomass ashes, well established slagging indices are not available (Masia et al., 2007).

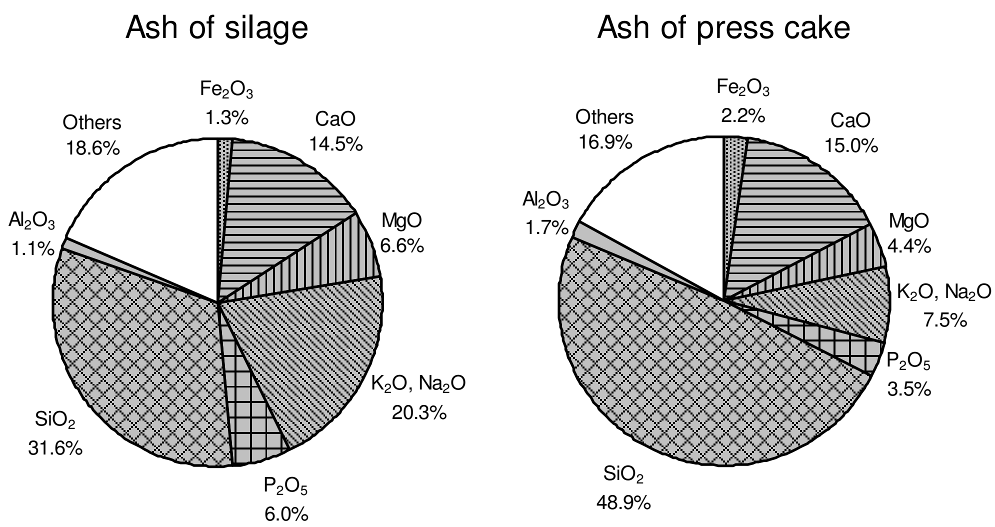

Figure 4.1 Ash composition of silage and press cake by mean values of 18 grassland biomasses.

4.3.2 Determination of ash melting temperatures

Results of the experimental determination of the ash melting behaviour are shown in Figure 4.2. At all characteristic temperatures (softening, spherical, hemisphere and flow temperature) the press cake outperformed the silage values, thereby confirming the conclusions of fuel improvement drawn from the slagging indices in the previous chapter. While softening of the untreated silage fuel ash started at about 1,000°C, it occurred in the press cake ash at about 1,050°C. At the spherical, hemisphere and flow temperature the differences between silage and press cake were even bigger and ranged from 63 to 67K.

Findings of improved ash melting behaviour of the press cake ashes in connection with the changes of chemical compounds were well in line with the results of other studies. As major drivers for lowering of the ash melting temperature, the formation of sulphates, chloride, silicates and hydroxides by alkali metals, which were remarkably reduced by silage treatment, has been identified (Dayton et al., 1999). During combustion, K normally is transformed to chloride (KCl), sulphate (K_2SO_4) or carbonate (K_2CO_3). These compounds particularly contribute to the decrease of softening temperature. For example, melting points of $Na_2S_2O_7$ and $K_2S_2O_7$ range at 401 and 325°C, respectively (Pronobis, 2005). Thus, the decrease of K in the press cake could partly explain the increase of the softening temperature of the press cake. Rise of ash softening temperatures at decreased K and increased Mg, Ca, Fe and Al were also determined by Niu et al. (2010). Similar findings were obtained by Steenari et al. (2009), who observed on the one hand highest sintering temperatures at high Si levels and low K, P, Cl, S and Ca contents, and high sintering temperatures at the absence of any KCl and K_2SO_4 compounds on the other hand. In addition, chlorides, sulphates and phosphates were present in the sample with the lowest melting point and a high K/Ca ratio (K/Ca = 2) (Steenari et al., 2009). Lindström et al. (2010) identified high alkali metal contents in connection with a certain Si concentration as a prerequisite for slagging propensity. According to Gilbe et al. (2008), this is promoted by the absence of alkali earth metals, thereby supporting the formation of alkali-silicate compounds that contribute to slagging due to melting temperatures below 800°C. The presence of chlorine additionally facilitates the reactions between alkali elements and Si (Arvelakis et al., 1999). The depletion of compounds lowering the melting temperature through fuel leaching was also observed by Masia et al. (2007).

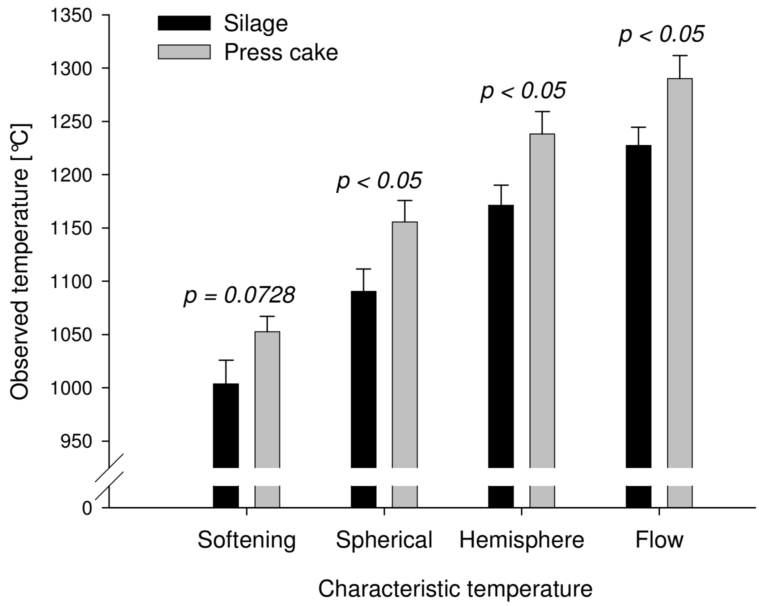

Figure 4.2 Softening, spherical, hemisphere and flow temperature of ash from silage and press cake and significance of ANOVA between silage and press cake.

Although there was a reduction of slagging tendency through silage treatment, the increase of the softening temperature was lower than expected from the calculation of slagging indices. Furthermore, values calculated with the empirical formula of Hartmann (2009), who suggested to predict the softening temperature by the equation AST (°C) = 1172 - 5.39 x K + 25.27 x Ca - 78.84 x Mg (g kg^{-1}, dry basis), did not show any relationship with the experimental values obtained in this study.

Compared to other solid fuels, as reported by Hartmann (2009), softening temperatures of the ash from press cake were in the range of lignite (1,050°C), but lower than those of hard coal (1,250°C) and by far lower than those of wooden fuels (1,280-1,430°C). By contrast, they were increased in comparison to softening temperatures of biofuels from untreated straw and grasses that mainly range between 700 and 1,000°C. However, the results of ash melting behaviour of the press cake implies, with regard to practical use in small scale furnaces less than 100 kW, that there are increased requirements of boiler design and operating conditions than those of established wood burners, in addition to fuel pretreatment. Commercial pellet burners reach temperatures of more than 1,000°C in the firebed, resulting in a risk of slagging (Vamvuka and Kakaras, 2011) when using the above mentioned press cakes.

4.3.3 Relationship between fuel parameters and ash melting behaviour

The use of slagging indices proved to be suitable indicators when characterising coal ashes with small sample size, but when applied to biomass ashes, poor quality of prediction was frequently observed (Seggiani, 1999; Steenari et al., 2009). This was confirmed in this study by regression models that were performed to test for relationships between the slagging indices and the ash softening temperature (AST). R^2 of the models was generally below 0.2, indicating that the indices were not applicable to the data set of this study. For this reason, multiple linear regression models were developed to identify relationships between AST and fuel constituents of silages and press cakes from semi-natural grassland biomass.

In all models for the press cakes, K and Ca were identified as the fuel parameters with the strongest influence on the AST. Two models were found, which additionally take into account Si and Al (model A) and Si and Na (model B), respectively, and which were able to predict the AST with high accuracy (R^2 = 0.88, 0.89, respectively) (Table 4.3). Plots of fit with observed and predicted values are shown in Figure 4.3.

Predictions of model A (Figure 4.4) revealed that Ca generally increases the AST. This effect particularly applied at levels of K (A1).

The lower the K content was the higher was the AST. Increasing Ca content also increased the AST in the interaction with Si, while the effect was higher at low Si levels (A2). The increasing effect of Ca on AST was low at low Al levels and higher at increased Al contents (A3).

Model B identified as well a decreasing effect of K on the AST (B1). It showed also a significant interaction of Ca and Si, however, there was a negative influence of Ca on AST at high Si contents (B2). Si increased the AST in the interaction with Na at average and high Na contents, but decreased the AST at low Na contents.

Table 4.3 Coefficient of determination, parameter estimates [g kg^{-1} DM], standard error of means (s.e.) [g kg^{-1} DM] and P value of the models of ash softening temperature [°C] of the press cake.

	Model A			Model B		
			P			*P*
R^2	0.88		*<0.01*	0.89		*<0.001*
R^2 adj.	0.75			0.83		
	Estimates	s.e.	*P*	Estimates	s.e.	*P*
Intercept	1114.978	78.146	*<0.001*	997.4971	29.3164	*<0.001*
K	-12.322	25.775	*0.645*	-32.5629	5.5441	*<0.001*
Ca	-22.635	18.426	*0.254*	48.7413	6.525	*<0.001*
Si	15.291	3.574	*<0.01*	14.922	2.6209	*<0.001*
Al	-421.247	143.55	*<0.05*			
Na				-368.2413	70.5423	*<0.001*
K^2	-24.221	8.321	*<0.05*			
Al^2	113.463	46.937	*<0.05*			
K x Ca	20.19	7.475	*<0.05*			
Ca x Si	-3.017	0.726	*<0.01*	-4.3868	0.6359	*<0.001*
Ca x Al	78.096	21.917	*<0.01*			
Si x Na				31.6237	6.1197	*<0.001*

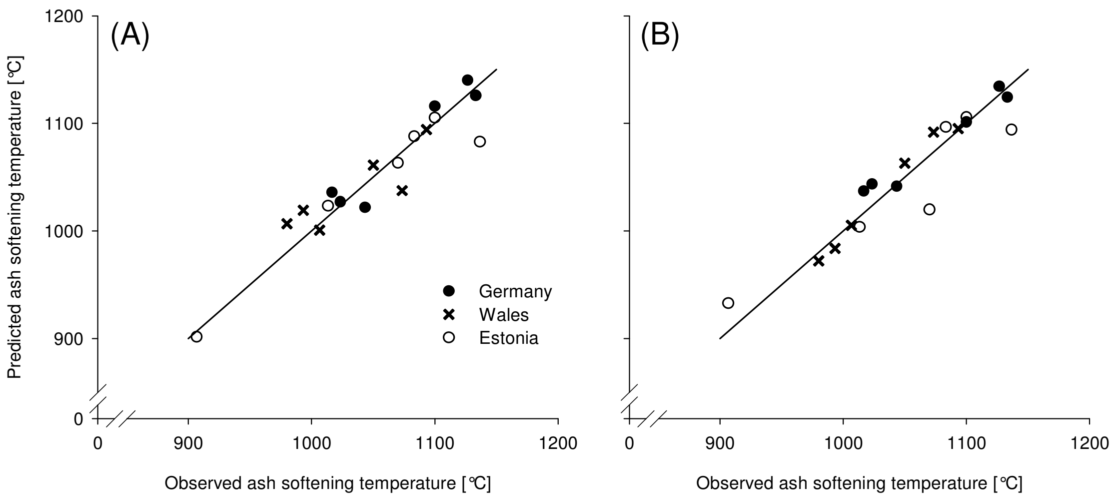

Figure 4.3 Observed and predicted softening temperatures of press cake ash of model A (A) and B (B). Samples originate from Germany, Wales and Estonia.

Results of the multiple linear regression models in general confirmed findings of other studies. High K contents might have decreased the AST due the formation of chloride, sulphate or carbonate, which have very low melting temperatures (Pronobis, 2005). The influence of Ca on AST heavily depended on the presence of alkalis and Si. An increasing effect on AST with higher Ca and lower K contents was observed by Xiong et al. (2010) and Niu et al. (2010). Interaction of Ca and Si was observed by Gilbe et al. (2008), who reported higher slagging tendencies at high Si contents and low Ca contents due to the increased formation of alkali silicates. Increasing effects of Si and Al were reported by Steenari et al. (2009) due to their ability to adsorb alkali metals ending up with minerals (e.g. $KAlSiO_4$) that have a significantly increased melting point. The increasing effect of Al has also been observed by Van Dyk (2006). It was attributed to the ability of Al_2O_3 to keep the oxygen molecules more strongly attached to the mineral molecule than the other mineral components. Furthermore, Al_2O_3 favors the formation of potassium aluminosilicates, which have a higher melting point than potassium silicates (Miller and Miller, 2007).

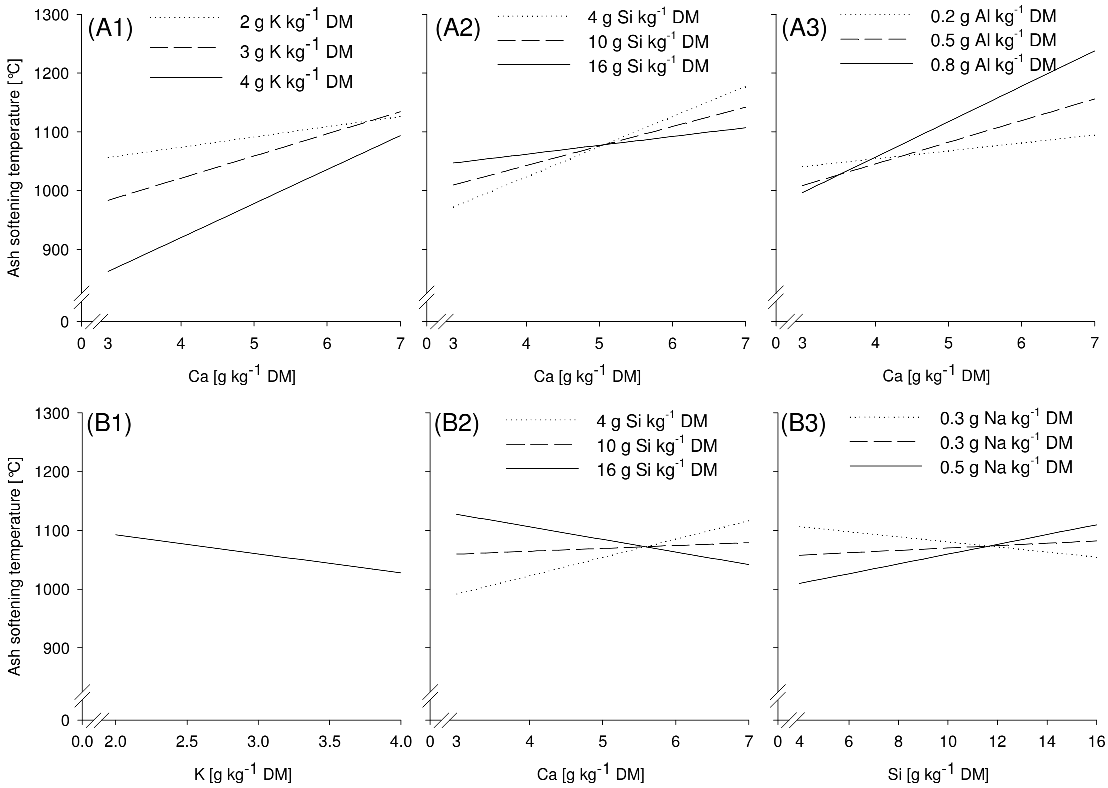

Figure 4.4 Predictions of softening temperature of the press cake ash. Model A: (A1) interaction of Ca and K, (A2) interaction of Ca and Si, (A3) interaction of Ca and Al. Model B: (B1) main effect of K, (B2) interaction of Ca and Si, (B3) interaction of Si and Na. Mean values were used for regressor variables not shown.

The models A and B have also been tested for their ability to predict the spherical, hemisphere and flow temperature. Highest levels of accuracy were obtained for the spherical temperature with R^2 of 0.99 for model A and 0.92 for model B. The reason might be a more precise visual determination of the shape of the ash at this temperature. R^2 of the models when predicting the hemisphere and flow temperature were 0.79 and 0.79 (model A), and 0.84 and 0.85 (model B), respectively. Models have also been applied to the ash melting behaviour of the silages and the combined data set of both silages and press cakes. For the ashes from silages, R^2 were even higher (0.91-0.98 for model A and 0.89-0.97 for model B). However, when the models were applied to the combined data set of silages and press cakes, R^2 were lower (0.67-0.77 for model A and 0.53-0.79 for model B).

Linear regression models showed significant relationships between press cake parameters and AST. However, from the application of the models to the combined data set including both silage and press cake it became evident that models, which are based on only few chemical constituents, have a high accuracy for AST prediction only in case of a narrow range of fuel composition. To predict the ash melting behaviour of a wider composition range, chemistry has to be considered in addition to elemental fuel composition. Thus, further research is necessary to strengthen the reliability of AST prediction. More experiments should be done with an enhanced sample size, an increased range of concentrations of the fuel constituents and also taking into account the complex chemistry during ash formation.

4.4 Conclusions

Based on the analysis and assessment of 18 ash samples from silage and press cake, originating from semi-natural grassland biomass, the following conclusions can be drawn:

1. Silage treatment led to high reductions of the concentration in the fuel of Cl, K and Na of more than 73%. Above-average reductions were obtained for P, Mg and Mn of 59, 53 and 53%, respectively. By contrast, there was an increase of Si, Al and Fe content of only 9, 10 and 16%, respectively. Looking at the ash composition, SiO_2 content considerably increased from 32% to almost 50%, while the alkalis were reduced from 20% in the silage ash to 8% in the press cake ash.

2. Softening, spherical, hemisphere and flow temperature of the ash from press cake was higher than those of the ashes from silage. Softening of the untreated silage fuel ash started at about 1,000°C, whereas the press cake ash started to soften at about 1,050°C. At the spherical, hemisphere and flow temperature the differences between silage and press cake ashes were even bigger and ranged from 63 to 67K.

3. Linear regression models, which were based on the fuel content of K, Ca, Si, Al and Na, were able to predict the ash softening temperature (AST) with high accuracy (R^2 = 0.88-0.89). Models showed that an increasing content of K led to decreasing AST. By contrast, AST was positively influenced by increasing contents of Ca. The effect of Si depended on the content of alkalis and earth alkalis. Models fitted even better when applied to the silage data set (R^2 = 0.89-0.98), but worse when applied to the combined data set of both silages and press cakes (R^2 = 0.53-0.79).

5 Comparative life cycle assessment of the integrated generation of solid fuel and biogas from biomass (IFBB) and whole crop digestion (WCD) in Germany

Abstract Today's bioenergy systems are very different in cultivation, conservation, conversion of the biomass as well as in the form of the final energy. The assessment of bioenergy systems concerning environmental impacts is increasingly up for discussion. Future challenges will be the development of procedures which reconcile high-yielding and efficient approaches with environment friendly production. Against this background the system of Integrated Generation of Solid Fuel and Biogas from Biomass (IFBB) was suggested to increase net energy yields over a wide range of energy crops in order to obtain a higher biodiversity in energy crop cultivation. In the IFBB procedure the ensiled biomass is separated into a liquid phase for biogas production and into a solid fraction for combustion.

This work is aimed at the assessment of the IFBB system in comparison to whole crop digestion (WCD). The assessment is based on crop production in a double-cropping system where winter rye and maize are grown subsequently within one growing season. The main parameters investigated are the efficiency of the whole process, primary energy and greenhouse gas savings as well as potentials of acidification and eutrophication according to principles of Life Cycle Assessment. The calculation of energy efficiency shows a superiority of the IFBB system due to a mainly thermal use of the biomass. Savings of fossil primary energy average at a similar level, whereas greenhouse gas savings are slightly higher for WCD. Investigations on acidification and eutrophication show that both bioenergy systems caused higher emissions compared to the fossil-based reference technique.

5.1 Introduction

The use of arable crops for an energetic use has increased in Germany in recent years. About 1.8 Mio hectares, respectively 17%, of the total crop land are used for the cultivation of renewable plant resources in 2007. Together with forest resources biomass has the major share in renewable energies in Germany (FNR, 2007). National as well as European policies aim at a further increase of biomass utilisation for energy production. According to the European National Biomass Action Plans (EC, 2005) the contribution of biomass use to the primary energy consumption should be increased to 12% in 2010 and the German Biomass Action Plan gives an increase of the renewable heat and power production by 100%, which should be achieved until 2020 (BMU, 2008). The main reasons for the political support of bioenergy production are the reduction of the dependence of fuel import, saving of greenhouse gas emissions and the stimulation of the rural development (EC, 2005). Furthermore, biomass utilisation may contribute to a secure energy supply through the storability of energy crops through drying or ensiling (BMU, 2008).

Studies on the availability of land resource for bioenergy production in Germany show a wide range, which largely depends on the assumptions of those studies (Bringezu et al., 2008; Zeddies, 2006). Several economic, ecological and social constraints may limit biomass potentials and affect biomass utilisation for energy recovery in general. Against the background of an increasing world population (Lutz et al., 1997) bioenergy will compete with food production on a world scale (Johansson and Azar, 2007; EPEA, 2007). Regarding Germany, food demand will remain constant (Zeddies, 2006), but global markets will promote competition on national level as well (Zeddies, 2008). Further restrictions result from requirements of nature conservation (Wiegmann and Fritsche, 2005). In the past, political promotion of bioenergy often led to monotonous cultivation methods with a dominance of a few crop species. Regarding German biogas production, 80% of the energy crop biomass is maize resulting in a high demand of plant protection and an increased risk of soil erosion and nutrient leaching (FNR, 2005; Graß and Scheffer, 2005). Furthermore, environmentally sound biomass production for energy recovery is an important precondition for social acceptance (Rohracher, 2004).

Against this background future bioenergy production systems should aim at high-yielding and efficient cultivation and conversion methods in conjunction with low environmental impacts. With the objective of reconciling these goals the University of Kassel developed a bioenergy production system including crop husbandry and conversion technique. The basic principle of the cultivation of energy plants is the double-cropping system (Scheffer and Stülpnagel, 1993; Stülpnagel et al., 2008a). The main element of the conversion procedure, the Integrated Generation of Solid Fuel and Biogas from Biomass (IFBB), is the mechanical dehydration after hydro-thermal conditioning of the ensiled biomass, which produces a solid fibrous fraction for thermal use and a liquid fraction with easily fermentable constituents for biogas production (Richter et al., 2009). The fuel quality of the mechanically dehydrated whole crop silages is improved in comparison to the untreated biomass because of the partial displacement of mineral compounds and nitrogen which are detrimental during combustion and result in increased emissions (Graß et al., 2009; Wachendorf et al., 2009).

This study is aimed at the integrated assessment of the IFBB process for arable energy crops by using the Life Cycle Assessment (LCA) methodology (DIN, 2006b). This approach comprises the calculation of energy balances and the determination of environmental impacts caused by polluting emissions. The assessment of the IFBB technique is conducted in comparison to the conventional anaerobic digestion of untreated whole crop silages (WCD), which has increased rapidly in Germany in recent years and which is suitable for a comparison, as the same crops are used and the same energy carriers are produced, i.e. electricity and heat. The results of the Life Cycle Assessment are related to the impacts of energy generation from fossil fuels. In this connection the paper adresses the following questions:

1. How do the IFBB and WCD system perform concerning internal energy flows and what degree of conversion efficiency can be achieved?
2. To what extent do IFBB and WCD contribute to savings of non-renewable primary energy and emission of greenhouse gases?
3. How big is the environmental impact regarding acidification and eutrophication by implementation of IFBB and WCD?

5.2 Materials and methods

The study was carried out according to Life Cycle Assessment methodology after DIN EN ISO 14040 (DIN, 2006b) providing a comprehensive analysis of the energy and environmental performance of a production system. The LCA tool is accomplished in four phases: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment and (4) interpretation. The calculations were implemented by using Microsoft Excel® software.

5.2.1 Parameters and assumptions

The study focuses on the development of a net energy balance as well as the environmental impacts of non-renewable primary energy consumption, greenhouse gas, acidification and eutrophication effects. The valuation of net greenhouse gas savings was based on global warming potentials from the Intergovernmental Panel on Climate Change (IPCC) considering the greenhouse gas emissions carbon dioxide, methane and nitrous oxide over 100 year time horizon (Forster et al., 2007). Carbon dioxide release from soils and sequestration has been included by calculations of humus decomposition through plant cultivation and humus increase through digestate return (VDLUFA, 2004). Evaluations of acidification potentials were carried out by means of emissions of sulphur dioxide, nitrogen oxides, ammonia and hydrogen chloride and expressed as sulphur dioxide equivalents. The eutrophication potential was calculated on the basis of the emissions of nitrogen oxides and ammonia expressed as phosphate equivalents (Guinée et al., 2002).

The findings were calculated to relate to 1 ha of crop land used as the functional unit. The allocation of the infrastructure, i.e. the manufacturing of all installations, was disregarded. Fritsche et al. (1994) assessed the energy input for building of power plants or installation engineering below 10% of total energy volume. The energy expenditure for the provision of the infrastructure of biogas plants including all engines accounts for less than 10% of total energy volume based on a period of 20 years according to Lootsma (2006). Primary energy demand for additional equipment of the IFBB system compared to WCD including material production and assembly is marginal and amounts to 126 kWh ha^{-1} a^{-1} for which reason it was not included in the energy balance. Thus, only energy and material flows resulting from the continuous operation were taken into consideration. All calculations are geographically referred to Germany under contemporary conditions.

Dimensioning of the IFBB and WCD plant was based on the assumption that 10,000 tons of dry matter are processed yearly, corresponding to 412 ha used for crop production. All plant components were dimensioned according to that annual amount of biomass. Field size was assumed to be 20 ha on average and the distance between the bioenergy plant and the field to be 4 km.

5.2.2 System description and inventory data

Several process steps are identical for the two conversion techniques. Thus, the same data were used where possible, which is a precondition for significant statements in comparative LCA calculations. When same data were applied, they are given solely in the description of the IFBB technique.

5.2.2.1 Integrated generation of solid fuel and biogas from biomass

The conversion process and essential balance parameters are shown in Figure 5.1. Data for the cultivation of winter rye and maize are derived from 2-years lasting field trials conducted at seven sites in Germany according to a common protocol (Stülpnagel et al., 2008a) (Table 5.1). The crops were grown in a double-cropping system and 150 kg nitrogen/ha were applied to each energy crop. Phosphorus and potassium supply was assumed to match the actual demand, considering the amount of nutrients recycled with the digestates. Weeding was carried out exclusively mechanical.

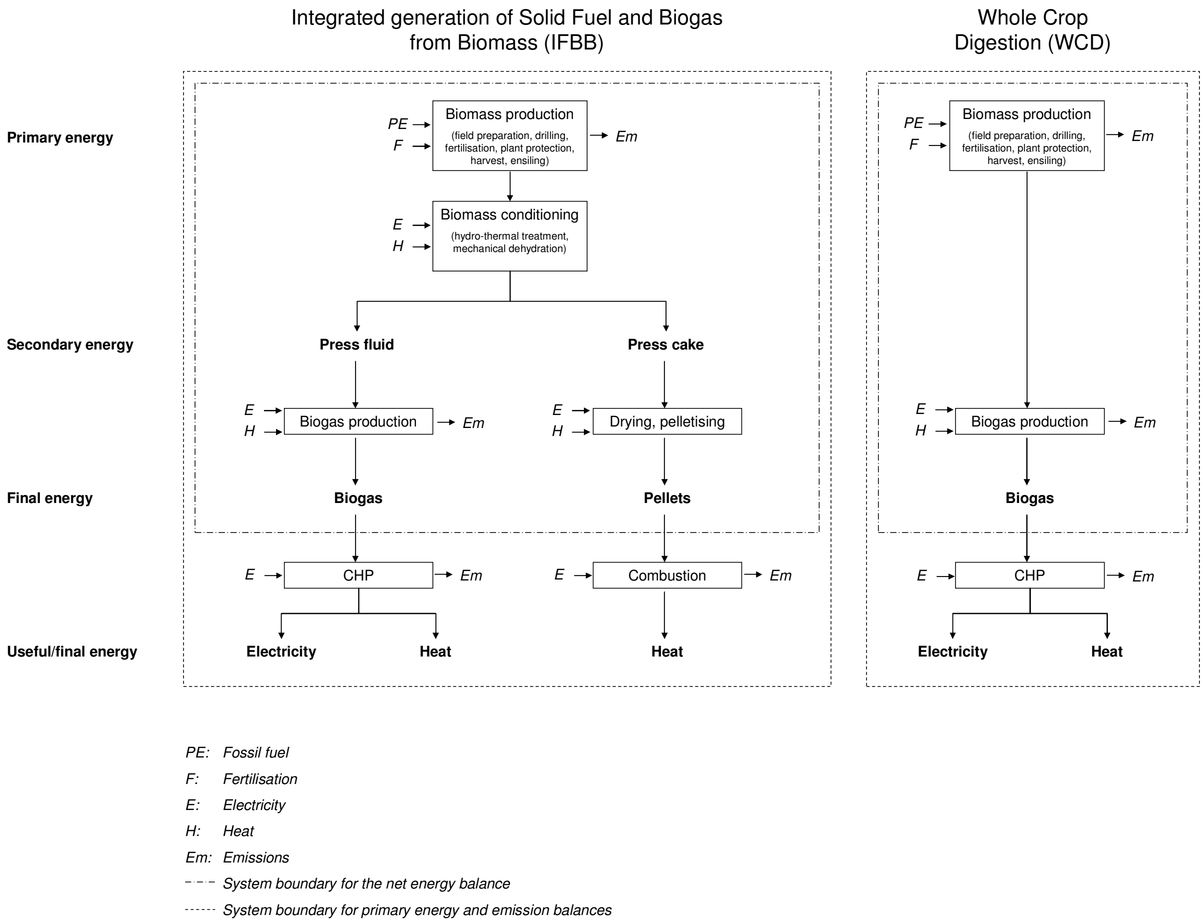

Figure 5.1 Structure and main balance parameters of the IFBB and WCD process.

Calculation of primary energy consumption and emissions resulting from cultivation, supply of operating facilities and soil emissions was based on KTBL (2005a), Kaltschmitt and Reinhardt (1997), Heinz et al. (1999) and Eggleston et al. (2006) and is listed in tables A, B and C in the appendix. Biomass yields and chemical composition were taken from Stülpnagel et al. (2008a) and losses of dry matter in the course of ensiling were estimated to be 12% (KTBL, 2006) (Table 5.2).

Energy and material flows within the IFBB process are heavily depending on the hydro-thermal treatment of the biomass. For this reason, biomass conditioning was varied in three scenarios on the basis of experimental results and estimations (Graß et al., 2009; Scheffer et al., 2007). The scenarios refer to different treatments in water mashing and thermal disintegration (Table 5.3). Maximum temperature of 60 °C was chosen because higher levels would lead to coagulation of starch with detrimental effects in the mechanical dehydration (Graß et al., 2009). Energy consumption of the screw press for mechanical dehydration was determined with different raw materials and accounts for 41.6 kWh t^{-1} DM (Bühle, 2008).

Table 5.1 Field operation data for the cultivation of winter rye and maize in the double-cropping system (Stülpnagel et al., 2008a; KTBL, 2005a; KTBL, 2006).

Operation	**Time**	**Tractor**	**Equipment**	**Fuel diesel consumption**
	(1 yr^{-1})	(kW)		(l ha^{-1} yr^{-1})
Cultivation of winter rye				
Lime spreading	0.33	67	Wheel loader	0.10
Lime spreading	0.33	67	Fertiliser spreader (8 m^3)	0.60
Stubble processing	2	120	Disk harrow (6 m)	7.21
Digestate return	1	120	Slurry tanker (15 m^3)	15.40
Ploughing	1	120	Reversible plough (6-furrows)	23.71
Drilling	1	120	Tipping trailer	0.10
Drilling	1	120	Power harrow and sowing machine (4 m)	11.80
Mineral fertiliser spreading	1	67	Fertiliser spreader (1.5 m^3)	1.02
Harvest	1	250	Self-propelled chopper (5.2 m)	19.10
Harvest	1	120	Silage trailer (40 m^3)	10.50
Harvest	1	105	Wheel loader	4.80
Silage removal	1	67	Wheel loader	8.30
Cultivation of maize				
Digestate return	1	120	Slurry tanker (15 m^3)	15.40
Stubble processing	1	120	Disk harrow (6 m)	7.21
Stubble processing	1	83	Power harrow (4.5 m)	8.87
Drilling	1	54	Pneumatic precision airplanter (6 m)	1.79
Plant protection	1	67	Mechanical hoe (12-rows)	3.30
Mineral fertiliser spreading	1	67	Fertiliser spreader (1.5 m^3)	1.02
Harvest	1	250	Self-propelled chopper (6-rows)	20.40
Harvest	1	102	Silage trailer (33 m^3)	12.05
Harvest	1	105	Wheel loader	4.80
Silage removal	1	67	Wheel loader	8.30

Biogas yields resulting from fermentation of the press fluids have been calculated according to Buswell and Müller (VDI, 2004) on the basis of the elemental composition of the press fluids and their respective digestibility. Digestibility of press fluids was determined in previous digestion experiments as 95% (Bühle et al., 2007). Due to the high digestibility retention time in the digester was set to 20 days.

Digestates were returned completely to the fields as liquid fertiliser. The biogas was used in a combined heat and power plant with a total efficiency of 80.5% (electrical: 37.5%, thermic: 43.0%). Specific emissions of the CHP were based on data from recent investigations on operating plants (LFU, 2007). Uncontrollable emissions during fermentation process are assumed to amount to 1% of the produced methane (Bachmaier et al., 2008).

Table 5.2 Dry matter yield and content, gross energy yield (lower heating value) and plant compounds of winter rye and maize as grown in the double-cropping system (Stülpnagel et al., 2008a).

Energy crop	DM yield	DM content	LHV	Compounds								
				Ash	N	K	P	Cl	S	C	H	O
	(t DM ha^{-1})	(% of fresh matter)	(MWh ha^{-1})	(% of DM)								
Winter rye	10.0	31.0	46.1	6.5	1.1	1.9	0.3	0.5	0.1	44.3	6.0	42.1
Maize	14.3	23.8	66.1	6.2	1.3	1.8	0.2	0.1	0.1	44.2	6.1	42.3

Table 5.3 Mass flow of crop compounds in mechanical dehydration after hydro-thermal conditioning at different temperature levels (Graß et al., 2009; Scheffer et al., 2007).

Scenario	Treatment	Crops	Mass flow into the press cake (%)				
			DM	Ash	N	K	P
IFBB_0	No Treatment	Winter rye	81.0	63.0	43.0	51.0	48.0
		Maize	83.0	66.0	72.0	54.0	48.0
IFBB_12	Water mashed at 12 °C	Winter rye	79.0	53.0	37.0	40.0	23.0
		Maize	66.0	37.0	46.0	24.0	23.0
IFBB_60	Water mashed at 60 °C	Winter rye	46.0	31.0	30.0	12.0	15.0
		Maize	46.0	31.0	30.0	12.0	15.0

Energy yields from solid fuels have been assessed on the basis of the elemental composition of the press cake resulting from the dehydration process after the formula of Boie (Kaltschmitt and Hartmann, 2001). For drying of the press cake to 85% DM waste heat of CHP and additional heat by combustion of press cake was used. Vaporization heat was assessed to 1.1 kWh kg^{-1} water (Raussen and Lootsma, 2008). Air ventilation was managed by an axial blower with an electrical power input of 9 kW. Electrical energy consumption for pelletising including mill, pressing, cooling and storing accounted for 113 kWh t^{-1} DM (Sokhansanj and Fenton, 2006). Transport of pellets was carried out by trucks (Kaltschmitt and Reinhardt, 1997) in a radius of 30 km around the plant. Combustion occurred in distributed combustors (forwardacting reciprocating grate) adapted to characteristics of pellets from herbaceous biomass. Calculation of emissions is based on combustion tests of dehydrated maize silage (Anonymous, 2007). Contrary to the complete nutrient return in anaerobic digestion of whole-crop silages, in IFBB not all nutrients can be recycled as fertiliser due to losses during combustion. While most of the N is lost as gaseous nitrogen oxide, 85% of P and 20% of K remain in the coarse and grate ashes after burning. The calculations are based on the assumption that the coarse and grate ashes are completely redirected to the fields.

5.2.2.2 Conventional whole crop fermentation

Data for crop cultivation in WCD are very similar to those of the IFBB procedure (Figure 5.1). Differences only occur in case of fertilisation due to increased amounts of digestate which are redirected to the field and increased emissions of ammonia during application caused by a lower infiltration into the soil (KTBL, 2005a). In general, substitution of nutrients by application of mineral fertiliser is reduced in comparison to the IFBB procedure. Within the WCD procedure biomass is converted exclusively by anaerobic digestion. Methane yields account for 348 l_N CH_4 kg^{-1} oM for silage of rye and 300 l_N CH_4 kg^{-1} oM for silage of maize (KTBL, 2005b). Electrical efficiency of the CHP was assessed to 40%, slightly higher than in the calculations of the IFBB procedure due to larger biogas plants. Uncontrollable emissions have been estimated to be 1% of the produced methane. Internal heat consumption for the digestion at 37°C was calculated on the basis of the amount of silage, its thermal capacity and the corresponding losses of transmission heat. The need for electrical power to run the plant devices was estimated to be 4% of the produced electricity (FNR, 2005).

Three scenarios have been developed for the WCD concept, differing in the extent of utilisation of waste heat. In today's biogas production about 20% of the waste heat are used for heating or drying purposes and thus may substitute fossil fuels (BMU, 2008). Regarding feed-in systems into the gas grid much higher values can be achieved. Therefore, a wide range of waste heat utilisation is covered by the WCD scenarios: 20, 50 and 80% of total waste heat available in the CHP, which is referred to as WCD_20, WCD_50 and WCD_80.

5.2.2.3 Energy supply by fossil fuels

Any assessment of environmental impacts in bioenergy production is conducted in comparison to non-renewable alternatives. The impact by the implementation of renewable energies is considerably dependent on the reference technique for fossil energy production. In the present study, data for fossil power production refer to the contemporary composition of conventional techniques, i.e. 46% coal, 24% nuclear power, 13% natural gas (GEMIS, 2007). In case of fossil heat production the today's mixture of heating oil (41%) and natural gas (57%) consumption has been taken as a basis (Table D of the appendix) (BMU, 2008).

5.2.2.4 Agricultural reference system

The agricultural reference system describes an alternative land use where bioenergy production is not carried out. It needs to be exactly defined due to the significant influence on the results of the LCA study (Jungk and Reinhardt, 2000). Based on the assumption that an alternative food or energy crop was displaced, the lost benefit needs to be taken into consideration. In the present study "fallow" was used as the reference system and thus no other land use systemwas displaced. Reasons for this assumption may be increasing yields or changed food behaviour of consumers with a reduced consumption of meat, both resulting in a release of acreage for an alternative use. Therefore, only such emissions from the soil were considered which are independent from the land use systems and do occur in any case.

5.3 Results and discussion

5.3.1 Energy efficiency of the conversion techniques

In order to assess the internal energy efficiency of the conversion techniques a comparison was accomplished on the basis of final energy, which is the supply of pelleted solid fuel and biogas in case of the IFBB procedure, whereas for WCD only the biogas yield is considered. Gross energy yields of pellets and biogas in IFBB range between 91.2 and 94.4 MWh ha^{-1} and achieve higher yields than WCD (63.4 MWh ha^{-1}). Proportion of biogas production within IFBB increases with intensified conditioning of the silage due to enhanced mass flows of dry matter into the press liquid. Internal energy consumption in IFBB (30.0-34.3 MWh ha^{-1}) is generally higher than in WCD and mainly consists of heat demand for drying of the press cake. This heat demand in turn depends on the amount of press cake produced and on its initial water content after mechanical dehydration. Primary energy input in IFBB decreases with larger press fluid and biogas production due to enhanced recycling of nutrients and subsequently reduced energy demand for nitrogen fertiliser production which is applied to compensate the losses through pellet combustion. Internal energy demand of WCD is relatively low as no energy demand for drying and pelletising occurs and only few energy is needed for nutrient substitution. Net energy production of IFBB calculated by subtracting the internal energy consumption from the gross energy production generally outperforms WCD (56.1 MWh ha^{-1}) and shows a maximal value for IFBB_12 (63.5 MWh ha^{-1}). Results do not differ among the WCD scenarios as the use of waste heat is not considered in the final energy calculation.

In relation to the gross energy yield from the field excluding any losses of ensiling process the net energy yield accounts for 57% in case of IFBB_12. IFBB_0 and IFBB_60 achieve 53% both whereas the WCD procedure shows a conversion efficiency of 50% (Figure 5.2).

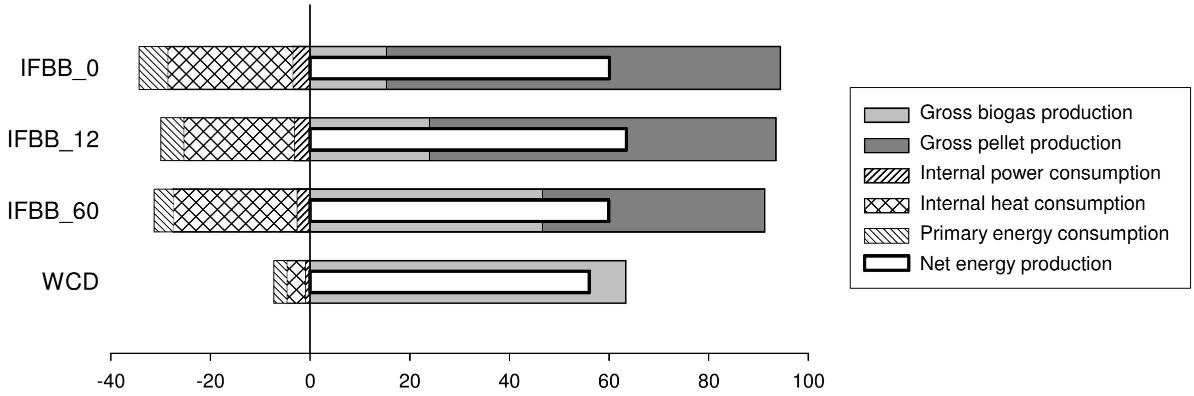

Figure 5.2 Area-related gross energy production, internal energy consumption and net energy production of the IFBB (integrated generation of solid fuel and biogas from biomass) and WCD (whole crop digestion) procedure by using rye and maize (double-cropping system).

5.3.2 Primary energy and greenhouse gas saving

Calculations on non-renewable primary energy and greenhouse gas saving potentials have been carried out on the basis of useful energy (heat and electricity).

Primary energy savings by IFBB mainly consist of avoided heat production whereas WCD particularly leads to saving of fossil fuels for power production due to increased biogas production (Figure 5.3). Savings similar to IFBB_12 (86.7 MWh ha^{-1}) and IFBB_60 (89.1 MWh ha^{-1}) can only be achieved by WCD_80 (88.4 MWh ha^{-1}) where a high proportion of the waste heat is used. Primary energy input in IFBB (3.8-5.7 MWh ha^{-1}) is slightly higher as less nutrients are recycled to the field. This results in an increased demand for mineral fertiliser whose production has quite a high energy demand. Primary energy input in WCD accounts for 2.6 MWh ha^{-1} in each scenario because only the degree of using waste heat was varied. The resulting net savings of primary fossil fuels range between 75.2 and 85.3 MWh ha^{-1}

for IFBB and between 68.5 and 85.9 MWh ha^{-1} for WCD. Thus, an almost complete use of the waste heat within WCD is necessary to match the values of the IFBB system. Although IFBB shows a higher net energy production than WCD, both techniques achieve similar net primary energy savings in the respectively most efficient scenarios (IFBB_60, WCD_80). Non-renewable power production is connected with a lower conversion efficiency in comparison to heat production. Thus, the substitution effect of WCD where non-renewable electricity production is replaced by biogas-based electricity production is more pronounced compared to the replacement of fossil heat production by biogenic solid fuels in IFBB.

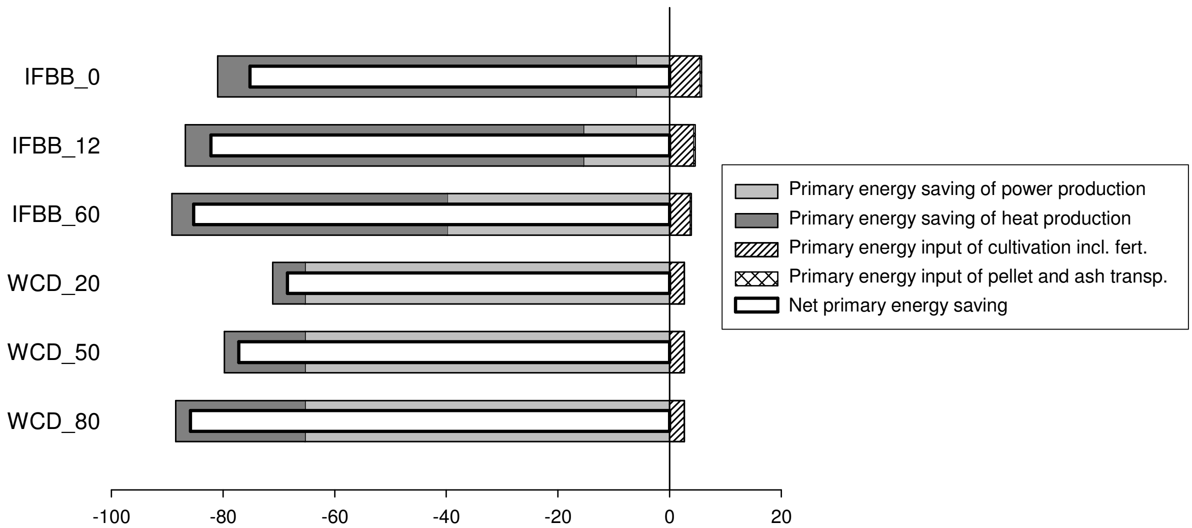

Figure 5.3 Area-related savings, inputs and net savings of non-renewable primary energy of the IFBB (integrated generation of solid fuel and biogas from biomass) and WCD (whole-crop digestion) procedure by using rye and maize.

Savings of greenhouse gases mainly consist of avoided CO_2 emissions (Figure 5.4). CH_4 savings largely result from avoided losses in natural gas use and transport. N_2O emissions do not occur to a great extent in fossil energy production.

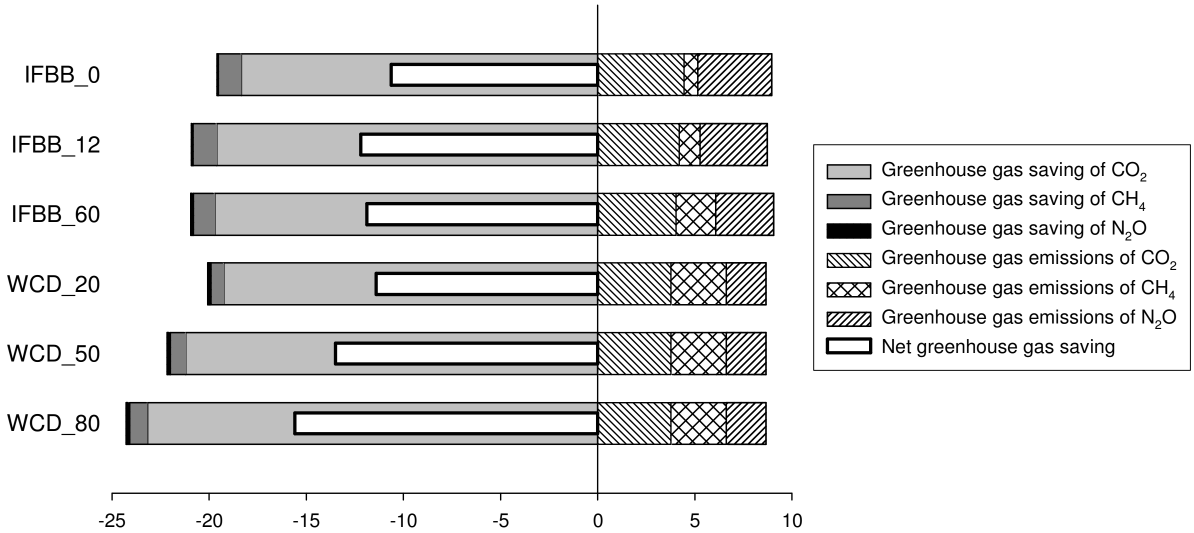

Figure 5.4 Area-related savings, inputs and net savings of greenhouse gases of the IFBB (integrated generation of solid fuel and biogas from biomass) and WCD (whole-crop digestion) procedure by using rye and maize.

Gross greenhouse gas savings of IFBB range from 19.6 to 20.9 t $CO_{2\text{-eq}}$ ha^{-1}. Savings for WCD (20.1-24.3 t $CO_{2\text{-eq}}$ ha^{-1}) are at a higher level due to increased C sequestration in the soils through digestate return and depend strongly on the extend of heat use (Table 5.4). WCD achieves higher values as IFBB, when more than 20% of the waste heat is used. Greenhouse gas emissions of IFBB (8.7-9.1 t $CO_{2\text{-eq}}$ ha^{-1}) mainly consist of CO_2 release from humus decomposition and N_2O largely caused by production, application and transformation of nitrogen fertiliser. Emissions of WCD account for 8.7 t $CO_{2\text{-eq}}$ ha^{-1} and mainly consist of CO_2 release from soils as well as CH_4 losses in connection with biogas production and use. Maximum net savings of greenhouse gases amount to 12.2 t $CO_{2\text{-eq}}$ ha^{-1} for IFBB_12 and 15.6 t $CO_{2\text{-eq}}$ ha^{-1} for WCD_80.

Calculations on soil organic carbon (SOC) dynamics are based on Table 5.4. Losses of SOC add up to 840 kg C ha^{-1} due to rye and maize cultivation for both IFBB and WCD. As there are only low amounts of digestate in the IFBB system the CO_2 balance is negative and amounts for approximately -3.0 t CO_2 ha^{-1}, whereas the SOC reduction and increase are almost at the same level in case of WCD.

Table 5.4 Soil organic carbon (SOC) reduction and increase by implementation of the IFBB and WCD system (VDLUFA, 2004).

	SOC reduction		Digestate application	SOC increase			CO_2 balance
	(kg C ha^{-1})	(t CO_2 ha^{-1})	(t DM ha^{-1})	(kg C t^{-1} DM digestate)	(kg C ha^{-1})	(t CO_2 ha^{-1})	(t CO_2 ha^{-1})
IFBB_0	840.00	3.08	0.24	150.00	35.53	0.13	-2.95
IFBB_12	840.00	3.08	0.37	150.00	55.06	0.20	-2.88
IFBB_60	840.00	3.08	0.10	150.00	15.75	0.06	-3.02
WCD	840.00	3.08	8.43	128.57	1083.91	3.98	0.90

5.3.3 Emissions leading to acidification and eutrophication

With regard to the influence on acidification, all conversion systems considered are bound up with higher emissions than the reference value (Figure 5.5). Emissions of the IFBB range from 79.5 to 82.2 kg SO_{2-eq} ha^{-1}, mainly caused by NO_x and SO_2 emissions from biogas and pellet combustion. Savings largely consist of NO_x and SO_2 avoiding, HCl does not occur to a great extent and NH_3 is not emitted in fossil energy production. Acidifying emissions of WCD are somewhat higher (89.2 kg SO_{2-eq} ha^{-1}), which is due to increased NH_3 emissions. NH_3 release, mainly caused by evaporation during application of mineral and organic nitrogen fertiliser, is higher compared to IFBB because of the higher viscosity of the digestate which reduces infiltration into the soil. NO_x emissions of WCD are on a same level compared to IFBB though less N contained in the biomass is combusted. The reason is that NO_x emissions per unit N in the fuel are considerably higher for biogas than for solid fuels. HCl emissions are marginal as in WCD combustion of solid fuel does not happen. Overall, net contribution of WCD (64.4-68.4 kg SO_{2-eq} ha^{-1}) to acidification outperforms all IFBB scenarios (58.6-61.1 kg SO_{2-eq} ha^{-1}).

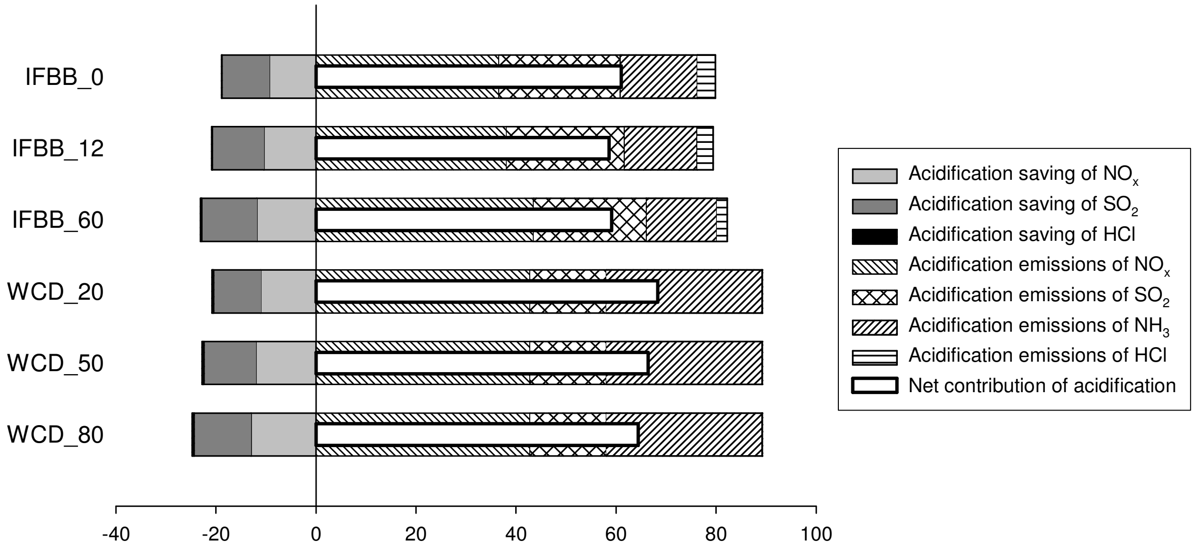

Figure 5.5 Area-related savings, inputs and net savings of emissions leading to acidification of the IFBB (integrated generation of solid fuel and biogas from biomass) and WCD (whole-crop digestion) procedure by using rye and maize.

Regarding the eutrophication potential (Figure 5.6), relevant emissions of the bioenergy procedures again exceed the savings of fossil-based energy production. Emissions of IFBB (9.6-10.7 kg $PO_{4\text{-eq}}$ ha^{-1}) of all scenarios are lower than in WCD (13.6 kg $PO_{4\text{-eq}}$ ha^{-1}) due to a reduced release of ammonia. NO_x emissions of IFBB increase with intensified conditioning of the biomass resulting in higher biogas production and enhanced specific NO_x emissions. Savings of avoided fossil energy production range from 1.7 to 2.2 kg $PO_{4\text{-eq}}$ ha^{-1} in IFBB and from 2.0 to 2.4 kg $PO_{4\text{-eq}}$ ha^{-1} in WCD procedure. Resulting net contributions are significantly lower in IFBB (7.8-8.4 kg $PO_{4\text{-eq}}$ ha^{-1}) compared to whole crop digestion (11.3-11.6 kg $PO_{4\text{-eq}}$ ha^{-1}).

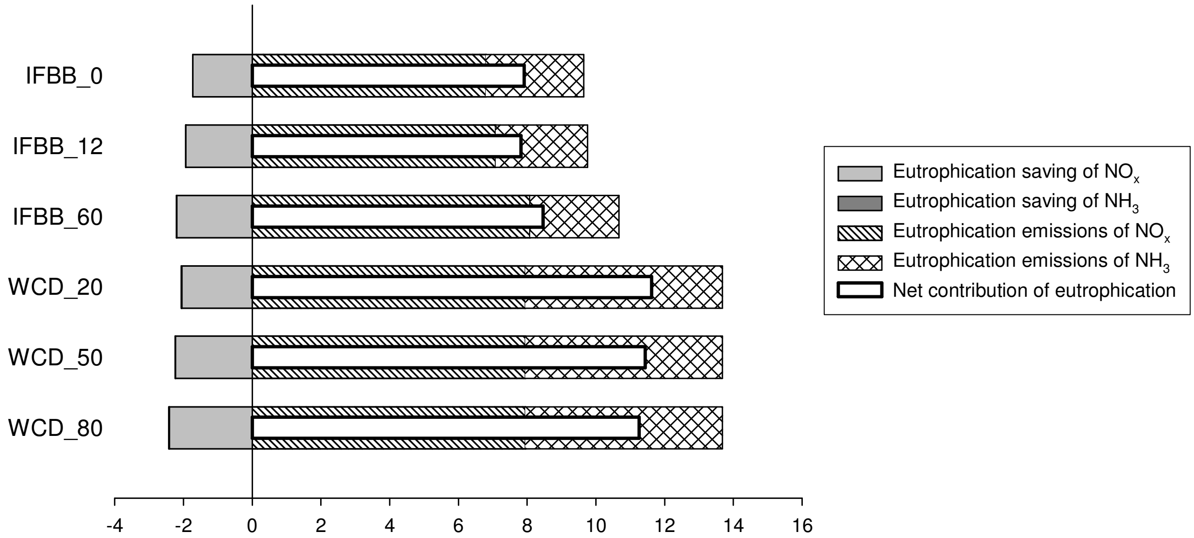

Figure 5.6 Area-related savings, inputs and net savings of emissions leading to eutrophication of the IFBB (integrated generation of solid fuel and biogas from biomass) and WCD (whole-crop digestion) procedure by using rye and maize.

5.3.4 Fuel quality

Chemical composition and combustion characteristics of the IFBB fuels (Table 5.5) are crucial for the prospects of the procedure. Considering the lower heating value, all IFBB scenarios fit the requirements of the European pellet classification (DEPI, 2010). In comparison to the untreated biomass (see Table 5.2) main compounds affecting the combustion performance can be reduced in each IFBB scenario. Except the sulphur content the mashing scenarios achieve best improvements of fuel quality. Nevertheless, level of EN B can only be reached in case of nitrogen content. Ash melting point was enhanced from 1,100°C to 1,250°C as calculated by Richter et al. (2010) for IFBB processed grassland biomass. As potassium is mainly responsible for ash melting, it should be comparable to maize and rye due to significant losses through mashing and separation. Regarding marketing of this kind of pellets regular and efficient combustion can either be achieved by using large furnaces with less requirements or to mix it with wooden pellets.

5.3.5 Consequences for soil carbon dynamics

Management of energy crops has a strong impact on the dynamic of humus and subsequently on greenhouse gas balances and soil fertility. While in WCD approximately 25-35% of the carbon exported with the crop is recycled with the digestates to the field, less than 5% of carbon is recycled with IFBB digestates. In WCD humus degradation can be balanced by recycling of the digestates (see Table 5.4). As nearly all C is oxidised either with biogas or solid fuel combustion, IFBB certainly leads soil carbon reduction when the technique is applied large-scale without any provisions to maintain soil C status. Thus, biomass production for IFBB should take place in crop rotations with a variety of other crops which have a positive C balance (e.g. food crops, catch crops). A recent study demonstrated that IFBB outperformed WCD in terms of energy efficiency and GHG saving when supplied with mature grassland biomass (Richter et al., 2010). Exploiting this biomass resource would not deplete soil C, as mineralisation processes on the permanent grassland occur at very low rates and pasture plants translocate 30-50% of assimilates below-ground through root exudation (Kuzyakov and Domanski, 2000).

Table 5.5 LHV and combustion relevant compounds of press cake from rye and maize in comparison to European pellet classification (DEPI, 2010), n.s. = not specified.

		Compounds				
	LHV	**Ash**	**N**	**K**	**Cl**	**S**
	(MJ kg^{-1})	(% of DM)				
IFBB_0	16.8	5.23	1.06	1.26	0.10	0.08
IFBB_12	16.9	4.08	0.77	0.85	0.10	0.09
IFBB_60	16.9	4.47	0.84	0.51	0.04	0.11
ENplus A1	16.5 - 19.0	≤ 0.7	≤ 0.3	n.s.	≤ 0.02	≤ 0.03
ENplus A2	16.3 - 19.0	≤ 1.5	≤ 0.5	n.s.	≤ 0.02	≤ 0.03
EN B	16.0 - 19.0	≤ 3.0	≤ 1.0	n.s.	≤ 0.03	≤ 0.04

5.4 Conclusions

Based on the results of this Life Cycle Assessment of the IFBB and WCD system the following conclusions can be drawn:

1. Gross energy yields of solid fuel and biogas in the IFBB scenarios (91.2-94.4 MWh ha^{-1}) significantly outperformed biogas yields of whole crop digestion (63.4 MWh ha^{-1}). Internal energy demand is higher in IFBB, but still its area related net energy production is higher than in WCD. The overall efficiency of pellet and biogas production related to the energy contained in the biomass amounted to 57% in IFBB and 50% in WCD.
2. IFBB achieved highest non-renewable primary energy net savings when the biomass was processed at 60 °C. This was brought about by an enlarged biogas and electricity production which in turn is coupled with increased substitution effects of fossil fuels. WCD achieved comparable net primary energy savings only when almost the complete waste heat was used. Savings of greenhouse gases of WCD were at a higher level than IFBB when use of the waste heat was more then 20% due to increased carbon storage in the soils by return of the digestates.
3. Concerning emissions leading to acidification and eutrophication of soil and water, both bioenergy systems performed worse than the fossil-based energy production, which was mainly due to increased NO_x and NH_3 emissions. Compared to IFBB, WCD resulted in a higher net contribution to acidification and eutrophication, as ammonia release in the course of fertilising with the highly viscous digestates is increased.

Looking at today’s biogas industry in Germany, a large number of biogas plants are situated in rural regions where few heat consumers are available and access to gas grids is not possible, resulting in an inefficient use of the biomass. It is precisely the situation where IFBB may provide a perspective to improve the efficiency by a complete use of the waste heat of anaerobic digestion and the delivery of a storable and transportable fuel. For a comprehensive life cycle assessment of the IFBB system future research should focus on the effects of residues from anaerobic digestion of press fluids on soil carbon dynamics and on strategies to compensate for humus losses through the thermal use of the biomass.

6 Life cycle assessment of the integrated generation of solid fuel and biogas from biomass (IFBB) in comparison to different energy recovery, animal-based and non-refining management systems

Abstract The study compares energy production from semi-natural grasslands by the integrated generation of solid fuel and biogas from biomass (IFBB) through mechanical separation of the biomass with the dry fermentation (DF) and hay combustion system (HC). In addition, traditional use for beef cattle production and non-refining systems of landscape conservation, i.e. mulching and composting, are considered. Highest conversion efficiency (45-54% of the gross yield), net savings of fossil fuels (44-54 GJ ha^{-1}) and net savings of greenhouse gases (2.9-3.7 t $CO_{2\text{-}eq}$ ha^{-1}) are obtained by HC and IFBB. Potentials of DF are limited due to low digestibility of the mature biomass.

6.1 Introduction

Due to their particular importance for biodiversity and landscape conservation, semi-natural grasslands strongly depend on the continuation of extensive agricultural practice (Halada et al., 2011). However, in many European regions an increasing abandonment of high-value grasslands has been observed over the past decades as a consequence of low economic return from grazing and forage production (Rösch et al., 2009). European nature conservation schemes and also local agricultural environmental programmes have been established aiming at the maintenance of an adapted management of the designated high-value vegetations, but they did not prove to be a sufficient framework to reduce the decline of semi-natural grasslands (Strijker, 2005). Recent evaluations of the situation of European high-value grassland have clearly stated the need to strengthen the measures to maintain the status of these sites (EC, 2009).

Apart from future strategies to improve the profitability of animal-based management of semi-natural grasslands, the use of grassland biomass for energy recovery has become increasingly relevant against the background of limited fossil energy resources, climate change and rising competition of food and energy crops on arable land (Prochnow et al., 2009; Tilman et al., 2006). Compared to biomass from high-yielding and intensively managed sites, semi-natural grasslands are highly diverse in plant and nutrient composition and rich in fibre content due to the delayed cut and, hence, have special demands on the technique used for conversion into energy carriers. Technical and economic constraints such as low anaerobic digestibility of the silage when used for biogas production as well as high proportions of minerals, nitrogen and sulphur affecting the thermal use of hay have been the main impediments to the exploitation of semi-natural grasslands for energy production up to now (Obernberger et al., 2006; Richter et al., 2009).

The present study aimed at the comprehensive assessment of a technological approach to producing energy from semi-natural meadows following the integrated generation of solid fuel and biogas from biomass (IFBB) (Wachendorf et al., 2009). The core element of this conversion system is the mechanical dehydration of the biomass after hydro-thermal conditioning. The main product is a solid fuel with improved combustion characteristics due to lower mineral content compared to the untreated biomass (Wachendorf et al., 2009). The resulting liquid is used for biogas production with a high degree of digestibility (Richter et al., 2009). The study was conducted according to the principles of life cycle assessment (LCA), considering the impact categories of conversion efficiency, non-renewable primary energy and greenhouse gas balance, as well as the acidification and eutrophication balance (DIN, 2006b). Beside the assessment of the IFBB system, alternative energy systems (dry fermentation, hay combustion), an animal based system (beef cattle husbandry) and non-refining systems (mulching, composting) have been evaluated to cover alternative management options that are in principle appropriate for maintaining the management of semi-natural grasslands. The study investigated (i) energy fluxes and conversion efficiency of the energy recovery systems, (ii) the performance of energy recovery systems in terms of non-renewable primary energy and greenhouse gas savings, as well as acidification and eutrophication potentials and (iii) the extent to which energy recovery systems differ from animal-based and non-refining systems, considering greenhouse gas, acidification and eutrophication balance.

6.2 Material and Methods

The study was based on the principles of LCA methodology according to DIN EN ISO 14040 (DIN, 2006b) providing a comprehensive analysis of the energy and environmental performance of a production system. It evaluated and compared seven management and utilisation systems of semi-natural grasslands: (1) energy recovery by the IFBB technology as a stand-alone system (IFBB-SA), (2) energy recovery by the IFBB technology as an add-on system to an agricultural biogas plant (IFBB-AO), (3) energy recovery by dry fermentation (DF), (4) energy recovery by hay combustion (HC), (5) animal-based utilisation by beef cattle husbandry (BC), (6) mulching of the grassland (MU) and (7) composting (CO) (Figure 6.1). The following sections show the conceptual framework of the study, the parameters, the assumptions made and descriptions of the systems.

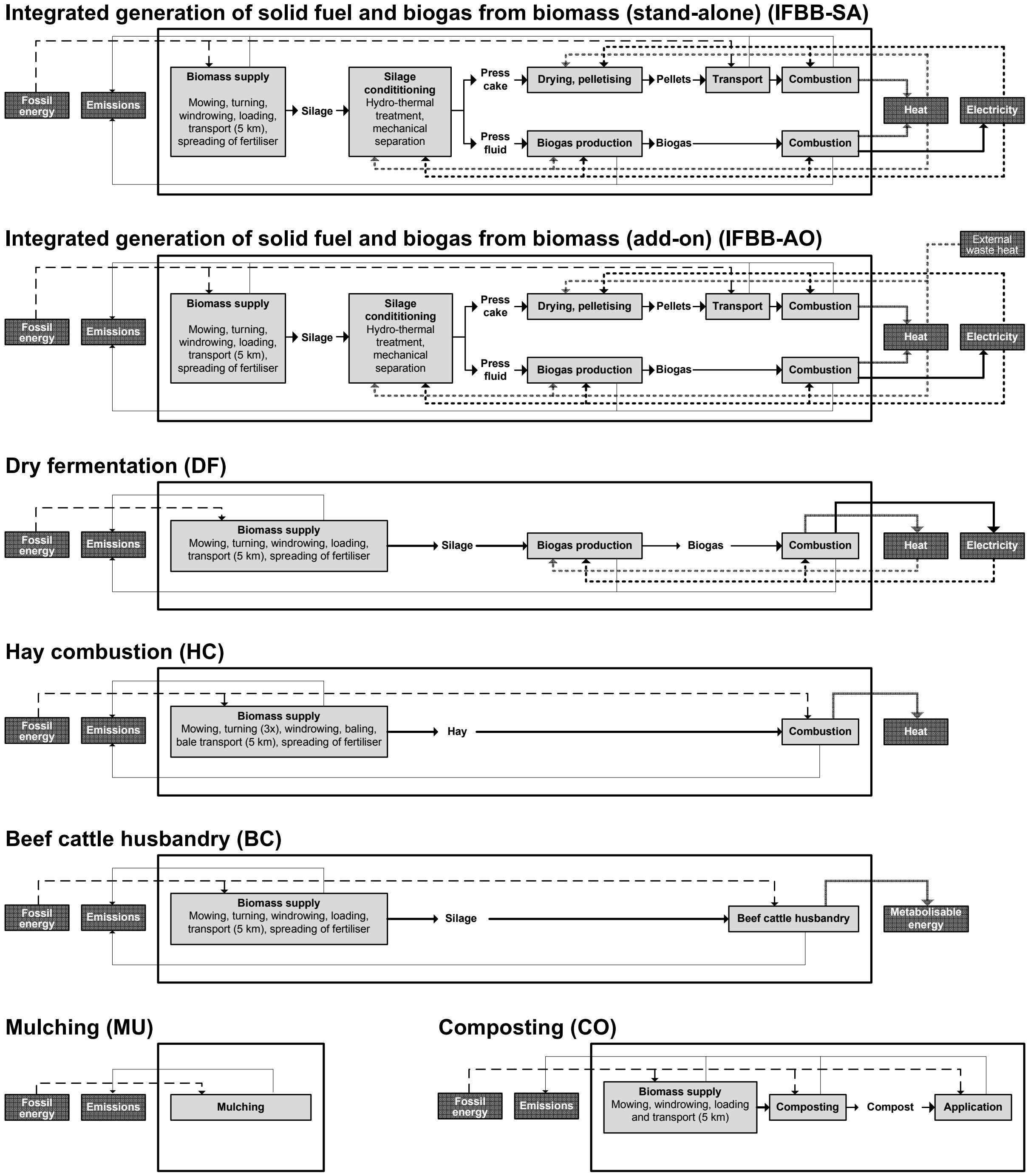

Figure 6.1 Simplified diagram of the energy recovery by the integrated generation of solid fuel and biogas from biomass as a stand-alone system (IFBB-SA), IFBB as an add-on system to an agricultural biogas plant (IFBB-AO), dry fermentation (DF), hay combustion (HC), forage use by beef cattle husbandry (BC) and the non-refining systems mulching (MU) and composting (CO).

6.2.1 Biomass feedstock

The present study was focused on semi-natural grassland swards which were established over a long period by regular grass-cutting and hay-making and which potentially are threatened by rural activity abandonment. Data used for the LCA referred to the average values of a broad evaluation of 18 European semi-natural grasslands (three sub-plots per area) in Germany, Wales and Estonia investigated within the European project PROGRASS. Regressive models (using SigmaPlot 9.0 Software) and analysis of variance (using R Software) were conducted by the data set of n = 54. The data set comprised most important habitat types of mowing management according to NATURA 2000 classification, which are listed in the Council Directive on the conservation of natural habitats and of wild fauna and flora and which are available in the particular countries. The gross biomass yield was 3.8 t DM ha^{-1} yr^{-1} resulting from a late cut in July. Data on the chemical composition of the biomass can be found in Table 6.1. Each scenario referred to biomass use from 500 ha, corresponding to an annual turnover of 1925 t DM with an average farm-to-field distance of 5 km.

6.2.2 Impact categories

The assessment was focused on the impact categories (1) conversion efficiency, (2) non-renewable primary energy balance, (3) greenhouse gas balance, (4) acidification balance and (5) eutrophication balance. These impact categories are most frequently used to characterise agricultural energy recovery systems, as they allow conclusions on the potential for saving fossil resources and for mitigating climate change, but also evaluate the negative impacts on air quality (Cherubini and Strømman, 2011). The greenhouse gas balance was based on the emissions of the three most important greenhouse gases carbon dioxide, methane and nitrous oxide over a 100 year time horizon and their global warming potentials, in accordance with the Intergovernmental Panel on Climate Change (expressed as carbon dioxide equivalents, $CO_{2\text{-eq}}$) (Forster et al., 2007). In terms of environmental concerns in soils, water bodies and atmosphere, the assessment of the acidification potential was implemented considering the emissions of sulphur dioxide, nitrogen oxides, ammonia and hydrogen chloride (expressed as sulphur dioxide equivalents, $SO_{2\text{-eq}}$). Regarding the eutrophication potential, emissions of nitrogen oxides and ammonia (expressed as phosphate equivalents, $PO_{4\text{-eq}}$) were taken into account.

Table 6.1 Mean values of chemical composition and energetic parameters of hay, silage and press cake from 18 European grasslands as well as transfer rates into the press fluid during mechanical dehydration (Bühle et al., 2011c; Bühle et al., 2011d).

	Hay	**Silage**	**Press cake**	**Transfer rate into the press fluid**
	(g kg^{-1} DM)			(%)
oM	931.0	917.4	941.9	18.4
Ash	69.0	82.6	58.1	43.2
N	14.6	15.4	12.7	34.5
S	1.3	1.6	1.0	47.0
K	8.8	10.6	2.9	78.1
Mg	2.1	2.5	1.2	58.6
Ca	5.4	6.5	5.0	37.4
Cl	3.1	3.8	0.7	83.9
P	1.5	1.8	0.7	66.8
XP		96.2		
XL		22.3		
XF		302.9		
NfE		496.0		
oNDF		601.1		
oADF		406.0		
oADL		87.5		
	(MJ ME kg^{-1} DM)			
ME^h		7.56		
	(°C)			
AST	1099.6	1085.3	1186.3	
	(MJ kg^{-1} DM)			
HVV	18.6	18.7	19.0	
LHV	17.5	17.7	17.9	

6.2.3 Functional unit and system boundary issues

The functional unit to which the input and output process data were normalised was one hectare of semi-natural grassland, as an area related unit allows the comparison of management systems with different output products. Furthermore, difficulties in the allocation of input flows on several output products can be avoided.

Inputs and outputs were taken into account along the entire process chain, including raw material acquisition, production and disposal following the cradle-to-grave principle used in LCA. Environmental impacts resulting from the supply of infrastructure such as buildings, machinery, and roads, were disregarded, as they contribute less than 10% to the total energy input over a time span of 20 years (Bühle et al., 2011a). Thus, only energy and material flows resulting from continuous operation were taken into consideration.

6.2.4 Reference system and carbon soil dynamics

Assessment of the energy recovery systems was conducted, assuming that fossil-based technologies with the same function of supply are replaced. Data for fossil systems related to the average of heat (50% natural gas, 50% fuel oil) and electricity production (43% coal, 21% nuclear power, 15% natural gas) under German conditions and were taken from GEMIS database (GEMIS, 2011). Comprehensive LCA of agricultural systems has to consider not only the replaced function, but also the displaced function of previous land use. Considering the increasing abandonment of semi-natural grasslands in Europe, it was assumed that the energy production from semi-natural grassland does not imply a displacement of food or energy crop systems. Thus, no reference system for displaced land use was considered. Only emissions of nitrous oxide from the soil were credited to the scenarios, as they occur in any case independent of the grassland use.

In general, soil carbon dynamics must be taken into account for LCA studies, particularly in the case of land use and management changes, due to their impact on greenhouse gas balances by C sequestration or release from soils. In the present study, the carbon level in the extensively managed grassland soils was assumed to be in equilibrium, without net sequestration or release of CO_2, as the previous management of regular cutting is consistent with the management considered in the LCA. C sequestration from organic residues, which are redirected to intensively managed grasslands in this study, was disregarded as well, as there are major uncertainties in terms of humus accumulation (Soussana et al., 2010). Studies report constant levels (Smith et al., 2001) as well as increases in soil organic carbon (Leifeld and Fuhrer, 2010) when organic residues are applied to permanent grasslands. Furthermore, the level of soil organic matter is more dependent on the turnover of products of decomposition and soil conditions than on the decomposition rate of the plant residues (Van Veen and Paul, 1981).

6.2.5 Systems descriptions

6.2.5.1 Integrated generation of solid fuel and biogas from biomass (stand-alone system, IFBB-SA)

Machinery and operation of harvesting and ensiling of the biomass and the related environmental impacts are shown in Table 6.2 and Table 6.3. Pick-up field and respiratory losses were assumed to be 18% (Voigtländer and Jakob, 1987). Hydro-thermal conditioning of the silage was performed at 40°C and subsequent mechanical dehydration was carried out by a screw press with an energy demand of 147.6 MJ_{el} t^{-1} DM (Bühle et al., 2011a). Material flows of plant compounds during dehydration and the chemical composition of the press cake are given in Table 6.1. Anaerobic digestion of the resulting press fluid took place in a fixed-bed digester at 37°C, with a retention time of 20 days and a methane yield of 406 l_N CH_4 kg^{-1} oM. The biogas was used by a combined heat and power plant (CHP, 50 kW_{el}, pilot injection gas engine) at 7,884 full load hours yr^{-1}, with a total efficiency of 85% (electrical: 35%, thermic: 50%) and a proportion of plant oil of 5%.

Data on emissions from biogas combustion are listed in Table 6.3. Uncontrolled emissions of methane were set as 1% of the produced methane during digestion (Bachmaier et al., 2010). Storing of the digestates took place in covered tanks. The electricity was used to run electrical devices. The waste heat of the CHP contributed to thermal drying of the press cake using a belt dryer with an efficiency of 3.92 MJ kg^{-1} water and a blower with a connected load of 13.75 kW. Additional heat for drying of the press cake to obtain a DM content of 85% was provided by solid fuel combustion. After drying, the press cake was compacted by pelletising after milling, with an electrical energy input of 406.98 MJ kg^{-1} DM. Transport distance between the IFBB plant and the pellet consumers was assumed to be 30 km. Combustion of the pellets occured with an efficiency of 84% (Kaltschmitt and Reinhardt, 1997) in decentralised staged grate firing systems and an electric energy consumption of 1.5% of the lower heating value of the fuel. The grate ash was redirected as fertiliser to intensively managed grassland sites combined with the residues from press fluid digestion. The amount of digestate applied was set at 30 m^3 ha^{-1}. It was assumed that 85% of P and K remain in grate ash after burning and serve as fertiliser. Data related to fertilisation of the digestate in terms of emissions and credits for the replacement of mineral fertiliser (nitrogen, phosphor, potassium) are shown in Table 6.3 and Table 6.4. Emissions of SO_2 and HCl during combustion were calculated assuming transfer rates into the ash of 45% and 89% for S and Cl, respectively (Kaltschmitt and Reinhardt, 1997).

Table 6.2 Field operation data for the IFBB, DF, HC, BC, MU and CO system at a farm-field distance of 5 km (KTBL, 2010).

Machinery	IFBB	DF	HC	BC	MU	CO	Fuel diesel consumption (l ha^{-1} yr^{-1})
Pasture harrow, 6 m, 54 kW	x	x	x	x			3.37
Rotary mower incl. conditioner, 3.2 m, 83 kW	x	x	x	x		x	4.59
Mulcher, 4.5 m, 83 kW					x		8.73
Rotary tedder, 8.5 m, 67 kW	x	x	x[g]	x			2.61
Rotary wind-rower, 7.5 m, 83 kW	x	x	x	x		x	3.35
Self-loading trailer, 40 m^3, 10.6 t, 175 kW	x	x		x		x	12.74
Ensiling, wheel loader, 13.5 t, 105 kW, 4 m^3	x	x		x		x	1.95
Round baling, 1,5 m, 320 kg/bale, 67 kW			x				3.36
Bale transport, 2 x 8 t, 1750 daN, 67 kW			x				2.34
Silage/hay feeding, wheel loader, 67 kW, 2 m^3	x	x	x	x			4.40
Digestate application, slurry tanker, 24 m^3, 12 m, 160 kW	x			x			17.44
Digestate/compost loading, wheel loader, 83 kW, 3 m^3		x				x	1.55
Digestate/compost spreading, manure spreader, 20 t, 102 kW		x				x	16.90

[g] tedding was conducted three times

6.2.5.2 Integrated generation of solid fuel and biogas from biomass (add-on system to agricultural biogas plant, IFBB-AO)

The large proportion of unused waste heat of conventional agricultural biogas plants with anaerobic digestion of whole crop silages is one of the biggest problems affecting the overall efficiency of this rapidly growing technology. On the other hand, the recently suggested IFBB system, which is particularly designed for fibre-rich substrates with low anaerobic digestibility, has an inherent lack of drying heat and thus, the combination of both technologies must be considered. Furthermore, much of the infrastructure can be used by both procedures, such as digester, CHP and farming machinery. The difference between this scenario and the stand-alone scenario was the source of the heat for drying of the press cake, which came from the CHP of the associated plant and which was assumed to be inapplicable to other heat consumers. Environmental impacts of the supply of the waste heat were allocated by the proportion of heat energy produced by the biogas plant.

Table 6.3 Non-renewable primary energy demand and emissions resulting from supply and use of diesel, plant oil, heat from a biogas plant and mineral fertiliser as well as emissions resulting from combustion of biogas, solid fuel (IFBB) and hay (LFU, 2007; GEMIS, 2011; Heinz et al., 1999).

	Primary energy	**CO_2**	**CH_4**	**N_2O**	**NO_x**	**SO_2**	**NH_3**	**HCl**
	($MJ\ MJ^{-1}$)	($g\ MJ^{-1}$)						
Diesel (agriculture)	1.15	85.26	0.02	1.92×10^{-3}	0.83	0.04	3.70×10^{-6}	0.75×10^{-3}
	($MJ\ tkm^{-1}$)	($g\ tkm^{-1}$)						
Diesel (transport)	1.31	97.69	0.05	1.22×10^{-3}	0.56	0.07	15.83×10^{-6}	1.43×10^{-3}
	($MJ\ MJ^{-1}$)	($g\ MJ^{-1}$)						
Plant oil (rape seed)	0.21	13.23	0.02	69.63×10^{-3}	0.07	0.02	92.45×10^{-3}	0.80×10^{-3}
	($MJ\ MJ^{-1}$)	($g\ MJ^{-1}$)						
Heat by biogas plant	0.29	17.21	0.06	17.36×10^{-3}	0.08	0.02	30.93×10^{-3}	0.19×10^{-3}
	($MJ\ kg^{-1}$)	($g\ kg^{-1}$)						
Nitrogen fertiliser	51.15	2946.28	6.13	15.12	16.11	4.64	6.69	0.08
Phosphor fertiliser	18.15	1174.16	1.59	0.06	9.81	11.91	0.01	0.02
Potassic fertiliser	18.98	1097.49	2.54	0.06	1.81	0.41	2.82×10^{-3}	0.08
	($MJ\ MJ^{-1}$)	($g\ MJ^{-1}$)						
Heat	1.36	88.51	0.19	0.91×10^{-3}	0.06	0.06	10.09×10^{-6}	0.47×10^{-3}
Electricity	2.27	156.11	0.19	6.95×10^{-3}	0.17	0.09	2.62×10^{-3}	3.25×10^{-3}
		($g\ MJ_{el}^{-1}$)						
Biogas			0.97	4.49×10^{-3}	1.53	23.7×10^{-6}	0.00	0.00
		($mg\ m^{-3}$)						
IFBB fuel			0.57	27.27	183.50	142.08	0.00	10.32
Hay			0.57	27.27	183.50	181.08	0.00	44.47

6.2.5.3 Dry fermentation (DF)

Anaerobic digestion of whole crop silages is a highly mature technology for converting wet conserved biomasses into energy, however, the use of grasslands in continuously working wet fermentation systems entails several problems due to floating layers and the resulting high energy input (Prochnow et al., 2009). Thus, in this study, the dry fermentation system was operated as a batch unit with percolation of the fluid. Feedstock and machinery related data were identical to those used for the IFBB system (Table 6.1 and Table 6.2). Methane yields for silages were assumed to be on the same level as wet fermentation systems (Weiland, 2010) and were calculated based on the stoichiometric potential multiplied by the respective digestibility of the organic compounds crude protein, crude fat, crude fibre and nitrogen-free extract and accounted for 213 l_N CH_4 kg^{-1} oM. The proportion of the waste heat used for substitution of fossil fuels was set at 50% of the exportable heat, as a year-round and complete use of the waste heat is rarely possible. Most of the assumptions on CHP performance corresponded to the IFBB scenario, whereas the electrical power was 227 kW due to complete use of the biomass for anaerobic digestion. The digestate was redirected to intensively managed grasslands after gasproof storage.

6.2.5.4 Hay combustion (HC)

Within the hay combustion system, the biomass was conserved by field drying and compacted by round baling (Table 6.2). Field losses were assumed to be 36% (Voigtländer and Jakob, 1987). After transport, the biomass was pelletised and then distributed with an average distance to the consumers of 30 km. Internal energy demand and emissions connected with transport, pelletising and combustion corresponded to the assumptions made for solid fuel of the IFBB scenario and are shown in Table 6.3. The grate ash was assessed by the fertiliser value of P and K as credits for the replacement of mineral fertiliser (Table 6.3).

6.2.5.5 Animal-based utilisation by beef cattle husbandry (BC)

Data for environmental impacts of the silage production as forage for beef cattle husbandry were concordant with the systems described for energy recovery. In contrast to the previously described scenarios of energy recovery, the reference system for beef cattle husbandry based on semi-natural grassland feedstock (BC) was a beef cattle system that is based on intensively managed grassland. Environmental impacts of the reference system, which were replaced by the beef cattle system fed by semi-natural grasslands, were calculated assuming that the supply of metabolisable energy (ME) for meat production is equivalent. Both BC and the reference system were assumed to be an indoor housing of animals, as the forage within the BC scenario comes from meadows, which were typically formed by mowing management and do not allow grazing. Dry matter intake was assumed to be 10 kg DM day^{-1} $animal^{-1}$. Intensive grassland management was defined as a three cut system with a fertiliser input of 240 kg N ha^{-1} by application of slurry and mineral fertiliser and a biomass yield of 11.0 t DM ha^{-1}. Its nutritive value was set at 10.4 MJ ME kg^{-1} DM compared to 7.6 MJ ME kg^{-1} for the semi-natural grassland sward, while acid detergent fibre (ADF) and acid detergent lignin (ADL) were assumed to be 312 and 57 g kg^{-1} DM, respectively for the intensive system (Ellis et al., 2007). Ammonia emissions of slurry application were derived from data shown in Table 6.4 and annual emission of indoor breeding was assumed to be 5 kg NH_3-N $animal^{-1}$ (Dämmgen and Hutchings, 2008), leading to ammonia emissions of 4.3 kg NH_3-N ha^{-1} for the extensively managed grassland feedstock at a stocking rate of 0.9 animals ha^{-1} assumed in this study. Methane emission from beef cattle was calculated according to the model of Ellis et al. (2007): CH_4 (MJ d^{-1}) = 2.94 (±1.16) + 0.059 (±0.0201) x ME (MJ d^{-1}) + 1.44 (±0.331) x ADF (kg d^{-1}) - 4.16 (±1.93) x ADL (kg d^{-1}), resulting in specific methane emissions of 2.55 (semi-natural grassland feedstock) and 2.16 g CH_4 MJ^{-1} ME (intensively managed grassland feedstock), respectively. The slurry from both extensive and intensive management systems was assessed by its fertiliser value for N, P and K, with a rate of utilisation by the beef cattle of 20%, applied to intensively managed grassland sites. Nutrient losses and exports on the farm level were compensated by application of mineral fertiliser within the intensive system.

Table 6.4 Field emission factors of nitrous oxide, nitrogen oxide and ammonia caused by application of nitrogen from the integrated generation of solid fuel and biogas from biomass (IFBB), dry fermentation (DF), beef cattle husbandry (BC), mulching and composting (Eggleston et al., 2006; Heinz et al., 1999; KTBL, 2005a; KTBL, 2007).

Emission factors of nitrous oxide		
N_2O-direct from applied nitrogen	(kg N_2O-N kg^{-1} N)	0.01
N_2O-indirect from atmospheric deposition	(kg N_2O-N kg^{-1} (NH_3-N+NO_x-N))	0.01
Emission factor of nitrogen oxide		
NO_x	(kg NO_x-N kg^{-1} N_2O_{direct}-N)	0.50
Database for the calculation of the emission factor of ammonia		
Ammonia content of IFBB derived digestate	(kg NH_4-N kg^{-1} N)	0.71
Ammonia content of DF derived digestate	(kg NH_4-N kg^{-1} N)	0.66
Ammonia content of BC derived slurry	(kg NH_4-N kg^{-1} N)	0.59
Ammonia loss during application of IFBB derived digestate	(kg NH_3-N kg^{-1} NH_4-$N_{appl.}$)	0.20
Ammonia loss during application of DF derived digestate and BC derived slurry	(kg NH_3-N kg^{-1} NH_4-$N_{appl.}$)	0.40
Ammonia loss during application of mineral fertiliser	(kg NH_3-N kg^{-1} NH_4-$N_{appl.}$)	0.02
Reduction of losses by hose-towed spreader for IFBB derived digestate	(%)	50.00
Reduction of losses by hose-towed spreader for DF derived digestate and BC derived slurry	(%)	30.00

6.2.5.6 Mulching system (MU)

Mulching as a non-refining management system of the grassland is conducted in many European regions to ensure a minimum level of maintenance of habitats as required by the European Union regulations (EC, 2003). Data on machinery and related environmental impacts are shown in Table 6.2 and Table 6.3. Decomposition of the remaining plant litter was assessed by emissions shown in Table 6.4 based on residual nitrogen.

6.2.5.7 Composting (CO)

If the grassland biomass cannot be used by energy recovery or animal-based procedures, and if national or local regulations prescribe annual removal of the biomass due to habitat protection reasons, composting is a frequent option for subsequent treatment of the harvested biomass. After harvest and transport to the compost plant, the grassland biomass was composted by aerating and mixing with an electrical energy demand of 540 MJ t^{-1} biomass (Margull and Stegmann, 1996) to reduce anaerobic decomposition. It was assumed that 81% of the initial carbon is transferred into CO_2 during the rotting process. Emission factors of the initial carbon were set at 1.7% for transfer into CH_4 and 0.04% into CO. 0.5% of initial nitrogen was transferred into N_2O and 1.2% into NH_3 (Hellebrand, 1998). The compost was spread as fertiliser on intensively managed grasslands with an average distance of 5 km to the compost plant. Credits for the fertiliser were taken into account for N, P and K.

6.3 Results and discussion

6.3.1 Internal energy fluxes and conversion efficiency of the energy recovery systems

Analysis of internal energy fluxes (disregarding the input of fossil energy) of IFBB-SA showed that hydro-thermal conditioning and separation of the silage led to a major transfer of the energy into the solid fraction, while approx. 20% were transferred into the liquid (Figure 6.2). Energy contained in the press fluid, which was converted to heat and electricity, was completely used to cover the internal energy demand. The internal heat demand was made up of 40.0% from waste heat of CHP and 60.0% from solid fuel combustion. This corresponded to an internal use of the pellets produced of 15.2%. Finally, this resulted in a solid fuel with an exportable heat output corresponding to 44.7% of the gross energy yield. When the system was combined with an agricultural biogas plant (IFBB-AO), the heat output could be raised to 52.9%, due to the fact that fewer pellets were required for drying. Within DF, the silage was completely directed into the fermenter for anaerobic digestion. Low degradability resulted in remarkable energy losses (51.1%) by the organic matter contained in the digestate. The internal electricity demand amounted to approx. 10% of the electricity production and only 0.9% of the gross energy yield. Assuming that 50% of the exportable heat was used, the heat output that actually served to replace fossil fuels was 7.0% of the gross energy yield. Heat and electricity output of DF added up to 16.9% of the gross energy yield, which could be increased in the case of full heat exploitation to 23.9%. Within HC, energy losses consisted of increased field losses through frequent turning and pick-up losses of the dry material as well as heat losses during combustion. HC had a conversion efficiency of 53.8% that was almost similar to IFBB-AO. These two technologies had the highest conversion efficiency among the energy recovery systems considered in this study.

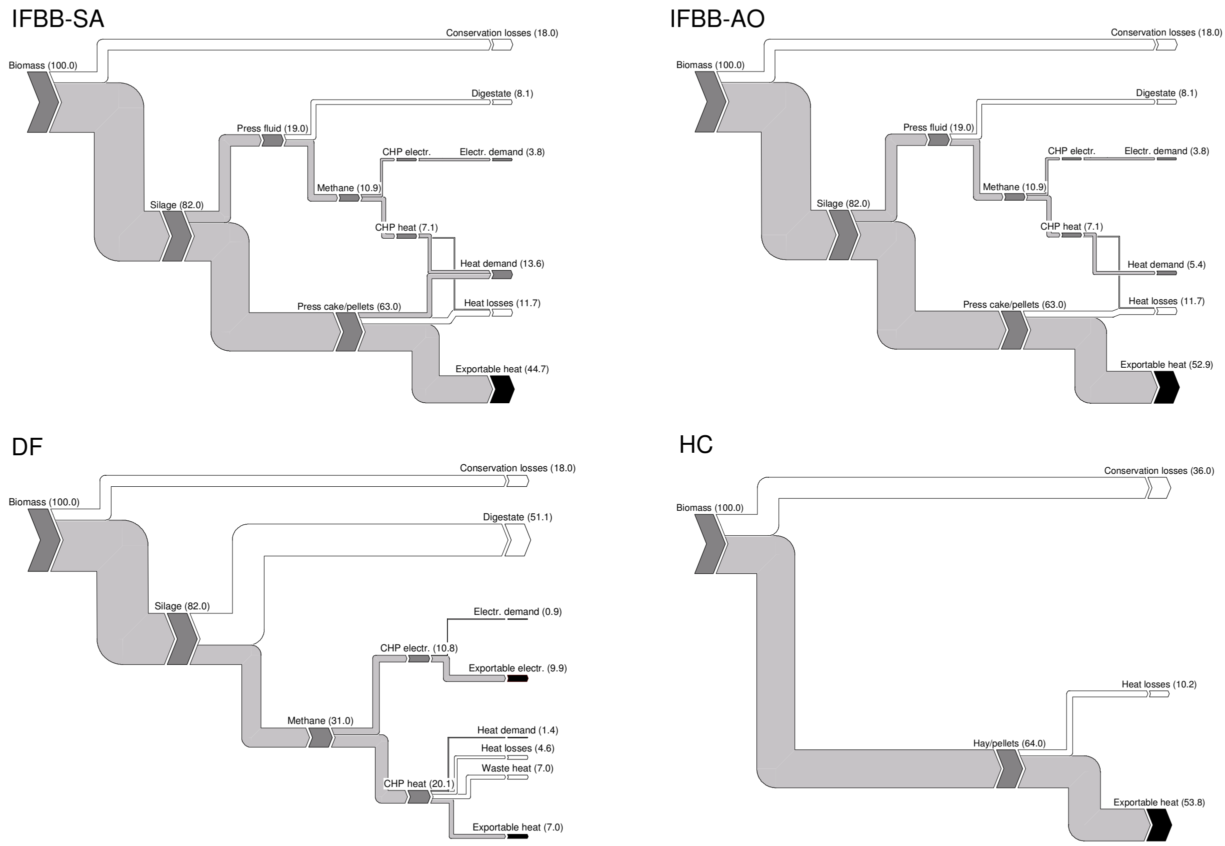

Figure 6.2 Sankey diagrams for the internal energy fluxes and conversion efficiency of the integrated generation of solid fuel and biogas from biomass as a stand-alone (IFBB-SA) and an add-on system (IFBB-AO), dry fermentation (DF) and hay combustion (HC) (primary energy demand disregarded). Numbers in brackets show the percentage of the gross energy yield.

6.3.2 Non-renewable primary energy balance

As opposed to the assessment of the conversion efficiency (see Section 6.3.1), the balance of non-renewable primary energy included the input of fossil energy and additionally rated the energy carriers by their primary energy value (Figure 6.3a). Gross savings of non-renewable primary energy by the IFBB system accounted for 65.0 GJ ha^{-1} and consisted of substitution of fossil heat production for the most part and of substitution of fossil power and fertiliser production to a lesser extent. Energy input added up to 21.2 GJ ha^{-1} for the stand-alone scenario and 10.8 GJ ha^{-1} for the add-on scenario which used the drying heat from an external biogas plant. Net energy savings were 43.8 GJ ha^{-1} for the stand-alone system and 54.3 GJ ha^{-1} for the add-on scenario. Low digestibility of the feedstock led to a low outcome within the dry fermentation system. Furthermore, its gross savings were highly dependent on the proportion of waste heat use, which was set at 50% in the scenario considered. Fertiliser credit was slightly higher than for IFBB, as anaerobic digestion allowed almost complete redirection of N, P and K to the field. Diesel input was somewhat higher, due to increased digestate spreading, whereas the thermal and electrical input was lower compared to the IFBB scenarios. Net energy savings finally accounted for 25.4 GJ ha^{-1}. Increased field losses and complete gaseous loss of nitrogen during thermal use within the hay combustion system, whose gross savings consist of 99% heat substitution, were responsible for lower outcomes than those of IFBB, but the low energy input of HC resulted in net savings of 44.7 GJ ha^{-1}. The mulching system showed small net consumption of non-renewable primary energy due to the absence of any credits. Though there was a substitution effect of mineral fertiliser within the compost system (3.2 GJ ha^{-1}), high input in the rotting treatment, which was needed to reduce anaerobic decomposition and the resulting release of greenhouse gases, led to net consumption of fossil energy of 11.4 GJ ha^{-1}. Linear regression models of non-renewable primary energy savings based on results from 18 x 3 grassland sites showed strong dependencies (r2 > 0.96) on the dry matter yield for all of the energy recovery systems considered (Figure 6.4a). In addition, analysis of variance revealed significant differences ($P < 0.001$) of net savings of the dry fermentation system compared to IFBB and hay combustion. Sensitivity analysis of the farm-field distance showed a minor impact of the fossil energy input for biomass transport on the outcome of the primary energy balance (Figure 6.4b). There was an increase in the diesel input ranging from 1 to 30 km distance of 106.2, 106.2, 121.3 and 32.1% for IFBB-SA, IFBB-AO, DF and HC, respectively. This resulted in a slight decrease of the non-renewable primary energy savings of 3.5, 2.8, 7.3 and 0.9% for IFBB-SA, IFBB-AO, DF and HC, respectively. The particularly low influence of the transport distance within HC was caused by a comparatively low diesel input for the transport of the field-dried biomass.

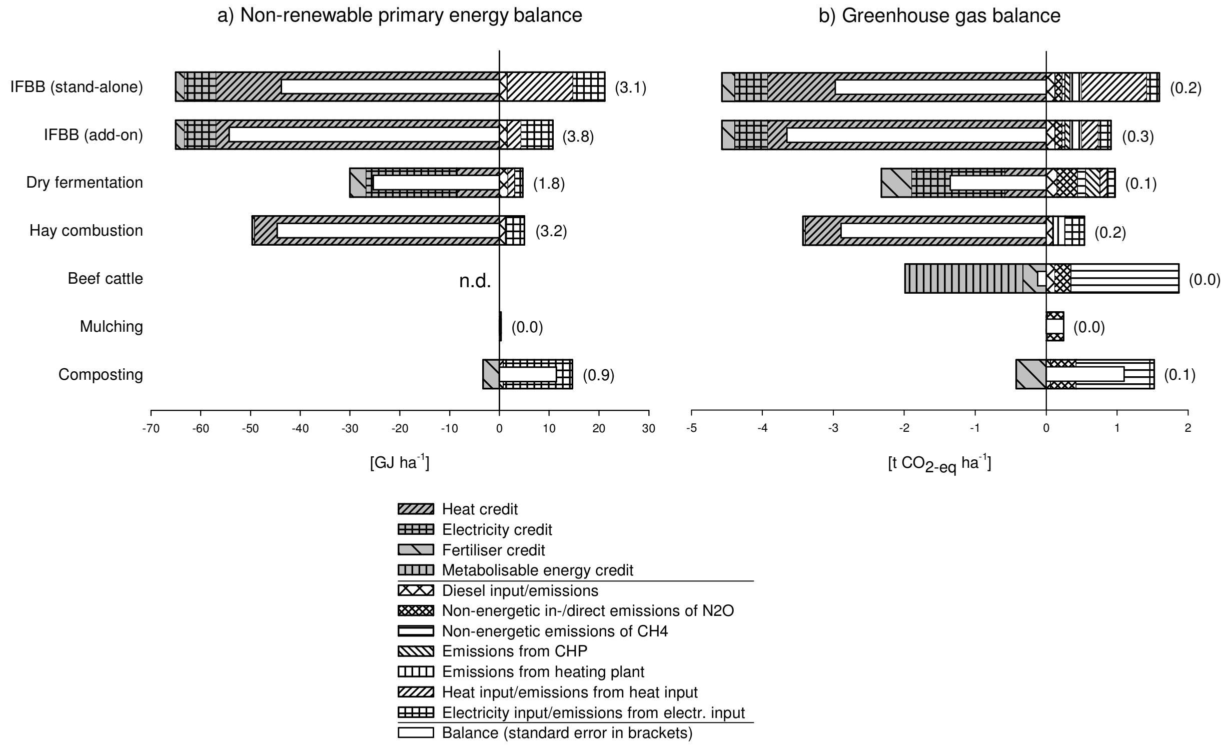

Figure 6.3 Area-related non-renewable-primary energy balance (a) and greenhouse gas balance (b) of the energy recovery by the integrated generation of solid fuel and biogas from biomass (IFBB) as a stand alone system, IFBB as an add-on system to an agricultural biogas plant, dry fermentation, hay combustion, animal-based utilisation by beef cattle husbandry and non-refining systems mulching and composting (n.d. = not determined).

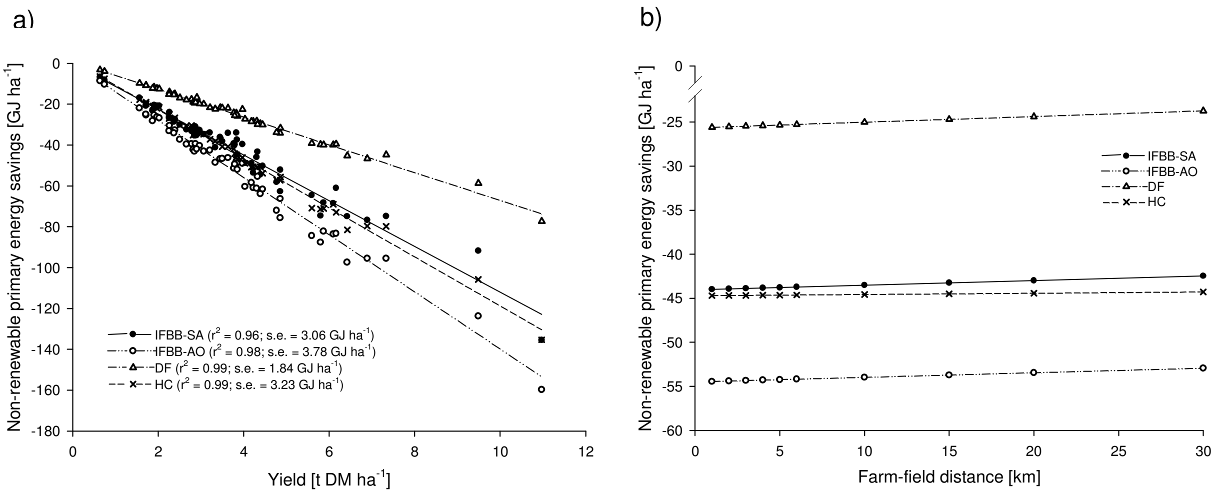

Figure 6.4 Impact of DM yield (a) and farm-field distance (b) on the non-renewable primary energy savings of the integrated generation of solid fuel and biogas frombiomass as a stand-alone system (IFBB- SA), IFBB system as an add-on system to an agricultural biogas plant (IFBB-AO), dry fermentation (DF) and hay combustion (HC).

Summarising the non-renewable primary energy balance, it can be concluded that the energy production systems with thermal use significantly outperformed the conversion by anaerobic digestion. Considering IFBB and HC, the assessment of the systems also has to take into account aspects that are not directly associated with energetic performance. Most important issues are the regional climatic conditions, which potentially do not allow field drying procedures in principle, and fuel quality related aspects concerning technical feasibility of the combustion process. The fuel that is produced following the IFBB system has considerably lower mineral contents (Table 6.1) and allows efficient use in conventional furnaces, with reduced risk of ash melting and lower potential of harmful emissions. Generally, the exploitation of the grassland biomass in terms of fossil fuel saving could be further increased if the solid fuel is used in combined heat and power systems. On the scale considered in this study, the use of solid fuels in combined heat and power systems is not common for economic reasons, so this scenario was not calculated.

6.3.3 Greenhouse gas balance

Gross savings of greenhouse gases amounted to 4.6 t $CO_{2\text{-eq}}$ ha^{-1} for the IFBB scenarios and, as mentioned for primary energy savings, were mainly based on heat supply (Figure 6.3b). Within IFBB-SA, 57.0% of the greenhouse gas emissions resulted from heat supply for drying of the press cake. Net greenhouse gas savings added up to 3.0 t $CO_{2\text{-eq}}$ ha^{-1}. Net greenhouse gas savings of the IFBB system could be improved by the add-on scenario (3.6 t $CO_{2\text{-eq}}$ ha^{-1}). Gross greenhouse gas savings of the dry fermentation system were lower overall and consisted of savings of fossil electricity production for the most part, as well as fossil heat and fertiliser savings. The fertiliser credit was higher for DF compared to IFBB due to increased recycling rates of organic residues. Greenhouse gas emissions were similar to the IFBB add-on scenario, the net greenhouse gas savings accounting for 1.4 t $CO_{2\text{-eq}}$ ha^{-1}. Net savings potentially could be increased to 1.8 t $CO_{2\text{-eq}}$ ha^{-1} in the case of full heat exploitation of the CHP. HC showed lowest emissions of greenhouse gases among the energy recovery systems. On the other hand, exclusively thermal use of the biomass led to marginal credits for fertiliser substitution. HC's net greenhouse gas savings (2.9 t CO_{2-eq} ha^{-1}) were on a similar level to the IFBB stand-alone scenario. The use of extensive grassland by beef cattle was linked to high emissions resulting from ruminant digestion, which added up to 80.7% of the total greenhouse gas emissions. Credits of replaced beef cattle husbandry, which was based on intensively managed grasslands, were similar to the emissions of the extensive system, meaning that the environmental impact in terms of greenhouse gases was almost equivalent for both procedures. Even though the product (i.e. supply of metabolisable energy) specific methane emissions were lower in the intensive system, the nutrient transfer from the extensive grassland to another land use system and its resulting greenhouse gas credit led to an almost neutral balance. The overall net greenhouse gas saving was marginal and amounted to 0.1 t CO_{2-eq} ha^{-1}. If the fertiliser credit for the extensive system were to be disregarded, there would be a net greenhouse gas contribution of 0.2 t CO_{2-eq} ha^{-1}. The mulching system showed considerable emissions of nitrous oxide released during the decomposition of the litter. The composting system obtained credits for fertiliser substitution, but was also associated with emissions during the rotting process, such as methane and nitrous oxide, which eventually exceeded the gross savings, resulting in a net contribution to global warming of 1.1 t CO_{2-eq} ha^{-1}. It has to be kept in mind that, in general, but particularly for the MU and CO system, the assumptions made for N_2O and CH_4 emissions have a strong impact on the results, but are based on data with high uncertainties.

6.3.4 Acidification and eutrophication balance

The acidification balance (Figure 6.5a) showed a predominance of the emissions of acidifying gases compared to the savings within the IFBB system, leading to a net contribution to acidification of 7.5 (IFBB-SA) and 7.8 (IFBB-AO) kg SO_{2-eq} ha^{-1}, respectively. Emissions mainly came from combustion of the pellets and the biogas but also from NH_3 emissions during application of the digestate and biogas conversion by the combined heat and power plant. Gross and net emissions of the dry fermentation system were on the highest level among the bioenergy procedures, particularly as a result of ammonia emissions of digestate. In the case of biogas, CHP operation also led to a higher release of acidifying gases than the thermal use of pellets related to their fuel energy content. Lowest net potential of acidification of the energy recovery systems was obtained by hay combustion (3.9 kg SO_{2-eq} ha^{-1}). Ammonia emissions of beef cattle husbandry were on a similar level for both extensive and intensive grassland management systems, leading to an almost equated balance of acidification potential. Mulching also had little impact on acidification, due to small energy input and absence of substitution effects. Emissions in CO, which particularly occur during the rotting process, exceeded savings, with a final net acidification potential of 2.0 kg SO_{2-eq} ha^{-1}.

The eutrophication balance (Figure 6.5b) revealed similar relations between the scenarios considered. Scenarios with thermal biomass utilisation (IFBB, HC) performed slightly better in relation to DF, as HCl emissions, which are released mainly during combustion, were irrelevant for assessment of eutrophication. As a result of the acidification and eutrophication balance, it can be concluded that the bioenergy systems in particular did not perform as well as the fossil alternative, whereas the impact of animal-based and non-refining management systems was low.

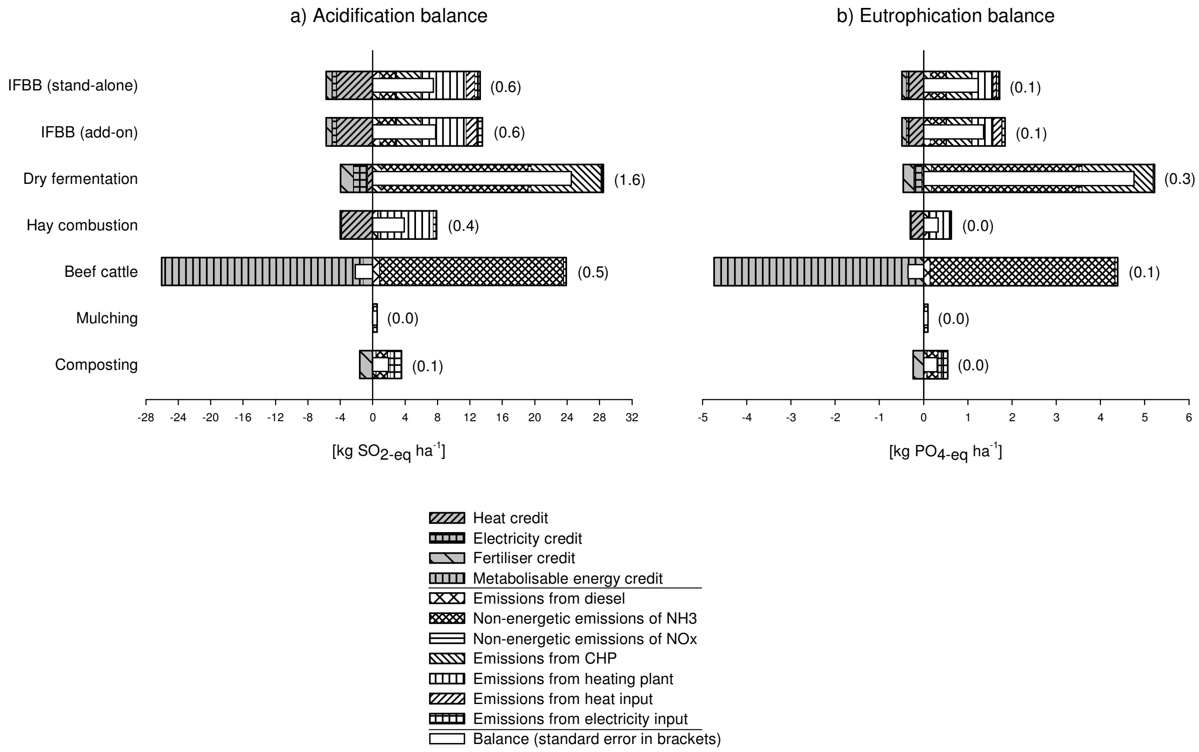

Figure 6.5 Area-related acidification (a) and eutrophication (b) balance of the energy recovery by the integrated generation of solid fuel and biogas from biomass (IFBB) as a stand-alone system, IFBB as an add-on system to an agricultural biogas plant, dry fermentation, hay combustion, the animal-based utilisation by beef cattle husbandry and the non-refining systems mulching and composting.

6.4 Conclusions

Energy recovery from semi-natural grassland achieved highest conversion efficiency (45-54% of the gross yield), net savings of fossil fuels (44-54 GJ ha^{-1}) and net savings of greenhouse gases (2.9-3.7 t CO_{2-eq} ha^{-1}) by HC and IFBB. Potential of DF was limited, due to low digestibility of the mature biomass. Considering acidification and eutrophication, energy systems did not perform as well as the fossil alternative. While forage use by BC showed an almost neutral greenhouse gas balance compared to the reference of an intensive system, MU and CO were associated with net release of greenhouse gases.

7 General discussion

7.1 Biological and chemical parameters

Anaerobic digestion and combustion, which have been in the focus of the first part of this thesis, are state of the art in the field of energy production from biogenic matters. However, the main products of the IFBB system, the press fluid and the press cake, are completely different from biomass types that are currently used by these technologies considering their physical and chemical properties. For this reason, this thesis investigated both press fluids and press cakes on parameters that are relevant for the respective conversion procedure to identify the required adaptions of established technologies to make the IFBB products technically usable.

Currently, agricultural biogas plants mostly use wet conserved energy crops beside the input of farmyard manure in Germany (Herrmann, 2013). The substrates mostly have a DM content of more than about 30% (FNR, 2009), which is considerably higher than the DM content of press fluids (see Table 3.4). Furthermore, the DM of the whole crop silage is characterised by a higher share of herbaceous compounds as the energy crops are simply chopped to a length of about 5 cm, whereas the particle size of the DM of the press fluid is less than 1.5 mm. In addition, the methane potential of whole crop silages is remarkably lower (Bauer et al., 2010) than those of the press fluid investigated in this work. Press fluid digestion also occures faster than whole crop digestion (Richter et al., 2009). All these factors indicate the need to adjust the press fluid digestion, compared to the use in established stirrer tank reactors of common biogas plants, to the requirements resulting from chemical and physical properties.

The rapid degradation of the organic matter of the press fluids suggests an operation of the digesters with low retention times, thereby allowing a reduced reactor volume, lower internal heat demand and cost savings. However, the absence of bulking material like stems or leaves makes the installation of additional surface patterns necessary in order to keep the microbiology in the digester, since the reproduction rate of methan forming bacteria (Ghosh and Pohland, 1974) is of similar duration than the intended retention times of press fluid digestion. Several technologies to reduce washout of microbiology have been used for decades in the field of waste water treatment, for example UASB reactors or fixed-bed digesters (Liu et al., 2002; Zaiat et al., 2000). However, these digestion systems can not be easily transferred for the use of press fluids, since waste waters have a considerably lower content of organic matter (Dignac et al., 2000).

This thesis investigated the use of a grinding fleece as fixed-bed material, and showed a significant improvement of the digestion dynamics compared to a standard stirrer tank reactor. Nevertheless, the results are not yet satisfactory and sufficient for large scale implementations. Further studies have to be conducted to test more fixed-bad materials and their geometrical design, as well as operation modes like feeding intervalls and recirculation modes.

In contrast to the mono-fermentation of press fluids, the extension of existing biogas plants using whole crop silages by an IFBB unit would be easier from the technical point of view. Press fluids might be used as a co-substrate, and if their share is low among the other input materials, it is unlike that technical adaptions are necessary. Beside the ecological benefits of the combination of common biogas plants with the IFBB system, shown in chapter 6 of this thesis, and beside the economical advantages (Blumenstein et al., 2012), also the technical implementation of press fluid digestion argues for the IFBB add-on plant design.

Considering the combustion of the press cake, this thesis investigated the ash melting behaviour, which is one of the most important quality aspects of biogenic fuels. In contrast to wooden fuels, herbaceous biomass, such as the here analysed press cake made from grassland silage, has a considerably higher ash content and the chemical composition of the ash leads to an increased risk of slagging even at low combustion temperatures (Obernberger et al., 2006). The results of this work showed that, though there is an increase of the ash softening temperature (AST) by 50K through conditioning and dewatering of the biomass up to 1,050°C on average, the AST is lower than those of wooden fuels. This indicates the need of adapted furnace design and settings to ensure a technically reliable combustion process.

Different techniques are available that are able to cope with the increased risk of slagging. Staged combustion systems allow a reduced temperature in the fuel zone through understochiometric air inlet, thereby avoiding ash softening during combustion and also lowering the emissions of NO_x (Kuang et al., 2011). Furthermore, cooled grates can be used to exclude slagging and adhesion of the ash (Kaltschmitt and Hartmann, 2001). In addition, blending of grassland press cake with high quality wood pellets is another option to remedy the problem of slagging. By adding limestone to the fuel the ash softening temperature increases as well (Steenari et al., 2009), which is in line with findings of this work that revealed the positive effect of Ca on the AST.

Linear regression models developed on the basis of the experimental results showed a high accuracy in terms of the prediction of the ash melting behaviour of press cake and silage. However, the predictability is limited to this type of biomass up to now, thus, further studies should be implemented with an extended sample set of different biomass types. In addition, models have to be developed that are able to predict the ash melting behaviour of both silages and press cakes with high quality of estimates.

To sum up the assessment of biological and chemical parameters, this thesis has helped to identify and evaluate crucial parameters of press fluid and press cake conversion considering the requirements of the large scale technique to be applied in future.

7.2 Life cycle assessment

The basic incentive for the development of the integrated generation of solid fuel and biogas from biomass was the development of a bioenergy system, that has an increased energy efficiency compared to established techniques and that has the potential to convert an enhanced spectrum of organic matters. To address these targets, this part of the thesis investigated the life cycle performance of the IFBB system when using different types of input materials and in comparison to alternative conversion systems.

Considering the methodological approach of LCA studies, various types of methods, target parameters and data bases have been used in previous studies on biomass conversion (Cherubini, 2010). Frequently, the data base of LCA is connected with high uncertainties (Mattila et al., 2012). These aspects reveal the difficulties in finding reliable results that, for example, can be the basis for political recommendations. For all this reasons, both LCA studies of this thesis aimed at a comparable approach, using the same data base for all scenarios considered whenever it was possible, to identify quantitative differences between several options of energy production from biomass.

However, difficulties in the assessment and use of data base were a major issue also in the study at hand. It became obvious that the findings heavily depend on the assumptions made. The first crucial question of a LCA is the definition of the agricultural reference system (Jungk and Reinhardt, 2000). The ecological performance of the alternative land use that is replaced by bioenergy production significantly influences the result of the study (Van Stappen et al., 2012). The definition of the reference system can be based on various arguments, for this reason, the most simple reference system "fallow" was chosen in this study. As this study followed a comparable approach, all considered scenarios were refered to the same reference system, thus, its impact on the qualitative findings is low. Furthermore, the inclusion of soil organic carbon aspects has a fundamental impact on the outcome, as already reported by Brandão et al. (2010). For example, while the return of organic matter within the IFBB system is low, higher rates are recycled within the whole crop digestion system, leading to effects of carbon sequestration after spreading of the digestates. Although literature on nutrient fluxes of organic matter from biogas slurry in the soil is very scarce (Möller, 2009), values were taken from guidelines developed by VDLUFA (2004), which are also the basis of the legal regulation of agricultural energy cropping in terms of the humus balance. Further long-term research is needed to quantify these aspects due to their huge impact on LCA results. Other uncertainties are related to N_2O emissions from energy cropping (Arnold, 2010). They influence the findings of the study, as their impact on global warming is approximately 300 times higher than those of CO_2 (Forster et al., 2007). They particularly play a role in the assessment of the agricultural reference system and during application of slurry and mineral fertiliser. Detailed knowledge and differentiated guidelines for its use are necessary in order to do not influence the statements of a LCA study in an incorrect way.

The LCA of this thesis of the use of arable energy crops considered the conversion of rye and maize by the IFBB system in comparison to common whole crop digestion, which is the most applied technique when using wet conserved biomass for energy production (FNR, 2013). Considering the parameters, which have been varied in the LCA scenarios and which were more related to the technical system than the above mentioned indirect effects, it became clear that the mashing temperature of the IFBB system influences the overall performance. Increasing transfer rates of organic matter into the liquid with higher mashing temperatures resulted in enhanced biogas and electricity production and led to higher primary energy and CO_2 substitution effects. This is in line with findings of Richter et al. (2010) for grassland biomass who found higher CO_2 savings for mashing at 60°C than for 5°C, but slightly decreased savings at 80°C. Highest conversion efficiency for IFBB processing of grassland biomass was identified at about 50°C (Richter at al., 2011). Looking at the parameter variation of the WCD system, the share of waste heat, which is actually used for the replacement of fossil fuels, is the crucial factor for the saving potentials of fossil primary energy and CO_2 emissions, what is in line with findings of Bachmaier et al. (2013). In Germany, latest laws on feed-in tariffs of electricity produced from agricultural biomass payed attention to this fact and made obligatory to use 60% of the waste heat (Anonymous, 2012). Beside the variation of the share of waste heat use, further research of the IFBB system should also based on different levels of biomass productivity, as only one yield was used in this study. To sum up, the comparable LCA showed that the IFBB system is a promising alternative to common biogas use where entire waste heat exploitation is not possible. But, in case of full use of the waste heat, the WCD system is the preferable way of conversion under the assumptions made.

The second LCA of this thesis investigated the conversion of semi-natural grassland biomass by the IFBB system and other options of energy recovery, as well as forage use and measures of landscape preservation (mulching and composting). Considering the scenarios of energy recovery, the add-on scenario of the IFBB technique showed best performance in terms of energy efficiency and saving potentials. The alternative combustion of the field dried hay obtained similar levels, however, the fuel qualitity of the untreated biomass is by far below the quality of IFBB fuels (Hensgen et al., 2012) and the chemical properties are worse than suggested by Obernberger et al. (2006) for thermal use. This has also an impact on the economical performance (Blumenstein et al., 2012). Furthermore, the IFBB system is more flexible in terms of harvesting as it does not rely on weather conditions that are necessary for hay making, and, frequently semi-natural grassland sites year-round waterlogged and therefore not appropriate for field drying. The conversion of the grassland biomass by whole crop digestion as dry fermentation did not show promising results. This is mainly due to the increased content of indigestible compounds leading to low methane yields. The qualitative differences of the ecological performance between the scenarios were observed in the same way by Richter et al. (2010). Forage use by beef cattle husbandry is frequently suggested to preserve the semi-natural grassland sites by increased subsidy payments, but the results of the LCA revealed only low savings of CO_2 emissions for replacing beef cattle husbandry based on intensively managed grasslands as assumed in this study. Both mulching and composting showed net consumptions of fossil energy carriers and net release of CO_2. This would even be the case if carbon storage effects would have been included in the LCA.

Summarising the outcomes of the LCA studies, the IFBB system showed promising results in terms of its saving potential of fossil energy carriers and CO_2 emissions compared to the other scenarios considered in this study. This particularly applies to the conversion of organic matters that show only low anaerobic digestibility such as semi-natural grassland biomass.

8 Conclusions

Based on the assessment of press fluid digestion and ash melting behaviour of press cakes, and based on the LCA of the IFBB system for different types of biomasses and in comparison to alternative options of biomass use, the following conclusions can be drawn:

(i) Methane yields of press fluids from mechanically dehydrated maize silages varied between 390 and 506 l_N CH_4 kg^{-1} VS. They decreased with increasing crop maturity. The total degree of degradatation of the VS was higher than 90%. Within the first four days of fermentation, 90% of methane production took place. This indicates a rapid degradation and the need of an adapted technology in comparison to the fermentation of the untreated maize silage caused by the reduced retention times. Continuous tests on press fluid digestion using a stirrer tank digester relied on retention times of more than 20 days for a stable fermentation, thus, common digesters did not prove to be suitable for this substrate. The use of fixed-bed digesters allowed the operation at retention times of eight days at low volume loads. However, the breakdown of methane production at volume loads of 5 g VS l^{-1} day^{-1} indicated that further research is necessary to identify more suitable anaerobic filters.

(ii) Softening, spherical, hemisphere and flow temperature of the ash from press cake was higher than those of the ashes from silage. Softening of the untreated silage fuel ash started at about 1,000°C, whereas the press cake ash started to soften at about 1,050°C. At the spherical, hemisphere and flow temperature the differences between silage and press cake ashes were even bigger and ranged from 63 to 67K. Linear regression models, which were based on the content of K, Ca, Si, Al and Na in the press cake, were able to predict the ash softening temperature (AST) with high accuracy (R^2 = 0.88-0.89). Models showed that an increasing content of K led to decreasing AST. By contrast, AST was positively influenced by increasing contents of Ca. The effect of Si depended on the content of alkalis and earth alkalis.

(iii) The conversion efficiency of solid fuel and biogas supply from rye and maize, grown as double-crops, by the IFBB system accounted for 57%, whereas the conventional whole crop digestion (WCD) performed with an efficiency of 50%. Savings of primary energy were highest for the IFBB system (85.3 MWh ha^{-1}) when hydro-thermal conditioning took place at 60°C. The increased transfer of organic matter into the fluid at higher temperatures of conditioning led to enlarged biogas and electricity production, which in turn is coupled with increased substitution effects of fossil fuels. WCD achieved comparable primary energy savings (85.9 MWh ha^{-1}) only when almost the complete waste heat was used. Savings of greenhouse gases of WCD were at a higher level than IFBB when use of the waste heat was more than 20% due to increased carbon storage in the soils by return of the digestates.

(iv) Highest efficieny (53%) during the conversion of semi-natural grassland biomass into heat and electricity was achieved by the IFBB system when applied as an add-on system to a biogas or waste water treatment plant. Conversion efficiency of hay combustion (HC) ranged at a similar level (54%), whereas the dry fermentation (DF) reached only low rates of 17% due to the low digestibility of the mature biomass. Savings of primary energy were in a range of 12 to 15 MWh ha^{-1} for the IFBB scenarios, whereas the DF obtained a saving potential of 7 and the HC 12 MWh ha^{-1}. Similar relations between the considered scenarios were found for the greenhouse balance. While forage use of the grassland biomass by beef cattle husbandry showed an almost neutral greenhouse gas balance compared to the reference of an intensive system, mulching and composting were associated with net consumption of fossil energy carriers and net release of greenhouse gases.

9 Summary

Limited efficiency of established conversion techniques to produce energy from biomass and dependencies on few species of energy crops led to the development of the integrated generation of solid fuel and biogas from biomass (IFBB). Its core element is the mechanical separation of the wet conserved biomass into a solid fuel for combustion and a liquid for anaerobic digestion with subsequent production of heat and electricity from the biogas.

The first part of this thesis investigated biological and chemical parameters of the IFBB process. Press fluids from maize silages were analysed for the methane potential in batch tests and parameters of continuous operation (methane yield, methane content, acetic acid equivalent, pH) using different types of digesters. Furthermore, silages and press cakes from 18 European grassland sites were tested on combustion relevant parameters and the derived ashes were analysed for the ash melting behaviour and its predictability from fuel parameters. In the second part, life cycle assessment (LCA) evaluated the overall energy efficiency as well as saving potentials of fossil primary energy and emissions of greenhouse gases ($CO_{2\text{-eq}}$) of the IFBB process along the entire process chain and in comparison to other options of biomass use. LCA studies were based on the use of arable energy crops (rye and maize in double-cropping) as well as semi-natural grassland biomass.

Considering the results of the first part, methane yields in batch tests from maize press fluids ranged between 390 and 506 l_N CH_4 kg^{-1} VS. The rapid degradation of the VS required fixed-bed digesters for continuous operation due to quick breakdown of the biology when using common stirrer tank digesters. Average softening temperatures (AST) of ashes derived from silages and press cakes from grassland biomass accounted for 1,000 and 1,050°C, respectively. AST of press cakes could be predicted by fuel composition by regression models with high accuracy (R^2 = 0.88-0.89). Looking at the results of the LCA, primary energy savings for the IFBB system were between 69 and 86 when using high-yielding energy crops and between 12 and 15 MWh ha^{-1} for the conversion of semi-natural grassland biomass, depending on the scenarios considered. Savings of CO_{2-eq} ranged between 10.6 and 12.2 and 3.0 and 3.6 CO_{2-eq} ha^{-1}, respectively. The alternative use of arable crops by common whole crop digestion (WCD) showed, at high shares of waste heat exploitation, comparable levels to IFBB for primary energy savings and even higher savings of CO_{2-eq} due to increased C sequestration effects. Considering semi-natural grassland biomass, IFBB outperformed WCD due the low digestibility of the mature grassland and the resulting limited methane yields.

10 Kurzfassung

10.1 Einleitung

Limitierte Verfügbarkeiten fossiler Energieträger, wachsende Konflikte um die verbleibenden Rohstoffe sowie der zunehmende Klimawandel haben auf europäischer und nationaler Ebene dazu geführt, Strategien zur Förderung erneuerbarer Energien zu entwickeln (Carvalho, 2012; Eskeland et al., 2012). Die Europäische Union hat sich zum Ziel gesetzt, bis zum Jahr 2020 einen Betrag der erneuerbaren Energien von 20% zum gesamten Energieverbrauch zu erreichen, mit unterschiedlichen Zielsetzungen der jeweiligen Mitgliedsstaaten (EC, 2006). Der Anteil der erneuerbaren Energien am Endenergieverbrauch stieg in Deutschland von 3,9% in 2000 auf 12,5% in 2011, und er soll im Jahr 2020 18% erreichen (BMU, 2012).

Unter den verschiedenen Technologien der regenerativen Energieerzeugung nimmt die energetische Biomassenutzuung eine besondere Stellung ein. Die Konversion organischen Materials erlaubt die Bereitstellung mehrerer Energieformen, wie Elektrizität, Festbrennstoff oder Flüssigkraftstoff (Ericsson and Nilsson, 2006; Faaij, 2006; Flamos et al., 2011). In Deutschland nahm die Fläche, die für den Anbau nachwachsender Rohstoffe genutzt wird, von 0,7 Mill. ha in 2000 auf 2,5 Mill. ha in 2012 zu, was heute einem Anteil von 15% der gesamten landwirtschaftlich genutzten Fläche entspricht (FNR, 2013).

In jüngster Vergangenheit wurde der rasante Anstieg der landwirtschaftlichen Energieerzeugung und deren Auswirkungen auf die Umwelt und die Gesellschaft zunehmend kontrovers diskutiert (Fritsche et al., 2010; Buchholz et al., 2009). Der Energiepflanzenanbau besteht im Wesentlichen aus zwei Kulturen: Raps für die Biodieselproduktion und Mais für die Biogaserzeugung (FNR, 2013). Der Anbau erfolgt häufig in hoher räumlicher Konzentration um die Bioenergieanlagen in einförmigen Fruchtfolgen (Herrmann, 2013), die sich negativ auf die Biodiversität und den landschaftsästhetischen Wert auswirken

(Fletcher at al., 2011; Dauber et al., 2010). In vielen Fällen ist der Anbau der Energiepflanzen mit einer Intensivierung der pflanzlichen Produktion verbunden, die zur Verschlechterung der Boden- und Wasserqualität führen kann (Erb et al., 2012; Love et al., 2011). Unter bestimmten Voraussetzungen kann ein gesteigerter Einsatz an Dünger, Pflanzenschutz und Treibstoff zu einem höheren Ausstoß an Treibhausgasen führen, als durch die Substitution fossiler Energieträger eingespart werden kann. Dies zeigt die Notwendigkeit von umfassenden Ökobilanzierungen der landwirtschaftlichen Energieproduktion (Crutzen et al., 2007; Fernando et al., 2010). Desweiteren führt der hohe Flächenanteil der Energiepflanzen zunehmend zur Konkurrenz zwischen der Energieproduktion und der Nahrungs- und Futtermittelerzeugung (Harvey and Pilgrim, 2011; Murphy et al., 2011).

Vor diesem Hintergrund gewinnt die Nutzung von bisher ungenutzen biogenen Reststoffen immer mehr an Bedeutung und gerät zunehmend in den Mittelpunkt der politischen Handlungsempfehlungen für den weiteren Biomasseausbau (EEA, 2011; Leopoldina, 2012; Tilman et al., 2009). Eine potenzielle Ressource stellt in diesem Zusammenhang das extensiv bewirtschaftete Grünland dar, das über Jahrzehnte durch eine minimale Nutzung entstanden ist und das aufgrund der biodiversen Artenzusammensetzung einen hohen naturschutzfachlichen Wert aufweist. In vielen europäischen Regionen, die über hohe Anteile dieser Grünlandform verfügen, haben strukturelle Entwicklungen zu einem Rückgang der Tierhaltung geführt, die bisher die Biomasse als Futter verwertete (Isselstein et al., 2005; Rösch et al., 2009). Demnach stehen in zunehmendem Maße jährlich große Mengen an Biomasse zur Verfügung, denn diese Grünlandflächen sind auf eine regelmäßige Mahd angewiesen, um das Arteninventar zu erhalten (Halada et al., 2011); alternative Nutzungsformen für das Grünland wie beispielsweise die energetische Verwetung sind dementsprechend gefragt, um eine Fortführung der regelmäßigen Bewirtschaftung zu gewährleisten.

Mit den Zielen, die Konversionseffizienz bestehender Bioenergieverfahren zu steigern und das Artenspektrum der verwerteten Energiepflanzen zu vergrößern, wurde das Verfahren der Integrierten Festbrennstoff- und Biogasproduktion aus Biomasse (IFBB) entwickelt (Wachendorf et al., 2009; Graß et al., 2009). Der zentralen Verfahrensschritte sind die hydrothermale Konditionierung der feucht konservierten Biomasse und die anschließende mechanische Separation in einen Presskuchen und einen Presssaft. Der Presskuchen wird nach der Trocknung und Kompaktierung als Festbrennstoff eingesetzt, während der Presssaft über die anaerobe Vergärung verwertet wird. Das dabei entstehende Biogas wird zur Erzeugung von Wärme und Strom genutzt.

Vorhergehende Studien zum IFBB-Verfahren zeigten, dass mittels der Behandlung der Biomasse organische Substrate nutzbar gemacht werden können, die über herkömmliche Techniken wie die Ganzpflanzenvergärung oder Verbrennung nicht verwertet werden können. Durch die mechanische Entwässerung der Biomasse werden die faserhaltigen Bestandteile mit geringem Biogaspotenziale weitestgehend in den Presskuchen überführt, während große Teile der Mineralstoffe, die im Brennstoff zum Risiko der Korrosion und der Verschlackung beitragen, und der leicht verdaulichen organischen Inhaltsstoffe in den Presssaft übergehen. Dementsprechend liegt die Brennstoffqualität des Presskuchens deutlich über der der unbehandelten Silage, und auf der anderen Seite wird ein Flüssigsubstrat mit hohem Methanbildungspotenzial erzeugt. Da die Mineralstoffe des Presssaftes während der Vergärung im Gärrest verbleiben, wird zusätzlich ein wertvoller Dünger mit landwirtschaftlich wichtigen Nährstoffen Bereit gestellt (Richter et al., 2009; Richter et al., 2010; Hensgen et al., 2012).

Das Ziel des ersten Teils dieser Arbeit (Kapitel 3 und 4) war die Untersuchung und Bewertung biologischer und chemischer Parameter der Vergärung des Presssafts und der Verbrennung des Presskuchens. Im Gegensatz zur Vergärung unbehandelter Ganzpflanzensilagen in herkömmlichen Biogasanlagen erfordert die Vergärung pflanzlicher

Presssäfte eine an die hohe Verdaulichkeit und geringe Verweilzeiten angepasste Technologie. Die Untersuchungen zielten sowohl auf die Erfassung der Methanausbeute sowie der Bewertung der Gärdynamik im kontinuierlichen Fermenterbetrieb und unter Verwendung unterschiedlicher Fermentertypen. Hinsichtlich der Presskuchenverbrennung ist das Ascheereichungsverhalten ein wichtiger Parameter. In experimentellen Untersuchungen wurde das Erweichungsverhalten charakterisiert und darauf aufbauend wurden Regressionsmodelle für die Vorhersage der Erweichungstemperatur in Abhängigkeit der Brennstoffzusammensetzung entwickelt.

Im zweiten Teil der Arbeit (Kapitel 5 und 6) wurde eine umfassende Ökobilanzierung des IFBB-Systems durchgeführt, um wichtige Kriterien der ökologischen Effizienz zu untersuchen und zu beurteilen. Die Ökobilanzierung erfolgte sowohl für die Verwertung hochproduktiver ackerbaulicher Kulturen als auch für Biomasse von extensiv bewirtschaftetem Grünland. Die gesamte Produktionskette von der Biomasseproduktion bis zur Energiebereitstellung wurde unter Berücksichtigung aller relevanter Energie- und Stoffströme bewertet. Die wesentlichen Untersuchungsparameter waren die Konversionseffizienz sowie die Einsparpotenziale an Primärenergie und Treibhausgasemissionen.

10.2 Forschungsziele

Die Ziele dieser Studie waren die Untersuchung biologischer und chemischer Parameter der Presssaftvergärung und der Verbrennung des Presskuchens sowie die Ökobilanzierung des IFBB-Systems.

Die Analyse der Presssaftvergärung wurde auf der Basis von Presssäften aus Maissilage durchgeführt. Anhand von Batch-Versuchen wurde die Methanausbeute ermittelt und in Langzeitversuchen wurde die Gärdynamik in Rührkessel- und Festbettreaktoren untersucht. Die Bestimmung des Ascheerweichungsverhaltens erfolgte experimentell in einem Hochtemperaturofen auf der Grundlage von 18 Silage- und Presskuchenproben von europäischen Grünlandflächen.

Im Rahmen der Ökobilanzierung wurde die energetische Verwertung ackerbaulicher Kulturen (Roggen und Mais als Zweikulturnutzungssystem) durch das IFBB-System und die herkömmliche Ganzpflanzenvergärung vergleichend bewertet. Darüberhinaus erfolgte eine Ökobilanzierung für die Verwertung von Grünlandbiomasse extensiv bewirtschafteter Flächen durch das IFBB-Verfahren im Vergleich zu alternativen Konverisonsverfahren sowie der tierischen Veredelung und Verfahren der Landschaftspflege.

Die übergeordneten Ziele der Untersuchungen waren

(i) die Bestimmung der Methanausbeute und des Abbaugrades bei der anaeroben Vergärung von Presssäften aus Maissilage und die Analyse der Gärdynamik im kontinuierlichen Betrieb von Rührkessel- und Festbettreaktoren

(ii) die Bestimmung des Ascheerweichungsverhaltens von Presskuchen aus entwässerter Silage vom Extensivgrünland im Vergleich zur unbehandelten Silage und die Untersuchung des Einflusses der inhaltsstofflichen Zusammensetzung des Brennstoffes auf das Ascheerwecihungsverhalten

(iii) die Bewertung des IFBB-Systems hinsichtlich der Energieeffizienz und den Einsparpotenzialen an Primärenergie und Treibhausgasen bei der Verwertung von Roggen und Mais im Zweikulturnutzungssystem und im Vergleich zur herkömmlichen Ganzpflanzenvergärung

(iv) die Bewertung des IFBB-Systems hinsichtlich der Energieeffizienz und den Einsparpotenzialen an Primärenergie und Treibhausgasen bei der Verwertung von Biomasse von extensiv bewirtschaftetem Grünland im Vergleich zu der Verwertung über die Trockenermentation, die Heuverbrennung, die tierische Veredelung, Mulchen und die Kompostierung.

10.3 Schlussfolgerungen

Auf der Grundlage der Untersuchungen zur Presssaftvergärung und zur Verbrennung des Presskuchens, sowie auf der Grundlage der Ökobilanzierungen des IFBB-Systems im Vergleich zu alternativen Nutzungsformen der Biomasse, können folgende Schlussfolgerungen gezogen werden:

(i) Die Methanausbeuten bei der anaeroben Vergärung von Presssäften aus Maissilage lagen in einem Bereich zwischen 390 and 506 l_N CH_4 kg^{-1} VS. Sie nahmen mit zunehmendem physiologischen Alter der Pflanzen ab. Der Abbaugrad der organischen Substanz lag bei über 90%. Innerhalb der ersten vier Tage der Vergärung fanden 90% der Methanproduktion statt. Dies bedeutet einen schnellen Abbau und macht aufgrund kurzer Verweilzeiten eine im Vergleich zur Vergärung der Ganzpflanzensilage angepasste Technik erforderlich. Die stabile kontinuierliche Vergärung der Presssäfte im Rührkesselreaktor war auf eine Verweilzeit von mehr als 20 Tagen angewiesen. Insofern erwies sich der Rührkesselreaktor nicht als die passende Vergärungstechnik für Presssäfte. Die Nutzung eines Festbettreaktors erlaubte bei geringer Raumbelastung eine Verweilzeit von acht Tagen. Der Zusammenbruch der Methanproduktion bei einer Raumbelastung von 5 g VS l^{-1} Tag^{-1} zeigt jedoch den Bedarf für weitere Entwicklungen in der Vergärungstechnik für pflanzliche Presssäfte auf, insbesondere bei der Identifizierung geeigneter Festbettmaterialien.

(ii) Die Erweichungs-, Sphärisch-, Halbkugel- und Fließtemperaturen der Asche von dem Presskuchen waren höher als diejenigen der Asche von der Silage. Die Erweichung der Asche der unbehandelten Silage begann bei ca. 1.000°C, während die Asche des Presskuchens bei etwa 1.050°C zu erweichen begann. Bei der Sphärisch-, Halbkugel- und Fließtemperatur war der Unterschied zwischen der Asche aus der Silage und dem Presskuchen noch höher und lag zwischen 63 und 67K. Linerare Regressionsmodelle auf der Basis der Gehalte an K, Ca, Si, Al und Na konnten die Ascheerweichungstemperatur des Presskuchens mit hoher Schätzgüte vorhersagen (R^2 = 0,88-0,89). Die Modelle zeigten, dass mit einem zunehmenden K-Gehalt eine abnehmende Erweichungstemperatur einhergeht. Im Gegensatz dazu führte eine Zunahme an Ca zu einer Erhöhung der Erweichungstemperatur. Der Einfluss von Si war abhängig vom Gehalt an Alkali- und Erdalkalimetallen.

(iii) Die Konversionseffizienz bei der Bereitstellung von Brennstoff und Biogas aus Roggen und Mais (Zweikulturnutzungssystem) lag bei 57% bei einer Verwerung durch das IFBB-System und bei 50% bei einer Biogasbereitstellung durch die herkömmliche Ganzpflanzenvergärung. Die höchsten Einsparpotenziale an Primärenergie wurden durch das IFBB-System (85,3 MWh ha^{-1}) erzielt, wenn die hydrothermale Konditionierung bei 60°C durchgeführt wurde. Der erhöhte Fluss der organischen Masse in den Presssaft bei höheren Maischtemperaturen führte zu gesteigerten Biogas- und Stromerträgen, was mit einem höheren Einspareffekt an Primärenergie verbunden ist. Die herkömmliche Ganzpflanzenvergärung konnte vergleichbare Einsparpotenziale (85,9 MWh ha^{-1}) erreichen, wenn die Abwärme der Biogasverstromung annähernd vollständig genutzt wurde. Die Einsparungen an Treibhausgasen der Ganzpflanzenvergärung waren höher als die des IFBB-System, wenn mehr als 20% der Abwärme genutzt wurden. Dies ist durch die Kohlenstoffrückführung über die Gärreste bedingt.

(iv) Die höchste Effizienz (53%) bei der Verwertung von Biomasse vom Extensivgrünland zu Wärme und Strom wurde durch das IFBB-System erzielt, wenn es in Kombination mit einer Biogasanlage mit Abwärme, beispielsweise eine herkömmlichen landwirtschaftliche Biogasanlage oder Kläranlage mit Faulung, ausgeführt wurde. Die Konversionseffizienz der Heuverbrennung lag bei auf einem ähnlichen Niveau (54%), während die

Trockenfermentation eine deutlich geringere Effizienz von nur 17% erreichte aufgrund der geringen Abbaubarkeit der spät geernteten Biomasse. Einsprungen an Primärenergie lagen zwischen 12 und 15 MWh ha^{-1} für die betrachteten IFBB-Szenarios, während die Trockenfermentation und die Heuverbrennung Einsparpotenziale von jeweils 7 und 12 MWh ha^{-1} erzielten. Ähnliche Relationen zwischen den betrachteten Verwertungswegen wurden für die Treighausgasbilanzen ermittelt. Während die Nutzung der Grünlandbiomasse über die tierische Veredelung eine nahezu ausgeglichene Bilanz im Vergleich zum Referenzszenario einer Nutzung von intensiv bewirtschaftetem Grünland aufzeigte, waren das Mulchen und die Kompostierung mit einem Verbrauch von Primärenergie und dem Ausstoß von Treibhausgasen verbunden.

10.4 Zusammenfassung

Geringe Konversionseffizienzen bestehender Bioenergieverfahren sowie deren Abhängigkeit von wenigen Energiepflanzen führte zu der Entwicklung der Integrierten Festbrennstoff- und Biogasproduktion aus Biomasse (IFBB). Dessen innovativer Kern ist die mechanische Entwässerung der feucht konservierten Biomasse in einen Festbrennstoff für die thermische Verwertung sowie einen Presssaft für die anaerobe Vergärung mit anschließender Wärme- und Stromproduktion.

Im ersten Teil dieser Arbeit wurden biologische und chemische Parameter des IFBB-Systems untersucht. Presssäfte aus Maissilage wurden in Batch-Versuchen auf ihre Methanausbeute analysiert und Parameter des kontinuierlichen Fermenterbetriebs (Methanausbeute, Methangehalt, Essigsäureäquivalent, pH-Wert) wurden sowohl im Rührkessel- als auch Festbettraktor ermittelt. Desweiteren wurden Silagen und Presskuchen von 18 europäischen Grünlandflächen auf verbrennungsrelevante Eigenschaften untersucht und das Erweichungsverhalten der Verbrennungsaschen wurde experimentell und regressiv charakterisiert. Im zweiten Teil dieser Arbeit erfolgte die Ökobilanzierung des IFBB-Systems. Die Ökobilanzierung bewertete die Konversionseffizienz sowie Einsparpotenziale an fossiler Primärenergie und Treibhausgasemissionen (CO_{2-eq}) des IFBB-Verfahrens entlang der gesamten Prozesskette und im Vergleich zu anderen Formen der Biomassenutzung. Hinsichtlich der verwerteten Biomassen betrachteten die Ökobilanzierungen sowohl ackerbauliche Kulturen (Roggen und Mais im Zweikulturnutzungssystem) als auch Biomasse von extensiv bewirtschaftetem Grünland.

Die experimentellen Untersuchungen des ersten Teils ergaben Methanausbeuten des Maispresssaftes zwischen 390 and 506 l_N CH_4 kg^{-1} VS lagen. Der rasche Abbau der organischen Substanz sowie der schnelle Zusammenbruch der Methanproduktion beim Einsatz von Rührkesselreaktoren zeigten, dass Festbettreaktoren für eine stabile Vergärung notwendig sind. Die durchschnittliche Ascheerweichungstemperatur der Grünlandsilagen lag bei ca. 1.000°C, während sie sich bei den Presskuchen auf ca. 1.050°C belief. Die Ascheerweichungstemperatur konnte mithilfe linearer Regressionsmodelle mit hoher Schätzgüte (R^2 = 0,88-0,89) vorhergesagt werden. Die Ergebnisse der Ökobilanzierung des IFBB-Verfahrens zeigten, in Abhängigkeit der betrachteten Szenarien, Einsparpotenzial an Primärenergie von 69 bis 86 MWh ha^{-1} bei der Verwertung von hochproduktiven Ackerkulturen auf, während die Einsparpotenziale bei der Nutzung von Grünlandbiomasse extensiv bewirtschafteter Flächen mit 12 bis 15 MWh ha^{-1} geringer ausfielen. Die Einsparpotenziale an Treibhausgasemissionen lagen in einem Bereich von jeweils 10,6 bis 12,2 und 3,0 bis 3,6 CO_{2-eq} ha^{-1}. Die alternative Verwertung ackerbaulicher Energiepflanzen über die herkömmliche Biogasproduktion aus Ganzpflanzensilage erzielte vergleichbare Werte bei einem hohen Nutzungsgrad der Abwärme hinsichtlich des Einsparpotenzials an Primärenergie und leicht höhere Werte in Bezug auf die Einsparpotanziale an Treibhausgasen als das IFBB-Verfahren. Dies ist auf die Rückführung des Kohlenstoffs mit den Gärresten zurückzuführen. Bei der Verwertung der Grünlandbiomasse erzielte die Ganzpflanzenvergärung aufgrund der limitierten Verdaulichkeit des spät geernteten Grünlands deutliche geringe Einsparpotenziale als das IFBB-Verfahren.

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Appendix

Table A Consumption-specific emissions in mechanised crop cultivation (Kaltschmitt and Reinhardt, 1997).

	CO_2	CH_4	N_2O	NO_x	SO_2	NH_3	HCl
	(g kg^{-1} diesel)						
Heavy work	3175.00	0.08	0.14	35.00	0.90	0.12	0.02
Normal work	3175.00	0.12	0.14	33.00	0.90	0.12	0.02
Light work	3175.00	0.19	0.14	48.00	0.90	0.12	0.02
Road transport	3175.00	0.24	0.14	22.00	0.90	0.12	0.02

Table B Primary energy consumption and emissions of supply of seeds, lime, fertiliser and fuel diesel (Heinz et al., 1999).

	Primary energy	**CO_2**	**CH_4**	**N_2O**	**NO_x**	**SO_2**	**NH_3**	**HCl**
	(MJ kg^{-1} seeds)	(g kg^{-1} seeds)						
Winter rye seeds	2.39	150.00	0.22	0.61	1.03	0.23	0.51	0.00
Maize seeds	3.88	259.00	0.26	0.98	1.70	0.32	0.88	0.01
	(MJ kg^{-1} CaO)	(g kg^{-1} CaO)						
Lime	2.06	262.00	0.26	0.02	0.34	0.08	0.00	0.01
	(MJ kg^{-1} N)	(g kg^{-1} N)						
Nitrogen fertiliser	47.00	2746.00	6.69	9.64	11.68	3.76	4.93	0.12
	(MJ kg^{-1} P_2O_5)	(g kg^{-1} P_2O_5)						
Phosphor fertilser	15.56	1083.00	1.42	0.06	10.28	14.13	0.01	0.04
	(MJ kg^{-1} K_2O)	(g kg^{-1} K_2O)						
Potassic fertiliser	9.25	527.00	1.01	0.01	0.88	0.07	0.00	0.05
	(MJ MJ^{-1} Diesel)	(g MJ^{-1} Diesel)						
Diesel	1.11	8.48	0.01	0.00	0.04	0.05	0.00	0.00

Table C Emission factors of nitrous oxide, nitrogen oxide and ammonia during cultivation (KTBL, 2005a; Heinz et al., 1999; Eggleston et al., 2006).

Emission factors of nitrous oxide		
N_2O-direct from applied nitrogen	(kg N_2O-N kg^{-1} N)	0.01
N_2O-direct from general soil emissions	(kg N_2O-N ha^{-1})	8.00
N_2O-indirect from atmospheric deposition	(kg N_2O-N kg^{-1} (NH_3-N+NO_x-N))	0.01
N_2O-indirect from washed-out nitrogen	(kg N_2O-N kg^{-1} $N_{washed-out}$)	0.01
Emission factor of nitrogen oxide		
NO_x	(kg NO_x-N kg^{-1} N_2O_{direct}-N)	0.50
Database for the calculation of the emission factor of ammonia		
Ammonia content of digestate	(kg NH_4-N kg^{-1} N)	0.65
Ammonia loss during application	(kg NH_3-N kg^{-1} NH_4-$N_{appl.}$)	0.20
Reduction of losses by hose-towed spreader	(%)	30.00
Reduction of losses by incubation after 1 h	(%)	80.00
NH3 from mineral nitrogen	(kg NH_3-N kg^{-1} N)	0.02

Table D Database for energy production by using fossil fuels (GEMIS, 2007).

	Primary energy (based on LHV)	**CO_2**	**CH_4**	**N_2O**	**NO_x**	**SO_2**	**NH_3**	**HCl**
	(kWh kWh_{el}^{-1})	(g kWh_{el}^{-1})						
Power production	2.69	574.88	0.85	0.02	0.61	0.36	0.00	0.01
	(kWh kWh_{th}^{-1})	(g kWh_{th}^{-1})						
Heat production (oil)	1.39	370.30	0.10	0.00	0.23	0.35	0.00	0.00
Heat production (gas)	1.34	262.69	1.20	0.00	0.21	0.02	0.00	0.00

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Today's bioenergy systems are frequently characterised by limited conversion efficiency and dependencies on few species of energy crops leading to low biodiversity in plant production. With the aim to improve the ecological performance of biomass production and processing and to convert a wider spectrum of biomass resources, the integrated generation of solid fuel and biogas from biomass (IFBB) was developed. Its core element is the mechanical separation of the wet conserved biomass into a solid fuel for combustion and a liquid for anaerobic digestion with subsequent production of heat and electricity from the biogas.
This study investigated biological and chemical parameters of the IFBB process. Furthermore, life cycle assessment was conducted to evaluate the overall energy efficiency as well as saving potentials of fossil primary energy and emissions of greenhouse gases of the IFBB process along the entire process chain.