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# Examining European semi-natural grassland silages and urban green cut as input sources for the integrated generation of solid fuel and biogas from biomass

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University of Kassel

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# Examining European semi-natural grassland silages and urban green cut as input sources for the integrated generation of solid fuel and biogas from biomass

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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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Witzenhausen, November 2013 *Frank Hensgen*

## LIST OF PUBLICATIONS

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Chapter 5: Hensgen F., Bühle L., Donnison I., Heinsoo K., Wachendorf M., (2014): Energetic conversion of European semi-natural grasslands: Energy yields and the fate of organic compounds. Bioresource Technology, 154, 192-200.

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## ABBREVIATIONS

| | |
|---|---|
| AD: | Anaerobic digestion |
| ADF: | Acid detergent fibre |
| ADL: | Acid detergent lignin |
| a.s.l.: | Above sea level |
| AST: | Ash softening temperature |
| CEC: | Cation exchange capacity |
| CF: | Crude fibre |
| COD: | Chemical oxygen demand |
| CP: | Crude protein |
| DC: | Direct combustion |
| DE: | Germany |
| DM: | Dry matter |
| EE: | Ether extract |
| EST: | Estonia |
| EU: | European Union |
| FM: | Fresh matter |
| GHG: | Greenhouse gases |
| HC: | Hay combustion |
| HHV: | Higher heating value |
| ICP-OES: | Inductively coupled plasma-optical emission spectroscopy |
| IFBB: | Integrated generation of solid fuel and biogas from biomass |
| LCA: | Life cycle assessment |
| LHV: | Lower heating value |
| MF(s): | Mass flow(s) |
| NDF: | Neutral detergent fibre |
| NFC: | Non fibre carbohydrates |
| NFE: | Nitrogen free extract |
| OM: | Organic matter |

| | |
|---|---|
| PC: | Press cake |
| PCDD: | Poly-chlorinated-dibenzo-dioxins |
| PCDF: | Poly-chlorinated-dibenzo-furans |
| PF: | Press fluid |
| RM: | Raw material |
| RMC: | Raw material after conditioning |
| SCNR: | selective non-catalytic reduction |
| SCR: | selective catalytic reduction |
| UK: | United Kingdom |
| VS: | Volatile solids |
| WCD: | Whole crop digestion |
| WRB: | World reference base for soil resources |

# 1 General introduction

To counteract the negative effects of climate change, the European Union (EU) has increased its efforts in the field of renewable energies. This led to the definition of national and EU wide targets for the share of energy from renewable sources in gross final consumption of energy by the year 2020 for each EU-Member state and the Union as a whole through the directive 2009/28/EC of the European parliament and of the council (Anonymous, 2009). Germany, as an example, has to increase its share of renewable energy in gross final consumption from 5.8% (2005) to 18% by 2020. For the EU the goal is 20% by 2020. Therefore the production of renewable energy from biomass was supported politically (for example: Anonymous, 2009b) stimulating a considerable growth of the biogas sector in Germany, with an increase in biogas plants from 1750 to 7515 in the years 2003 to 2012 (FNR, 2013). Energy from biomass is supposed to play an important role in the future energy mix (Beurskens and Hekkenberg, 2011) as the biomass can be easily stored, transported and used for supply of different forms of end energy carriers. But the rapid increase in production of renewable energy from biomass has also been criticised. It is of great concern that the use of renewable crops from agricultural systems for bioenergy production in practice is nearly limited to the use of intensively managed maize for biogas production and rape seed, which leads to monotonous landscapes and negative environmental effects like soil erosion, nutrient leaching and loss of biodiversity (Herrmann, 2013, Fletcher at al., 2011, Dauber et al., 2010, Love et al., 2011). The overall environmental balance of bio-fuels from intensive agricultural cropping systems, for instance, is often negative and even worse than the use of fossil fuels (Zah et al., 2007) and under certain conditions even the greenhouse gas balance of renewable energy systems can be negative due to emissions in the agricultural cropping system or direct or indirect land use changes (Crutzen et al., 2008, Tonini et al., 2012). In addition, in times of growing world population and limited land resources there is an ongoing discussion

in science and media about the conflict between "food and fuel". Several authors have pointed out that there is a strong conflict for land between the production of renewable energy from agricultural crops on the one hand and feeding the world's population, nature conservation and other purposes on the other hand (Johansson and Azar, 2007, Hoogwijk et al., 2003, Bergsma et al., 2007).

Considering the negative effects of renewable biomass energy carriers from intensive agricultural systems for energy recovery, it has been suggested that the biomasses for renewable energy production should primarily come from sources such as landscape conservation material, urban green cut, food waste and other organic "waste" resources (Zah et al., 2007, Tilman et al., 2009). A number of these resources can be found in urban areas, where a reasonable amount of e.g. green waste is collected and used for compost production rather than energy recovery (Kern et al., 2010, Anonymous, 2008). Further residue biomass can also be found in European rural areas, where considerable amounts of extensive grassland biomasses are not used anymore or will not be used in the near future due to economic reasons and declining numbers of animals, as described by Rösch et al. (2009) and Isselstein et al. (2005). These grasslands are in need of an extensive management, i.e. late regular cutting and none or low fertilisation, to maintain their status as hotspots of biodiversity (Ostermann, 1998, Halada et al., 2011). Both resources, urban green cut as well as extensive grassland silage, have in common that they are very heterogeneous and not easily converted into renewable energy by means of combustion or biogas production. Especially the high lignin concentration in the urban green cut and the often late cut semi-natural grassland biomass hinder their use in biogas plants. It has been shown by a lot of investigations that material rich in lignin hampers biogas production (Chen et al., 2009) and leads to low overall methane yields and conversion efficiencies and long retention times (Shiralipour and Smith, 1984, Richter et al., 2009). On the other hand, high concentrations of minerals detrimental for combustion hinder the use of those biomasses in direct combustion. Herbaceous biomass and

especially green cut is a problematic material for energy production, as it is extremely heterogeneous (Hartmann, 2009) and contains higher concentrations of nitrogen (N), sulphur (S), chlorine (Cl), calcium (Ca), magnesium (Mg) and potassium (K) as wood, the most common and unproblematic fuel for combustion (Obernberger et al., 2006, Prochnow et al., 2009b, Jenkins et al., 1998). To overcome these difficulties and also aiming to increase energy efficiency of biomass conversion, the University of Kassel developed an innovative system called the "integrated generation of solid fuels and biogas from biomass" (IFBB), described by Wachendorf et al. (2009) and Graß et al. (2009). The biomass is subjected to a pre-treatment before combustion consisting of hydrothermal conditioning and subsequent dewatering with a screw-press. Thereby the biomass is separated into two fractions, the fibre rich press cake (PC) and the press fluid (PF) which contains the easily digestible organic parts of the biomass and also the larger part of the minerals of the biomass that are detrimental to combustion. After drying and compacting, the PC can be used as a solid fuel for combustion with better fuel quality than the biomass had before. The enriched PF can be used for the production of heat and electricity via biogas production whereby the heat and electricity produced through biogas combustion can be used within the system for the hydrothermal conditioning, the dewatering and the drying and compaction of the PC. Although the innovative IFBB system is not yet fully integrated into the market, a reasonable amount of scientific studies have been done on that system. Different kind of substrates have been investigated, including grassland silages from extensive mountain pastures in the southern part of Germany (Wachendorf et al., 2009, Richter et al., 2009, Richter et al., 2010) grassland silages from one lowland hay meadow at consecutive cutting dates (Richter et al., 2011 a, b) and 18 semi-natural grassland sites across Europe (Bühle et al., 2012a, Blumenstein et al., 2012). Also agricultural crops were included in the investigations by Bühle et al. (2011, 2012b). Different steps of the IFBB system were researched. Wachendorf et al. (2009) investigated the mass flows of mineral and organic compounds into

PF and PC and the solid fuel quality of the PC. The solid fuel quality and mass flows of mineral compounds were also of interest for Richter et al. (2010, 2011a), whereas in another manuscript Richter et al. (2011b) described the mass flows of organic compounds and the effects of that mass flows on energy conversion efficiency of the IFBB system. Three experiments investigated the anaerobic digestion of PF in comparison to whole crop digestion (WCD) (Richter et al 2009, 2011b, Bühle et al., 2012b). The economics of the IFBB system were investigated by Blumenstein et al. (2012). The complete system was analysed in form of life cycle assessment (LCA) by Bühle et al. (2011) for maize and winter rye and by Bühle et al. (2012a) for grassland silages. Special investigations on the effects of sward maturity and chemical composition of the silage on mass flows and mineral concentrations (Richter et al., 2011a) and on the organic compounds and total energy conversion efficiency (Richter et al., 2011b) were carried out. The effects of different hydrothermal conditioning temperatures were the focus of several studies (Wachendorf et al., 2009, Richter et al., 2009, 2010, 2011a, b). The ash softening temperature (AST) of the IFBB solid fuel as one important combustion parameter was investigated by Bühle et al. (2014).

The results of the former studies can be summarised as follows:

- The IFBB system proofed its suitability to reduce the concentrations of minerals detrimental for combustion by providing high mass flows of these nutrients, especially K, Cl, and Mg, into the PF (Wachendorf et al., 2009, Richter et al., 2010, 2011a). Reductions of N and Ca were rather low and in some experiments not statistically significant (Richter et al., 2010).
- The solid fuel quality was improved through a lower concentration of minerals, but also through an enrichment of fibres in the PC. These led to a higher ash softening temperature and an increase of the higher heating value (HHV) through the use of the IFBB procedure (Wachendorf et al., 2009, Richter et al., 2010, Bühle et al., 2014).

- The IFBB system is under certain circumstances an economically reasonable alternative for the management of semi-natural grasslands compared to other alternatives (Blumenstein et al., 2012). Best results for IFBB could be achieved if the system was adapted to an existing heat producer.
- The IFBB PF is a highly digestible substrate for anaerobic digestion, with high substrate related methane yields and short retention times in the digester (Richter et al., 2009, Bühle et al., 2012b)
- In terms of net energy savings and energy conversion efficiency the IFBB system proofed to be superior to WCD of silages and in the range of direct combustion (DC) (Richter et al., 2011b, Bühle et al., 2011, 2012a). Highest results for IFBB could be achieved if the system was attached to an existing heat producer (Bühle et al., 2012a).
- In terms of greenhouse gas (GHG) mitigation the IFBB system showed best results when the plant was calculated as an add on version to another heat producer and if late cut grassland silage was used as a substrate (Bühle et al., (2012a). If maize or winter rye is used as a substrate, WCD saved higher amounts of GHG if a heat use concept is applied and more than 20% of the produced heat is utilised (Bühle et al., 2011).
- The acidification and eutrophication balance for the IFBB system for extensive grassland silage is clearly outcompeting WCD (Bühle et al., 2012a).
- The effect of temperature of hydrothermal conditioning was subject to a number of investigations (Wachendorf et al., 2009, Richter et al., 2009, 2010, 2011a, b). Low temperatures of hydrothermal conditioning (<30°C) showed lower mass flows of nutrients into the PF and were therefore not favourable. High temperatures (>60°C) showed higher mass flows and thereby yielded better fuel qualities but also showed significantly worse energy conversion efficiencies and net energy gains. Therefore

mean temperatures in the range of 30-60°C proofed to be the best choice for achieving good fuel qualities with high energy conversion efficiencies.

- Richter et al. (2011a, b) showed that it is possible to predict the mass flows of mineral and organic compounds as well as energy conversion efficiencies of the whole IFBB system with high values of accuracy by multiple linear regression models using the hydrothermal conditioning temperature and the content of DM and NDF in the silage as explanatory variables.

The aim of this thesis is to fill some of the remaining knowledge gaps in the understanding of the IFBB system that still exist despite thorough research. Therefore, two experimental studies were carried out that culminated in three scientific manuscripts. In the first study (Chapter 3), urban green cut, a new input material was investigated. The composition of urban green waste and its use within the IFBB system were investigated for all process steps along the IFBB chain, including mass flows, mineral composition of the PC, the anaerobic digestion of PF as well as an energy balance for green cut comparing the IFBB system with the direct combustion. The second study (Chapter 4, 5) concentrated on extensive grassland silage. The parameters investigated were the same as in the studies mentioned above, but for this study a broad base of 18 semi-natural grassland areas was investigated, spread across Europe (Wales, Germany and Estonia). Also a mobile prototype of the IFBB technique was used to process the biomass samples providing a bigger scale than the so far used laboratory equipment. The models developed by Richter et al. (2011a, b) were also subject to closer investigation, alterations to these models were developed by including also botanical data.

# 2 Research objectives

The objective of this study was to further broaden the knowledge about the IFBB system and its feasibility for different kinds of biomasses that are nowadays only sparsely used for bio-energy production. For that purpose silage from European semi-natural grasslands and from urban green cut were investigated thoroughly. It was the aim of the study to investigate the IFBB process chain for both kinds of substrate, including the chemical analyses for nutrient and mineral composition of biomass silage and PC, the calculation of mass flows and minerals into the PF and PC, the anaerobic digestion of PFs, the calculation of AST and heating value for the PC, the calculation of energy balances and multiple linear regression models for a better understanding of the effect of botanical and chemical biomass parameters on fuel quality and energy yield.

The urban green cut was collected at two dates and treated with two different temperatures in the IFBB system. A three step series of mixtures between grassland silage (0-100%) and green cut (100-0%) were treated accordingly. Chemical analyses were done, both with the biomass silage and the PC to assess the fuel quality. Mass flows were calculated to test the efficiency of the IFBB system regarding the removal of nutrients detrimental for combustion. Digestion experiments were carried out to determine the methane yield of PF from green cut material. An energy balance was calculated to compare the IFBB system with the DC of green cut.

For the silage from European semi-natural grassland a similar research strategy was applied. Silages from 18 areas in three countries in Europe were investigated with three biomass samples per area in two consecutive years. The samples were processed in a first prototype of a mobile IFBB plant. The samples were treated with one temperature in the IFBB plant. In addition to chemical analyses and mass flow calculation, anaerobic digestion experiments were also conducted. Furthermore AST and HHV were calculated. Based on the anaerobic digestion experiments and the HHV a gross energy balance was

calculated, comparing IFBB with hay combustion (HC) and WCD. With the help of linear regression models a deeper understanding of the complex interaction between botanical and chemical silage parameters and solid fuel quality of PC and the gross energy yield of the IFBB system was possible.

The specific objectives of the experiments were:

(i) to determine the feasibility of the IFBB system with a new input source, green cut material, especially focussing on methane yield potential of press fluids and the quality of solid fuels in comparison to former results with grass silage.

(ii) to investigate the relationship between the chemical and botanical characteristics of extensive grassland silage and the mass flows and solid fuel quality within the IFBB system.

(iii) to investigate the relationship between the chemical characteristics of extensive grassland silage and the mass flows on organic compounds within the IFBB system and their effect on anaerobic digestion results.

(iv) to evaluate the IFBB system with regard to the energy yields obtained from green cut and extensive grassland silage in comparison to whole crop digestion and hay combustion.

# 3 Integrated generation of solid fuel and biogas from green cut material from landscape conservation and private households

**Abstract** Green cut material is a potential source of renewable energy which is not fully exploited through conventional energy recovery systems. A new energy conversion process, the integrated generation of solid fuel and biogas from biomass (IFBB), which includes mechanical separation after hydrothermal conditioning, was investigated. Ash softening temperature and lower heating value of the solid fuel were increased through the IFFB process in comparison to the untreated raw material. The net energy yield of IFBB at 40° C conditioning temperature ranged between 1.96 and 2.85 kWh $kg^{-1}$ dry matter (DM) and for the direct combustion between 1.75 and 2.65 kWh $kg^{-1}$ DM. Conversion efficiencies for the IFBB system were 42 to 68% and for direct combustion 42 to 63%. The IFBB system produces storable energy from material which is nowadays not used for energy conversion.

## 3.1 Introduction

In order to reduce anthropogenic climate gas emissions and thus to act against the global climate change, the European Union has enacted the European Biomass Action plan to oblige its member states to reach specific amounts of renewable energy production (Anonymous, 2009). The European Union committed to produce 20% of its total primary consumption from renewable energy sources by the year 2020. Besides wind and solar energy, biomass is a major source of renewable energy, which is still not fully exploited. The intensified use of biomass from arable crops is limited as the cultivation of bioenergy crops requires agricultural land which leads to competition between food and bioenergy production (Johansson and Azar, 2007, Hogwijk et al., 2003, Bergsma et al., 2007), eventually resulting in higher prices for food. From an ecological point of view, cultivation of energy crops is controversial. The use of agricultural crops for biofuel production can lead to higher climate gas emissions (Crutzen et al., 2008) and higher

negative ecological impacts (Zah et al., 2007) than the use of fossil fuels. Due to the negative impacts of agricultural crops it was proposed to enhance the use of waste products to increase renewable energy production (Zah et al., 2007). Waste products can be industrial or agricultural residual products such as material from landscape conservation measures, road cut and railway cut as well as driftwood (Kern et al., 2010) or material from households, like kitchen residues and garden cuts. Up to now this material is mostly used to produce compost (Anonymous, 2008), which helps to close nutrient cycles and improves soil quality, but is also an energy requiring process (Edelmann and Schleiss, 2001). However, herbaceous biomass and especially green cut is a problematic material for energy production, as it is extremely heterogeneous (Hartmann, 2009), leading to difficulties in common ways of energy recovery from biomass, i.e. anaerobic digestion and combustion. Compared to wood, which is the most common solid biofuel, herbaceous materials contain higher concentrations of nitrogen (N), sulphur (S), chlorine (Cl), calcium (Ca), magnesium (Mg) and potassium (K) (Obernberger et al., 2006). As most of the N contained in fuels is converted into $N_2$ or $NO_x$, high N contents can lead to increased $NO_x$ emissions (Van Loo and Koppejan, 2008). High S and Cl contents lead to emissions as $SO_2$ and HCl and cause corrosion problems, thus reducing the availability and lifetime of the combustion plant (Obernberger at al., 2006). In addition, high Cl contents increase the risk of emissions of polychlorinated dibenzodioxins (PCDD) and polychlorinated dibenzofurans (PCDF) (Obernberger et al., 2006). K is also involved in corrosion processes in the furnace and leads to low ash melting temperatures, which in turn increase the danger of slagging and fouling inside the combustion chamber (Van Loo and Koppejan, 2008).

As green cut usually consists partly of wood and shrub material, it can be expected to be highly lignified. It is well known that anaerobic digestion of lignified material leads to low methane yields and conversion efficiencies (Shiralipour and Smith, 1984, Richter et al., 2009).

The University of Kassel has developed a system for energy production from heterogeneous and senescent plant material, the integrated generation of solid fuel and biogas from biomass (IFBB; Wachendorf et al., 2009). Its main principle is to subject biomass to hydrothermal conditioning and subsequent dehydration using a screw-press, which results in a press fluid for biogas production and a press cake for combustion as solid fuel. Drying of the press cake with the waste heat from the biogas combustion is a key aspect of this procedure. This system is capable to produce energy from biomass of extensive grasslands, which causes difficulties in traditional anaerobic digestion or direct combustion as hay (Richter et al., 2009, 2010). The IFBB technique produces a storable solid fuel with improved combustion qualities and an easily digestible press fluid with high methane yields.

The aim of this study is to test the feasibility of the IFBB process to obtain renewable energy from green cut. Therefore, the objective was to investigate 1) the methane yield of press fluids from green cut and 2) the quality of solid fuels from green cut, considering nutrient and mineral content, ash softening temperature and heating value and 3) the energy balance of the IFBB system in comparison to direct combustion of green cut.

## 3.2 Material and Methods

The green cut material used in this study was collected at the composting facility of the city of Baden-Baden with an annual amount of green cut of about 3200 t DM. Baden-Baden is a town in the south-western part of Germany with 53260 inhabitants and has extended sanatorium and spa facilities with high amounts of green cut from parks and private gardens.

### 3.2.1 Separation, chopping and ensiling of raw material

Since green cut is heterogeneous, the material was sorted into four fractions: herbaceous, shrub, wood and soil material (Fig. 1).

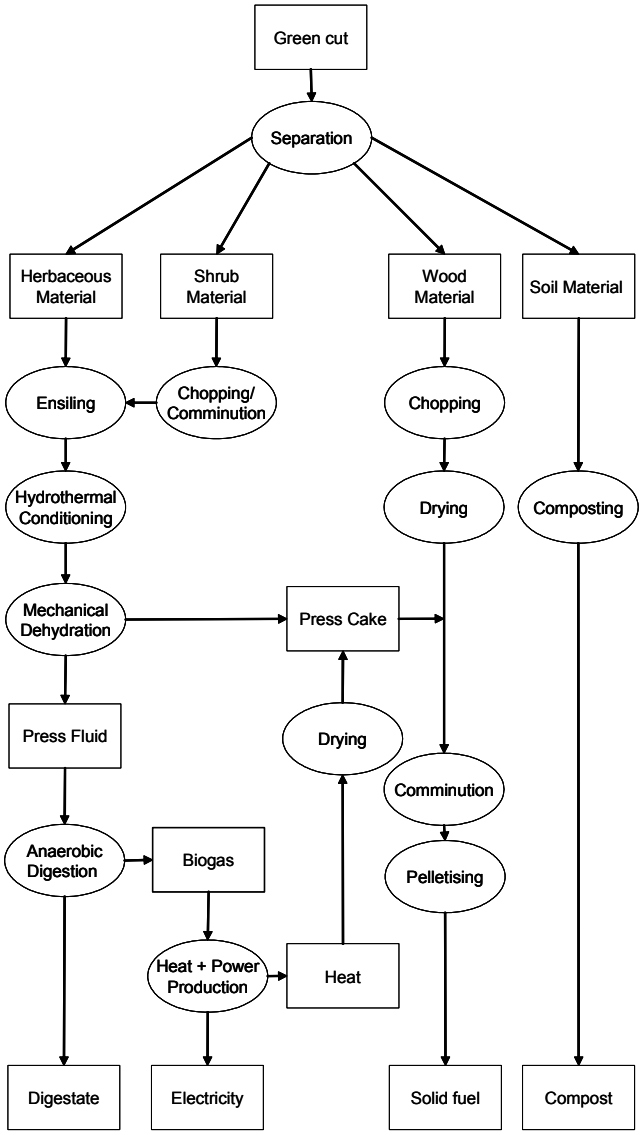


Fig. 1: Process scheme of the integrated generation of solid fuel and biogas from biomass (IFBB) system for green cut

The soil fraction was used for conventional composting, and larger wood pieces were chopped and used for combustion. Therefore only herbaceous material and shrub cuttings were processed according to the IFBB approach. The shrub fraction, containing smaller wood, branches, roots, leaves and small amounts of grass, was chopped (Willibald SR5000, Willibald Ltd., Wald-Sentenhart, Germany) to a particle length of 5 to 10 cm and milled with a hammer mill using a 20 x 20 mm sieve (B. Maier Zerkleinerungstechnik Ltd., Bielefeld, Germany) prior to ensiling. The herbaceous material, containing grass, leaves, hay, straw, fine hedge cut, lawn cut and small amounts of

wood, was directly chopped and ensiled. The comminuted material was compacted and closed air tight in 60L polyethylene barrels. The herbaceous and the shrub material were ensiled both in pure non-mixed fractions (S0 and S100, respectively) and in mixtures containing 33,50 and 67% of shrub-fraction (S33, S50 and S67, respectively). Samples were taken at two dates, 26.08.2008 and 31.10.2008, for all fractions and mixtures (S0, S33, S50, S67 and S100). The ensiling should provide a secure conservation of the raw material without losses due to decomposition processes. As an accessory benefit, the low pH and the activity of bacteria during the ensiling process should enhance the disintegration of the plant material and thereby promote the later use in the process by enhancing the mass flow (MF) of minerals and nutrients into the press fluid (PF).

### 3.2.2 Hydrothermal conditioning and mechanical dehydration

After ensiling, the samples went through a hydrothermal conditioning process. Two process temperatures, 40°C and 60°C, were investigated. The hydrothermal conditioning took place in a modified concrete mixer, which was filled with raw material (RM) and water in a proportion of 1:4 (RM : water). The material was heated by gas burners and continuously stirred for 15 minutes, followed by mechanical dehydration using a screw-press (Type Av, Anhydro Ltd., Kassel, Germany). The conical screw had a pitch of 1:6, the rotational speed was 6 revolutions $min^{-1}$ and the cylindrical screen encapsulating the screw had a perforation of 1.5 mm. Samples of RM before and after conditioning, PF and press cake (PC) were analysed for DM content after 48 h drying at 105°C. Crude ash was determined through burning of an aliquot of the same sample in a muffle type oven at 550°C.

### 3.2.3 Chemical analyses and mass flow calculation

Concentrations of potassium (K), magnesium (Mg), calcium (Ca), chlorine (Cl) and sulphur (S) in RM and PC were determined by x-ray-fluorescence-analysis. The concentration of carbon (C), hydrogen (H),

oxygen (O) and nitrogen (N) were determined by using an elemental analyser (EA 1106, Carlo Erba Ltd., Rodano, Italy).

The concentration of a specific component (Z) in the PF was calculated from the proportions of PC and PF in the raw material after conditioning (RMC) according to:

$$Z_{PF} = \frac{DM_{RMC} * Z_{RM} - Y * DM_{PC} * Z_{PC}}{X * DM_{PF}},$$

where X and Y are the quantities of the PF and the PC as a proportion of the raw material after hydrothermal conditioning, respectively, which were calculated by:

$$X = \frac{DM_{PC} - DM_{RMC}}{DM_{PC} - DM_{PF}} \qquad Y = 1 - X$$

The MF of DM and of any other compound (Z) from the RM into the PF (equations 1 and 3) and the PC (equations 2 and 4) were determined by:

(1) $$MF\_DM_{PF} = \frac{X * DM_{PF}}{DM_{RMC}}$$

(2) $$MF\_DM_{PC} = 1 - MF\_DM_{PF}$$

(3) $$MF\_Z_{PF} = \frac{X * DM_{PF} * Z_{PF}}{DM_{RMC} * Z_{RMC}}$$

(4) $$MF\_Z_{PC} = 1 - MF\_Z_{PF}$$

The ash softening temperature (AST) was calculated based on the concentrations of K, Ca and Mg (g $kg^{-1}$ DM) in the silage and the PC according to Hartmann (2009):

AST [°C] = 1172 - 5.39 * K + 25.27 * Ca - 78.84 * Mg

### 3.2.4 Digestion experiments

Experiments were carried out in a batch process described by Zerr (2006) and Richter et al. (2009) according to the German Standard (VDI 4630, 2004) with two replicates to investigate methane yields. Polyethylene containers (20L) were used for digestion of the material. Eighteen digesters were filled with 15 kg inoculum and 1.5 kg of PF. Two digesters were used as controls and therefore filled with 15 kg

inoculum and 1.5 kg water. Electrical stirrers mixed the material every 3 h for 15 minutes. The temperature of the digesters was maintained at 37°C through a warmed water basin equipped with a heating unit, a circulating pump, and a temperature sensor.

The inoculum for the experiments was taken from an anaerobic wastewater treatment plant of a paper factory. The gas discharge from the digesters passed through a gas-proof nozzle into aluminium gas containers. Twenty-four hours after filling of the barrels and daily thereafter the first gas yield and measurement of methane concentration took place. The total daily biogas volume was determined by a wet drum gas meter (TG1, Ritter Ltd., Bochum, Germany). The composition of the biogas was measured with a landfill gas analyser (LFG 20, Bernt Ltd., Düsseldorf, Germany) through infrared detection. The fermentation time was 12 days, determined according to VDI 4630 (2004). The content of organic dry matter, the chemical oxygen demand, the amount of biogas and the methane concentration were measured. Methane yield and degree of decomposition of organic matter was calculated. The degree of degradation ($\eta_{gas}$), indicating the decomposition of organic matter in the substrate and its transformation to biogas, was determined by relating the mass (m) of $CH_4$ and $CO_2$ obtained to the mass of volatile solids (VS) according to VDI 4630 (2004):

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

where VS was set at 0.93, as it was assumed that about 0.07 would be decomposed but used for the production of bacterial biomass.

### 3.2.5 Calculation of energy balances

Energy balances were calculated for the IFBB conversion and direct combustion (DC) based on the same raw material to evaluate the energy producing potentials of green cut. For DC, the assumption was that the material was sorted into a soil fraction for composting and another fraction for combustion, comprising all wood, shrub and

herbaceous materials. The combustion fraction would be chaffed and burned directly in a combustion chamber at the site of delivery. The system boundaries for both DC and IFBB procedure excluded delivery to the compost plant and separation and ensiling of the fractions as these steps were identical for both procedures. Furthermore, transport of the materials to the composting plant has to be done also for compost production, so this transport is not an energy input necessary for the energy recovery systems. The energy needed for conversion of the ensiled biomass into pellets and for the transport of the solid fuels to the place of their usage, assumed to be in 30 km distance, was included (Table 1).

Table 1: Energy input and output parameters for energy balances of direct combustion and the IFBB procedure.

| Energy input parameters | Combustion | IFBB | According to: |
|---|---|---|---|
| **Diesel:** | | | |
| Chopper | 9.59 kWh $t^{-1}$ FM | 9.59 kWh $t^{-1}$ FM | own calculations, Willibald Ltd. |
| Transport of pellets (30km) | | 6.45 kWh $t^{-1}$ FM pellets | Bühle (2008) |
| **Electricity:** | | | |
| Screw-press | - | 14 kWh $t^{-1}$ FM silage | Bühle (2008) |
| Biogas plant operation | - | 0.45 kWh $t^{-1}$ pressfluid | Bühle (2008) |
| Drying blower for press cake / raw material | | 6.94 kWh $t^{-1}$ FM | Bühle (2008) |
| Pelleting press cake / raw material | | 113 kWh $t^{-1}$ FM | Sokhansanj and Fenton (2006) |
| Comminution of shrub (hammer mill) | - | 28 kWh $t^{-1}$ FM | Sokhansanj and Fenton (2006) |
| **Heat:** | | | |
| Hydrothermal conditioning 40°C | - | 32 kWh $t^{-1}$ FM silage | Own calculations |
| Hydrothermal conditioning 60°C | - | 52 kWh $t^{-1}$ FM silage | Own calculations |
| Drying of press cake / raw material [a] | | 289 - 602 kWh $t^{-1}$ FM | Lootsma and Raussen (2008) |
| **Indirect energy input** | | | |
| | 10% of total energy input | 10% of total energy input | Bachmaier et al. 2008 |
| **Energy output parameters** | **Combustion** | **IFBB** | **According to:** |
| | **Efficiency burning oven** | **Efficiency of CHP / burning oven** | |
| Electricity from pressfluid | - | 0.37 | Scholwin et al., 2006 |
| Heat from press fluid | - | 0.48 | Scholwin et al., 2006 |
| Heat from press cake/ pellets | 0.9 | 0.9 | Bühle et al. 2011 |

The energy balance also included an indirect energy input figure for infrastructure, estimated to be 10% of the direct energy costs (Lootsma, 2006, Bachmaier et al., 2008). The net energy yield was calculated per kg RM as the difference between energy input and energy output. Energy input parameters are shown in Table 1. The value for energy input via diesel for chopping was provided by the manufacturer (Willibald Ltd., Wald-Sentenhart, Germany). The heat demand (Q) for hydrothermal conditioning of a specified amount of silage (m= 1g) was calculated based on the specific heat capacity of silage ($c=3.6 J C°^{-1} g^{-1}$) and the temperature difference of the silage before and during hydrothermal conditioning ($\Delta T$) according to:

$Q \times m^{-1} = c \times \Delta T$.

In a full scale IFBB plant the water used for the hydrothermal conditioning is supposed to be captured and reused as conditioning liquid. Losses of temperature of recycled water were estimated to be 2°C, so that there was a need to reheat the recycled water, which was calculated according to the equation $Q \times m^{-1} = c \times \Delta T$, using the heat capacity of water ($c=4.1826 J °C^{-1} g^{-1}$). The fermentation temperature was 37°C, but because the PF was preconditioned at 40°C and 60°C, respectively, there was no need for external energy to heat the digesters. It was assumed that the PFs were stored until they cooled down to 37°C and therefore energy input for cooling was not considered. The electrical and thermal efficiencies of the combined heat and power plant were estimated to be 37 and 48%, respectively (Scholwin et al., 2006). The thermal energy efficiency of the combustion unit for burning of the solid fuel and for DC was estimated to be 90%.

The energy conversion efficiency was calculated as the ratio between the net energy yield of each conversion technique and the gross energy contained in the raw material.

### 3.2.6 Statistics

Statistics were carried out using SPSS (IBM SPSS Statistics, Version 19). An ANOVA with a Post Hoc test (Tukey HSD) was used with treatment (none for raw material, hydrothermal conditioning at 40°C and 60°C, respectively) and material mixture (S0-S100) as fixed factors to test for effects of hydrothermal conditioning and conditioning temperature and the effects of the material mixture (S0-S100) as well as for interactions between those two effects on MFs of minerals and the amount of biogas produced from the press fluid. The same statistical method was applied for mineral contents, lower heating value and ash softening temperature of the press cake.

## 3.3 Results and Discussion

### 3.3.1 Mass flows of DM and elements into the press fluid

MF of DM into PF was comparable for both temperature treatments and varied between 11 (S100) and 20 % (S0) at 40°C and between 10 (S100) and 21% (S0) at 60°C. As no significant effect of temperature on MFs was detected (except for the content of crude ash; Table 2), only the MFs for the 40°C treatment are shown (Table 3). MF of DM was highest in herbaceous material (S0) and decreased with an increasing contribution of shrub material. For ash MFs ranged between 42% (S33) and 29% (S100) with a decreasing trend with increasing shrub content. MF of K was comparable for the mixtures and S0 (81 to 84%), but much lower for the pure shrub material (48%). MF of Mg was 58% for S0, similar for the mixtures and highest for the pure shrub material with 71%. MF of Ca was equally high for the mixtures with an average of 45%, intermediate for S0 (35%) and lowest for pure shrub material with 28%. For Cl, which is a very soluble element, MF was above 98% for all materials. Contrary, MF of N was considerably lower (4% for S0 to 26% for S33). It was even lower than the MF of DM in the case of S0, S50 and S100 material, resulting in a relative enrichment of N in the PC for these materials. MF of S ranged between 45% and 63% with no distinct pattern and with the lowest value for the pure shrub material. MF of P ranged between 47% and 66% with a tendency to decrease with increasing shrub content in the mixtures.

Table 2: Levels of significance of ANOVA for the effects of mixture of materials (M) used and treatment (T) and M x T on mass flow of plant compounds into the press fluid. Significant results ($p < 0.05$) are given in bold numbers

| **Source of Variation** | **df** | **DM** | | **Ash** | | **K** | | **Mg** | | **Ca** | | **Cl** | | **N** | | **S** | | **P** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | F | p | F | p | F | p | F | p | F | p | F | p | F | p | F | p | F | p |
| Mixture (M) | 4 | 10.3 | **0.001** | 3.8 | **0.039** | 4.9 | **0.020** | <0.1 | 0.997 | 5.6 | **0.012** | 0.8 | 0.537 | 8.4 | **0.003** | 3.2 | 0.064 | 1.6 | 0.248 |
| Treatment (T) | 1 | 0.1 | 0.718 | 10.0 | **0.010** | 0.7 | 0.409 | 2.7 | 0.129 | 0.1 | 0.917 | <0.1 | 0.856 | 0.1 | 0.802 | <0.1 | 0.979 | 0.1 | 0.794 |
| M*T | 4 | 0.2 | 0.919 | 0.3 | 0.862 | 2.0 | 0.172 | 1.3 | 0.337 | 0.8 | 0.986 | 0.2 | 0.929 | 1.2 | 0.362 | 0.1 | 0.991 | <0.1 | 0.997 |
| Error | 10 | | | | | | | | | | | | | | | | | | |

Table 3: The relative mass flow of plant compounds into press fluid with standard error of mean for a hydrothermal conditioning treatment at 40°C. S0, S33, S50, S67, S100 = 0, 33, 50, 67, 100 wt % of shrub material

| **Variable** | **SO** | **S33** | **S50** | **S67** | **S100** |
|---|---|---|---|---|---|
| DM | 20 ± 0,4 | 20 ± 1,9 | 17 ± 1,5 | 14 ± 0,8 | 11 ± 0,6 |
| Ash | 37 ± 7,5 | 42 ± 0,5 | 40 ± 0,5 | 36 ± 2,5 | 29 ± 7,0 |
| K | 81 ± 0,6 | 83 ± 5,9 | 84 ± 4,9 | 83 ± 0,5 | 48 ± 11,4 |
| Mg | 58 ± 1,6 | 58 ± 4,8 | 58 ± 5,9 | 59 ± 3,9 | 71 ± 16,4 |
| Ca | 35 ± 2,5 | 43 ± 1,5 | 42 ± 4,1 | 46 ± 0,5 | 28 ± 9,4 |
| Cl | 99 ± 0,6 | 99 ± 0,8 | 99 ± 0,1 | 98 ± 1,4 | 99 ± 0,4 |
| N | 04 ± 6,4 | 26 ± 3,9 | 12 ± 9,2 | 16 ± 1,5 | 06 ± 1,9 |
| S | 55 ± 0,7 | 60 ± 5,8 | 59 ± 7,2 | 63 ± 0,5 | 45 ± 12,2 |
| P | 64 ± 6,6 | 66 ± 13,1 | 62 ± 8,2 | 57 ± 9,3 | 47 ± 8,9 |

The IFBB process is well investigated for different kind of materials. Bühle et al. (2011) investigated the use of this process for whole crop silages of rye and maize, Wachendorf et al. (2009) for semi natural grasslands and Kolár et al. (2010) for a mixed substrate containing haylage, maize silage and cattle slurry. For DM the observed MFs in this study were lower than for semi natural grasslands (Wachendorf et al., 2009, Richter et al., 2011a) and remarkably lower than for maize silage (Bühle et al., 2011) but similar to the results reported by Kolár et al. (2010). For Mg, Ca, S, P, Cl and K the MFs were in the same range as observed in the above mentioned studies. Only the MF of N was remarkably lower. Kolár et al. (2010) showed that the MF of mineral N is very high (89-95%), whereas the MF for total N was also on a low level (20-26%). N occurs in plants in two forms, protein N (PN) and non-protein N (NPN), comprising inorganic N compounds (e.g. nitrate and ammonium) or soluble organic-N compounds (e.g. amino-acids). In young plant tissue, the concentrations of NPN and soluble N are higher than in mature tissue, where N occurs predominantly in structurally insoluble proteins (Mattson, 1980). The green cut material in this study was sampled in August and October, when plant material was mature and low in soluble N, resulting in low MFs for N.

In a study with biomass from semi-natural grasslands temperature of hydrothermal conditioning had an influence on MFs and thereby on fuel quality and energy yield (Richter et al., 2011 a, b). Wachendorf et al. (2009) showed that temperatures of 40-60°C increased the MFs of various crop constituents in comparison to a low temperature water treatment, whereas a further increase of temperature did not increase MFs. The results from the present study are in accordance with the results of the two studies mentioned above and show that with green cut it was possible to obtain similar MFs both for the 40°C and 60°C conditioning temperatures.

### 3.3.2 Methane yield from anaerobic digestion of press fluids

There was no significant effect of conditioning temperature or type of material on the amount of methane produced from the press fluids. The gas yield showed a tendency to decrease with increasing shrub content (Fig. 2), although this decrease was not statistically significant. For S0 the average methane yield was 359 and 351 $L_N$ $CH_4$ $kg^{-1}$ VS for the 40°C and the 60°C treatment, respectively, whereas for S100 it was 254 and 281 $L_N$ $CH_4$ $kg^{-1}$ VS, respectively. Parallel to the methane yield, the degree of degradation decreased with increasing shrub content in the material. While the S0 material showed degrees of degradation of 81% (40°C) and 78% (60°C), the S100 material only degraded by 59% (40°C) and 72% (60°C).

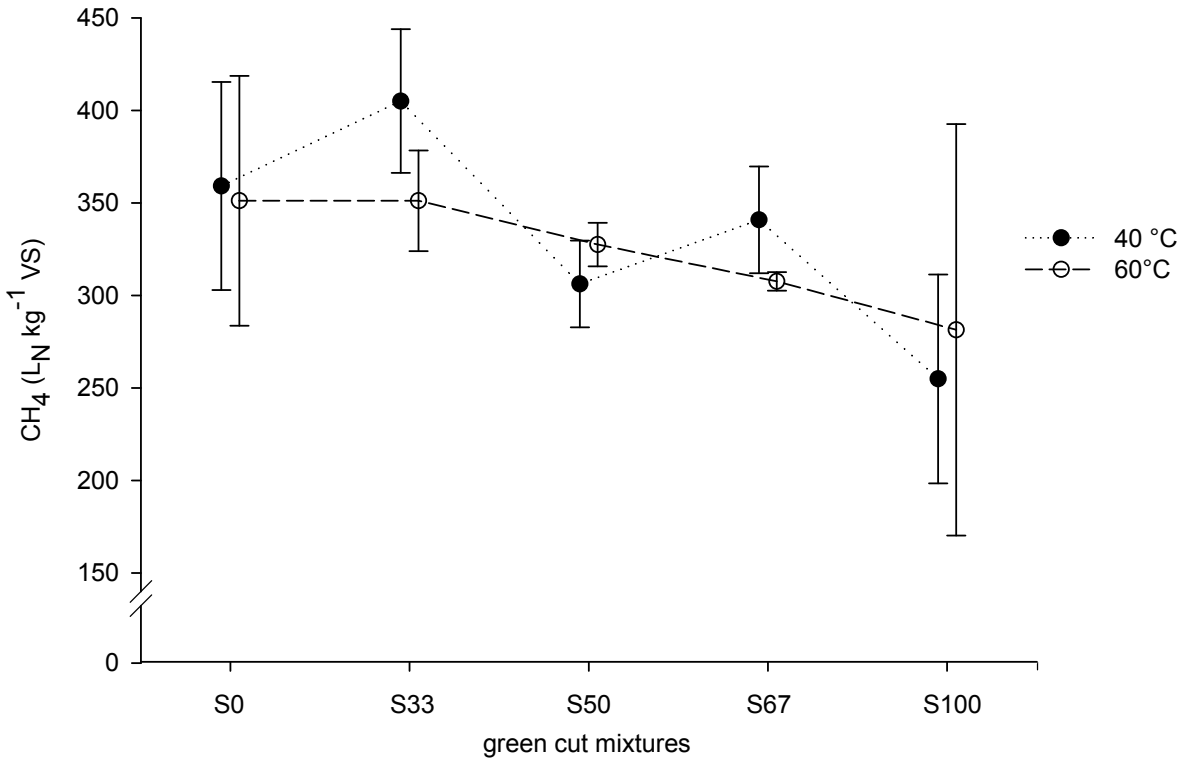


Fig. 2: Methane yield of press fluid after hydrothermal conditioning at 40°C and 60°C. S0, S33, S50, S67, S100 = 0, 33, 50, 67, 100 wt % of shrub material, respectively. Error bars indicate standard error of mean.

This may be explained by the fact that wood-like material in general contains higher lignin concentrations than herbaceous material. Lignin leads to low methane yields and degradation levels (Shiralipour and Smith, 1984). Methane yield and degree of degradation were lower compared to PF from silage of semi natural grassland (396-415 $L_N$ $CH_4$ $kg^{-1}$ VS; 88-90%; Richter et al., 2009). Compared to anaerobic digestion of whole crop silage from semi-natural grassland (methane yield: 218 $L_N$ $CH_4$ $kg^{-1}$ VS; degree of degradation: 55%) reported by Richter et al. (2009), PF in this study showed higher methane yield and degree of degradation, as only the soluble and more easily digestible parts of the material were transferred into the PF, whereas major parts of lignin and cellulose remained in the PC.

### 3.3.3 Quality of solid fuel

For all measured variables, except Ca and N, concentrations in the PC were significantly lower than in the raw material due to the conditioning and dehydration process (Fig. 3 and Table 4), but no significant differences occurred between the 40°C and 60°C treatment (data not shown).

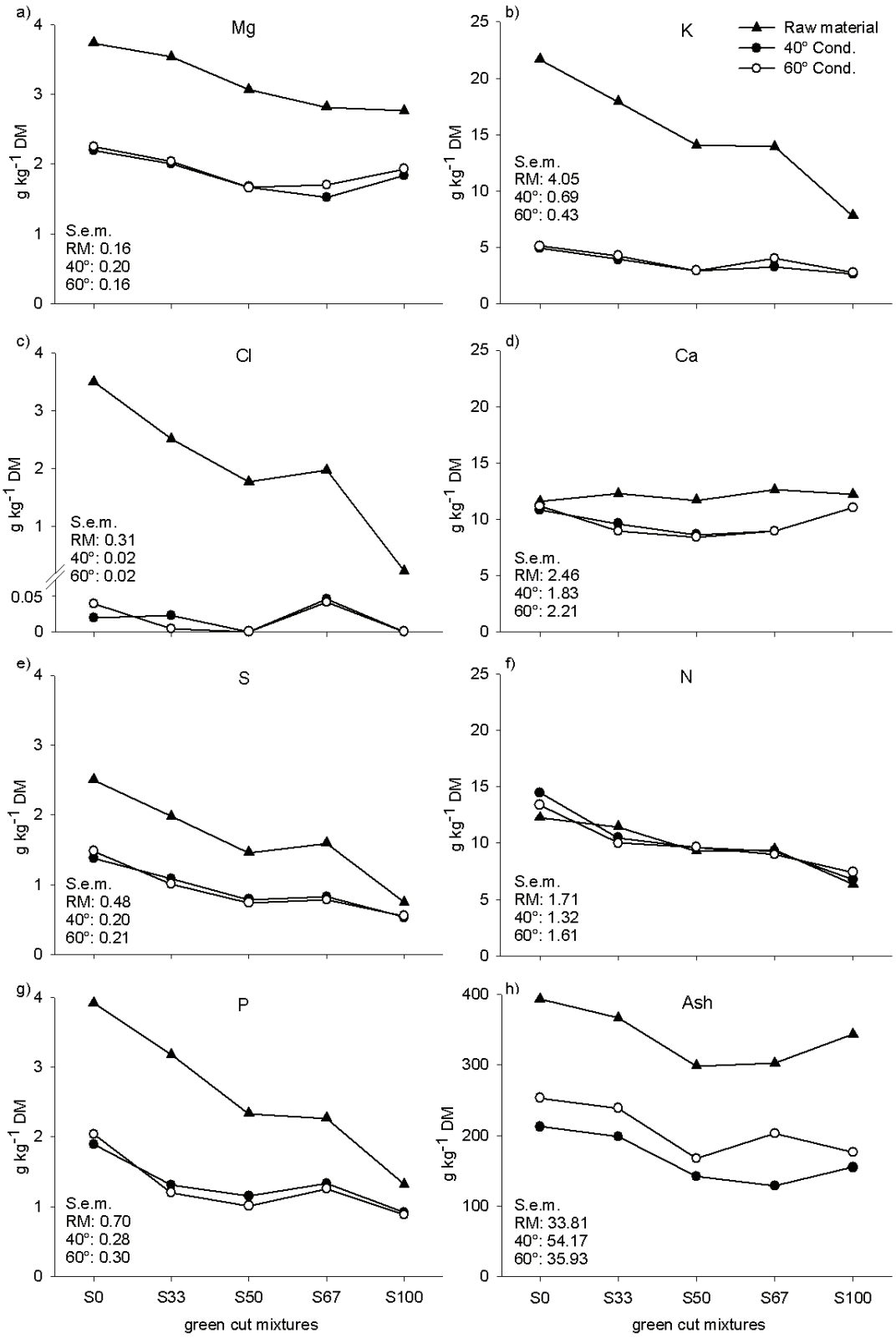


Fig. 3: Concentration of a) Mg, b) K, c) Cl, d) Ca, e) S, f) N, g) P and h) ash in raw material and press cake after hydrothermal conditioning at 40°C. S0, S33, S50, S67, S100 = 0, 33, 50, 67, 100 wt % of shrub material, respectively. Standard error of mean (s.e.m.), shown are means for raw material (RM) and conditioning temperatures of 40°C and 60°C

Table 4: Levels of significance of ANOVA for the effects of mixture of materials (M) used and treatment (T) and M x T on concentration of minerals in raw material and press cake. Significant results ($p < 0.05$) are given in bold numbers.

| **Source of Variation** | **df** | **Ash** | | **K** | | **Mg** | | **Ca** | | **Cl** | | **N** | | **S** | | **P** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | F | P | F | p | F | P | F | p | F | p | F | p | F | p | F | p |
| Mixture (M) | 4 | 1.88 | 0.169 | 1.87 | 0.168 | 6.73 | **0.003** | 0.32 | 0.860 | 7.52 | **0.002** | 5.05 | **0.009** | 3.81 | **0.025** | 2.55 | 0.082 |
| Treatment (T) | 2 | 19.13 | **<0.001** | 26.71 | **<0.001** | 71.17 | **<0.001** | 1.66 | 0.223 | 98.54 | **<0.001** | 0.05 | 0.950 | 5.97 | **0.012** | 7.13 | **0.007** |
| M*T | 8 | 0.09 | 0.999 | 0.74 | 0.658 | 0.64 | 0.737 | 0.12 | 0.997 | 7.13 | **0.001** | 0.15 | 0.995 | 0.25 | 0.974 | 0.36 | 0.926 |
| Error | 15 | | | | | | | | | | | | | | | | |

For K, which is responsible for corrosion problems and leads to a low AST in combustion (Obernberger et al., 2006), the reductions ranged from 64 to 79% and the concentrations in the PC were between 2.68 and 5.13 g $kg^{-1}$ DM. These values ranged in the same magnitude as in willow wood (2.60 g $kg^{-1}$ DM) and wheat straw (4.60 g $kg^{-1}$ DM) (Hartmann, 2009).

Concerning Mg, the reductions were between 30% and 46% and the concentrations in the PC were between 1.53 and 2.25 g $kg^{-1}$ DM, which is somewhat higher than in wheat straw and willow wood (0.5 and 1.3 g $kg^{-1}$ DM, respectively), as reported by Hartmann (2009). High Mg contents in the solid fuel reduce the calculated AST (Hartmann, 2009); whereas Obernberger et al. (2006) reported that Mg increases the AST. Therefore the results of calculated AST have to be interpreted carefully, as the effect of Mg on AST is controversial.

Lower reductions occurred for Ca (3 to 29%) and the concentrations in the PC ranged between 8.44 and 11.17 g $kg^{-1}$ DM which is higher than in wheat straw (0.5 g $kg^{-1}$ DM) and willow wood (6.8 g $kg^{-1}$ DM). Ca increases ash softening temperature (Hartmann, 2009, Obernberger et al., 2006), through transformation of potassium rich phosphates into phosphates with increased calcium and magnesium proportion, which have a higher melting point than the easily melting potassium rich phosphates (Steenari et al., 2009). Maximum reduction rates were achieved for the highly water soluble Cl. Nearly all Cl was washed out through hydrothermal conditioning with reduction rates of at least 97%. Cl concentration in the PC was between 0.001 and 0.051 g $kg^{-1}$ DM which is comparable to willow wood (0.04 g $kg^{-1}$ DM) and lower than in wheat straw (22.80 g $kg^{-1}$ DM). The high reduction rates of Cl lead to an improvement of fuel quality, as Cl is responsible for corrosion, particulate emissions and contributes to the emission of dioxins and furans (PCDD and PCDF). For these reasons, Cl content in the fuel should be kept below 1.0 g $kg^{-1}$ DM (Obernberger et al., 2006). No significant reduction was achieved for N (Table 4). For both pure fractions, S0 and S100, there was an increase in N concentration, though this increase was not significant. N concentrations in PC were

between 6.77 g $kg^{-1}$ DM (S100) and 14.45 g $kg^{-1}$ DM (S0) while willow wood contains 5.4 g N per kg DM and wheat straw up to 22.8 g $kg^{-1}$ DM. N leads to emission problems and increases the $NO_x$ emissions, therefore an N concentration of 6.0 g N $kg^{-1}$ DM should not be exceeded (Obernberger et al., 2006). Concentrations in the PC were above this value, especially for the herbaceous material. However, there are several technological possibilities to reduce $NO_x$ emissions (Nussbaumer, 2003), including air staging or fuel staging combustion and, if necessary, secondary measures like selective non-catalytic reduction (SCNR) and selective catalytic reduction (SCR) described by Obernberger et al. (2006). S was significantly reduced, with reduction rates between 26% and 51%. Concentrations of S in the PC were between 0.54 (S100) and 1.48 g $kg^{-1}$ DM (S0), which was higher than in willow wood (0.45 g $kg^{-1}$ DM) and comparable to wheat straw (1.2 g $kg^{-1}$ DM). Because S contributes to corrosion and causes emissions a value of 1.0 g S $kg^{-1}$ DM is set as a limiting parameter by Obernberger et al. (2006). Samples from S0 and S33 exceeded this limit, whereas samples with higher shrub content showed S concentrations below the threshold value. Reduction rates for P were significant (Table 4) and between 31% and 62%. The content of P was low in the shrub fraction with 0.89 g $kg^{-1}$ DM and somewhat higher in PC of S0 (2.04 g $kg^{-1}$ DM). The value for S100 PC is on the same level as those reported for willow wood (0.90 g $kg^{-1}$ DM). Processing the material according to the IFBB system reduced the content of crude ash in the PC significantly (Table 4) with reduction rates between 33% and 57%. Ash content in the PC was reduced to 129-213 g $kg^{-1}$ DM for the 40° C treatment and to 176 to 253 g $kg^{-1}$ DM for the 60° C treatment. The ash content declined with increasing shrub content by trend.

Table 5: Ash softening temperature and lower heating value of raw material and press cake with hydrothermal conditioning at 40°C and 60°C. S0, S33, S50, S67, S100 = 0, 33, 50, 67, 100 wt % of shrub material.

| | **S0** | **S33** | **S50** | **S67** | **S100** |
|---|---|---|---|---|---|
| **Ash softening temperature [°C]** | | | | | |
| Raw material | 1053 | 1102 | 1148 | 1194 | 1244 |
| Press cake (40°C) | 1245 | 1235 | 1242 | 1260 | 1287 |
| Press cake (60°C) | 1249 | 1215 | 1238 | 1243 | 1216 |
| **Lower heating value [MJ kg$^{-1}$ DM]** | | | | | |
| Raw material | 12.26 | 12.16 | 13.19 | 13.38 | 12.89 |
| Press cake (40°C) | 16.45 | 15.79 | 16.37 | 16.66 | 16.47 |
| Press cake (60°C) | 15.50 | 15.01 | 15.98 | 15.15 | 15.96 |

For fuels with low ash softening temperatures there is an increased risk of hard deposits and slagging in the furnace, which leads to the disruption of the combustion process, to higher service costs and shortens the operating time of the combustion plant (Hartmann, 2009). Compared to the RM, PC showed a significantly higher AST (Table 5 and Table 6) mainly caused by the reduction of K through the hydrothermal conditioning process and the relatively low reduction of Ca.

Table 6: Levels of significance of ANOVA for the effects of mixture of materials (M) used and treatment (T) and M x T on ash softening temperature and lower heating value (LHV) of raw material and press cake. Significant results ($p < 0.05$) are given in bold numbers.

| **Source of Variation** | **df** | **AST** | | **LHV** | |
|---|---|---|---|---|---|
| | | F | p | F | p |
| Mixture (M) | 4 | 0.72 | 0.594 | 0.55 | 0.703 |
| Treatment (T) | 2 | 3.83 | **0.045** | 25.34 | **< 0.001** |
| M*T | 8 | 0.20 | 0.986 | 0.17 | 0.993 |
| Error | 15 | | | | |

While the calculated AST for S0 increased markedly through conditioning (RM: 1053°C; 40°C and 60°C treatment: 1245°C and 1249°C, respectively), the treatment effect was less pronounced for the material with higher shrub content and vanished completely for S100 (RM: 1244°C; 40°C and 60°C treatment: 1287°C and 1216°C, respectively). The values obtained from the processed material were in the range of those of willow wood (1283°C) and considerably higher

than those from wheat straw (998°C). However, the results calculated according to the formula of Hartmann (2009) have to be interpreted with care, as this formula has a relatively low prediction accuracy ($r^2$ = 0.60) with a standard error of mean of 88.2°C and was developed with data from 67 samples of different kind of materials (e.g. wood, straw, hay, Hartmann et al., 2000).

The lower heating value of the PC was higher for both temperature treatments than that of the RM but no significant difference occurred between both temperatures (Table 6). The LHV for S0 increased from 12.26 MJ $kg^{-1}$ DM to 16.45 MJ $kg^{-1}$ DM (40°C) and 15.50 MJ $kg^{-1}$ DM (60°C) which is relatively low compared to unconditioned material from landscape conservation and perennial ryegrass (Lolium perenne) with 17.4 and 16.5 MJ $kg^{-1}$ DM, respectively, as reported by Hartmann (2009). The conditioning effect was similar for the mixtures and for S100 with the highest value for the 40°C treatment. LHV of the PC was lower than for wheat straw (17.2 MJ $kg^{-1}$ DM) and willow wood (18.5 MJ $kg^{-1}$ DM).

### 3.3.4 Energy balance and energy conversion efficiency

The energy output of the conversion of green cut material by the IFBB technique is composed of electricity from PF (10% of total net energy produced) and heat from PF and PC (90% of total net energy produced), and ranged from 3.47 to 3.82 kWh $kg^{-1}$ DM for the 40°C treatment (Fig. 4a). For 60°C treatment, energy output ranged from 3.33 to 3.73 kWh $kg^{-1}$ DM (data not shown). The amount of energy consumed in the conversion process was between 0.93 and 1.76 kWh $kg^{-1}$ DM (40°C) and between 1.08 and 1.72 kWh $kg^{-1}$ DM (60°C).

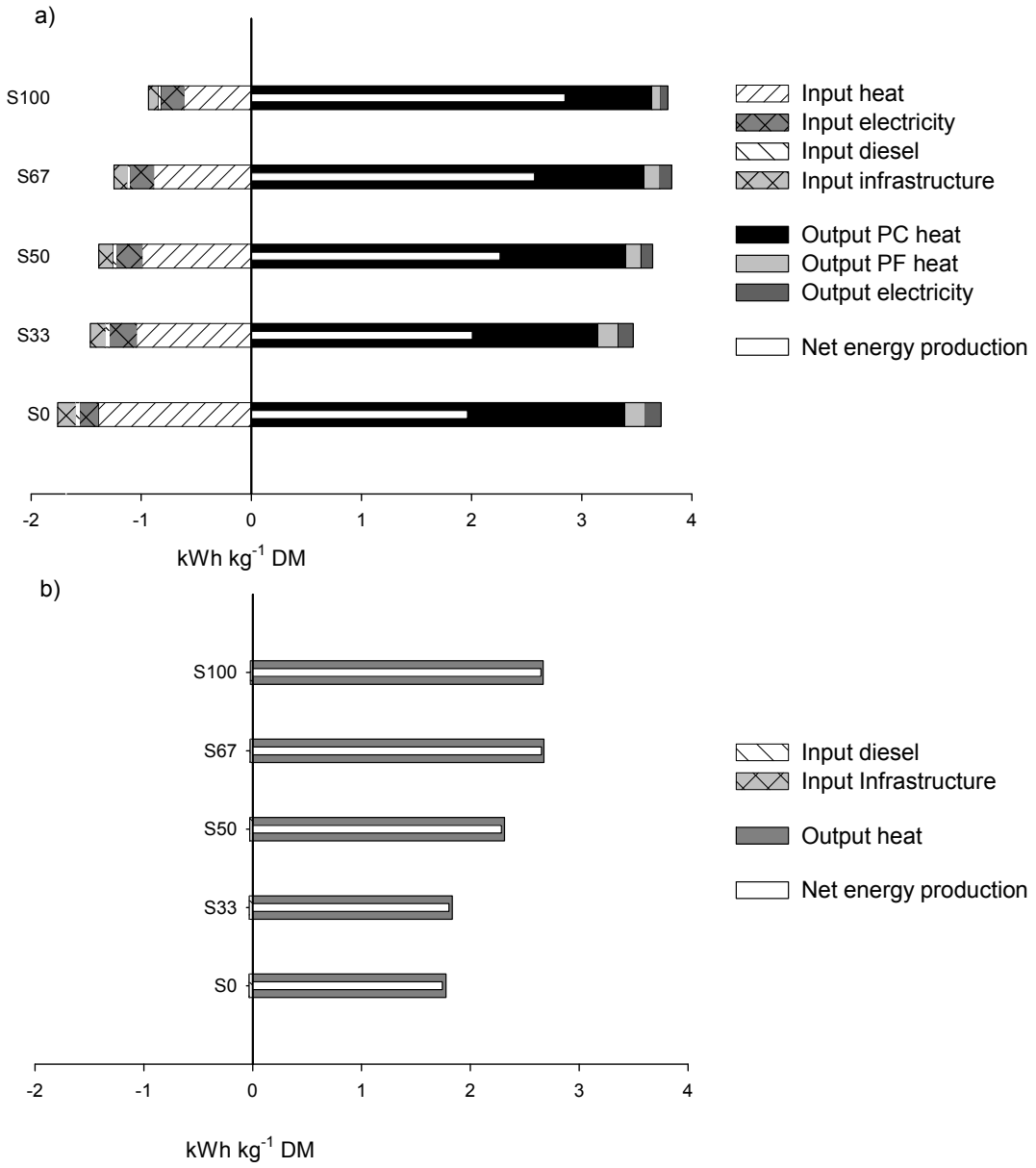


Fig. 4: Energy balance of a) the IFBB procedure and b) direct combustion for the conversion of green garden waste. S0, S33, S50, S67, S100 = 0, 33, 50, 67, 100 wt % of shrub material, respectively

In both cases the energy input was highest for the pure herbaceous material and lowest for the pure shrub material, as the heat needed for drying the relative moist herbaceous material is by far the most important input factor. The net energy yield, calculated by subtracting the energy input from the energy output, ranged from 1.96 to 2.85 kWh $kg^{-1}$ DM at 40°C and from 1.74 to 2.65 kWh $kg^{-1}$ DM at 60°C. At both levels of temperature energy yield was lowest for the pure

herbaceous material and increased with increasing shrub content in the material. Compared to the 60°C treatment, conditioning at 40°C was superior for all tested materials.

The energy input for conversion by DC was much lower than by IFBB (Fig. 4b). It varied between 0.02 for S100 and 0.03 kWh $kg^{-1}$ DM for S0. Due to the high water content of the RM, the output was also lower than for the IFBB process. It ranged between 1.78 (S0) and 2.68 (S67) kWh $kg^{-1}$ DM. The resulting net energy yield was between 1.74 kWh $kg^{-1}$ DM (S0) and 2.65 kWh $kg^{-1}$ DM (S67, S100).

A comparison between investigated IFBB systems revealed that the net energy yield for the 40°C treatment was constantly higher than for the 60°C treatment. Compared to DC, the 40°C IFFB process showed higher net energy yields for S0, S33 and S100, but lower yields for the S50 and S67 material. The results for the 60°C treatment were similar to the net energy results from direct combustion. The conversion efficiency rates ranged from 48% to 68% for IFBB 40°C treatment and 42% and 63% for the IFBB 60°C treatment. Shrub content of mixtures and conversion efficiency were positively correlated, the lowest conversion efficiencies for all treatments were observed for the S0 material. For S0, S33 and S100 the 40°C IFBB treatment showed the best conversion rates. The conversion efficiency for DC ranged between 42% and 63%. S50 and S67 showed better conversion rates if used through DC than through IFBB.

In Germany, most of the green cut material is composted or used in anaerobic digestion (AD). Composting is an energy requiring process (Edelmann and Schleiss, 2001), with big differences among the various methods. Enclosed composting needs more energy than open windrow composting. However, compost is a fertiliser which can be used as a substitute for mineral fertilisers and thereby help reduce $CO_2$ emissions through the avoidance of fossil energy use for fertiliser production. But even if this replacement of fertiliser is added as a bonus to the energy balance, it is still negative with -11.8 kWh $t^{-1}$ FM

bio waste in open windrow composting systems and -350.3 kWh $t^{-1}$ FM bio waste in enclosed systems (Edelmann and Schleiss, 2001).

Kern et al. (2010) stated that the energy costs of composting ranged between 11 and 100 kWh $t^{-1}$ FM bio-waste. They also observed an increase in the use of bio-waste for energy purposes, mainly in the form of AD. The trend towards energy production from bio-waste instead of composting has also been criticized, because compost is used as a substitute for peat and thereby reduces energy and climate gas emissions (Kranert et al., 2010). According to Kranert et al. (2010) composting of green cut reduces $CO_{2eq}$ emissions by as much as DC of the same material, if the replacement of peat is calculated as a bonus for the composting process. Kranert et al. (2010) stated that DC should only be used for woody material, whereas for herbaceous material composting is the better alternative in terms of climate gas savings. An alternative for the herbaceous part of green cut material is AD. However, Richter et al. (2011b) reported that AD has very low conversion efficiencies (18-25%) when applied to mature and highly lignified grassland material and that the IFBB system leads to higher conversion efficiencies (32-54%) for such material. Calculations by Kern et al. (2010) for the potential material of bio-waste and green cut under German conditions show that there is a constant flow of 4.36 Mio. t FM $a^{-1}$ of green cut material to the composting plants and that there is an additional potential from landscape conservation measures like roadside cut and railway side cut and driftwood. They calculated the technical potential of herbaceous roadside cut material to be 100,000 - 150,000 t FM, the potential of wood-like material from roadside cut to be 250,000 - 550,000 t FM, the potential of wood like material from railway side cut, driftwood and riverside vegetation to be 95,000 -125,000 t FM. To use these materials for energy production, conservation (e.g. through ensiling) would be necessary. Losses due to microbial activities would be unavoidable and have been calculated to be approximately 12% (Rieckmann, 2006). If all these biomasses would be used according to the IFBB system at a conditioning temperature of 40°C, an annual energy yield of 4145 - 4473 GWh could be realised,

calculated on the basis of the net energy yields of herbaceous and woody materials from this study. In contrast, through DC a net energy recovery of 3976 - 4290 GWh could be realised. The IFBB system does not only allow slightly higher energy recovery values than DC, but also produces a higher quality fuel which leads to less problems in combustion and reduced emissions. Furthermore, part of the energy output in the IFBB system is electrical power, whereas DC only generates thermal energy. As the demand for heat is not distributed equally throughout the year, DC may cause an overproduction in summertime. Within the IFBB System, the produced heat is completely used for drying of the PC, which can be pelletised and stored to be used at a time when it is needed. The differences in quality of energy carriers produced in both systems also affect the potential climate gas savings. Under German conditions, 604 g $CO_{2equ}$ are released to produce one kWh of electric energy, compared to 328 g $CO_{2equ}$ for one kWh of thermal energy (Bühle et al., 2011). Thus, the thermal and electric energy producing IFBB system would save higher amounts of greenhouse gases compared to the thermal energy producing direct combustion system.

## 3.4 Conclusions

Based on the data derived from this study, the following conclusions can be drawn:

1) The methane yields of press fluids were between 254 (S100, 40°C) and 359 (S0, 40°C) $L_N$ $CH_4$ $kg^{-1}$ VS and degrees of degradation ranged between 59% (S100, 40°C) and 81% (S0, 40°C). There was no statistically significant effect of hydrothermal conditioning temperature or input material used to be found.
2) The fuel quality was considerably improved by the IFBB system; the PC showed significantly reduced contents of K, Cl, Mg, S and P and thereby increased AST and a reduced risk of ash slagging and harmful emissions or corrosion.

3) The energy balance of the IFBB process was superior to direct combustion for herbaceous material. For shrub material the energy balances converged. Hydrothermal conditioning at a temperature of 40°C showed higher energy efficiencies compared to 60°C. Further research is needed to investigate how the varying composition and quality of green cut material through the year affects the energy recovery by means of changes in mass flows and biogas yield.

# 4 Mineral concentrations in solid fuels from European semi-natural grasslands after hydrothermal conditioning and subsequent mechanical dehydration

**Abstract** The integrated generation of solid fuel and biogas from biomass (IFBB) is particularly designed for the conversion of semi-natural and high biodiversity grassland biomass into energy. This biomass is problematic in common energy conversion techniques, e.g. biogas conversion or combustion, because of its chemical composition. The IFFB process separates the material into a fibre rich solid fuel and a fluid, which is rich in minerals and highly digestible constituents and is used for anaerobic digestion. Biomasses from 18 European semi-natural grassland sites have been processed in an IFBB prototype. The impact of different chemical and botanical parameters on mass flow of mineral plant compounds and their concentrations in the fuel has been investigated. Fuel quality was significantly influenced by chemical and botanical parameters and the quality could be significantly improved during processing. Biomass with a high grass proportion and fibre content showed the best fuel qualities after IFBB treatment.

## 4.1 Introduction

Semi-natural grasslands constitute a major part of the cultural landscape in Central Europe and harbour a vast diversity of plant and animal species. This diversity is threatened by intensification and abandonment (Isselstein et al., 2005). The conservation of these grasslands is therefore one of the main goals of European nature conservation policy. Regular cut of semi-natural grassland is necessary to conserve the current plant inventory, but is often not implemented due to decreasing economic returns from animal husbandry (Ostermann, 1998; Rösch et al., 2009). The use of biomass from species-rich grasslands for bioenergy recovery can be considered as one option to maintain the biodiversity status of endangered grassland through profitable use. Chemical characteristics of grassland biomass from nature conservation areas demand specialised techniques for

conversion into usable energy carriers. The conventional method, biogas production from digestion of silage, results in a low gas yield due to limited digestibility of the highly senescent biomass produced by late harvest (Richter et al., 2009). Combustion of semi-natural grassland hay is also affected by technical constraints, because of high proportions of minerals, nitrogen and sulphur, leading to problems of ash melting (K, Mg), corrosion (K, Cl, S) and increased emissions (N, S) (Obernberger et al., 2006, Prochnow et al., 2009b). Furthermore, producing hay from these herbage-rich grassland swards leads to increased dry matter (DM) losses during field drying and harvest and is strongly dependent on weather conditions.

A newly developed approach that aims at the thermal use of the grassland biomass by improving the fuel quality through extraction of minerals is the object of the present paper. The core element of the integrated generation of solid fuel and biogas from biomass system (IFBB, Fig. 5) is the mechanical dehydration after hydrothermal conditioning of the ensiled biomass.

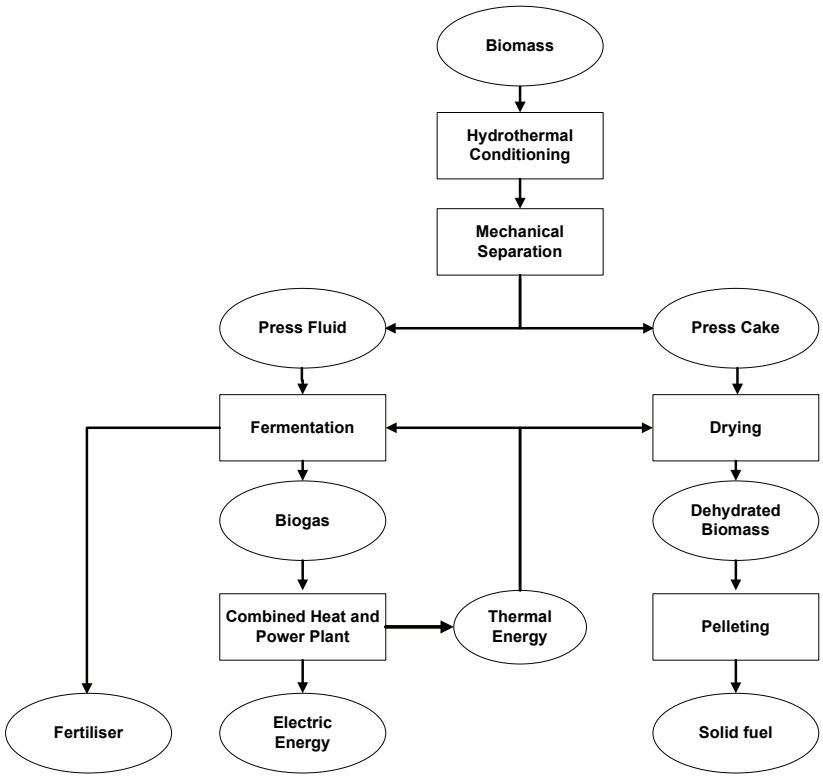


Fig. 5: Process diagram of the integrated generation of solid fuel and biogas from biomass (IFBB).

IFBB produces a solid fibrous fraction for thermal use (press cake, PC) and a liquid fraction with easily digestible constituents for biogas production (press fluid, PF). The fuel quality of the mechanically dehydrated silage is improved in comparison to the untreated biomass, because of the partial elution of organic and mineral compounds, which are detrimental to combustion (Wachendorf et al., 2009). The IFBB process has been investigated comprehensively for a selection of biomasses from German semi-natural grasslands on a lab scale (Wachendorf et al., 2009, Richter et al., 2009, Richter et al., 2010). The present study aimed at a broadly based analysis of 18 European semi-natural grassland sites with a wide range of different vegetation types and the conversion performance of the IFBB process on the scale of a prototype plant. The investigation comprised site characterisation, including soil and vegetation parameters, as well as grassland productivity and quality. Recent research (Richter et al., 2011a, b) has shown that mass flows and fuel quality in the IFBB system can be predicted by regression equations, including the concentrations of DM and neutral detergent fibre (NDF) in the silage as regressor. The implementation of such equations would allow an efficient control of important technical parameters based on chemical characteristics of the biomass.

The present study was conducted to answer the following questions:

1) How does the quality and quantity of biomass originating from different semi-natural European grasslands affect its usability for combustion?
2) Are the elemental mass flows into the PF and the concentrations of minerals in the PC obtained from an up-scaled continuous process comparable to results from small-scale laboratory studies?
3) Are the botanical composition of the grassland vegetation and the chemical parameters of the parent silage correlated with elemental mass flows into the PF and with the concentrations of minerals in the PC?

## 4.2 Materials and methods

### 4.2.1 Site characterisation and experimental set-up of grassland plots

Six experimental sites each in Germany (DE I-VI), the United Kingdom (UK I-VI) and Estonia (EST I-VI) were included in this study. The German sites were situated in the Vogelsberg region, which is a part of the state of Hessen. The long-time average (1961-1990) temperature was, depending on the altitude of the weather station, 8.04 °C (454 m a.s.l.) to 6.67 °C, (606 m a.s.l.). The average annual precipitation was between 923 and 1211 mm, respectively. Precipitation was distributed throughout the year with peaks in summer (June/July) and winter (December/January) (PIK, 2009).

The sites in the United Kingdom were situated in the western part of Wales in the region of Ceredigion. Wales has a maritime climate that is often cloudy, wet and windy but mild. Long-time data (1961-1990) for annual temperature in the study area showed a minimum average temperature of 5.6 °C in winter and a maximum average temperature of 13.3 °C in summer. Average rainfall was 1174 mm (UK Meteorological Office, 2011). The Estonian sites were established in South-East of Tartu country region (EST II, EST V, EST I, EST IV) or Jögeva region (EST III, EST VI). The long-term (1971-2000) weather characteristics in the area showed 637 mm of precipitation and 5.4 °C. (EMHI, 2011).

The sites were chosen to represent typical grassland vegetations of the respective region and to display the large diversity of semi-natural grasslands. For the botanical inventory, one permanently marked study area of 5 by 5 m was established within each plot. Vegetation coverage in total and separately for grasses, sedges, forbs and legumes was determined according to Londo (1975). NATURA 2000 habitat types (Anonymous, 2007) and data on various vegetation parameters of the experimental areas are shown in Table 7.

Table 7: Botanical characteristics of European grassland sites for solid fuel production

| Site[a] | | NATURA 2000 habitat type | Date of harvest 2009/ 2010 | Altitude [m a.s.l] | Dominant species | Plant Nr. | Plant Cov. [%] | Grasses Nr. | Grasses Cov. [% ] | Sedges Nr. | Sedges Cov.[%] | Forbs Nr. | Forbs Cov. [%] | Legumes Nr. | Legumes Cov. [%] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DE | I | Lowland hay meadow (6510) | 14/07/ 07/07 | 570 | *Festuca rubra, Agrostis capillaris* | 54 | 130 | 16 | 68 | 0 | 0 | 32 | 60 | 6 | 15 |
| | II | Lowland hay meadow (6510) | 13/07/ 05/07 | 420 | *Festuca rubra, Agrostis capillaris* | 62 | 133 | 16 | 71 | 1 | 1 | 39 | 40 | 6 | 10 |
| | III | Mountain hay meadow (6520) | 13/07/ 06/07 | 580 | *Festuca rubra, Sanguisorba officinalis* | 77 | 128 | 18 | 67 | 6 | 5 | 46 | 56 | 7 | 6 |
| | IV | Species-rich Nardus grasslands (6230) | 13/07/ 08/07 | 580 | *Festuca rubra, Nardus stricta* | 61 | 119 | 17 | 80 | 6 | 14 | 30 | 25 | 8 | 10 |
| | V | Molinia meadow (6410) | 21/07/ 20/07 | 500 | *Deschampsia cespitosa, Juncus acutiflorus* | 68 | 134 | 16 | 62 | 8 | 25 | 41 | 47 | 3 | 11 |
| | VI | Humid tall herb fringes of watercourses and woodlands (6431) | 08/09/ 07/09 | 380 | *Scirpus sylvatica, Filipendula ulmaria* | 18 | 100 | 2 | 5 | 5 | 80 | 11 | 15 | 0 | 0 |
| UK | I | Degraded raised bogs still capable of natural regeneration (7120) | 18/09/ 24/08 | 190 | *Molinia caerulea, Juncus acutiflorus* | 49 | 140 | 8 | 92 | 10 | 29 | 28 | 17 | 3 | 3 |
| | II | Degraded raised bogs still capable of natural regeneration (7120) | 22/09/ 07/10 | 160 | *Juncus effusus, Deschampsia cespitosa* | 35 | 142 | 4 | 51 | 9 | 78 | 22 | 13 | 0 | 0 |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | III | Degraded raised bogs still capable of natural regeneration (7120) | 16/09/ 22/09 | 400 | *Juncus effusus, Agrostis canina* | 35 | 143 | 10 | 47 | 9 | 85 | 15 | 12 | 1 | 0 |
| | IV | European dry heaths (4030) | 06/08/ 09/09 | 560 | *Vaccinium myrtillus, Deschampsia cespitosa* | 25 | 139 | 7 | 82 | 9 | 4 | 9 | 53 | 0 | 0 |
| | V | Not classifiable | 27/07/ 12/08 | 300 | *Pteridium aquilinum, Agrostis capillaris* | 45 | 157 | 14 | 87 | 1 | 0 | 27 | 66 | 3 | 4 |
| | VI | Blanket bogs (7130) | 18/08/ 16/09 | 440 | *Molinia caerulea, Festuca ovina* | 17 | 145 | 8 | 108 | 5 | 35 | 4 | 2 | 0 | 0 |
| EST | I | Northern boreal alluvial meadows (6450) | 30/06/ 05/07 | 40 | *Alopecurus pratensis, Filipendula ulmaria* | 60 | 146 | 12 | 48 | 9 | 35 | 37 | 62 | 2 | 2 |
| | II | Fennoscandian lowland species-rich dry to mesic grasslands (6270) | 01/07/ 07/07 | 40 | *Alopecurus pratensis, Deschampsia cespitosa* | 23 | 130 | 7 | 102 | 1 | 1 | 13 | 25 | 2 | 2 |
| | III | Fennoscandian wooded meadows (6530) | 29/06/ 07/07 | 60 | *Scorzonera humilis, Brachypodium pinnatum* | 63 | 164 | 13 | 58 | 4 | 2 | 41 | 102 | 5 | 2 |
| | IV | Northern boreal alluvial meadows (6450) | 30/06/ 05/07 | 40 | *Carex disticha, Carex cespitosa* | 34 | 129 | 11 | 23 | 3 | 82 | 18 | 22 | 2 | 1 |
| | V | Fennoscandian lowland species-rich dry to mesic grasslands (6270) | 01/07/ 07/07 | 40 | *Anthsicus sylvestris, Veronica longifolia* | 33 | 152 | 9 | 84 | 4 | 2 | 17 | 63 | 3 | 3 |
| | VI | Fennoscandian wooded meadows (6530) | 29/06/ 06/07 | 60 | *Galium boreale, Anthriscus sylvestris* | 47 | 172 | 10 | 67 | 2 | 1 | 33 | 104 | 2 | 1 |

The grassland sites comprised ten different habitat types and showed a high diversity in plant species numbers, community composition and the relative coverage of different plant species (Table 7). The German sites were selected to represent the types of vegetation typical for extensively managed grasslands in lower mountain regions. Sites DE I and II represented the *Arrhenatherum* elatius dominated grasslands typical for lower altitudes with an average water and nutrient availability. These sites were dominated by *Festuca rubra rubra*, *Arrhenatherum elatius* and *Agrostis capillaris*, but also showed species typical for higher altitudes, as our experimental sites lay on the upper altitude level of lowland grasslands areas. DE III and IV were typical representatives of semi-natural grasslands of higher mountain altitudes, representing mountain meadows and *Nardus stricta* dominated grasslands. Both areas proved to be species rich. Areas DE V and VI, on the other hand, represented wet types of semi-natural grassland, where area DE V was relatively dryer and species richer and area DE VI was wet grassland dominated by plants from the Cyperaceae family, especially *Scirpus sylvaticus*. The UK sites represented the difficulties Welsh farmers have with four recently spreading species that have very low nutritional value, i.e. *Molinia caerulea*, *Nardus stricta, Juncus effusus* and *Pteridium aquilinum*. Area UK I was an example of a lowland area covered by spreading *Molinea caerulea*, due to serious under-grazing in recent years. Areas UK II and UK III stood for wet areas dominated by *Juncus effusus* and *Molinia caerulea*, typical for wet and extensively used areas in Wales. Area UK IV and VI represented higher mountain areas which are steep and hard to access and also low in nutrient availability. This leads to a low forage quality of these *Vaccinium ssp.* and *Nardus stricta* dominated grasslands. Area UK V was chosen to investigate the spreading plant species *Pteridium aquilinum*, which is a poisonous plant for ruminants and therefore is of great concern for Welsh farmers. In Estonia, we investigated three types of grassland vegetation, each represented by two areas. Areas EST I and IV were floodplain meadows on river banks, with annual nutrient input from alluvial sediments. Nutrient availability and relatively high yield of these areas make them attractive for biomass production, despite harvest

problems due to wet soil. Areas EST II and V were typical mesic meadows which were dominated by grass species, i.e. *Festuca rubra*, *Agrostis capillaris*, *Deschampsia cespitosa*. This meadow type was selected as it includes the largest areas of Estonian semi-natural grasslands and was therefore assumed to have a large biomass potential. Areas EST III and VI represented highly diverse habitat of Fennoscandian wooded meadows. These grasslands are relicts from traditional labour intensive farming systems of Fenno-Scandinavia used for wood and hay production, which are no longer profitable and therefore often abandoned. However, due to their very high value for biodiversity, continuous management of the sites is the priority of local nature conservation legislation.

Soil type was classified according to WRB (IUSS, 2007). The site specific data of soil parameters, shown in Table 8, display a high diversity of soil types and cation exchange capacities as well as soil carbon and important nutrients, especially N and K. Soils of the German sites were Cambisols or soils with stagnic or gleyic properties. The influence of water was dominant for all soils of the UK sites, characterized by Histosols or hyperhumic Cambisols. In Estonia the soil variability was high within a site, but water was also the dominant soil factor. Soil texture of the Estonian soils varied. Dominant soil texture of the German sites was silt loam. The upper soil layer of most soils was moderately to very strongly acidic; at the UK site dominated by *Pteridium aquilinium*, pH was even ultra-acidic. At some Estonian sites soils were slightly acidic because of the presence of carbonate. Content of organic matter was high in the organic soils of the UK, low for two sites in Estonia, and moderate for German soils, which is typical for soils under grassland. At the German and UK sites high contents of phosphorus occurred in the upper soil layer and contents were lower in Estonian soils. With the exception of two sites in the UK, soils were usually low in potassium. Three plots serving as replicates of 10 by 10 m were established at each experimental site. Soil samples were taken at the beginning of the investigation in July 2009 at depths of 0-15, 15-30 and 30-60 cm. Two samples per plot and depth were merged for chemical analyses.

Table 8: Soil characteristics of experimental sites; arithmetic mean values of 3 plots at 0-15cm depth, total soil concentrations of N, P and K.

| Site[a] | | Soil Unit[b] | Soil Texture[c] | pH ($CaCl_2$) | $CEC_{eff}$ [$cmol_c(+)$ $kg^{-1}$] | $C_{org}$ [mg $g^{-1}$] | $N_{tot}$ [mg $g^{-1}$] | P [mg $g^{-1}$] | K [mg $g^{-1}$] |
|---|---|---|---|---|---|---|---|---|---|
| DE | I | Haplic Cambisol (Colluvic Siltic) | Silt loam | 5.25 | 26.6 | 45.2 | 4.6 | 2.10 | 2.90 |
| | II | Haplic Stagnosol (Siltic) | Silt loam | 4.59 | 15.3 | 46.8 | 4.8 | 1.08 | 3.25 |
| | III | Haplic Cambisol (Humic Siltic) | Silt loam | 5.07 | 21.1 | 55.0 | 5.2 | 1.06 | 3.45 |
| | IV | Haplic Cambisol (Humic Siltic) | Silt loam | 4.57 | 16.9 | 63.4 | 5.5 | 1.27 | 4.35 |
| | V | Haplic Stagnosol (Siltic) | Silt loam | 4.79 | 17.2 | 53.2 | 5.2 | 0.77 | 3.32 |
| | VI | Gleyic Fluvisol (Humic Siltic) | Silty clay loam | 4.95 | 7.6 | 109.1 | 9.6 | 1.63 | 3.47 |
| UK | I | Cambisol (Hyperhumic) | Silt loam | 4.09 | 9.0 | 163.7 | 10.0 | 1.03 | 9.66 |
| | II | Histosol (Dystic) | n.d.[d] | 4.21 | 8.9 | 213.7 | 13.5 | 1.10 | 13.26 |
| | III | Histosol (Dystic) | n.d. | 3.93 | 10.4 | 449.1 | 28.6 | 2.15 | 2.08 |
| | IV | Histosol (Dystic) | n.d. | 2.98 | 7.6 | 452.2 | 24.8 | 1.21 | 3.69 |
| | V | Cambisol (Hyperhumic) | Loam | 4.83 | 10.5 | 63.8 | 5.4 | 0.99 | 21.89 |
| | VI | Histosol (Dystic) | n.d. | 3.21 | 23.4 | 384.1 | 26.0 | 1.69 | 6.41 |
| EST | I | Sapric Histosol (Eutric) / Haplic Gleysol (Epiclayic) | Silt loam | 6.33 | 14.3 | 91.2 | 7.0 | 0.78 | 2.21 |
| | II | Haplic Albeluvisol (Arenic Drainic) / Endogleyic Albeluvisol (Arenic) | Sand | 4.57 | 23.9 | 12.4 | 1.0 | 0.42 | 0.70 |
| | III | Endogleyic Cambisol (Humic) | Silt loam | 5.85 | 10.7 | 53.1 | 4.2 | 0.80 | 2.60 |
| | IV | Haplic Fluvisol (Epiclayic) | Silt loam | 6.49 | 5.0 | 100.4 | 9.5 | 2.10 | 3.78 |
| | V | Haplic Albeluvisol (Arenic Drainic) / Endogleyic Albeluvisol (Arenic) | Loamy sand | 4.71 | 5.1 | 15.9 | 1.4 | 0.40 | 0.67 |
| | VI | Endogleyic Cambisol (Humic) | Silt loam | 5.76 | 15.7 | 56.5 | 4.7 | 0.64 | 2.62 |

[a] DE = Germany, UK = United Kingdom, EST = Estonia
[b] According to World Reference Base for Soil Resources classification.
[c] According to Soil Survey Staff (1993) at 0-15cm depth
[d] n.d.: not determined

### 4.2.2 Harvest, yield determination and conservation of the grassland biomass

Harvest was carried out by a finger-bar mower in Germany and Wales and by a trimmer in Estonia at a cutting height of 5 cm. The harvesting time was site-specific and varied between June and October in 2009 and 2010. The harvest dates were chosen according to the usual local harvesting regime. Without wilting, the biomass of about 20 kg was chopped to an average fibre length of 5 cm and then compacted and ensiled in 60-L polyethylene barrels without application of additives. Ensiling lasted for at least 6 weeks. Yield measurement was carried out by weighing of fresh biomass from 5 $m^2$ and subsequent determination of the DM content in the drying oven at 105°C for 48 h. Harvesting, ensiling and biomass yield estimations were conducted on all 18 sites with three replicates each. For one site (UK IV) yield measurement in 2010 was not possible due to unintended grazing by sheep.

### 4.2.3 Processing of the grassland biomass

Pre-treatment and mechanical dehydration of the silage was conducted by a mobile research and demonstration prototype (Fig. 6) with a daily silage throughput of 300 kg.

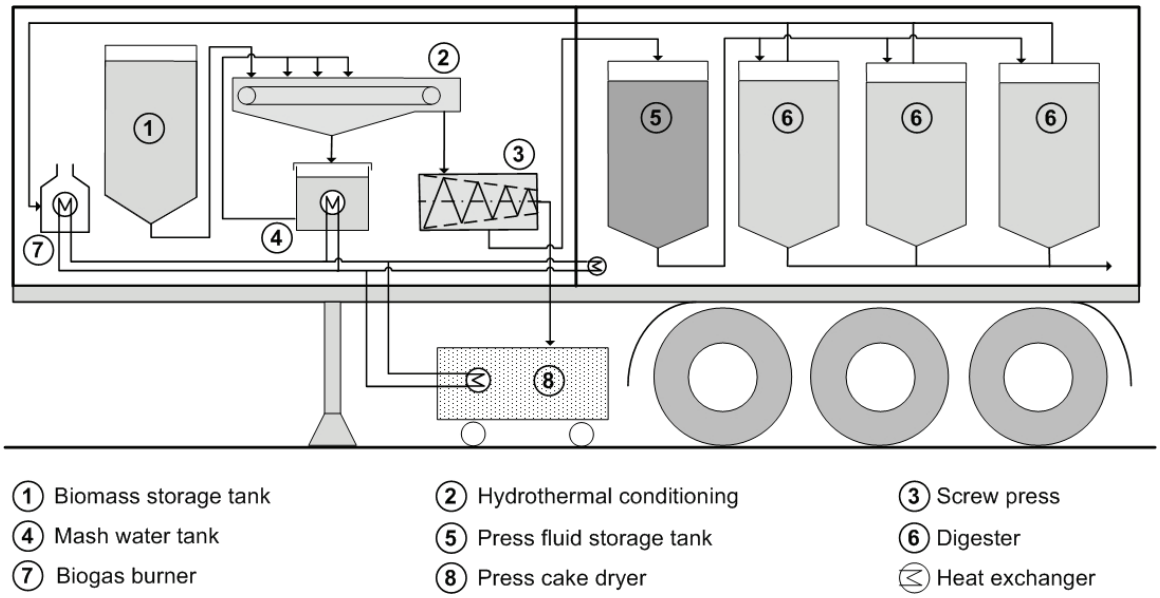


Fig. 6: Setup of the mobile prototype used for hydrothermal conditioning and mechanical separation of the silage into press cake and press fluid.

The IFBB prototype was installed into two standard ISO freight containers which were permanently mounted on a semi-trailer. The target of the prototype conception was to simulate the main technical processing steps of the IFBB procedure. This included hydrothermal conditioning of the grassland silage, mechanical dehydration and separation into the PC and PF, as well as PC drying and PF digestion and subsequent biogas combustion in three fixed-bed digesters with a volume of 1.35m³ each. Apart from continuous plant operation, the prototype was designed to process small test samples manually. In this case, about 20 kg of silage was hydrothermally conditioned for 30 minutes at 25° C using fresh water. The silage was then separated by a screw-press (type AV, Anhydro Ltd., Kassel, Germany). The conical screw had a pitch of 1:6 and a rotational speed of 3 rev $min^{-1}$. The cylindrical screen encapsulating the screw had a perforation of 1.5 mm. For chemical analysis the samples of the silage and the PC were dried at 60° C for 24 h. DM content was determined by oven-drying at 105°C for 48 h.

### 4.2.4 Chemical analyses and calculation of mass flows and fuel quality parameters

The soil samples were air dried and sieved to 2mm after removal of roots and stones. Soil texture was identified according to US soil taxonomy (Soil Survey Division Staff, 1993). The pH value was determined using the $CaCl_2$ method according to Bassler (1976). The cation exchange capacity (CEC) was analysed by summation of exchangeable $Ca^{2+}$, $Mg^{2+}$, $Na^{+}$, $K^{+}$, and $H^{+}$. Base cations were extracted by leaching with $NH_4Cl$ and analysed with ICP-OES. The values of C, N and H were analysed using an elemental analyser (Vario MAX CHN Elementar Analysensysteme GmbH, Hanau, Germany). Total K and P concentrations were determined by digestion with $HNO_3$ (Heinrichs et al. 1986) and analysed by ICP.

The silage and the PC were analysed for C, H and N using the same elemental analyser as that used for the soil samples. Content of K, Na, Mg, Ca, Cl, S and P were determined by x-ray-fluorescence-analysis.

Weende and Van Soest constituents (crude ash, crude protein (CP), ether extract (EE), crude fibre (CF), neutral detergent fibre (NDF), acid detergent lignin (ADL), acid detergent fibre (ADF) and nitrogen-free extract (NFE)) were measured according to standard methods (Bassler, 1976) and near infrared spectroscopy (Foss NIRSystems, Hillerød, Denmark). Mass flows of chemical elements from the silage into PC and PF were calculated by relating the nutrients contained in the PC and PF, respectively, to the nutrients of the silage according to the formulae:

$$MF\_X_{PC} = \frac{M_{PC} * C\_X_{PC}}{M_{Sil} * C\_X_{Sil}}$$

$$MF\_X_{PF} = 1 - MF\_X_{PC}$$

where:

$MF\_XP_C$: Relative mass flow of a nutrient X into the press cake

$M_{PC}$ : Weight of the press cake [kg]

$C\_XP_C$: Concentration of a nutrient X in the press cake [g kg$^{-1}$]

$M_{Sil}$: Weight of the silage [kg]

$C\_X_{Sil}$: Concentration of a nutrient X in the silage [g kg$^{-1}$]

$MF\_XP_F$: Relative mass flow of a nutrient X into the press fluid

The ash softening temperature (AST) was calculated based on the concentrations of K, Ca and Mg (g kg$^{-1}$ DM) in the silage and the PC according to Hartmann (2009):

AST [°C] = 1172 - 5.39 * K + 25.27 * Ca - 78.84 * Mg

The lower heating value was calculated based on the concentrations of C, H, N, S and O (% DM) in the silage and the PC according to Hartmann (2009):

LHV [MJ kg$^{-1}$] = 43.8 * C + 93.9 * H +10.5 * S + 6.3 * N - 10.8 * O

### 4.2.5 Statistical analysis

Statistical analyses were done using the Software R (R Development Core Team, 2011). Analyses of variance were performed to test for the differences of yields between the European regions and the effect of IFBB treatment on plant compounds in the PC.

Multiple linear regression analyses were performed to test for the effect of chemical constituents and botanical composition of the parent biomass on mass flows of nutrients and on elemental concentrations in the PC.

Previous studies have revealed a strong correlation between neutral detergent fibre (NDF) and DM content of the silage and elemental concentration in the press cake (Richter et al., 2011a, b). Therefore, these factors were included in our preliminary model. Also data about botanical composition, coverage estimates of grasses, forbs, legumes and sedges were included. The quadratic terms and twofold interactions between each plant group cover and NDF content of silage were included in the starting model, if their significance was above 5%. To test for multicollinearity among the terms involved, Pearson's correlations were performed and the tolerance calculated as

$$Tolerance = 1 - Rj^2,$$

where $Rj^2$ is the coefficient of determination of a regression of explanator j on all the other explanators. Because sedge coverage and DM showed high correlations and low tolerance values, indicating strong multicollinearity, they were excluded, leaving NDF content of the silage and coverage of grasses, forbs and legumes as explaining factors used for model building. Model development followed the statistical model selection methods described by Draper and Smith (1998) and obeyed the rules of hierarchy and marginality (Nelder and Lane, 1995). The principle of hierarchy means that a term is included in the model if it appears as a part of a higher order interaction or quadratic term. The marginality principle implies that 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 (Connolly and Wachendorf, 2001). The test for homogeneity of variances of the model was done graphically; the test for normal distribution of the data was done with the Shapiro-Wilk test. Data mismatching the prerequisites of normal distribution and homogeneity of variances were log-transformed.

## 4.3 Results and Discussion

### 4.3.1 Biomass yield and elemental composition of the silage

Dry matter yields of the German sites in 2009 and 2010 ranged between 1.9 and 9.5, with an average of 3.9 t DM $ha^{-1}$ $yr^{-1}$ (Table 9).

Table 9: Arithmetic mean, standard deviation, minimum and maximum values of DM yield of eighteen European semi-natural grassland sites, two year data (2009, 2010). DE = Germany, UK = United Kingdom, EST = Estonia.

| | Arithmetic mean | Standard deviation | Minimum | Maximum |
|---|---|---|---|---|
| DE | 3.90 | 1.66 | 1.91 | 9.49 |
| UK | 3.65 | 1.97 | 1.25 | 10.97 |
| EST | 2.91 | 0.99 | 0.64 | 4.85 |

The DM concentration of the silage varied between 217.6 and 417.4 g $kg^{-1}$ FM, with an average of 312.8 g $kg^{-1}$ FM (Fig. 7). DE I to DE IV, which had been regularly managed in the years prior to the experiment, showed similar yields in both years. In contrast, yields of DE V and DE VI, which have been managed infrequently or have been unused in recent years, decreased in 2010. Comparable yields of German semi-natural grasslands have been observed by Tonn et al. (2010), ranging between 4.0 and 8.0 t DM $ha^{-1}$ $yr^{-1}$ for similar grassland types in mountainous regions, also showing a high variation in yield. Wachendorf et al. (2009) showed productivities between 3.4 and 5.8 t DM $ha^{-1}$ $yr^{-1}$ for semi-natural grasslands in lower mountain areas.

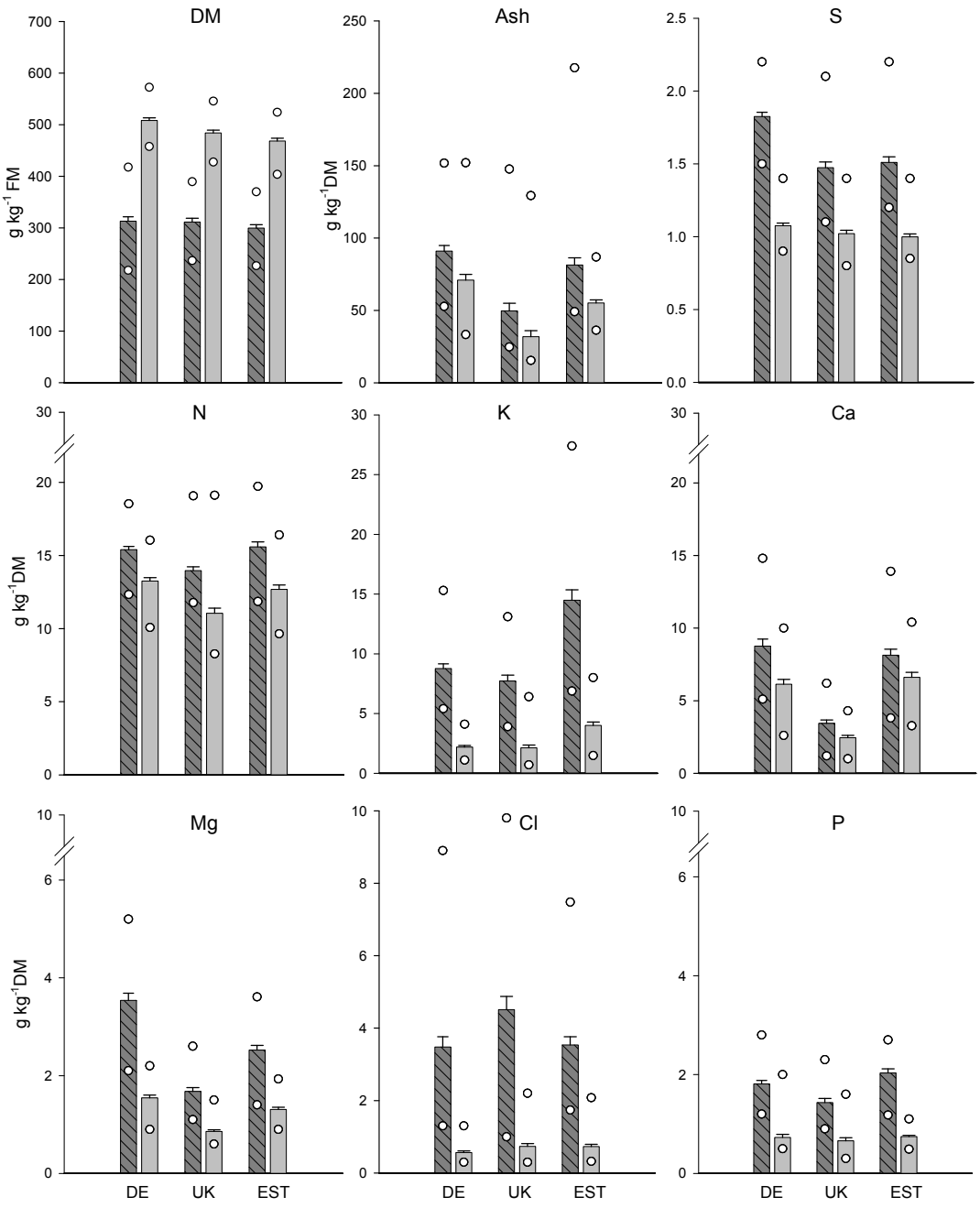


Fig. 7: Average DM concentration (g kg$^{-1}$ FM), ash concentration (g kg$^{-1}$ DM) and mineral concentration (g kg$^{-1}$ DM) of silage (dark grey and black columns) and press cake (light grey columns) from eighteen European semi-natural grassland sites (DE = Germany, UK = United Kingdom, EST = Estonia), with standard error of means and dots indicating minimum and maximum value. Differences between silage and PC were all highly significant ($p<0.001$).

The Welsh sites featured an even larger variability (1.3 to 11.0 t DM $ha^{-1}$ $yr^{-1}$) among the different sites, the experimental plots and the two years (Table 9). The average yield of sites decreased in the second year from 4.6 to 2.5 t DM $ha^{-1}$. The average silage DM concentration was 310.1 g $kg^{-1}$ FM, ranging between 236.4 and 389.4 g $kg^{-1}$ FM. Similar proportions of biomass yields have been observed by Tallowin and Jefferson (1999) for unfertilised semi-natural grasslands in the lowlands of the UK (1.5 to 6.0 t DM $ha^{-1}$ $yr^{-1}$).

Estonian grasslands showed the lowest productivity of 0.6 to 4.9 t DM $ha^{-1}$ $yr^{-1}$, with an average of 2.9 t DM $ha^{-1}$ $yr^{-1}$ (Table 9). Silages from the Estonian sites had the lowest DM concentrations, with an average of 300.0 g $kg^{-1}$ FM and minimum and maximum values of 226.4 and 369.7 g $kg^{-1}$ FM, respectively. There was a decrease in the yield in the second year for four sites, but for both Fennoscandian wooded meadow sites there was a remarkable increase. In a previous study, Heinsoo et al. (2010) investigated Estonian semi-natural grasslands in 2007 and observed biomass yields ranging between 1.6 and 5.7 t DM $ha^{-1}$ $yr^{-1}$.

NDF concentration in the silage ranged between 483.9 and 736.7 g $kg^{-1}$ DM, with average values of 562.5, 647.2 and 573.5 g $kg^{-1}$ DM for German, Welsh and Estonian sites, respectively. The higher average NDF concentrations in Wales reflect the later harvest date of the Welsh sites (Table 7). The ash content of the silage was between 24.7 and 217.6 g $kg^{-1}$ DM, with average values of 91.0, 50.0 and 94.2 g $kg^{-1}$ DM for German, Welsh and Estonian sites, respectively (Fig. 7). Average values were well within the range of former experiments by Richter et al. (2011a) and Wachendorf et al. (2009), who found ash contents between 63.5 and 101.0 g $kg^{-1}$ DM for German semi-natural grassland sites. The ash content of the fuel is important as many components of the combustion technique have to be adapted to high ash contents (Obernberger et al., 2006). It is not only the concentration of ash but also its composition that is relevant for combustion. High concentrations of K and Mg lower the ash melting point, which causes

problems through slag formation and sintering and thereby reduces plant availability and lifetime (Obernberger et al., 2006). The amount of K in the silage samples was between 3.9 and 27.4 g $kg^{-1}$ DM, comparable with the values of 17.4 to 27.4 g $kg^{-1}$ DM found by Richter et al. (2011a). Concentrations of K were especially high in Estonian silage, where the average value was 14.7 g $kg^{-1}$ DM, whereas in Germany and UK the averages were 8.8 and 7.7, respectively. The concentration of Mg ranged between 1.1 and 5.2 g $kg^{-1}$ DM, with the highest values for German sites and the lowest values for Estonian sites. In general, the concentration of K and Mg in common wooden fuels like beech wood is considerably lower (1.5 and 0.4 g $kg^{-1}$ DM, respectively, Hartmann et al., 2009), indicating a lower ash melting point for the semi-natural biomass fuel in comparison to beech wood. For Ca, an element which has an increasing effect on ash softening temperature, we found average values of 8.8, 3.4 and 8.1 g $kg^{-1}$ DM for German, Welsh and Estonian sites, respectively. The average ash softening temperature calculated for the silages was 1067°C for German sites, 1085°C for UK sites and 1108°C for Estonian sites, compared to 1260°C for Austrian beech wood reported by van Loo and Koppejan (2008). Further problems of biomass fuel from grassland involve emissions and corrosion, mostly caused through high contents of sulphur, nitrogen and chlorine in the fuel. Obernberger et al. (2006) proposed recommended values for the concentration of N (6.0 g $kg^{-1}$ DM), S (1.0 g $kg^{-1}$ DM) and Cl (1.0 g $kg^{-1}$ DM) in the fuel which should not be exceeded, to reduce the impact on human health and reduce the risk of corrosion. For German, Welsh and Estonian study sites, the concentrations of N, S and Cl in the silage exceeded these limits in all cases (Fig. 7). The results clearly indicate that untreated biomass from extensive grasslands under nature conservation management is not suitable for common combustion techniques, due to the large amount and unfavourable composition of fuel ash, as well as high levels of the elements responsible for emissions and corrosion. This confirms previous findings by Wachendorf et al. (2009) and Richter et al. (2011a) for German semi-natural grassland silages.

### 4.3.2 Mass flows into press fluid and influencing parameters

Approximately 20% of the DM of the silage was transferred into the PF (Table 10).

Table 10: Arithmetic means of mass flow of DM, ash, nitrogen, sulphur, potassium, magnesium, calcium, chlorine and phosphorus into the press fluid in % with standard error of mean and minimum (min) and maximum (max) values for German (DE), Welsh (UK) and Estonian (EST) sites.

| | DE | | | UK | | | EST | | |
|---|---|---|---|---|---|---|---|---|---|
| | Mass flow [%] | min | max | Mass flow [%] | min | max | Mass flow [%] | min | max |
| DM | 19.42 ± 0.93 | 10.00 | 31.41 | 19.43 ± 2.06 | 3.36 | 49.23 | 18.92 ± 1.09 | 5.47 | 33.73 |
| Ash | 37.93 ±1.58 | 12.41 | 54.10 | 49.40 ± 2.49 | 21.98 | 73.96 | 43.86 ± 1.77 | 18.33 | 70.65 |
| N | 30.63 ± 1.17 | 19.36 | 43.76 | 36.34 ± 2.06 | 15.71 | 60.05 | 33.49 ± 1.20 | 18.94 | 45.03 |
| S | 52.27 ± 1.00 | 40.18 | 65.62 | 43.57 ± 1.81 | 20.80 | 60.11 | 45.74 ± 1.02 | 32.51 | 59.65 |
| K | 80.14 ± 0.73 | 67.92 | 87.29 | 78.97 ± 1.29 | 56.59 | 89.12 | 77.43 ± 0.69 | 67.76 | 85.08 |
| Mg | 64.20 ± 0.99 | 49.63 | 74.28 | 57.33 ± 1.96 | 30.14 | 72.31 | 57.27 ± 0.90 | 44.50 | 70.16 |
| Ca | 42.60 ± 1.86 | 18.38 | 60.98 | 40.31 ± 2.64 | 4.00 | 67.15 | 33.60 ± 1.39 | 20.15 | 50.96 |
| Cl | 86.19 ± 0.77 | 75.16 | 93.03 | 85.62 ± 1.31 | 65.03 | 94.40 | 82.80 ± 0.60 | 77.40 | 94.15 |
| P | 67.73 ± 2.03 | 27.04 | 78.19 | 62.66 ± 2.60 | 20.84 | 80.92 | 68.94 ± 1.50 | 34.20 | 81.13 |

The highest variation was found at UK sites, where MFs of DM ranged from 4 to 49%. The average MF for DM is in the range of previous laboratory results carried out with the same method protocol (Wachendorf et al., 2009, Richter et al., 2011a). This leads to the conclusion that scaling-up to prototype size did not affect the effectiveness of the process. The same is true for the MFs of the plant mineral compounds, which are in the range of previous results. MFs for P and Mg were intermediate (57-69%), whereas MFs for K and Cl were higher (>77%), and MFs for S, N and Ca were lower (31- 52%). For ash the average MFs were between 38 and 49%.

Richter et al. (2011a) showed that NDF and DM content of the silage and temperature of the dewatering treatment are the factors influencing the MFs of nutrients into the PF. In this study, the temperature was kept constant and DM content as a predictor was replaced by botanical parameters. MFs into the PF (Table 11) showed results with low determination coefficients for all MFs ($R^2$ = 0.21 … 0.63). Richter et al. (2011a) achieved $R^2$ from 0.88 to 0.99.

Table 11: Coefficient of determination and parameter estimates for the models of mass flow of nutrients into the press fluid (N=50).

| | DM | Ash | N | S | K | Mg | Ca | Cl | P |
|---|---|---|---|---|---|---|---|---|---|
| $R^2$ | 0.63 | 0.27 | 0.55 | 0.57 | 0.55 | 0.49 | 0.58 | 0.49 | 0.21 |
| $R^2$adj. | 0.56 | 0.21 | 0.48 | 0.49 | 0.50 | 0.41 | 0.50 | 0.43 | 0.14 |
| Sign. | *** | ** | *** | *** | *** | *** | *** | *** | * |
| DF[a] | 8 | 5 | 7 | 7 | 5 | 7 | 8 | 5 | 4 |
| *Estimates* | | | | | | | | | |
| Intercept | -199.3000 | -61.1100 | -152.0000 | -75.9400 | 50.7981 | -29.9700 | 408.7000 | 71.1451 | 16.1362 |
| Grasses (G)[b] | 1.5030 | | 1.3070 | 1.0140 | -0.1304 | -0.1645 | 1.9600 | -0.1278 | |
| Forbs (F)[b] | 1.3630 | | 1.1270 | 1.5850 | | 1.8180 | -0.6185 | 0.7175 | |
| Legumes (L)[b] | 7.7970 | 7.8520 | 1.6400 | 2.8650 | 8.4228 | 8.9000 | 2.9330 | 0.5126 | 10.7345 |
| NDF[c] | 0.3637 | 0.1682 | 0.3065 | 0.2074 | 0.0554 | 0.1542 | -1.4330 | 0.0342 | 0.0770 |
| $G^2$ | | | | | | | | | |
| $F^2$ | | 0.0012 | | | | | 0.0049 | | |
| $L^2$ | -0.1361 | | -0.1033 | -0.1441 | -0.0912 | -0.1691 | -0.1510 | | -0.1536 |
| $NDF^2$ | | | | | | | 0.0014 | | |
| G x NDF | -0.0026 | | -0.0021 | -0.0018 | | | -0.0034 | | |
| F x NDF | -0.0023 | | -0.0020 | -0.0029 | | -0.0031 | | -0.0013 | |
| L x NDF | -0.0101 | -0.0137 | | | -0.0118 | -0.0099 | | | -0.0140 |

The lower prediction accuracies may not only be due to the fact that explanatory variables like temperature and DM content had been changed in favour of botanical parameters. In this study the variation and heterogeneity of sampled areas was larger than in the experiment by Richter et al. (2011a). However, it could be shown that there is an influence of NDF content and botanical composition on MFs in the IFBB system, as they do explain some of the variation in MFs. Further experiments will have to investigate which parameters are most suitable for prediction of MFs.

### 4.3.3 Fuel quality of the press cake and influencing parameters

The DM content of the PC was significantly higher than the DM content of the silage, with average values of 470.7 to 508.3 g $kg^{-1}$ FM (Fig. 7). The PC produced by the prototype had a higher dry matter content compared to former results with laboratory equipment (Richter et al., 2011a), which ranged between 388.4 and 451.5 g $kg^{-1}$ FM. The PC still requires thermal drying to 850 g $kg^{-1}$ FM to be suitable for storage. The average ash content of the solid fuel could be significantly reduced compared to untreated silage, but was still

highly variable, with single values ranging from 15.4 to 152.0 g $kg^{-1}$ DM (Fig. 7).

The fuel N content, which is critical because of its influence on $NO_x$ emissions, could be significantly reduced compared to untreated silage, but this reduction did not lead to acceptable N contents in the PC to prevent $NO_x$ emissions when using standard and small-scale pellet ovens (Obernberger et al. 2006). Additional technical measures would be necessary for burning the PC from the IFBB system, like air staged or fuel staged combustion as a way of dealing with a higher fuel N content. The S contents in the PC were lower than in the silage. Average values (1.08, 1.03, 1.02 for DE, UK, EST sites, respectively) were close to the value of 1.0 g $kg^{-1}$ DM that Obernberger et al. (2006) proposed for an unproblematic combustion. Former studies (Richter et al., 2010) revealed that the comparatively low temperature of hydrothermal conditioning that was applied in this study is not the optimal temperature for reduction of S. A higher temperature of 60°C (Richter et al., 2010) resulted in a lower concentration of S and other mineral elements in PC. The recommended value for Cl (1.0 g $kg^{-1}$ DM, Obernberger et al., 2006) could be achieved with average concentrations in the PC of 0.6, 0.7 and 0.7 g $kg^{-1}$ DM for German, Welsh and Estonian sites, respectively. Concerning the elements with a decreasing effect on ash melting behaviour, K and Mg, significant reductions could be achieved, being highest for K and moderate for Mg, which leads to an average calculated ash melting point of the PC of 1193, 1155 and 1214 °C for DE, UK and EST sites, respectively. However, the formula according to Hartmann (2009) has a relatively low prediction accuracy ($r^2$ = 0.60), with a standard error of mean of 88.2 C°, and was developed with a limited set of samples of different fuels. Thus, the results for the ash softening temperature have to be interpreted with care.

The P content was significantly lower in the PC than in the silage. P is an important plant nutrient; and high transfer rates of P into the PF are

favourable, as the digestates are used as a fertiliser after anaerobic digestion.

DM and mineral element content in the PC were related to botanical and chemical parameters of the parent material (Table 12).

Table 12: Coefficient of determination and parameter estimates for the models of concentration of plant compounds in the press cake (N=50).

| | **DM** | **Ash (log)** | **N** | **S** | **K (log)** | **Mg** | **Ca (log)** | **Cl (log)** | **P** |
|---|---|---|---|---|---|---|---|---|---|
| $R^2$ | 0.63 | 0.70 | 0.73 | 0.45 | 0.64 | 0.79 | 0.74 | 0.56 | 0.34 |
| $R^2$adj. | 0.56 | 0.67 | 0.71 | 0.37 | 0.60 | 0.77 | 0.73 | 0.50 | 0.25 |
| Sign. | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| DF[a] | 8 | 4 | 4 | 6 | 5 | 6 | 3 | 6 | 6 |
| *Estimates* | | | | | | | | | |
| Intercept | -1419.0000 | 8.7112 | 34.0479 | 2.1800 | 4.6861 | 1.8810 | 5.2030 | -2.6550 | 0.2571 |
| Grasses (G)[b] | -1.0000 | -0.0045 | | -0.0025 | 0.0072 | -0.0018 | 0.0111 | 0.0032 | 0.0298 |
| Forbs (F)[b] | 5.1380 | | | -0.0016 | | 0.0405 | | 0.0634 | |
| Legumes (L)[b] | 11.6600 | -0.3269 | -1.0440 | -0.1271 | -0.7861 | 0.0225 | | -0.4348 | -0.2159 |
| NDF[c] | 5.9170 | -0.0077 | -0.0346 | -0.0015 | -0.0066 | -0.0014 | -0.0062 | 0.0035 | 0.0008 |
| $G^2$ | 0.0067 | | | | | | -0.0001 | | |
| $F^2$ | | | | | | | | | |
| $L^2$ | -0.5369 | | 0.0153 | 0.0013 | 0.0052 | -0.0001 | | | 0.0038 |
| $NDF^2$ | -0.0045 | | | | | | | | |
| G x NDF | | | | | | | | | 0.0001 |
| F x NDF | -0.0088 | | | | | -0.0001 | | -0.0001 | |
| L x NDF | | 0.0006 | 0.0013 | 0.0002 | 0.0012 | | | 0.0007 | 0.0003 |

[a] Degrees of freedom
[b] cover of plant functional group in percent
[c] concentration in the silage in g $kg^{-1}$ DM
*** $p < 0.001$

With the exception of P and S, the concentration of elements in the PC could be predicted with botanical parameters and the NDF content in the silage with an accuracy of $R^2 = 0.5$ or higher. Comparable to a study by Richter et al. (2011a), the influence of NDF in the silage as a parameter reflecting the maturity of the sward (Richter et al. 2011a) proved to be important. For German, Welsh and Estonian semi-natural grassland material, the content of most elements (N, Mg, Ca) and total ash in the PC decreased with higher NDF contents. Concerning other elements, the effect of NDF was not independent of plant cover parameters. The overall increase in fuel quality of PC with increasing senescence of the parent material has also been shown by Richter et al. (2011a). Tahir et al. (2011) showed that a delayed harvest leads to improved fuel quality of biomass with lower P, K, S and Cl concentrations, but also made clear that delayed harvest is not an economically sound and reliable alternative for fuel production under the climatic conditions given in the midwestern United States of America, due to difficulties in harvest management.

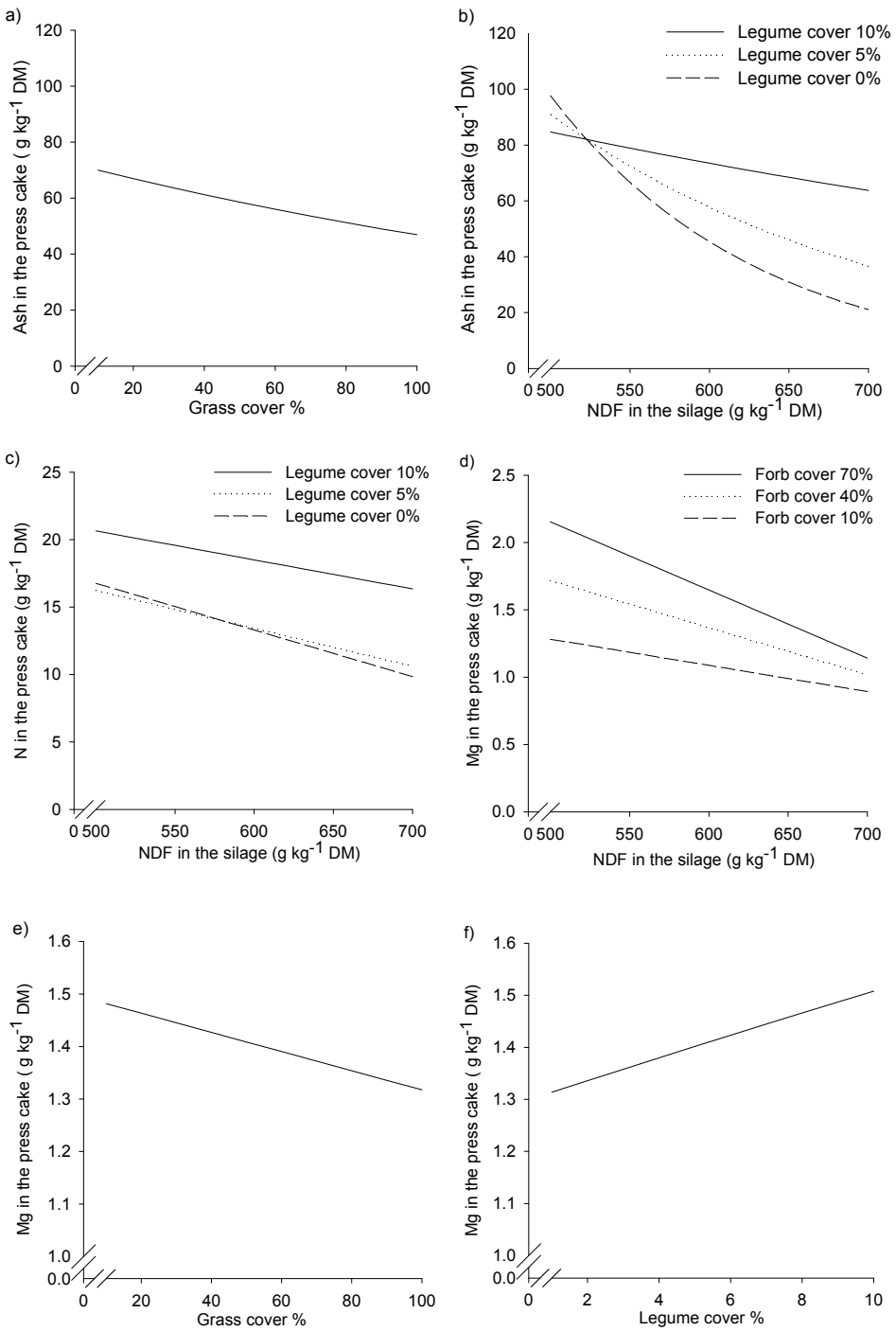


Fig. 8: Predictions of ash (a,b), N (c) and Mg (d, e, f) concentrations in the press cake: a) and e) cover of grasses (%) at a mean cover of forbs, legumes (%) and a mean NDF concentration in the silage (g $kg^{-1}$ DM); b) and c) the interaction of NDF in the silage (g $kg^{-1}$ DM) and legume cover (%) at a mean cover of forbs and grasses (%); d) the interaction of NDF in the silage (g $kg^{-1}$ DM) and forb cover (%) at a mean cover of legumes and grasses (%); e) cover of grasses (%) at a mean cover of forbs and legumes (%) and mean concentration of NDF in the silage (g $kg^{-1}$ DM) f) cover of legumes(%) at a mean cover of forbs and grasses (%) and a mean concentration of NDF in the silage (g $kg^{-1}$ DM).

Ash content in the PC decreased with increasing grass cover in the swards (Fig. 8a). Furthermore, ash content was lower the higher the NDF content in the silage (Fig. 8b), and its decrease was more pronounced the lower the legume cover. This may be explained by the fact that mineral content in legumes is usually higher than in grasses (Ruano-Ramos et al., 1999).

N content in the PC decreased with increasing NDF content in the silage (Fig. 8c), the reduction being slightly more pronounced the lower the legume cover in the sward. However, average N content increased with increasing legume cover, which confirms findings by Garcia-Ciudad et al. (1997), who reported higher N contents for leguminous plants as compared to grasses and forbs.

Mg concentration in the PC was negatively correlated with grass cover in the sward (Fig. 8e) and responded positively to increasing legume covers (Fig. 8f), which reflects the fact that legumes have a higher Mg concentration than grasses (Ruano-Ramos et al., 1999). Mg concentration in the PC decreased with increasing NDF content in the silage and increased with increasing cover of forbs, but this increase was less pronounced at higher levels of NDF (Fig. 8d). Overall, the botanical parameters proved to be helpful in developing models for the prediction of solid fuel properties, as, contrary to Richter et al. (2011a), NDF content alone failed to predict mineral element concentration in the PC in the present study. While the models of Richter et al. (2011a) are based on one experimental sward, the present study covers a larger variation in botanical composition of swards. Hence, the importance of botanical parameters in most models is not surprising. Confirming results of previous studies by Richter et al. (2011a, b), NDF concentration in the silage was the only chemical constituent with predictive power in all models for mineral element concentration in PC.

## 4.4 Conclusions

Based on the data derived from this study, the following conclusions can be drawn:

1) Semi-natural grassland silages are a suitable input material for the IFBB-System, although yield and chemical composition of semi-natural grasslands were highly variable on a Europe-wide scale, which aggravates the energetic conversion of such biomasses through combustion.
2) The IFBB treatment of hydrothermal conditioning and subsequent dewatering in a large-scale prototype plant produced comparable results to those of small-scale applications in previous studies and proved to be successful in significantly reducing all elements including those detrimental to combustion.
3) Correlations between botanical and chemical parameters of the silage and mass flows of plant compounds as well as the fuel quality of the press cake could be shown. Higher NDF concentrations and higher grass covers led to better fuel properties.

# 5 Energetic conversion of European semi-natural grasslands: Energy yields and the fate of organic compounds

Abstract Twelve European habitat types were investigated to determine the influence of the IFBB technique (integrated generation of biogas and solid fuel from biomass) on the fate of organic compounds and energy yields of semi-natural grassland biomass. Concentration of organic compounds in silage and IFBB press cake (PC), mass flows within that system and methane yields of IFBB press fluids (PF) were determined. The gross energy yield of the IFBB technique was calculated in comparison to hay combustion (HC) and whole crop digestion (WCD). The IFBB treatment increased fibre and organic matter (OM) concentrations and lowered non-fibre carbohydrates and crude protein concentrations. The PF was highly digestible irrespective of habitat types, showing mean methane yields between 312.1 and 405.0 $L_N$ $CH_4$ $kg^{-1}$ VS. Gross energy yields for the IFBB system (9.75 to 30.19 MWh $ha^{-1}$) were in the range of HC, outperformed WCD and were influenced by the habitat type.

## 5.1 Introduction

The concern on climate change and the limitation of fossil energy resources leads to a growing demand of energy from renewable resources. The European Union has enacted the European Biomass Action plan and is determined to reach the aim of producing 20% of its total primary energy consumption from renewable energy sources by the year 2020 (Anonymous, 2009). The demand for land and resources to produce renewable energy will lead to competition with other land uses like food production and nature conservation (Johansson and Azar, 2007, Hoogwijk et al. 2003). On the other hand, Isselstein et al. (2005) described the trend of abandonment of grassland management for economic reasons in Europe, leaving a potential of renewable resources unused. The abandoned areas are predominantly extensively managed grasslands, bearing a large variety of plant and animal species. This biodiversity is endangered by abandonment due

to succession. Therefore, it is necessary to find new alternative management regimes in order to maintain the biodiversity in European manmade landscapes (Poschlod et al., 2005). Such might be found in cutting and using the material for bioenergy systems. However, material from semi-natural grasslands is often originated from a late cut, and thus is senescent and has high contents of lignin and cellulose and high mineral concentrations. The material is hardly suitable for economically efficient biogas production, as it leads to low methane yields and long retention times (Richter et al., 2009). Beyond that it is a difficult feedstock for combustion because of high element concentrations causing ash slagging (K, Mg), corrosion (Cl, S) or emissions (Cl, S, N) (Jenkins et al., 1998, Obernberger et al., 2006). The system of the integrated generation of solid fuel and biogas from biomass (IFBB, Wachendorf et al., 2009) was developed to cope with these problems. The main element of this conversion procedure is the mechanical dehydration after hydrothermal conditioning of the ensiled biomass, which produces a solid fibrous fraction for thermal use (press cake, PC) and a liquid fraction with easily fermentable constituents for biogas production (press fluid, PF). The liquid fraction is used to produce biogas which is converted by a combined heat and power plant to produce electricity and heat, which is in turn used to dry the solid fraction. The fuel quality of the mechanically dehydrated silage is improved in comparison to the untreated biomass because of the partial elution of organic and mineral compounds (Wachendorf et al., 2009). Thorough research has been done on the mass flows of mineral compounds and the mineral properties of the solid fuel and the parameters affecting the mass flows (Hensgen et al., 2012, Richter et al., 2011a), but there is a lack of knowledge concerning the fate of organic plant compounds within the IFBB technique. Plant compounds like lignin, cellulose, proteins, lipids and sugars are important for the energy conversion efficiency of the IFBB technique. High concentrations of oxidisable elements, mainly C and H, in cellulose, hemicellulose and lignin lead to a high heating value for these organic compounds, whereas they are not suitable for anaerobic

digestion as they are less fermentable and in case of lignin inhibit microbial activity and biogas production (Chen et al., 2009). Richter et al. (2011a, b) analysed the fate of mineral and organic compounds in the IFBB technique using a stationary experimental setting on a laboratory scale with biomass from a restricted sample of German semi-natural grasslands. The present study aims to close important gaps in the knowledge considering the effects of different input biomasses by including typical semi-natural grasslands from a wide range of European origins. Furthermore, the study brings forward the practical implementation of IFBB by using an up-scaled continuous-flow system for the hydrothermal conditioning and dewatering procedure, which was described in detail by Hensgen et al. (2012). The study focuses on the fate of organic compounds during IFBB processing of biomasses and on biogas yields resulting from digestion of the PF. Furthermore, the partition of energy flows into PC and PF was investigated. Statistical analyses were performed to search into the relationship between chemical parameters of the grassland biomass and energy yields of PF and PC. The total gross energy was calculated and compared with conventional energy recovery systems, namely hay combustion (HC) and whole crop digestion (WCD). The main questions addressed were:

1. How does the IFBB technique affect the mass flows of organic compounds of biomasses from different European semi-natural grassland habitat types?
2. Which methane yields can be achieved through the anaerobic digestion of press fluids?
3. Which gross energy yields can be realised through anaerobic digestion of press fluids and thermal use of press cake in comparison to conventional energy conversion systems such as HC and WCD?
4. In which way do the chemical characteristics of the silage influence the total gross energy yield through the IFBB technique?

## 5.2 Material and Methods

### 5.2.1 Basic experimental set-up and site characterisation

Six experimental areas have been investigated each in Germany (DE), Wales (UK) and Estonia (EST), which were partner regions in the European project PROGRASS (Hensgen et al., 2012). Each area was within or adjacent to a NATURA 2000 site and all but one site could be described as a NATURA 2000 habitat type, displaying the large diversity of European semi-natural grasslands (Table 13). Detailed vegetation and soil information were published (Hensgen et al., 2012). The German areas were placed in the Vogelsberg region in the state of Hessen, which is an elevated region featuring low annual mean temperatures and high amount of precipitation. The Welsh areas were situated in the western part of Wales in the region of Ceredigion. The climate is of a maritime type, with mild and wet winters. One site in Wales could not be described as a habitat type according to the NATURA 2000 classification as it was heavily dominated by Pteridium aquilinum (L.) Kuhn. Vast grassland areas in Welsh upland regions are lost for animal nutrition and biodiversity as they are covered by this species which is cancerogeneous to animals (Fenwick, 1988). The species can be dealt with through regular cutting. Therefore we included it in our research to evaluate its availability as a substrate for bioenergy, as there are currently no other forms of utilisation. The Estonian sites were established each two sites in two regions around the cities of Tartu and Jögeva, and the remaining two sites located between these two regions. Three plots served as replicates at each area, every plot a square of 10 by 10 m.

Table 13: Site description and two year average of yield data of eighteen semi-natural European grassland sites

| Site | | NATURA 2000 habitat type | Date of first cut 2009 / 2010 | Altitude [m a.s.l] | Dominant species | FM yield [t ha$^{-1}$] | DM content [% FM] | DM yield [t ha$^{-1}$] |
|---|---|---|---|---|---|---|---|---|
| DE | I | Lowland hay meadow (6510) | 14.07. / 07.07. | 570 | *Festuca rubra, Agrostis capillaris* | 21.70 | 22.35 | 4.85 |
| | II | Lowland hay meadow (6510) | 13.07. / 05.07. | 420 | *Festuca rubra, Agrostis capillaris* | 18.92 | 25.94 | 4.91 |
| | III | Mountain hay meadow (6520) | 13.07. / 06.07. | 580 | *Festuca rubra, Sanguisorba officinalis* | 15.32 | 28.38 | 4.35 |
| | IV | Species-rich Nardus grasslands (6230) | 13.07. / 08.07. | 580 | *Festuca rubra, Nardus stricta* | 8.46 | 42.27 | 3.58 |
| | V | Molinia meadow (6410) | 21.07. / 20.07. | 500 | *Deschampsia cespitosa, Juncus acutiflorus* | 18.82 | 29.91 | 5.63 |
| | VI | Humid tall herb fringes of watercourses and woodlands (6431) | 08.09. / 07.09. | 380 | *Scirpus sylvatica, Filipendula ulmaria* | 27.12 | 23.74 | 6.44 |
| UK | I | Degraded raised bogs still capable of natural regeneration (7120) | 18.09. / 24.08. | 190 | *Molinia caerulea, Juncus acutiflorus* | 9.57 | 36.30 | 3.49 |
| | II | Degraded raised bogs still capable of natural regeneration (7120) | 22.09. / 07.10. | 160 | *Juncus effusus, Deschampsia cespitosa* | 13.35 | 26.58 | 3.63 |
| | III | Degraded raised bogs still capable of natural regeneration (7120) | 16.09. / 22.09. | 400 | *Juncus effusus, Agrostis canina* | 14.83 | 31.58 | 4.84 |
| | IV | European dry heaths (4030) | 06.08. / 09.09. | 560 | *Vaccinium myrtillus, Deschampsia cespitosa* | 13.62 | 36.92 | 4.95 |
| | V | Not classifiable (*Pteridium aquilinum* dominated) | 27.07. / 12.08. | 300 | *Pteridium aquilinum, Agrostis capillaris* | 13.11 | 27.71 | 3.69 |
| | VI | Blanket bogs (7130) | 18.08. / 16.09. | 440 | *Molinia caerulea, Festuca ovina* | 5.33 | 37.06 | 1.97 |
| EST | I | Northern boreal alluvial meadows (6450) | 30.06. / 05.07. | 40 | *Alopecurus pratensis, Filipendula ulmaria* | 11.21 | 29.38 | 3.10 |
| | II | Fennoscandian lowland species-rich dry to mesic grasslands (6270) | 01.07. / 07.07. | 40 | *Alopecurus pratensis, Deschampsia cespitosa* | 10.07 | 33.93 | 3.39 |
| | III | Fennoscandian wooded meadows (6530) | 29.06. / 07.07. | 60 | *Scorzonera humilis, Brachypodium pinnatum* | 5.94 | 27.47 | 1.63 |
| | IV | Northern boreal alluvial meadows (6450) | 30.06. / 05.07. | 40 | *Carex disticha, Carex cespitosa* | 11.84 | 31.90 | 3.79 |
| | V | Fennoscandian lowland species-rich dry to mesic grasslands (6270) | 01.07./ 07.07. | 40 | *Anthriscus sylvestris,Veronica longifolia* | 10.26 | 31.08 | 3.17 |
| | VI | Fennoscandian wooded meadows (6530) | 29.06. / 06.07. | 60 | *Galium boreale, Anthriscus sylvestris* | 9.09 | 26.74 | 2.41 |

### 5.2.2 Harvest, conservation of the grassland biomass and yield determination

The areas were harvested in 2009 and 2010 between the 15th of June and the 15th of October (Table 13). Harvest was done once a year or twice, if re-growth was sufficient for a second cut, which was the case for sites DE I, II, III and V. Second cut was done in the first two weeks of September 2009 and 2010. Cutting was done with a finger bar mower at a cutting height of 5 cm. The biomass was chopped and put into 60L polyethylene barrels for ensiling, without application of additives. Ensiling lasted at least 6 weeks. Yield determination was carried out by cutting 5m² per plot.

### 5.2.3 Processing of the grassland biomass

Within the PROGRASS project a prototype of a continuous-flow IFBB bioenergy plant was built and used to process the ensiled plant material. Detailed description is available in Hensgen et al. (2012). 20 kg of each silage were taken as a sample. The sample was transported into the prototype and laid on a slowly moving band conveyor, where it was sprinkled with 25°C warm tap water for 30 minutes. The relation of biomass to mash water was 1:8. After that the mashed biomass was dewatered by a screw-press (type AV, Anhydro Ltd, Kassel, Germany). The conical screw had a pitch of 1:6 and a rotational speed of 3 rev $min^{-1}$. The cylindrical screen encapsulating the screw had a perforation of 1.5 mm. Samples of the silage and the PC were dried at 60°C for 24 h for chemical analysis. Dry matter (DM) content was determined by oven-drying at 105°C for 48 h.

### 5.2.4 Chemical analysis and calculation of mass flows

The silage and the PC were analysed for C, H and N using an elemental analyser (Vario MAX CHN, Elementar Analysensysteme GmbH, Hanau, Germany). Weende constituents (van Soest and Wine, 1967), crude ash, crude protein (CP), ether extract (EE), neutral detergent fibre (NDF), acid detergent fibre (ADF), acid detergent

lignin (ADL), were measured according to standard methods (Bassler, 1976) and near infrared spectroscopy (Foss NIRSystems, Hillerød, Denmark), non-fibre carbohydrates (NFC) were calculated as the sum of organic matter subtracted by Ash, CP, EE and NDF. Mass flows of organic compounds from the silage into PC and PF were calculated according to the formulae:

$$(1)\ MF\_X_{PC} = \frac{M_{PC} * X_{PC}}{M_{Sil} * X_{Sil}}$$

$$(2)\ MF\_X_{PF} = 1 - MF\_X_{PC}$$

With:

$MF\_X_{PC}$: Mass flow of a specific element X into the press cake

$M_{PC}$: Weight of the press cake in kg

$C_{PC}$: Concentration of a specific element X in the press cake in g $kg^{-1}$

$M_{Sil}$: Weight of the silage in kg

$X_{Sil}$: Concentration of a specific element X in the silage in g $kg^{-1}$

$MF\_X_{PF}$: Mass flow of a specific element X into the press fluid.

### 5.2.5 Determination of biogas production from press fluid

Determination of biogas production of the PF from the IFBB system was performed in batch experiments in accordance with the German Standard (VDI 4630, 2004) with three replicates. Fermentation of the substrates took place in gas proof 20-L polyethylene containers. Mixing of the digester content was carried out for 15 min every 3 h. The experiments were performed at 37°C, with a fluctuation of ±1 °C. Digested slurry from a biogas plant was used as inoculum (8 kg FM). 4 kg FM of PF were used and the fermentation time was 14 days. Measurement of gas fluxes started 24 h after incubation and was repeated once a day. The total daily biogas volume was determined with a wet drum gas meter (TG1, Ritter Ltd., Germany). The biogas composition (percentage of $CH_4$) was measured with an infrared

spectrometer (GS Messtechnik, type GS IRM 100, Ratingen, Germany). Methane volumes were measured under laboratory room conditions, converted to standard conditions (273.15 K, 101.325 kPa) and expressed as normal litre ($L_N$) or normal cubic meter ($m^3_N$). These methane volumes were referred to as methane yields when they were related to the amount of volatile solids (VS) or chemical oxygen demand (COD) in the substrate ($L_N$ $kg^{-1}$ VS or $L_N$ $kg^{-1}$ COD resp.) and to the area harvested ($m_N^3$ $ha^{-1}$). It is well documented that the content of dry matter in silages is higher than the dry matter determined by oven drying, because of volatile components lost during the drying procedure (Porter and Murray, 2001). Therefore, it can be assumed that the drying procedure led to DM values of the PF that underrate the real DM content. To correct the oven measured DM content, a formula was used, which was developed by Weißbach and Strubelt (2008) for grassland silages. As this formula was not intended to be used for PF, we also measured COD and used the COD derived substrate yields for further calculations and statistics.

### 5.2.6 Calculation of gross energy yield

Gross energy yields for IFBB, WCD and HC were calculated substrate related and area related. The basis for the substrate related calculation was kg DM of raw biomass (DM raw biomass), excluding losses through harvest and conversion technology. The basis for area related gross energy yield was one ha, also excluding losses through harvest and conversion technology.

For the IFBB system energy contained in the PC was calculated as higher heating value [HHV, kJ $kg^{-1}$ DM (press cake)]. The calculation was based on the concentrations of C, H, and N [g $kg^{-1}$ DM (press cake)] using the following equation for bio-fuels by Friedl et al (2005):

(3) $$HHV = 0.0355 * C^2 - 23.2 * C - 223 * H + 0.512 * C * H + 13.1 * N + 20600$$

As a second energy carrier in the IFBB system the energy contained in the PF was calculated. The measured $CH_4$ yields of PF were multiplied with the heating value of methane (36.4 MJ m³ $CH_4$). Total IFBB gross energy yield was calculated as gross energy yield of PC plus gross energy yield of PF.

For the gross energy of HC the formula (3) of Friedl et al. (2005) was used to calculate the HHV of the biomass, using the concentrations of C, H and N in the raw biomass.

The theoretical methane potential of the silage for the calculation of the gross energy yield of WCD was calculated according to the following formula from German guidelines of VDI 4630 (VDI, 2006), also used in former experiments (Richter et al.2009):

$$(4)\quad Methane\ yield_{\max} = \frac{373 \times (CF + NFE) + 1000.8 \times EE + 560 \times CP}{1000 \times \frac{VS}{DM}} \quad [NL\ kg^{-1}\ VS]$$

for a realistic estimation of methane yields, digestibility values (D) of the organic compounds have to be considered (VDI 4630, 2004). In this study, they were based on feeding experiments with ruminants (University of Hohenheim, 1997), as these data are well proven and provide a good indication for a system that is comparable to some extent, even if there are differences in the conditions inside the rumen and the digester (Richter et al.2009). The actual methane yield was calculated according to the formula:

$$(5)\quad Methane\ yield = \frac{(CF * D_{CF} + NfE * D_{NfE}) * 373 + EE * D_{EE} * 1000.8 + CP * D_{CP} * 560}{1000 * \frac{VS}{DM}} \quad [NL\ kg^{-1}\ VS]$$

### 5.2.7 Statistical analysis

Statistical analyses were done using the Software R (R Development Core Team, 2011).

Analysis of variance (ANOVA) was performed to test if there was an effect of habitat type and IFBB treatment and an interaction between both variables on the concentration of organic compounds in PC and also if there was an effect of habitat type on the mass flows of organic compounds into the PC. Further ANOVA was performed to test if there was an effect of habitat type on substrate and area related methane yields of the PF. ANOVA was carried out to test for the effects of habitat type and conversion system and possible interaction of habitat type and conversion system on the substrate and area related gross energy yield of the biomass from European semi-natural grassland habitats. Assumptions of the analysis were tested and outliers were removed.

If ANOVA showed significant results, post hoc tests were performed using Hochberg multiple test procedure.

## 5.3 Results and Discussion

### 5.3.1 Organic compounds of silage and press cake

The material harvested from the twelve semi-natural habitat types in Wales, Germany and Estonia showed consistently high fibre contents and low contents of protein (Table 14), which is caused through the late cutting date.

Table 14: Concentration of organic compounds (OM= organic matter, CP = crude protein, EE = ether extract, NFC = non fibre carbohydrates, NDF = neutral detergent fibre, ADF = acid detergent fibre, ADL = acid detergent lignin, in g $kg^{-1}$ DM) in silage (Si) and IFBB presscake (PC) from twelve European semi-natural grassland habitat types (n = number of samples per habitat type), arithmetic means of two year data.

| Natura 2000 | Natura 2000 | | OM | | CP | | EE | | NFC | | NDF | | ADF | | ADL | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Habitat Type | Code | n | Si | PC | Si | PC | Si | PC | Si | PC | Si | PC | Si | PC | Si | PC |
| Lowland hay meadow | 6510 | 12 | 907.5 | 933.2 | 103.0 | 91.5 | 24.4 | 23.2 | 273.5 | 175.1 | 506.6 | 643.4 | 391.6 | 496.9 | 61.8 | 91.6 |
| Mountain hay meadow | 6520 | 6 | 909.9 | 923.4 | 92.3 | 83.7 | 25.3 | 24.4 | 251.5 | 190.0 | 540.9 | 625.2 | 382.8 | 460.6 | 74.5 | 94.4 |
| Species rich nardus grasslands | 6230 | 6 | 935.3 | 952.0 | 96.5 | 75.6 | 24.6 | 24.4 | 199.9 | 137.1 | 614.3 | 715.0 | 366.5 | 441.4 | 47.7 | 62.7 |
| Molinia meadow | 6410 | 6 | 913.6 | 936.9 | 94.5 | 76.8 | 21.0 | 20.0 | 189.8 | 133.4 | 608.4 | 706.6 | 395.2 | 459.5 | 74.5 | 91.5 |
| Humid tall herb fringes | 6431 | 6 | 880.4 | 896.0 | 88.4 | 77.9 | 10.7 | 10.1 | 183.1 | 116.7 | 598.3 | 691.3 | 412.6 | 475.7 | 87.9 | 102.8 |
| Degraded bogs | 7120 | 18 | 955.8 | 974.3 | 82.1 | 62.9 | 19.2 | 17.9 | 178.1 | 118.0 | 676.4 | 775.6 | 411.5 | 472.2 | 79.8 | 93.8 |
| European dry heaths | 4030 | 6 | 972.6 | 979.0 | 91.5 | 73.5 | 25.6 | 24.8 | 240.1 | 201.4 | 615.4 | 679.3 | 475.2 | 532.2 | 156.4 | 175.5 |
| Pteridium dominated | | 6 | 894.4 | 922.1 | 98.1 | 93.6 | 17.7 | 16.2 | 200.3 | 152.4 | 578.2 | 659.9 | 447.2 | 523.9 | 137.8 | 165.2 |
| Blanket bogs | 7130 | 6 | 965.6 | 981.3 | 90.0 | 65.8 | 24.9 | 24.7 | 190.5 | 136.9 | 660.2 | 753.9 | 419.1 | 473.7 | 86.5 | 98.7 |
| Alluvial meadows | 6450 | 12 | 928.1 | 951.3 | 98.8 | 82.2 | 24.2 | 23.0 | 218.4 | 162.5 | 586.8 | 683.5 | 388.9 | 452.4 | 70.4 | 80.2 |
| Mesic grasslands | 6270 | 12 | 906.3 | 944.8 | 92.0 | 74.2 | 24.9 | 24.4 | 201.7 | 129.2 | 587.8 | 716.9 | 354.1 | 445.9 | 55.7 | 62.1 |
| Wooded meadows | 6530 | 12 | 913.0 | 938.0 | 100.9 | 81.5 | 26.2 | 25.6 | 240.1 | 162.6 | 545.9 | 668.3 | 393.2 | 470.0 | 68.0 | 76.3 |
| Arithmetic mean | | | 924.9 | 947.1 | 93.7 | 77.5 | 22.6 | 21.7 | 218.2 | 148.9 | 594.4 | 699.0 | 399.4 | 473.0 | 78.9 | 94.0 |

This result matches the results shown by Richter et al. (2011b). The IFBB treatment led to an increase in total organic matter by decreasing the ash content of the PC. As shown by Hensgen et al. (2012), this reduction in ash is caused by elution of minerals harmful for combustion and is therefore one of the main goals of the IFBB system to provide an improved solid fuel. There is a decrease of CP concentration to be observed by comparing the PC to the silage. The reduction of CP ranged from 4.6% in case of the "Pteridium dominated" areas to 26.9% in case of the "Blanket bogs". The reduction of CP is an important goal of the IFBB treatment, as the N contained in the CP will increase the danger of $NO_x$ emissions during combustion. However, adapted combustion techniques, i.e. staged air technique, can reduce the risk of $NO_x$ emissions by converting the

biomass-N into elemental $N_2$. Only minor reductions could be observed for the EE fraction. The content of non-fibre carbohydrates (NFC) was also reduced in the PC, with reduction rates ranging from 16.1% for "European dry heaths" to 35.3% for "Humid tall herb fringes", respectively. The reductions were very variable for the different habitat types. There was a significant interaction term of habitat type and IFBB treatment in the analysis of variance model for NFC (data not shown). Fibre fractions measured as concentrations of NDF, ADF and ADL increased significantly in the PC through the IFBB process. It can be concluded, that IFBB PCs have higher fibre contents and lower concentrations of easier soluble organic compounds like NFC and CP than the silages. The mass flows of organic compounds into the PC are shown in Table 15.

Table 15: Mass flow of organic compounds into the IFBB press cake (PC) for organic matter (ODM), crude protein (CP), ether extract (EE), non fibre carbohydrates (NFC), neutral detergent fibre (NDF), acid detergent fibre (ADF) and acid detergent lignin (ADL) in % for twelve European semi-natural grassland habitat types (n= number of samples per habitat type), arithmetic means of two year data ± standard error of means.

| Natura 2000 | Natura 2000 | | ODM | CP | EE | NFC | NDF | ADF | ADL |
|---|---|---|---|---|---|---|---|---|---|
| Habitat Type | Code | n | | | | | | | |
| Lowland hay meadow | 6510 | 12 | 79.3 ± 1.5 | 68.8 ± 2.4 | 73.7 ± 1.9 | 49.7 ± 2.1 | 97.9 ± 1.9 | 98.1 ± 2.6 | 116.5 ± 4.5 |
| Mountain hay meadow | 6520 | 6 | 80.0 ± 2.6 | 71.8 ± 3.6 | 75.9 ± 2.1 | 60.7 ± 4.8 | 91.5 ± 4.2 | 95.1 ± 3.5 | 103.6 ± 8.7 |
| Species rich nardus grasslands | 6230 | 6 | 81.6 ± 0.9 | 62.8 ± 1.0 | 79.3 ± 1.9 | 56.2 ± 3.3 | 93.5 ± 1.1 | 96.6 ± 0.8 | 105.9 ± 3.8 |
| Molinia meadow | 6410 | 6 | 87.9 ± 1.1 | 69.7 ± 1.4 | 81.9 ± 1.7 | 60.3 ± 3.2 | 99.6 ± 1.4 | 99.8 ± 2.2 | 106.6 ± 4.3 |
| Humid tall herb fringes | 6431 | 6 | 86.1 ± 2.2 | 74.3 ± 1.7 | 82.2 ± 3.5 | 52.5 ± 2.8 | 97.8 ± 2.6 | 97.5 ± 2.4 | 98.9 ± 2.2 |
| Degraded bogs | 7120 | 18 | 76.1 ± 3.3 | 57.0 ± 2.7 | 69.2 ± 3.0 | 49.1 ± 2.1 | 85.8 ± 4.0 | 85.8 ± 4.0 | 88.4 ± 4.6 |
| European dry heaths | 4030 | 6 | 92.9 ± 2.8 | 74.0 ± 1.9 | 89.0 ± 2.6 | 77.8 ± 3.6 | 102.1 ± 3.9 | 103.4 ± 3.1 | 103.3 ± 2.6 |
| Pteridium dominated | | 6 | 88.6 ± 1.1 | 82.0 ± 4.3 | 78.7 ± 3.8 | 65.3 ± 5.1 | 97.9 ± 2.0 | 100.8 ± 1.2 | 104.5 ± 3.8 |
| Blanket bogs | 7130 | 6 | 88.3 ± 1.3 | 63.6 ± 1.0 | 86.4 ± 1.8 | 62.2 ± 1.9 | 99.3 ± 1.5 | 98.3 ± 0.9 | 99.5 ± 3.7 |
| Alluvial meadows | 6450 | 12 | 86.5 ± 2.1 | 70.3 ± 1.9 | 80.1 ± 2.2 | 62.9 ± 2.2 | 98.3 ± 2.6 | 98.0 ± 2.1 | 96.5 ± 2.7 |
| Mesic grasslands | 6270 | 12 | 84.3 ± 2.3 | 65.2 ± 2.5 | 79.2 ± 1.9 | 62.8 ± 3.2 | 98.7 ± 2.6 | 101.6 ± 2.4 | 89.1 ± 2.2 |
| Wooded meadows | 6530 | 12 | 81.5 ± 2.1 | 64.1 ± 2.0 | 77.6 ± 1.2 | 53.7 ± 1.6 | 97.3 ± 3.0 | 95.0 ± 2.9 | 89.4 ± 3.7 |
| Arithmetic mean | | | 83.1 ± 0.8 | 67.0 ± 1.0 | 77.9 ± 0.9 | 57.8 ± 1.6 | 95.7 ± 1.0 | 96.4 ± 1.0 | 97.4 ± 1.5 |

The ODM mass flow into the PC is only slightly higher than the DM mass flow (Hensgen et al. 2012). Mass flow of CP into the PC was very variable among habitat types between 57% for "Degraded bogs" and 82% for "Pteridium dominated" vegetation. The mass flow of EE was in the same range as for total OM. The mass flow for NFC was constantly lower than for VS, resulting in a reduction of NFC in the PC, as shown in Table 15. The mass flow of NFC is significantly influenced by habitat type ($p<0.001$), the habitat types with low ODM mass flow also showed a low mass flow of NFC and vice versa. The mass flows of NDF, ADF and ADL into the PC were very high and all significantly influenced by habitat type ($p<0.05$, 0.01, 0.001 for NDF, ADF, ADL, respectively). In some cases, mass flows above 100 % were measured for NDF, ADF and ADL. We assumed that during the IFBB procedure with high pressure and temperatures in the screw-press, parts of the NFC and CP fractions formed organic compounds that were measured as fibre in analysis, even if they have not been generic cellulose, hemicellulose or lignin fibres. It has been shown by Manas et al. (1995) that during dietary fibre analysis of fruits, legumes and cereals, proteins form acid resistant complex products, which would then be analysed as part of the ADF fraction. The mass flows for most organic compounds (NDF, ADF, ADL, NFC and CP) were significantly influenced by habitat type (data not shown). This influence might be due to the different vegetation composition of the habitat types, but might also be caused by the different harvesting dates, as King et al. (2012) have shown a marked influence of harvest date on mass flows, with higher mass flows into the PF at earlier harvest dates.

### 5.3.2 Methane yields of press fluids

Although the investigated grassland habitats varied in botanical composition (Hensgen et al. 2012), harvest time (Table 13), chemical composition of the silage (Table 14) and the mass flows of organic compounds into the PC (Table 15), there was no significant effect of habitat type on the substrate related methane yield of the PF (Table 16, Fig. 9).

Table 16: Analysis of variance on the effects of habitat type and conversion technology on substrate related methane yields, area related methane yields, substrate related gross energy yields and area related gross energy yields

| Parameter/Effect | Df | F value | P |
|---|---|---|---|
| **Substrate related methane yield** | | | |
| Habitat type (H) | 11 | 1.36 | 0.21 |
| Residuals | 91 | | |
| **Area related methane yield** | | | |
| Habitat type (H) | 11 | 9.47 | *** |
| Residuals | 91 | | |
| **Substrate related gross energy yield** | | | |
| Habitat type (H) | 11 | 6.57 | *** |
| Conversion system (C) | 2 | 3378.16 | *** |
| H x C | 22 | 3.25 | *** |
| Residuals | 273 | | |
| **Area related gross energy yield** | | | |
| Habitat type (H) | 11 | 18.87 | *** |
| Conversion system (C) | 2 | 161.89 | *** |
| H x C | 22 | 1.92 | ** |
| Residuals | 273 | | |

Significance codes: * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$

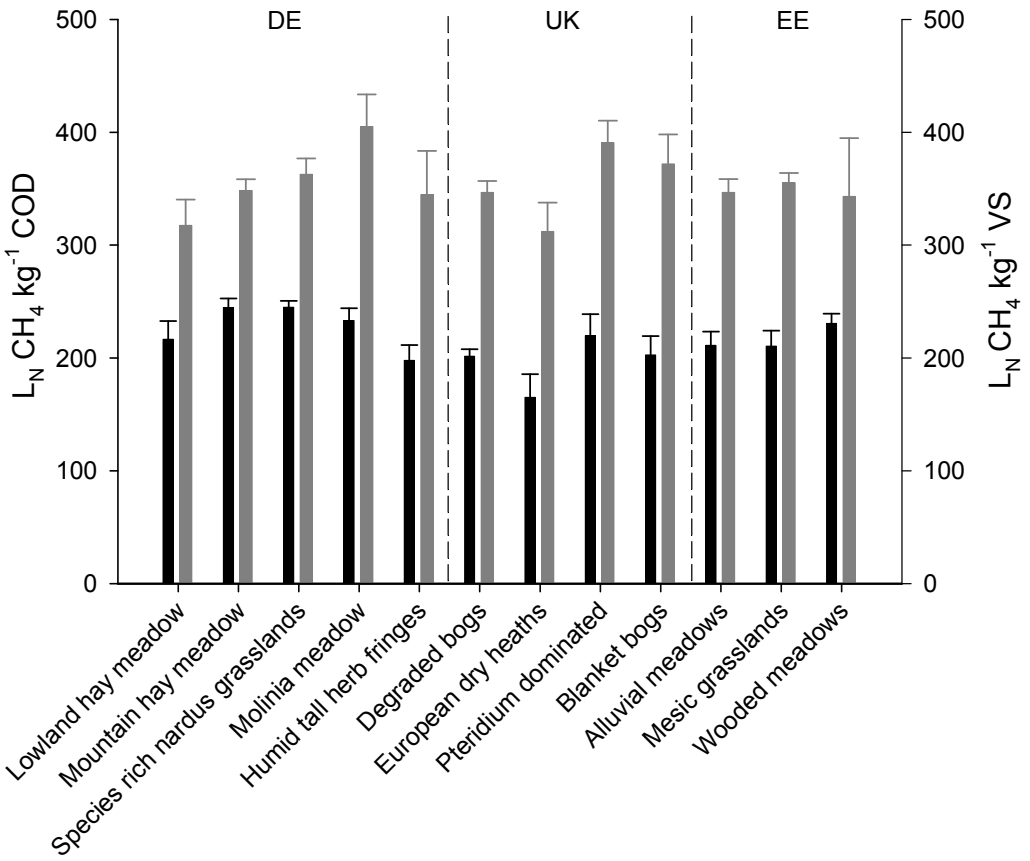


Fig. 9: Substrate related methane yield (arithmetic means with standard error of means, two-year data) of press fluids for twelve European semi-natural grassland habitat types (COD: black columns; VS: dark grey columns).

The COD based methane yields varied between 165.1 and 244.8 $L_N$ $CH_4$ $kg^{-1}$ COD and the VS based assessment showed methane yields between 312.1 and 405.0 $L_N$ $CH_4$ $kg^{-1}$ VS. These values were in the range of former results by Richter et al. (2009) and Nayono et al. (2010). Richter et al. (2009) reported PF methane yields between 304 and 522 $L_N$ $CH_4$ $kg^{-1}$ VS for different vegetation types and temperatures during hydrothermal conditioning. Nayono et al. (2010) reported methane yields of 270 $L_N$ $CH_4$ $kg^{-1}$ COD and 490 $L_N$ $CH_4$ $kg^{-1}$ VS from press fluid from the organic fraction of municipal solid waste. Regression analysis did not show any relationship between substrate related methane yield and any organic compound concentration of the silage material or botanical parameter of the vegetation, i.e. cover estimates of functional groups (legumes, grasses and herbs). This lack

of relationship may be partly due to the highly variable mass flows of organic compounds. For the implementation of the IFBB technology in a commercial energy conversion plant the result of rather uniform methane yields from very different parent materials can be assessed positively, as it underlines the ability of IFBB to convert a heterogeneous biomass from a wide range of vegetation and harvest dates into renewable electricity without being dependent on specific material input parameters.

Although the substrate related methane yields did not significantly differ among the twelve investigated habitat types, the area related methane yields varied significantly (Fig. 10, Table 16).

This variation can be explained by the highly variable DM yield (Table 13) and the varying mass flow of organic matter and compounds (Table 15). Area related methane yields ranged from 55.2 to 330.4 $m_N^3$ $CH_4$ $ha^{-1}$ (COD) and from 60.8 to 279.5 $m_N^3$ $CH_4$ $ha^{-1}$ (VS). Richter et al. (2011b) found area related methane yields between 196 and 479 $m_N^3$ $CH_4$ $ha^{-1}$ (VS) for biomasses from a submontane hay meadow in northern Hessen, Germany. The vegetation types in the UK showed both low DM yields and high mass flows of DM into the PC, therefore they yielded very little methane through anaerobic digestion of the PF.

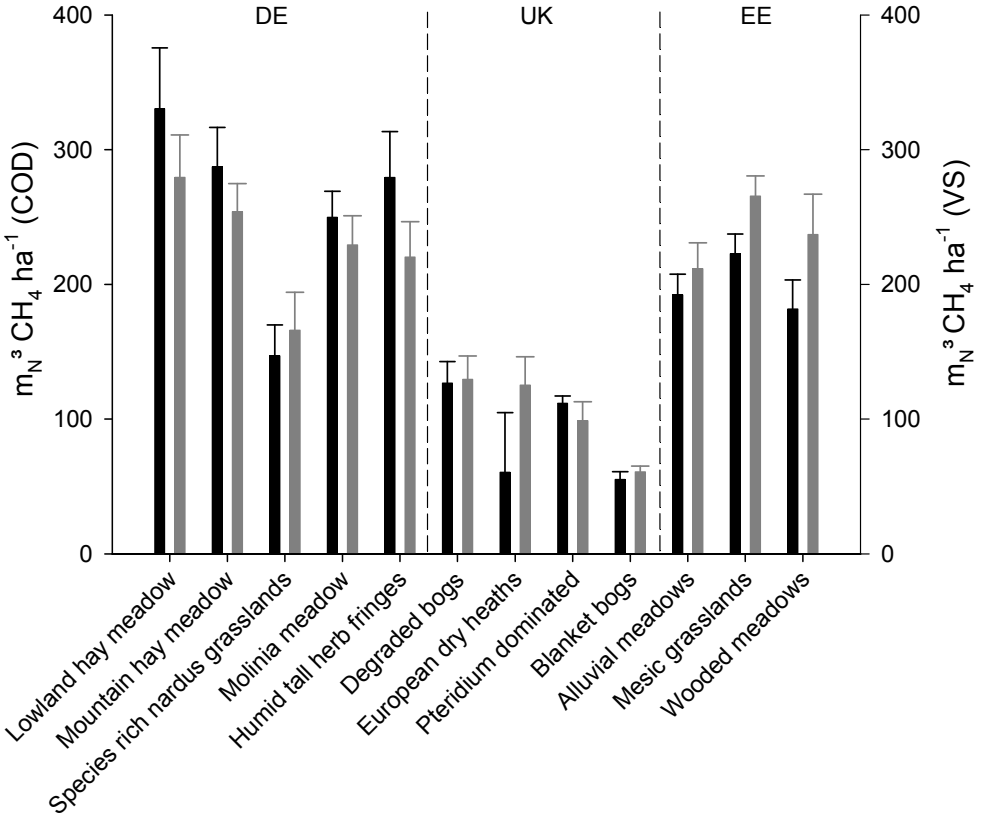


Fig. 10: Area related methane yield (arithmetic means with standard error of means, two-year data) of press fluids for twelve European semi-natural grassland habitat types (COD: black columns; VS: dark grey columns).

As the IFBB technique is a heat demanding process it is reasonable to connect an IFBB plant to existing plants with excessive waste heat, as e. g. conventional biogas plants or waste water treatment plants with sewage sludge anaerobic digestion, and use the PF from the IFBB process as an additional feedstock. Hidaka et al. (2013) recommended the use of shredded grass from urban green cut in sewage sludge anaerobic fermentation. By this it was possible to increase methane yield of waste water sewage sludge digestion, but at the same time it was noted that there were problems in the handling of the material, as grass tends to float on top of the digester slurry and fibres might block pumps and stirrers. The PF of grass silage would be more suitable as an additional feedstock, as it yields higher substrate related methane yields and is readily digestible in a short time span (Bühle et al., 2012b) and at the same time avoids problems grass fibres would cause in

conventional anaerobic digestion plants. Furthermore, a shortened digestion time opens possibilities for a flexible "on-demand" biogas production, as described by Hahn et al. (2014) enabling electricity production at peak times when demand is high and prices for electricity are higher.

### 5.3.3 Energy yields

Substrate related total gross energy yields of the twelve semi-natural grassland habitats were consistently lower for the IFBB conversion system than for the direct combustion of hay, but gross energy yields of both technologies were more than double the gross energy yields of whole crop digestion (Fig. 11).

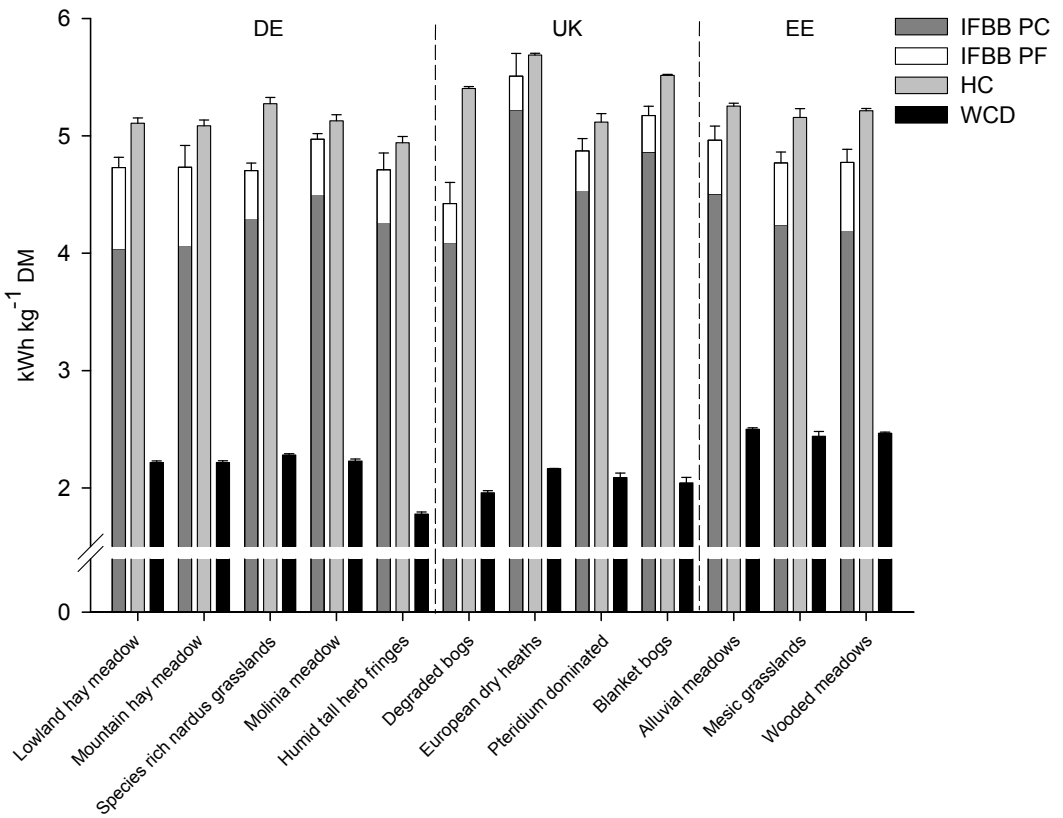


Fig. 11: Substrate related gross energy yield (kWh $kg^{-1}$ raw biomass DM) of different energy conversion technologies (integrated generation of biogas and solid fuel from biomass (IFBB), hay combustion (HC), whole crop digestion (WCD)) for twelve European semi-natural grassland habitat types, arithmetic means of two year data, error bars representing standard error of means.

Gross energy yields for the IFBB system consisted both of the energy from PF (i.e. electricity and heat) through its anaerobic digestion and subsequent burning of the biogas in a CHP and the energy (i.e. heat) from direct combustion of the PC. The substrate related gross yield for the two IFBB energy carriers produced varied between 0.29 and 0.69 kWh $kg^{-1}$ DM (raw biomass) for PF and between 4.03 and 5.22 kWh $kg^{-1}$ DM (raw biomass) for the PC. Mean values for HC ranged between 4.94 and 5.69 kWh $kg^{-1}$ DM (raw biomass) and for WCD between 1.78 and 2.50 kWh $kg^{-1}$ DM (raw biomass). It has to be taken into account that the gross energy yields have to be corrected for the energy inputs necessary for operating the conversion procedure. Applying data for conservation losses and conversion system specific losses, as reported by Bühle et al. (2012 a), allows the calculation of net energy yields. On average of 18 European semi-natural grassland areas Bühle et al. (2012 a) calculated that the net conversion efficiency of the IFBB system was between 44.7 and 52.9%, meaning that roundabout half of the gross energy in the biomass is converted into unable heat by the IFBB system. The net conversion efficiency for HC was little higher with 53.8 % (Bühle et al. 2012 a). Though the net energy output per kg parent material input would be higher for hay combustion in comparison to the IFBB system, but quality parameters of solid fuels are strongly improved by IFBB through increased energy contents and reduced contents of detrimental components (Hensgen et al., 2011, 2012). Thus, IFBB fuels allow an efficient use in furnaces with a lower risk of ash slagging and emissions compared to direct combustion.

Differences in substrate related gross energy output among the conversion system varied among the habitat types (i.e. significant H x C interaction, see Table 16). For the IFBB technique, lowest yields were calculated for "degraded bogs" showing low PC energy yield and very low PF energy yield. Low PC yields were also calculated for the two German "lowland hay meadow " and "mountain hay meadow" habitat types, but in these cases low PC energy yields were partially made up for by high PF energy yields. Highest yields could be realised for IFBB technique and HC for material from "European dry heaths",

whereas for the WCD the highest yields could be realised with material from "Alluvial meadows". Both IFBB and HC clearly outperformed the whole crop anaerobic digestion conversion technology, as could be expected for these fibre rich biomasses that only show low degradability in anaerobic digestion. However, it should be made clear, that with IFBB and HC a different energy carrier (i.e. solid fuel) is provided than with WCD, which is intended to produce electricity. Thus, any comparison between these conversion techniques should consider this inadequacy and the results should be interpreted with care and regard to the specific situation.

The area related gross output is a function of DM yield and substrate related output per kg DM (raw biomass), thus, it is also highly variable among the different habitat types and conversion techniques (Fig. 12).

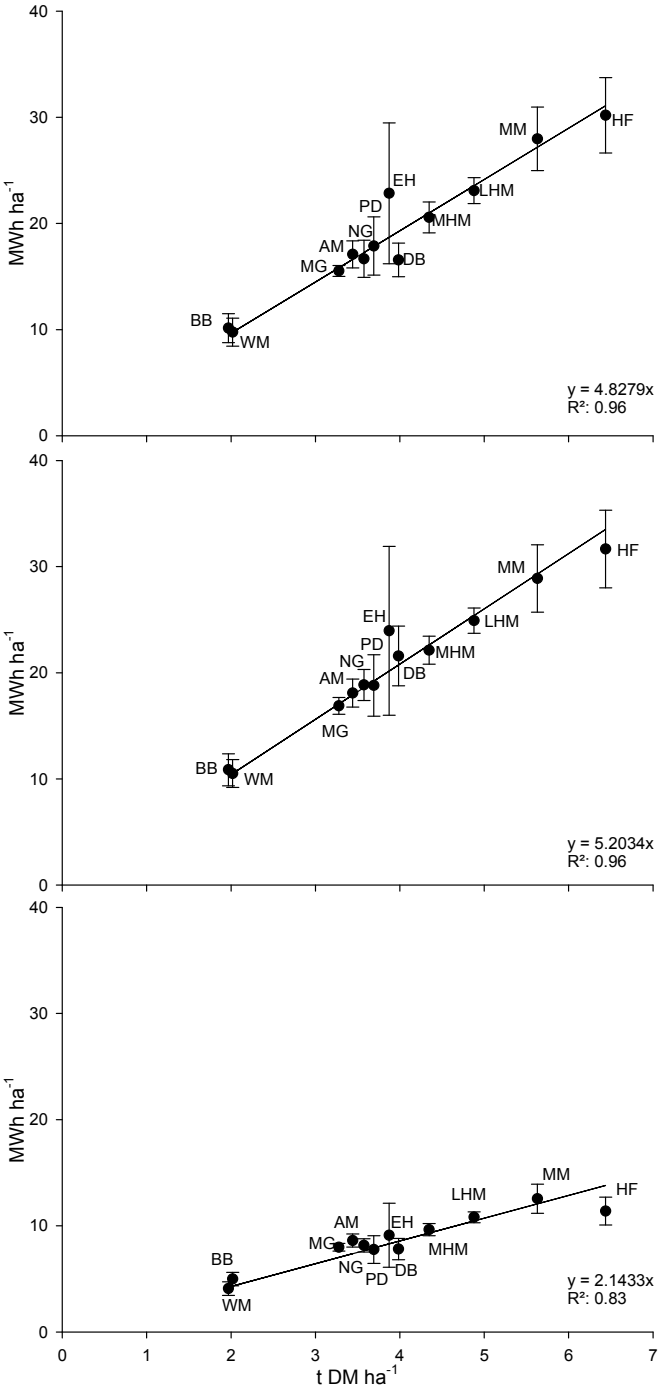


Fig. 12: Area related gross energy yield (MWh $ha^{-1}$) of different energy conversion technologies (integrated generation of biogas and solid fuel from biomass (IFBB), hay combustion (HC), whole crop digestion (WCD)) as a function of DM yield (t DM $ha^{-1}$) from twelve European semi-natural grassland habitat types (LHM = Lowland hay meadow, MHM = Mountain hay meadow, NG = Species rich nardus grassland, MM = Molinia meadow, HF= Humid tall herb fringes, DB = Degraded bogs, EH = European dry heaths, PD = Pteridium dominated, BB = Blanket bogs, AM = Alluvial meadows, MG = Mesic grasslands, WM = Wooded meadows) , arithmetic means of two year data, error bars representing standard error of means.

Gross energy yields varied between 0.56 and 3.33 MWh $ha^{-1}$ for energy from IFBB PF, 8.52 and 27.37 for IFBB PC and for total gross energy yield between 9.75 and 30.19 MWh $ha^{-1}$ for the IFBB conversion system. For HC the area related gross energy output was between 10.51 and 31.66 MWh $ha^{-1}$ and for WCD between 4.08 and 12.55 MWh $ha^{-1}$. Fig. 12 shows the dependency of gross energy yields on DM yields, which is especially true for IFBB and HC, whereas for WCD the dependency is less strong, as a higher DM content of the material might lead to a lower digestibility, indicating a possible trade off for WCD between quantity and quality of biomass, which is not the case for the two thermal conversion technologies. The area related gross energy yields are much higher in thermal conversion systems than in the biochemical conversion system of anaerobic fermentation. As the IFBB conversion system is nearly at the same level as HC across all habitat types, also if conversion losses are considered (Bühle et al., 2012 a), the IFBB technique would be preferable, as it delivers improved fuel characteristics (Hensgen et al., 2012).

The influence of chemical characteristics of the silage on energy outputs of the IFBB system via PF or PC was investigated through extended regression analysis but did not show any significant relationship. This is in strong contrast to previous results by Richter et al. (2011b) who showed that substrate specific output via PF, as well as total IFBB output increased with decreasing DM and increasing NDF concentration in the parent material. It is worth to mention that in the study by Richter et al. (2011b) differences in chemical composition of the silages were brought about by harvesting the biomass at various dates throughout an uninterrupted spring growth of a homogeneous grassland sward. Thus, no differences in botanical composition occurred which possibly could have masked the correlations. Contrary, in the present study botanical composition of the parent material and harvest date of the grassland was very heterogeneous, resulting in variable mass flows of organic compounds, which made it obviously difficult to predict the influence of a certain organic compound on any energy output parameter.

## 5.4 Conclusions

Based on the data derived from this study, the following conclusions can be drawn:

1. The IFBB technique effectively increased organic dry matter and fibre content in the PC and lowered CP and NFC concentration. Mass flows and concentrations in the PC were highly variable for the investigated habitat types.
2. Furthermore, it produced a highly digestible PF with methane yields between 312.1 and 405.0 $L_N$ $CH_4$ $kg^{-1}$ VS that were not significantly influenced by habitat type. Area related methane yields ranged from 55.2 to 330.4 $m_N^3$ $CH_4$ $ha^{-1}$ (COD) and from 60.8 to 279.5 $m_N^3$ $CH_4$ $ha^{-1}$ (VS) and were significantly influenced by habitat type.
3. Gross energy yields for the IFBB system (9.75 to 30.19 MWh $ha^{-1}$) were in the range of HC (10.51 to 31.66 MWh $ha^{-1}$) and outperformed WCD (4.08 to 12.55 MWh $ha^{-1}$).
4. The energy yields were affected by botanical and technical parameters (habitat type and conversion system), which interact in a complex manner. Further research is necessary to clarify the effect of chemical composition of the silage on energy output from the IFBB technique.

# 6 General discussion

## 6.1 Integrated generation of solid fuel and biogas from green cut material from landscape conservation and private households

The first experiment of this thesis (Chapter 3) investigated a new input material for energetic conversion through the IFBB system. The green cut material from landscape conservation and private households, grass silage and mixtures of both materials were subjected to the IFBB system and a complete analysis was conducted. As a result of this study it can be stated that the green cut proofed to be a suitable input material. The single results are discussed below.

### 6.1.1 Mass flows of DM and elements into the press fluid

The MFs of DM, Ash, K, Ca and N into the PF were significantly influenced by the type of input material, all except N showing lower MFs into the PF for the green cut material (S100) in comparison to the silage material (S0). For Mg, Cl, P and S there was no significant effect of type of input material on MFs. The MFs in this study in general (except K and Cl) were lower than in the study of Wachendorf et al. (2009) with grassland silage and comparable to the results by Kolár et al. (2010) for a mixed substrate containing haylage, maize silage and cattle slurry pre-treated with 60°C conditioning temperature. The MFs were considerably lower than those measured for maize silage by Bühle et al. (2011). The MFs are influenced by the chemical characteristics of the input material, which was shown by Richter et al. (2011a). The MFs of elements is negatively correlated with DM and NDF content in the silage, with the exception of K, where the NDF content does not show an effect. That is one explanation for the low MFs found for the green cut samples whilst they were prepared in late August and October and had higher DM concentrations and can be expected to also have higher NDF contents than the maize silage investigated by Bühle et al. (2011) and the grass silages investigated by Wachendorf et al. (2009) that were harvested in July and August. That

is especially the case for the fibre rich and wood like parts of the S100 fraction. But there are more factors influencing the MFs than just the chemical parameters as shown in Chapter 4. The promising results by Richter et al. (2011a) that NDF and DM content of the silage and temperature of the dewatering treatment are the main factors explaining the MFs of nutrients into the PF with high degrees of fit ($R^2$ above 0.88), could not be reproduced for a more heterogeneous range of input materials as the degrees of determination were considerably lower ($R^2$: 0.21 - 0.63).

No effect of temperature of hydrothermal conditioning was detected on MFs for green cut except for the crude ash fraction. That might be due to the little variation in temperature in the current study, as Wachendorf et al. (2009) found some significant differences between cold water treatment (5°C) and hot water treatments (60 / 80°C). Richter et al. (2011a) also showed a clear trend of increasing MFs with increasing temperature treatments by using a broader range of temperature settings. He also showed that the effect of increasing MFs with higher temperatures is especially pronounced with young material with low NDF and DM contents and is less pronounced for mature grassland silages. Kolár et al. (2010) again found higher MFs for the 60°C treatment than for the 15°C treatment. The MFs found by Kolár et al. (2010) were generally lower than for the S0 fraction but in the range of the S100 fraction. The authors ascribe their lower MFs compared to other IFBB studies to the properties of the used mixed material and also to the achieved axial force of the used screw-press that they assumed to have been lower even though the same perforation size of the conical part of the press (1.5 mm) and slope of the body (1:7.5) were used. However, Kolár et al. (2010) do not give any hint at the speed settings of their screw-press. King et al. (2012) also investigated different temperatures of hydrothermal conditioning (20, 40, 60°C) and found no significant effect of the pre-treatment temperatures on MFs, but for that experiment a hydraulic press instead of a screw-press was used, which minimises the comparability of results.

From the results in the current study it can be concluded that a 40°C treatment proofed to be equal to the 60° C treatment in terms of MFs for the green cut fractions and that there is no need to further increase the temperature of mashing beyond 40°C. The 40°C pre-treatment variant has the additional advantage of higher net energy yields through lower energy input.

### 6.1.2 Methane yield from anaerobic digestion of press fluids

There was no significant effect of temperature of hydrothermal conditioning or material type on substrate related methane yields to be found. That might be explained by the low gradient of temperatures and by the non significant differences in MFs of elements into the PF. For the material type, where some significant differences in MFs but not in methane yield could be found, it might be explained through high variations in batch tests and low number of samples (N=20). Variations were highest for the S100 fraction. Biogas batch digestion tests are sophisticated laboratory systems which are prone to a series of error sources. Although not statistically significant in this study, the substrate related methane yields did show a pattern of decline from the pure silage over the mixtures to the pure shrub fraction. That could be explained through the higher amount of lignin in the shrub fraction which than in turn leads to a higher amount of lignin in the PF (Richter et al., 2011b), although the biggest part of crude fibre goes into the PC (Wachendorf et al.2009), and thereby leads to a reduced methane yield, as lignin hampers the biogas production (Chen et al. 2008). However, also shown in the second experiment of this thesis (Chapter 5), there were no differences to be found between PF from silages of different origins and chemical composition. The range of measured methane yields and degrees of degradation was within the range measured by Richter et al. (2009) and in the second experiment of this thesis (Chapter 5), but especially for the shrub material at the lower boundaries. Bühle et al. (2012b) showed higher substrate related methane yields for maize silages. From that stock of data the conclusion can be drawn, that it is possible to achieve a PF with high

substrate related methane yields and degrees of degradation even from input material with high DM and crude fibre contents, but that there is the tendency of higher PF methane yields if the input material is rich in readily digestible non fibre carbohydrates instead of fibres. More detailed and planned research is needed on the exact influence of chemical characteristics of input material on the outcomes of PF digestion.

### 6.1.3 Quality of solid fuel

The results obtained for the quality of solid fuel from green cut pure and in mixture are remarkably similar to results derived by Richter et al. (2010) and to own results described in chapter 4 of this thesis for grassland silages. The values for all elements except Cl are in the same range as in those two experiments. The difference between shrub or grass silage within the study was only significant for Mg, Cl, N and S, showing lower concentrations of elements in the shrub fraction and also in the shrub fractions PC, let alone for Mg. At the example of Mg it can be clearly shown that there is not a simple linear connection between the concentration of an element in input materials and the concentration of that element in the specific PC, as there was considerably less Mg in the shrub fraction than in the grass fraction, but in the PC the concentration was nearly the same. That is pointing out that not only the total amount of an element is important for its prediction of behaviour in the IFBB system, but also the form in which it is embedded in the material and also other factors as well like the physical appearance of the silage and the concentration of other elements. It can be concluded from the experiment that the solid fuel quality of green cut used in the IFBB system is similar to that from grass silages, no matter if it is used pure or in mixture with grass silage. Again, there was no effect of temperature on the small range investigated here. Ash softening temperature did rise through the IFBB treatment to about 1250°C which is again exactly in the range of former experiments by Richter et al. (2010). AST was not dependent on shrub or grass content, but significantly influenced by the IFBB

treatment, with no differences for temperature of hydrothermal conditioning. However, the results calculated according to the formula of Hartmann (2009) have to be interpreted with care, as this formula has a relatively low prediction accuracy ($R^2$ = 0.60) with a standard error of mean of 88.2°C and was developed with data from 67 samples of different kind of materials (e.g. wood, straw, hay, Hartmann et al., 2000). High Mg contents, for instance, reduced the calculated AST (Hartmann, 2009), whereas Obernberger et al. (2006) reported that Mg increases the AST. Steenari et al. (2009) showed that the question of ash sintering temperature is more complex than the simple formula to its calculation imposes and parameters as the Ca/K ratio in the fuel as well as the Si content have to be regarded as well. Therefore the results of calculated AST have to be interpreted carefully and experiments should be conducted to measure the AST of IFBB PC from different input materials to check the calculated values. Such experiments have been conducted for semi-natural grassland silages from the same 18 areas described in Chapter 4 and 5 by Bühle et al. (2014) by applying different calculation indices of ash slagging temperatures from mineral concentrations and measuring of the same samples. The results showed decreasing contents of N, S, Cl, Ca, Mg, K and Na in the PC compared to the silage and increased Si, Fe and Al concentrations. That led to higher measured AST, which increased from 1000°C for the silage to 1050°C for the PC. The calculated AST indices showed only low relationship to the measured values with degrees of fit below 0.2 ($R^2$). For that reason, Bühle et al. (2014) developed multiple linear regression models from the dataset and identified two models with high coefficients of determination, including the concentrations of K, Ca, Si, Al and Na in the fuel and their interactions and quadratic terms. The models showed a negative correlation of the AST with K concentrations in the fuel, but a positive effect of Ca concentrations. The other effects were interdependent on the concentrations of Ca and K. From that data, it can be concluded, that the IFBB treatment leads to higher AST as it lowers the concentration of K in the PC to a higher

extent than the concentration of Ca, leading to an increased Ca/K ratio.

### 6.1.4 Energy balance and energy conversion efficiency

The overall energy balance for green cut used in the IFBB system was evaluated positively. The IFBB system yielded better results than the compared DC. Also the effect of using green cut consisting of shrub material was positive compared to the grass silage used. In all treatments, the net energy yield increased with increasing shrub content. This is mainly explained by the higher DM content of the shrub material. In comparison to other results, the net energy yields were a little lower, but still in the range of former experiments by Richter et al. (2011b) and Bühle et al. (2012). The temperatures of hydrothermal conditioning showed a distinct effect, as the 40°C treatment proofed to yield a higher net energy gain as the 60°C and also showed higher energy conversion efficiencies. Richter et al. (2011b) showed that there is an optimum of energy conversion efficiency at medium temperatures of hydrothermal conditioning for grassland silages between 40 and 60°C, Bühle et al. (2011) also found higher yields at 60°C temperature than at 12°C. From the data in this study and the mentioned studies by Bühle et al. (2011) and Richter et al. (2011b) as well as the study described in Chapter 5, it can be concluded, that the IFBB system is superior to WCD in terms of energy conversion efficiency of fibre rich material and comparable to DC with only small differences between DC and IFBB.

## 6.2 Integrated generation of solid fuel and biogas from extensive grassland of European origin in a mobile prototype

### 6.2.1 Biomass yield and elemental composition of the silage

The biomass yields observed in this study were low, as was expected for extensive semi-natural grasslands, but they were also highly variable. The DM yields varied considerably between the areas and especially between the different types of vegetation investigated.

There were fluctuations in DM yield from 0.64 to 10.97 t DM $ha^{-1}$ $yr^{-1}$ although all areas were classified as extensively used grasslands. The quality of the late harvested grasslands was expectedly low with high fibre concentrations and despite the late harvest date still high mineral concentrations compared to wood. Average values were well within the range of former experiments by Richter et al. (2011a) and Wachendorf et al. (2009). The results clearly indicated that untreated biomass from extensive grasslands under nature conservation management is not suitable for common combustion techniques, due to the large amount and unfavourable composition of fuel ash, as well as high levels of the elements responsible for emissions and corrosion. This confirms previous findings by Wachendorf et al. (2009) and Richter et al. (2011a) for German semi-natural grassland silages.

### 6.2.2 Mass flows of elements and mineral compounds into press fluid and influencing parameters

Although hydrothermal conditioning was only carried out at low temperature of 25°C, the average MF for DM was in the range of previous laboratory results carried out with different temperatures by Wachendorf et al. (2009) and Richter et al. (2011a). This leads to the conclusion that scaling-up to prototype size did not affect the effectiveness of the process, nor did the different mashing technique or the slightly lower hydrothermal conditioning temperature. The same is true for the MFs of the plant mineral compounds, which are in the range of previous results. MFs for P and Mg were intermediate (57-69%), whereas MFs for K and Cl were higher (>77%), and MFs for S, N and Ca were lower (31- 52%). For total ash the average MFs were between 38 and 49%.

The promising results by Richter et al. (2011a) that NDF and DM content of the silage and temperature of the dewatering treatment are the main factors explaining the MFs of nutrients into the PF with high degrees of fit ($R^2$ above 0.88), could not be reproduced in this experiment with a fixed temperature setting and a broader range of input materials as the degrees of determination were considerably

lower. Even introducing botanical parameters as explanatory variables to increase the degree of determination did not lead to high determination coefficients ($R^2$ ranging from 0.21 to 0.63). The lower prediction accuracies may not only be due to the fact that explanatory variables like temperature and DM content had been changed in favour of botanical parameters. In this study the variation and heterogeneity of samples was larger than in the experiment by Richter et al. (2011a). However, it could be shown that there is an influence of NDF content and botanical composition on MFs in the IFBB system, as they do explain some of the variation in MFs. Further experiments will have to investigate which parameters are most suitable for prediction of MFs. It might be promising to categorise the input materials for botanical composition or harvest date or chemical characteristics of the silage and investigate regression models adapted for certain categories of input materials.

### 6.2.3 Fuel quality of the press cake and influencing parameters

The fuel quality in the PC was within the expected results for all elements. In the case of DM slightly higher results could be achieved than by Richter et al. (2011b). That maybe due to slower speed setting of the screw-press (3 revs $min^{-1}$ vs. 6 revs $min^{-1}$) and thereby a prolonged stay of the biomass in the dewatering device, but maybe also due to higher DM concentrations of the silage input material. The ash concentration was significantly reduced, but still highly variable in the PC. The AST was slightly increased to about 1200 °C but as discussed for the green cut, these values are only calculated. The measured values shown by Bühle et al. (2014) increased by 50°C from 1000°C in the silage to 1050°C in the PC.

With the exception of P and S, the concentration of elements in the PC could be predicted with botanical parameters and the NDF content in the silage with an accuracy of $R^2$ = 0.56 - 0.79. The coefficients of determination were lower than for the dataset of Richter et al. (2011a), mainly due to the high prediction value of temperature treatment that was not of interest in the current study and therefore not considered

and the more homogenous dataset in the study by Richter et al. (2011a). Comparable to Richter et al. (2011a), the influence of NDF in the silage as a parameter reflecting the maturity of the sward proved to be important. The content of most elements (N, Mg and Ca) and total ash in the PC decreased with higher NDF contents. Concerning other elements, the effect of NDF was not independent of plant cover parameters of functional groups (grasses, herbs, legumes). The overall increase in fuel quality of PC with increasing senescence of the parent material has also been shown by Richter et al. (2011a) and could be verified in this study for a broader dataset. As mentioned before, the late harvest leads to better fuel quality in the biomass, for instance shown by Tahir et al. (2011) who demonstrated that a delayed harvest leads to improved fuel quality of biomass with lower P, K, S and Cl concentrations. Tonn et al. (2012) have shown in a leaching experiment, where biomass was treated with water but not pressed afterwards, that the concentration of some elements (Cl, K) after the treatment was dependent on the concentrations before the treatment. The effect of botanical parameters was less pronounced, but still there was some effect to be found. Grasses had an overall positive effect, as higher grass cover in the sample areas decreased the concentration of ash and Mg in the PC. The cover of forbs (Mg) and legumes (Ash, Mg, N) had a negative influence, as their increase increased also the concentrations of those elements in the PC. This might be explained by higher concentrations of these elements in the silage if it is herbage or legume rich and lower concentrations if it is grass rich (Ruano-Ramos et al., 1999, Garcia-Ciudad et al., 1997). Overall, the botanical parameters proved to be helpful in developing models for the prediction of solid fuel properties, as, contrary to Richter et al. (2011a), NDF content alone failed to predict mineral element concentration in the PC in the present study. While the models of Richter et al. (2011a) are based on one experimental sward, the present study covers a larger variation in botanical composition of swards. Hence, the importance of botanical parameters in most models is not surprising. Confirming results of previous studies by Richter et al. (2011a, b), NDF

concentration in the silage was the only chemical constituent with predictive power in all models for element concentration in PC. More research is necessary to understand the mechanisms in the partition of elements into PF and PC in the screw-press to better predict the outcome of the IFBB system in terms of fuel quality and to adjust the system settings to the properties of input materials accordingly to produce a good fuel quality.

### 6.2.4 Organic compounds of silage and press cake

Chapter 5 showed, in accordance with Richter et al. (2011b) and Prochnow et al. (2009a) that late cut semi-natural grassland silages were high in fibre content and low in content of digestible components, which is why the material for economical reasons is not suitable for animal feeding or bio-energy generation from biogas. It could also be shown, that the IFBB PCs have higher fibre contents and lower concentrations of easier soluble organic compounds like NFC and CP than the silages and are therefore suitable for combustion, whereas the PF is suitable for digestion. Although these results are well in line with former results by Wachendorf et al. (2009) and Richter et al. (2011b) a problem of methodology was detected. Laboratory results of the Weende constituents of the silages and the PC showed MFs of fibre fractions (NDF, ADF, ADL) of more than 100% into the PC. The standard laboratory method used to determine the fibre constituents seems to analyse other plant compounds in the PC as fibres. It has been reported by Manas et al. (1995) for dietary fibre analysis of fruits, legumes and cereals that proteins formed acid resistant complex products during the employment of the laboratory method, which were then analysed as part of the ADF fraction. If that also were the case for the IFBB treatment, where high axial forces and temperatures put force on the plant material, the fibre fractions would be overestimated, whereas the CP fraction would be underestimated. It also has to be discussed that the PF in the experiments had very low contents of DM of about 0.5-2.0 %, as it was produced with fresh water mashing of the silage. For the application of the IFBB system in

common practice biogas plants, the IFBB PF should have higher DM concentrations to gain higher net energy yields and reduce the amount of water to be transported with the digestate after biogas production. This could be achieved through a recycling technique of the PF, using parts of it for hydrothermal conditioning instead of fresh water. This technique has to be developed and investigated yet, however it should focus on the aims of increasing the PF DM concentrations, decreasing the use of fresh water and by the same time still provide acceptable fuel quality. This is a part of the IFBB system, where further research is necessary.

### 6.2.5 Methane yields of press fluids

Although the investigated grassland habitats varied in botanical composition, harvest time, chemical composition of the silage and the mass flows of organic compounds into the PC, there was no significant effect of habitat type on the substrate related methane yield of the PF. The substrate related methane yields of the PF (312-405 $L_N$ $CH_4$ $kg^{-1}$ VS) were in the magnitude of results by Richter et al. (2009). Compared to methane yields from grassland silages, reviewed by Prochnow et al. (2009a), which ranged from 80 (landscape management) to 641 (cut mid may, meadow fescue) $L_N$ $CH_4$ $kg^{-1}$ VS the PF showed higher yields than the comparable late cut extensive silages and showed yields on the same level than highly intensive, early cut, fertilized grassland silages.

In contrast to Richter et al. (2011b) regression analysis did not show any relationship between substrate related methane yield and any organic compound concentration of the silage material or botanical parameters of the vegetation, i.e. dry matter contribution of functional groups (legumes, grasses and herbs). This lack of relationship may be partly due to the highly variable mass flows of organic compounds. However, although the substrate specific methane yields were not connected to these parameters, the area specific methane yields were, as they were dependent on the highly variable DM yield.

### 6.2.6 Energy yields

In terms of energy yields from semi-natural grasslands, the IFBB system proofed once again its superiority against WCD from the same material, showing that it is by far more efficient to use the semi-natural grassland biomass in a combustion system than in an anaerobic digestion system. This has also been shown by Bühle et al. (2012a). The direct combustion of hay would also show good results in terms of energy yields (Bühle et al. 2012a), but as shown in this study, the fuel produced with the IFBB process has superior quality. The use of hay in combustion would surely lead to problems in combustion with ash slagging and emissions (Obernberger et al., 2006, Van Loo and Koppejan, 2008). Some studies especially from northern Europe showed that a delayed harvest of grass in winter time also led to a reasonable decrease of minerals and an increase of ash melting temperature in the plant material (Burvall, 1997, Hadders and Olsson, 1997, Landström et al., 1996, Christian et al., 2006) but also showing that the net DM yield is significantly reduced by that late cut as well (Christian et al., 2006) and that in some years no harvest at all was possible in a delayed harvest system due to bad weather conditions (Tahir et al., 2011). Furthermore, to conserve the high biodiversity found in semi-natural European grasslands, timing of harvest is a crucial point and the late winter cut might not be suitable to conserve biodiversity. The IFBB system on the other hand combines solid fuel of good quality and the flexibility of timing the harvest at the optimum for nature conservation with slightly higher (Chapter 3) or slightly lower (Chapter 5) energy yields as direct combustion. The reason that the IFBB system can also yield higher net energy than direct burning, even if there is more energy input needed and part of the material goes into the less efficient anaerobic digestion, is found in two factors. One is the DM content of the material. The drying by a screw-press is more energy efficient than drying with a belt dryer which is assumed for DC or burning of the wet material, which would lower the heating value of the material. The second factor is losses in the field for hay conservation in case of direct combustion or for preparing silage. If

losses for silage are low and high for hay preparation, IFBB becomes more favourable. These losses have been assessed for example by Elawad et al. (2002) and ranged between 18.5 and 48.7 % and a mean value at 32.9% for preparation of hay and between 7.2 and 44.1% and a mean value of 21.7% for preparation of silage, being dependent on a lot of factors, such as stage of harvest, harvest number, period of harvest, tedding times, dry matter harvested, temperature, rainfall, humidity and wind velocity. Therefore these losses are not easy to assume for an energy balance and their influence on the outcome of the balance is marked.

# 7 Conclusions

Based on the assessment of urban green cut and European semi-natural grassland biomasses the following conclusions can be drawn:

(i) The methane yields of IFBB press fluids were between 254 (shrub material, 40°C) and 359 (grass silage, 40°C) $L_N$ $CH_4$ $kg^{-1}$ VS and degrees of degradation ranged between 59% (shrub material, 40°C) and 81% (grass silage, 40°C). There was no statistically significant effect of temperature of hydrothermal conditioning or input material type to be found. The fuel quality of the urban green cut was considerably improved by the IFBB system; the PC showed significantly reduced contents of K, Cl, Mg, S and P, no significant reductions occurred for Ca and N. An increased AST was calculated and a reduced risk of ash slagging and harmful emissions or corrosion could be assumed for the PC from urban green cut.

(ii) Semi-natural grassland silages proofed to be a suitable input material for the IFBB system, although yield and chemical composition of semi-natural grasslands were highly variable on a Europe-wide scale. The IFBB treatment of hydrothermal conditioning and subsequent dewatering in a large-scale prototype plant produced comparable results to those of small-scale applications in previous studies and proofed to be successful in significantly reducing the concentration of elements (N, S, K, Ca, Mg, Cl, P) including those detrimental to thermal use. Correlations between botanical parameters (cover estimates of grasses, forbs and legumes) and NDF as a chemical parameter NDF of the silage and mass flows of plant compounds ($R^2$: 0.21-0.63) as well as the fuel quality of the press cake ($R^2$: 0.34-0.79) could be shown. Higher NDF concentrations and higher grass covers led to better fuel properties, while higher legume covers decreased the fuel quality in terms of mineral concentrations.

(iii) The IFBB treatment effectively increased organic dry matter and fibre content in the PC and lowered CP and NFC

concentration. Mass flows and concentrations in the PC were highly variable for the twelve investigated semi-natural grassland habitat types. Furthermore, the IFBB treatment produced a highly digestible PF from grassland silage with methane yields between 312 and 405 $L_N$ $CH_4$ $kg^{-1}$ VS that were not significantly influenced by habitat type. Area related methane yields ranged from 55 to 330 $m_N^3$ $CH_4$ $ha^{-1}$ (COD) and from 60 to 279 $m_N^3$ $CH_4$ $ha^{-1}$ (VS) and were significantly influenced by habitat type. Regression analysis did not show any relationship between substrate related methane yield and any organic compound concentration of the silage material or botanical parameter of the vegetation, i.e. cover estimates of functional groups (legumes, grasses and forbs). This lack of relationship may be due to the highly variable mass flows of organic compounds. For the implementation of the IFBB technology in a commercial energy conversion plant the result of rather uniform methane yields from very different parent materials can be assessed positively, as it underlines the ability of IFBB to convert heterogeneous biomasses from a wide range of vegetation and harvest dates into renewable energy.

(iv) Considering urban wastes from green cut, the energy balance of the IFBB process was superior to direct combustion of herbaceous material. For shrub material the energy balances converged. Hydrothermal conditioning at a temperature of 40°C showed higher energy efficiencies compared to 60°C. As only two sampling dates could be investigated, further research is needed to investigate how the varying composition and quality of green cut material through the year affects the energy recovery by means of changes in mass flows and biogas yield. Considering the energy yield of European semi-natural grassland silages, gross energy yields for the IFBB system (9.75 to 30.19 MWh $ha^{-1}$) were in the range of HC (10.51 and 31.66 MWh $ha^{-1}$) and outperformed WCD (4.08 to 12.55 MWh $ha^{-1}$). The gross energy yields would have to be corrected for harvest

and process technology losses. The energy yields were affected by botanical and technical parameters i.e. habitat type and conversion system, which interact in a complex manner. Further research is necessary to clarify the effect of chemical composition and other parameters of the silage on energy output from the IFBB technique.

# 8 Summary

This thesis describes the use of two different input materials along the process chain of the IFBB process.

The first part of this thesis (Chapter 3) investigated the use of green cut material that is nowadays most often used for compost production and is build from a herbaceous fraction consisting to a large part of lawn cut, leaves, straw, hay, fine hedge cut, and a shrub fraction consisting of woody parts, branches, leaves, roots and the coarse part of hedge cut. The use of these fractions and their mixtures were investigated in the IFBB process and compared to the use in direct combustion. The samples were taken in August and October, subjected to a hydrothermal conditioning treatment at two temperatures and dewatered by a screw-press. Mass flows of elements unfavourable for combustion were investigated as well as the concentrations of these elements in the press cake. Ash softening temperature and heating value of the press cake were calculated, for the press fluid anaerobic digestion tests were done to assess their potential as a biogas substrate. An energy balance was carried out for the IFFB system in comparison to direct combustion. Considering the results, the methane yields of press fluids were between 254 (shrub material, 40°C) and 359 (grass silage, 40°C) $L_N$ $CH_4$ $kg^{-1}$ VS and degrees of degradation ranged between 59% (shrub material, 40°C) and 81% (grass silage, 40°C). There was no statistically significant effect of temperature during hydrothermal conditioning or type of input material to be found. Through high mass flows of minerals detrimental to combustion into the PF, the fuel quality of the urban green cut was considerably improved by the IFBB system; the PC showed significantly reduced contents of K, Cl, Mg, S and P, no significant reductions occurred for Ca and N. The calculated ash softening temperature was increased. The IFBB system at 40° C temperature of hydrothermal conditioning showed a better energy balance than the direct combustion.

The second part of the study investigated the use of grassland silage from 18 European semi-natural grassland sites, 6 placed each in Germany, Wales and Estonia for the IFBB energy conversion system in comparison to whole crop digestion and hay combustion. Chapter 4 showed the results for the mass flows of mineral elements within the IFBB system and also for fuel quality and the results of multiple linear regression models for the influence of botanical and chemical parameters on solid fuel quality. Chapter 5 showed the mass flows of organic compounds and their concentration in the IFBB press cake, as well as the results of anaerobic digestion tests with the press fluids and finally a calculation of gross energy yields achievable with the IFBB system in comparison to whole crop digestion and hay combustion. The results showed that semi-natural grassland silage is a suitable input material to be used in an IFBB plant. The concentrations of investigated elements (N, S, K, Ca, Mg, Cl and P) were significantly reduced. Correlations between botanical (cover estimates of grasses, forbs and legumes) and chemical parameters (NDF) of the silage and mass flows of plant compounds ($R^2$: 0.21-0.63) as well as the fuel quality of the press cake ($R^2$: 0.34-0.79) could be shown. Higher NDF concentrations and higher grass covers led to better fuel properties, while higher legume covers decreased fuel quality. The IFBB treatment effectively increased organic dry matter and fibre content and lowered CP and NFC concentration in the press cake and produced a highly digestible press fluid with methane yields between 312 and 405 $L_N$ $CH_4$ $kg^{-1}$ VS that were not significantly influenced by different habitat types. Area related methane yields ranged from 55 to 330 $m_N^3$ $CH_4$ $ha^{-1}$ and were significantly influenced by habitat type. Regression analysis did not show any relationship between substrate related methane yield and any organic compound concentration of the silage or botanical parameter of the vegetation, i.e. cover estimates of functional groups (legumes, grasses and forbs). Considering the energy yield of European semi-natural grassland silages, gross energy yields for the IFBB were in the range of hay combustion and outperformed whole crop digestion. The energy yields were affected by botanical and

technical parameters i.e. habitat type and conversion system. In conclusion it can be stated that the IFBB system offers the opportunity to use heterogeneous, fibrous and mineral rich biomasses as a source for renewable energy that are nowadays not used for energy production.

# 9 Kurzfassung

## 9.1 Einleitung

Um den negativen Effekten des Klimawandels entgegenzusteuern, verstärkte die Europäische Union (EU) ihre Anstrengungen auf dem Feld der erneuerbaren Energien. Dies drückte sich in der Festsetzung EU-weiter und nationaler Ziele für den Anteil von erneuerbaren Energien am Brutto-Endenergieverbrauch aus, festgeschrieben in der EU-Direktive 2009/28/EC (Anonymous, 2009). Demnach ist der EU-weite Zielanteil 20%; für Deutschland ist ein Ziel von 18% bis 2020 festgeschrieben, von einem Startpunkt in 2005 von 5.8%. Unter anderem aus diesem Grund wurde Energie aus Biomasse in den letzten Jahren politisch stark unterstützt, beispielsweise durch Erlass des sogenannten EEG (Anonymous, 2009b), was zu einem starken Wachstum unter anderem in der Anzahl der Biogasanlagen geführt hat, welche in Deutschland von 1750 auf 7515 Anlagen von 2003 bis 2012 gestiegen ist (FNR, 2013).

Energie aus Biomasse wird in einem zukünftigen Energiemix eine große Rolle spielen (Beurskens und Hekkenberg, 2011), da sie auf einfache Art und Weise gespeichert werden kann, transportabel ist und zur Erzeugung unterschiedlicher Endenergieträger genutzt werden kann. Aber der rapide Zuwachs der erneuerbaren Energie aus Biomasse wurde auch kritisiert. Der Hauptkritikpunkt setzt an der geringen Diversität der für die Energieerzeugung genutzten Feldfrüchte an, da zumeist intensiv genutzte Feldfrüchte wie Mais oder Raps angebaut werden (FNR, 2013). Dies führt zu einer Reihe negativer Effekte, wie Bodenerosion, Nährstoffauswaschung, Biodiversitätsverlust (Herrmann, 2013, Fletcher at al., 2011, Dauber et al., 2010, Love et al., 2011). Die umfassende Bilanzierung der Umwelteffekte führte zu dem Ergebnis, dass beispielsweise Biokraftstoffe von intensiven Agrarsystemen eine negative Umweltbilanz haben und teilweise schlechter abschnitten als die fossilen Referenzsysteme (Zah et al., 2007). Unter Umständen ist selbst die Treibhausgasbilanz der erneuerbaren Energien aus Agrarsystemen

negativ, insbesondere wenn $N_2O$ Emissionen und direkte und indirekte Landnutzungsänderungen mit betrachtet werden (Crutzen et al., 2008, Tonini et al., 2012). Zusätzliche Bedenken gegen die Nutzung von Biomasse zur Energieerzeugung speisen sich aus der Erkenntnis, dass es in Zeiten der zunehmenden Weltbevölkerung und limitierter Landressourcen einen Konflikt zwischen Nahrungsmittel- und Energieproduktion gibt. Verschiedene Wissenschaftler haben diesen Konflikt beschrieben, der sowohl zwischen Nahrungs- und Energieerzeugung als auch anderen Nutzungsanliegen, wie dem Schutz der Biodiversität besteht (Johansson und Azar, 2007, Hogwijk et al., 2003, Bergsma et al., 2007).

In Anbetracht dieser negativen Effekte der Erzeugung erneuerbarer Energien aus intensiv genutzten Agrarsystemen wurde wiederholt vorgeschlagen, zur Bioenergieerzeugung hauptsächlich Reststoffe zu verwenden, die bisher nicht energetisch genutzt werden und auch nicht in Konkurrenz zur Nahrungsmittelproduktion stehen (Zah et al., 2007, Tilman et al., 2009). Dies wären zum Beispiel Materialien aus der Landschaftspflege, städtischer Grünschnitt oder Lebensmittelreste. Diese Abfallstoffe können sowohl in urbanen Regionen gefunden werden, wo erhebliche Mengen an Grünschnitt anfallen, die heutzutage größtenteils zur Kompostherstellung genutzt werden (Kern et al., 2010, Anonymous, 2008). Sie können aber auch aus ländlichen Regionen stammen, wo erhebliche Mengen extensiver Grünlandbiomasse anfallen, die aus ökonomischen Gründen und aufgrund der sinkenden Anzahl an Rauhfutterverwertern ungenutzt sind oder in naher Zukunft sein werden (Rösch et al., 2009, Isselstein et al., 2005). Der Erhalt der Biodiversität dieser Grünlandflächen setzt eine extensive Bewirtschaftung, d.h. einen späten Schnitt, geringe oder keine Düngung, voraus (Ostermann, 1998, Halada et al., 2011). Beide Ressourcen, sowohl urbaner Grünschnitt als auch Silage aus extensiver Nutzung haben gemein, dass ihre Nutzung in üblichen Energieverwertungssystemen wie Verbrennung und Vergärung schwierig ist. Hohe Konzentrationen insbesondere an Lignin verhindern die Nutzung dieser Materialien in Biogasanlagen, da

Lignin die Biogasbildung stört (Chen et al., 2009) und zu langen Verweilzeiten und geringen Methanerträgen führt (Shiralipour und Smith, 1984, Richter et al., 2009). Auf der anderen Seite erschweren die hohen Konzentrationen an schädlichen Inhaltstoffen wie K, Cl, S und Mg sowie die Heterogenität des Materials die Nutzung dieser Biomassen in der Verbrennung (Hartmann, 2009, Obernberger et al., 2006, Prochnow et al., 2009b, Jenkins et al., 1998). Um diese Schwierigkeiten zu beheben und die Effizienz der Umwandlung von Biomasse in erneuerbare Energie zu erhöhen, hat die Universität Kassel ein innovatives Verfahren entwickelt, die „Integrierte Erzeugung von Festbrennstoff und Biogas aus Biomasse“ (IFBB), beschrieben von Wachendorf et al. (2009) und Graß et al. (2009). Die Biomasse wird zunächst einer Vorbehandlung unterzogen, die aus einer Maischung und anschließenden Separation von Fest- und Flüssigphase mittels Schneckenpresse besteht. Dadurch erhält man einerseits den faserreichen Presskuchen und andererseits den mineralstoffreichen Presssaft. Nach Trocknung und Kompaktierung steht der Presskuchen als Festbrennstoff mit verbesserter Qualität zur Verfügung. Der angereicherte Presssaft kann als Substrat für die Biogaserzeugung genutzt werden. Das dabei entstehende Biogas wird verstromt und Abwärme sowie Strom werden systemintern verwendet. Auch wenn das IFBB Verfahren innovativ und noch nicht vollständig am Markt implementiert ist, gibt es doch schon einen umfangreichen Kenntnisstand, der sich in zahlreichen Publikationen zum Thema ausdrückt. Unterschiedliche Substrate wurden untersucht, inklusive Grünlandsilagen von extensiven Hochmähwiesen in Süddeutschland (Wachendorf et al., 2009, Richter et al., 2009, Richter et al., 2010), Grünlandsilagen von einer Flachlandmähwiese an acht aufeinanderfolgenden Schnittterminen (Richter et al., 2011 a, b) und extensiven Grünlandsilagen von 18 Flächen aus Wales, Deutschland und Estland (Bühle et al., 2012a, Blumenstein et al., 2012). Auch Ackerfrüchte wurden untersucht (Bühle et al., 2011, 2012b). Unterschiedliche Schritte des IFBB Verfahrens wurden ebenfalls betrachtet. Wachendorf et al. (2009) untersuchte die Massenflüsse von

mineralischen und organischen Bestandteilen der Biomasse in Presskuchen und Presssaft und die Festbrennstoffqualität des Presskuchens. Diese Parameter wurden auch von Richter et al. (2010, 2011a), untersucht und in einem weiteren Manuskript untersuchte Richter et al. (2011b) die Massenflüsse der organischen Elemente der Biomasse und die Energiekonversionseffizienz des gesamten Systems. Drei Experimente untersuchten die Vergärung des Presssaftes im Vergleich zur Ganzpflanzenvergärung (Richter et al., 2009, 2011b, Bühle et al., 2012b). Die ökonomischen Aspekte des IFBB Verfahrens wurden von Blumenstein et al. (2012) untersucht. Die umfassende Untersuchung des IFBB Verfahrens fand mittels LCA statt und wurde von Bühle et al. (2011) für Mais und Winterroggen und von Bühle et al. (2012a) für Grünlandsilagen berechnet. Spezifische Untersuchungen fanden statt zu den Effekten der Bestandesalterung und der chemischen Zusammensetzung der Silage auf die Massenflüsse und Festbrennstoffqualitäten (Richter et al., 2011a) und auf die organischen Bestandteile und die Konversionseffizienz (Richter et al., 2011b). Die Fragestellung der optimalen Temperatur der Maischung wurde besonders ausführlich untersucht (Wachendorf et al., 2009, Richter et al., 2009, 2010, 2011a, b).

Die Ergebnisse lassen sich wie folgt zusammenfassen:

- Das IFBB Verfahren ist dazu geeignet die Konzentrationen von Elementen, die in der Verbrennung stören, im Brennstoff zu reduzieren. Insbesondere K, Cl, Mg und S werden in den Presssaft ausgewaschen und sind daher in reduzierten Konzentrationen im Brennstoff zu finden (Wachendorf et al., 2009, Richter et al., 2010, 2011a). Die Reduktionen von N und Ca fielen geringer aus und waren teils nicht statistisch nachweisbar (Richter et al., 2010).
- Die Brennstoffqualität wurde nicht nur durch geringere Mineralstoffgehalte im Presskuchen verbessert, sondern auch durch einen erhöhten Faseranteil. Der Presskuchen wies sowohl eine höhere Ascheerweichungstemperatur als auch einen

erhöhten Brennwert auf (Wachendorf et al., 2009, Richter et al., 2010.).

- Das IFBB Verfahren kann eine ökonomisch sinnvolle Alternative für das Management extensiver Grünlandflächen darstellen (Blumenstein et al., 2012). Die besten Ergebnisse wurden erzielt, wenn das IFBB Verfahren gekoppelt mit einem Wärmeproduzenten berechnet wurde.
- Der IFBB Presssaft ist ein hochverdauliches Substrat für die anaerobe Vergärung. Er zeigt hohe substratspezifische Methanerträge und kurze Verweilzeiten (Richter et al., 2009, Bühle et al., 2012b).
- Das IFBB Verfahren ist in Bezug auf Energiebilanz und Konversionseffizienz dem Verfahren der Ganzpflanzenvergärung deutlich überlegen und liegt im Bereich der direkten Verbrennung (Richter et al., 2011b, Bühle et al., 2011, 2012a). Die besten Ergebnisse konnten auch hier erzielt werden, wenn das IFBB Verfahren an einen Wärmeproduzenten angekoppelt wird, bspw. an eine landwirtschaftliche Biogasanlage oder an eine anaerobe Klärschlammvergärung (Bühle et al., 2012a).
- In Bezug auf die möglichen Treibhausgaseinsparungen schneidet das IFBB Verfahren besser ab als die Vergleichssysteme, wenn das Verfahren in der gekoppelten Version realisiert wird und als Substrat Silage von extensiven Grünlandbeständen verwendet wird (Bühle et al., 2012a). Wenn dagegen Mais- oder Winterrogensilage eingesetzt wird, schneidet die Ganzpflanzenvergärung besser ab, insofern mehr als 20% der Abwärme genutzt werden (Bühle et al., 2011).
- In Bezug auf die Versauerungs- und Eutrophierungsbilanz schneidet das IFBB Verfahren besser ab als die Ganzpflanzenvergärung (Bühle et al., 2012a).
- Der Effekt der Temperatur der Maischung wurde in einigen Studien untersucht (Wachendorf et al., 2009, Richter et al., 2009,

2010, 2011a, b). Niedrige Maischtemperaturen (<30°C) führten zu geringeren Massenflüssen in den Presssaft und daher zu schlechteren Brennstoffqualitäten. Hohe Temperaturen (>60°C) zeigten höhere Massenflüsse und bessere Brennstoffqualitäten, aber signifikant schlechtere Konversionseffizienzen und Energiebilanzen. Mittlere Temperaturen im Bereich zwischen 30 und 60°C sind die beste Wahl um sowohl gute Brennstoffqualitäten als auch gute Energiebilanzen zu erzielen.

- Richter et al. (2011a, b) zeigten, dass es möglich ist, die Massenflüsse mineralischer und organischer Inhaltsstoffe und auch die Konversionseffizienz des gesamten Verfahrens anhand multipler linearer Regressionsmodelle mit den Inputparametern Temperatur der Maische, Trockenmasse und Fasergehalt (NDF) der Silage mit hoher Genauigkeit vorherzusagen.

Diese Doktorarbeit zielt darauf ab, bestehende Wissenslücken über das IFBB Verfahren zu schließen. Zu diesem Zweck wurden zwei Experimente durchgeführt, die in drei wissenschaftlichen Artikeln verarbeitet wurden. Im ersten Experiment (Kapitel 3) wurde ein neues Inputmaterial für das IFBB Verfahren untersucht, der urbane Grünschnitt. Untersucht wurde die Zusammensetzung des Grünschnitts und seine Verwertung im IFBB Verfahren inklusive aller Prozessschritte und einer Bilanzierung des Verfahrens für Grünschnitt. Das zweite Experiment (Kapitel 4 und 5) konzentrierte sich auf Grassilagen von Extensivgrünland in Europa. Die untersuchten Parameter waren dieselben wie in den bereits erwähnten Studien. Allerdings wurde in diesem Experiment die Datengrundlage erweitert, indem Material von 18 Grünlandflächen in Europa einbezogen wurde. Außerdem wurde ein mobiler Prototyp des IFBB Verfahrens zur Probenverarbeitung verwendet. Die von Richter et al. (2011 a, b) verwendeten Modelle wurden einer Validierung unterzogen anhand einer breiteren Auswahl an Biomasse und Veränderungen der Modelle wurden untersucht, insbesondere die Einbeziehung botanischer Parameter wie der Deckungsgrade botanischer funktionaler Gruppen.

## 9.2 Forschungsziele

Das Ziel dieser Studie war, die Kenntnisgrundlage über das IFBB Verfahren zu erweitern und seine technische Durchführbarkeit für unterschiedliche Biomassen zu demonstrieren, die aktuell kaum zur Energiegewinnung genutzt werden. Zu diesem Zweck wurden sowohl Silagen von europäischem Naturschutzgrünland als auch von urbanem Grünschnitt untersucht. Im Zentrum der Studie stand die Untersuchung der gesamten IFBB Prozesskette für beide Ausgangssubstrate, d.h. die Untersuchung der chemischen Zusammensetzung von Silage und Presskuchen, die Berechnung der Massenflüsse für Mineral- und Nährstoffe in Presssaft und Presskuchen, die anaerobe Vergärung der Presssäfte, die Berechnung der Ascheerweichungstemperatur und des Brennwertes für den Presskuchen, die Berechnung von Energiebilanzen und multiplen linearen Regressionsmodellen, um den Zusammenhang zwischen botanischen und chemischen Biomasseparametern und der Brennstoffqualität und dem Energieertrag besser zu verstehen.

Der urbane Grünschnitt wurde zu zwei Zeitpunkten gesammelt und mit zwei Temperaturniveaus behandelt. Zusätzlich zu reinem Strauchschnitt und reiner Grasssilage wurde eine 3-stufige Mischungsreihe untersucht. Chemische Analysen sowohl der Silage als auch des Presskuchens wurden durchgeführt um die Eignung als Brennstoff bewerten zu können. Massenflüsse in den Presssaft wurden berechnet, um die Effizienz des IFBB Systems für dieses Ausgangsmaterial nachzuweisen. Anaerobe Vergärungsversuche wurden durchgeführt um den Methanertrag aus Grünschnittmaterial-Presssaft zu untersuchen. Anschließend wurde eine Energiebilanzierung durchgeführt um das IFBB Verfahren mit einer anderen energetischen Verwertungsmöglichkeit, der direkten Verbrennung, vergleichen zu können.

Das Untersuchungsprogramm für die Grünlandsilagen umfasste dieselben Prozessschritte. Silagen von 18 europäischen Flächen in drei Ländern wurden jeweils in dreifacher Wiederholung untersucht. Die

Untersuchungen fanden in zwei aufeinanderfolgenden Jahren statt. Die Proben wurden im Prototyp einer mobilen IFBB Anlage verarbeitet. Im Gegensatz zu den Untersuchungen mit Grünschnitt wurde nur eine Temperaturstufe untersucht. Ebenso wie für den Grünschnitt wurden sowohl die chemischen Untersuchungen als auch die Massenflussberechnungen und die Gärversuche durchgeführt. Weiterführend wurden die Ascheerweichungstemperatur und der Brennwert berechnet. Basierend auf diesen Berechnungen wurde eine Brutto-Energiebilanz erstellt, die das IFBB Verfahren für das europäische Grünland vergleichend anderen energetischen Verwertungsmöglichkeiten, namentlich der Heuverbrennung und der Ganzpflanzenvergärung gegenüberstellt. Mithilfe von multiplen linearen Regressionsmodellen wurde ein vertieftes Verständnis der komplexen Interaktionen zwischen botanischen und chemischen Parametern der Ausgangssilage und der nach dem IFBB Verfahren resultierenden Brennstoffqualitäten ermöglicht.

Die Untersuchungsziele der Studien lassen sich wie folgt zusammenfassen:

(i) Die Bestimmung der Eignung des IFBB Systems für eine neue Ressource, Grünschnittmaterial, insbesondere fokussierend auf Methanertragspotential der Presssäfte und Brennstoffqualität der Presskuchen im Vergleich zu Ergebnissen früherer Untersuchungen mit Grasssilage.

(ii) Die Untersuchung des Zusammenhangs zwischen botanischen und chemischen Charakteristika der Grünlandsilage und dem Massenfluss und der Brennstoffqualität im IFBB System auf Basis des Prototyps.

(iii) Die Untersuchung des Zusammenhangs zwischen den chemischen Charakteristika der Grünland-Silage und dem Massenfluss von organischen Stoffen innerhalb des IFBB Systems und der Effekt auf die anaerobe Vergärung des Presssaftes.

(iv) Die Evaluierung des IFBB Verfahrens im Hinblick auf die möglichen Energieerträge insbesondere im Vergleich zu alternativen Verfahren wie der Direktverbrennung von Grünschnitt oder der Heuverbrennung oder Ganzpflanzen-vergärung von Grünlandsilage.

## 9.3 Schlussfolgerungen

Basierend auf den Studienergebnissen mit Grünschnitt und Grassilage können die folgenden Schlussfolgerungen gezogen werden:

(i) Es wurden Methanerträge der Presssäfte zwischen 254 (holziges Material, 40°C) and 359 (Gras, 40°C) $L_N$ $CH_4$ $kg^{-1}$ oTS und Abbaugrade zwischen 59% (holziges Material, 40°C) und 81% (Gras, 40°C) gemessen. Es gab keinen statistisch signifikanten Zusammenhang zwischen den Methanerträgen und Abbaugraden und dem Inputmaterial oder der Temperatur der hydrothermalen Konditionierung. Die Brennstoffqualität des Grünschnitts wurde erheblich verbessert; der Presskuchen zeigte signifikant reduzierte K, Cl, Mg, S und P Gehalte. Für N und Ca konnten keine signifikanten Reduktionen gefunden werden. Die Kalkulation der Ascheerweichungstemperatur ergab eine Erhöhung derselben durch das IFBB Verfahren

(ii) Silagen von extensiv genutztem Naturschutzgrünland bewiesen ihre prinzipielle Eignung für das IFBB System, auch wenn die Ertragsdaten und die chemische Zusammensetzung großen Schwankungen auf europäischem Niveau unterlagen. Das IFBB Verfahren der hydrothermalen Konditionierung und anschließenden Entwässerung in einem Prototyp zeigte vergleichbare Resultate zu bisherigen Laboruntersuchungen. Die Konzentrationen von N, S, K, Ca, Mg, Cl und P konnten signifikant reduziert werden. Korrelationen zwischen botanischen (Deckungsgraden von Gräsern, Kräutern und Leguminosen) und chemischen Parametern (NDF) der Silage und den Massenflüssen der Pflanzeninhaltsstoffe ($R^2$: 0.21-

0.63) sowie deren Konzentrationen im Presskuchen ($R^2$: 0.34-0.79) konnten nachgewiesen werden. Höhere NDF Konzentrationen und höhere Gräser-Bedeckungsgrade führten zu verbesserten Brennstoffeigenschaften, wohingegen höhere Leguminosenanteile zu einer Verschlechterung der Brennstoffqualität führten.

(iii) Das IFBB Verfahren erhöhte die organische Trockenmasse und den Fasergehalt im PC von Silagen aus extensiv genutztem Grünland, während die Gehalte an CP und NFC verringert wurden. Massenflüsse und in Folge Konzentrationen im Presskuchen waren sehr variabel für die 12 untersuchten Habitattypen. Der produzierte Presssaft zeigte hohe Methanerträge zwischen 312 und 405 $L_N$ $CH_4$ $kg^{-1}$ oTS die nicht vom Habitattyp beinflusst waren. Flächenbezogene Methanerträge variierten von 55 bis zu 330 $m_N^3$ $CH_4$ $ha^{-1}$, hier gab es einen statistisch nachweisbaren Einfluss des Habitattyps. Die Regressionsanalysen zeigten keinen Zusammenhang zwischen substratspezifischem Methanertrag und den organischen Inhaltsstoffen der Silage oder botanischen Parametern der Habitattypen. Dies kann durch die hoch variablen Massenflüsse der organischen Inhaltsstoffe erklärt werden. Für die Implementierung des IFBB Verfahrens in der Praxis sind diese Ergebnisse eines relativ einheitlichen Methanertrags bei sehr unterschiedlichen Eingangssubstraten positiv zu bewerten. Dies unterstreicht einmal mehr die Fähigkeit des IFBB Systems heterogene Biomassen unterschiedlicher Herkünfte und Erntezeitpunkte in erneuerbare Energie umzuwandeln.

(iv) Für den nicht-holzigen Teil des städtischen Grünschnitts war das IFBB Verfahren der direkten Verbrennung überlegen, wohingegen die Energiebilanzen für die holzreichen Fraktionen im selben Wertebereich lagen. Die Energiebilanz bei einer Konditionierungstemperatur von 40° C war deutlich positiver als bei einer Temperatur von 60°C. Da nur zwei

Zeitpunkte untersucht werden konnten, ist weitere Forschung in diesem Bereich notwendig, um zu erforschen, wie sich die unterschiedliche Zusammensetzung des Grünschnitts im Jahresverlauf auf das IFBB Verfahren auswirkt. Für die europäischen Grünlandsilagen kann festgehalten werden, dass die Bruttoenergieerträge für das IFBB System (9.75 bis 30.19 MWh $ha^{-1}$) in der Größenordnung der Heuverbrennung (10.51 bis 31.66 MWh $ha^{-1}$) lagen und diese beiden Systeme die Ganzpflanzenvergärung bei weitem übertrafen (4.08 bis 12.55 MWh $ha^{-1}$). Die Bruttoenergiebilanz muss um Ernteverluste und prozessinterne Verluste korrigiert werden, um auf Nettoenergieerträge schließen zu können. Die Energieerträge wurden beeinflusst von Habitattyp und Konversionsverfahren und Wechselwirkungen zwischen beiden Faktoren. Zukünftige Forschung ist notwendig, um die Effekte der chemischen und botanischen Parameter des Inputmaterials auf die Energiebilanz des IFBB Verfahrens genauer zu untersuchen.

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## 9.4 Zusammenfassung

Diese Dissertation beschreibt die Nutzung von zwei unterschiedlichen Eingangsmaterialien entlang der IFBB Nutzungskette.

Der erste Teil der Arbeit (Kapitel 3) untersuchte die Nutzung von städtischem Grünschnitt, welcher heutzutage zumeist für die Kompostbereitung genutzt wird. Dieser besteht aus einer krautigen und einer holzigen Fraktion. Die Nutzung für das IFBB Verfahren und die direkte Verbrennung dieser Fraktionen sowie dreier Mischungsstufen wurden untersucht. Die Proben wurden im August und Oktober entnommen und einer hydrothermalen Konditionierung bei zwei Temperaturstufen ausgesetzt und anschließend mittels Schneckenpresse entwässert. Sowohl die Massenflüsse von Inhaltsstoffen der Biomasse wurden untersucht als auch die Konzentration dieser Inhaltsstoffe im Presskuchen des IFBB Verfahrens. Die Ascheerweichungstemperatur und der Heizwert wurden berechnet, für den Presssaft wurden Vergärungstests im Labor durchgeführt um dessen Biogasbildungspotenzial zu untersuchen. Eine vollständige Energiebilanz wurde für das IFBB Verfahren und als Vergleich für die direkte Verbrennung des Grünschnitts durchgeführt. Die Ergebnisse zeigten, dass der Presssaft hohe Gaserträge aufweist, mit 254 (holziges Material, 40°C) bis 359 (krautiges Material, 40°C) $L_N$ $CH_4$ $kg^{-1}$ oTS und Abbaugraden zwischen 59% (holziges Material, 40°C) und 81% (krautiges Material, 40°C). Es gab keinen statistisch nachweisbaren Effekt der Temperatur der Maischung oder der Art des Inputmaterials auf den Methanertrag. Bedingt durch die hohen Massenflüsse der für die Verbrennung schädlichen Mineralstoffe (K, Cl, Mg, S) konnte die Brennstoffqualität des Presskuchens gegenüber dem Ausgangsmaterial signifikant gesteigert werden. Keine signifikanten Änderungen ergaben sich für Ca und N. Das IFBB System mit 40° Maisch-Temperatur zeigte eine bessere Energiebilanz als die direkte Verbrennung.

Der zweite Teil der Studie untersuchte die Nutzung von Silage von extensivem Grünland von 18 Flächen in Deutschland, Wales und

Estland für das IFBB Verfahren im Vergleich zu Ganzpflanzenvergärung und Heuverbrennung. Kapitel 4 zeigt die Ergebnisse der Massenflüsse der Mineralstoffe innerhalb des IFBB Systems sowie die Brennstoffqualität und Ergebnisse linearer multipler Regressionsmodelle für die Brennstoffqualität und beeinflussender Parameter wie chemische und botanische Zusammensetzung der Ausgangssilagen. Kapitel 5 behandelt die Massenflüsse der organischen Inhaltsstoffe und deren Konzentrationen im Presskuchen des IFBB Verfahrens, ebenso die Ergebnisse der anaeroben Vergärung der Presssäfte und abschließend die Bruttoenergieerträge des IFBB Verfahrens im Vergleich zu Ganzpflanzenvergärung und Heuverbrennung. Die Ergebnisse zeigten, dass die Silagen von extensivem Grünland als Inputmaterial für das IFBB Verfahren geeignet waren. Die Konzentrationen der untersuchten Elemente (N, S, K, Ca, Mg, Cl und P) wurden sämtlich signifikant reduziert. Korrelationen zwischen botanischen (Deckungsgrade Gräser, Kräuter und Leguminosen) und chemischen Parametern (NDF) der Silage und den Massenflüssen der Inhaltsstoffe ($R^2$: 0.21-0.63) und der Brennstoffqualität des Presskuchens ($R^2$: 0.34-0.79) konnten nachgewiesen werden. Hohe NDF Konzentrationen und hohe Deckungsgrade der Gräser führten zu einer besseren Brennstoffqualität, wohingegen Leguminosenanteile die Brennstoffqualität verschlechterten. Das IFBB Verfahren erhöhte die organische Trockenmasse und Faserkonzentrationen im Presskuchen und reduzierte die CP und NFC Konzentrationen. Außerdem entstand mit dem Presssaft ein hoch verdauliches Biogasssubstrat mit Methanerträgen zwischen 312 und 405 $L_N$ $CH_4$ $kg^{-1}$ oTS, statistisch unabhängig von den Ausgangshabitattypen der Silagen. Die flächenspezifischen Methanerträge lagen zwischen 55 und 330 $m_N^3$ $CH_4$ $ha^{-1}$ und waren signifikant abhängig vom Habitattyp. Die Regressionsanalysen zeigten keine signifikanten Zusammenhänge zwischen substratspezifischen Methanerträgen und den Inhaltsstoffen der Silage oder der botanischen Parameter. Bezüglich der Energieerträge zeigte das IFBB Verfahren Werte im Bereich der

Heuverbrennung und beide Verfahren waren der Ganzpflanzenvergärung deutlich überlegen. Die Energieerträge zeigten Abhängigkeiten von botanischen und chemischen Parametern, sowie technischen Parametern und deren Wechselwirkungen. Zusammenfassend kann festgehalten werden, dass das IFBB Verfahren die Möglichkeit bietet, heterogene, faser- und mineralstoffreiche Biomassen effizient in Energie umzuwandeln, insbesondere solche Biomassen, die heutzutage noch nicht für die Energieproduktion genutzt werden.

# 10 References

Anonymous, 2007. Council directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. The council of the European communities, (verified January 2011). http://eur-lex.europa.eu/LexUriServ/ LexUriServ.do?uri=CONSLEG:1992L0043:20070101:EN:PDF [21.02.2012].

Anonymous, 2008. Umwelt Abfallentsorgung 2006. Statistisches Bundesamt (Eds.) Fachserie 19, Reihe 1, Wiesbaden, Germany. http://www.bde-berlin.org/wp-content/pdf/2009/ statistik_abfallentsorgung_2006.pdf [04.03.2011].

Anonymous, 2009. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Off. J. Eur. Union 2009, 52, L140/16–L140/62. http://eur-lex.europa.eu/ LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0016:0062:EN:PDF [02.08.2013].

Anonymous, 2009b. Gesetz für den Vorrang Erneuerbarer Energien. http://www.gesetze-im-internet.de/bundesrecht/eeg_2009/ gesamt.pdf [05.11.2013].

Bachmaier, H., Effenberger, M., Lehner, A., Gronauer, A., 2008. Klimabilanz von Praxisbiogasanlagen. In: Kuratorium für Technik und Bauwesen in der Landwirtschaft. Ökologische und ökonomische Bewertung nachwachsender Energieträger, Darmstadt, 194-200.

Bassler, R., 1976. Methodenbuch Band III: Die chemische Untersuchung von Futtermitteln, mit Ergänzungslieferungen 1983, 1988 und 1993, VDLUFA-Verlag Darmstadt, Germany.

Bergsma, G.C., Kampmann, B., Croezen, H.J., 2007. The battle for land between food, biofuels and nature, in: ETA-Renewable Energies (Eds.) Proceedings of the 15th European Biomass Conference & Exhibition, Berlin, Germany, pp. 269-270.

Beurskens, L.W.M., Hekkenberg, M., 2011. Renewable Energy Projections as Published in the National Renewable Energy Action Plans of the European Member States. Petten, NL. Energy Research Centre of the Netherlands and European Environment Agency.

Blumenstein, B., Bühle, L., Wachendorf, M., Möller, D., 2012: Economic 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. Bioresour. Technol. 119, 312-323.

Bühle, L., 2008. Vergleichende Energie- und Emissionsbilanz der Wärme- und Stromproduktion nach dem IFBB-Verfahren und herkömmlicher Ganzpflanzenvergärung. Master thesis, Kassel, Germany: University of Kassel.

Bühle, L., Stülpnagel, R., 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 Bioenergy 35, 363-373.

Bühle, L., Hensgen, F., Donnison, I., Heinsoo, K., Wachendorf, M., 2012a. 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. Bioresour. Technol. 111, 230-239.

Bühle, L., Reulein, J., Stülpnagel, R., Zerr, W., Wachendorf, M., 2012b. Methane yields and digestion dynamics of press fluids from mechanically dehydrated maize silages using different types of digesters. Bioenergy Res. 5, 294-305.

Bühle, L., Dürl, G., Hensgen, F., Urban, A., 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.

Burvall, J., 1997. Influence of harvest time and soil type on fuel quality in reed canary grass (Phalaris Arundinacea L.). Biomass Bioenergy 12, 149-154.

Chen, Y., Cheng, J. J., Creamer, K. S., 2008. Inhibition of anaerobic digestion process: A review. Bioresour. Technol. 99, 4044-4064.

Christian, D.G., Yates, N.E., Riche, A. B., 2006. The effect of harvest date on the yield and mineral content of Phalaris arundinacea L. (reed canary grass) genotypes screened for their potential as energy crops in southern England. J. Sci. Food Agric. 86, 1181-1188.

Connolly, J., Wachendorf, M., 2001. Developing multisite dynamic models of mixed species plant communities. Ann.Bot. 88, 703-712.

Crutzen, P. J., Mosier, A.R., Smith, K.A., Winiwarter, W., 2008. $N_2O$ release from agro-biofuel production negates global warming reduction by replacing fossil fuels. Atmos. Chem. Phys. 8, 1389–1395.

Dauber, J., Jones, M.B., Stout, J.S., 2010. The impact of biomass crop cultivation on temperate biodiversity. GCB Bioenergy 2, 289-309.

Draper, N. R., Smith, H., 1998. Applied Regression Analysis, third ed. John Wiley & Sons, New York.

Edelmann, W., Schleiss, K., 2001. Ökologischer, energetischer und ökonomischer Vergleich von Vergärung, Kompostierung und Verbrennung fester biogener Abfallstoffe. Studie im Auftrag des Bundesamtes für Energie und Bundesamt für Umwelt, Wald und Landschaft. Baar, Switzerland. http://www.naturemade.ch/Dokumente/oekobilanzen/%C3%96kobilanz%20Feststoffverg%C3%A4rung.pdf [04.03.2011].

Elawad, S., Kumagai, H., Mitani, K., 2002. Measurement and estimation of dry matter losses during hay and silage making in field curing. Grassland Science 48, 110-119.

EMHI (Estonian Meteorological and Hydrological Institute), 2011. http://www.emhi.ee/ [09.12.2011].

Fenwick, G. R., 1988. Bracken (Pteridium aquilinum) - Toxic Effects and Toxic Constituents. J. Sci. Food. Agric. 46, 147-173.

FNR (Fachagentur Nachwachsende Rohstoffe e.V.), 2013. Basisdaten Bioeenergie Deutschland. http://mediathek.fnr.de/media/downloadable/files/samples/b/a/basisdaten_9x16_2013_web_neu2.pdf [04.11.2013].

Fletcher, R.J., Robertson, B.A., Evans, J., Patrick, J.D., Alavalapati, J.R.R., Schemske, D.W., 2011. Biodiversity conservation in the era of biofuels: risks and opportunities. Frontiers in Ecology and the Environment 9, 161-168.

Friedl, A., Padouvas, E., Rotter, H., Varmuza, K., 2005. Prediction of heating values of biomass fuel from elemental composition. Anal. Chim. Acta 544, 191–198.

Garcia-Ciudad, A., Ruano-Ramos, A., Vazquez de Aldana, B.R., Garcia-Criado, B., 1997. Interannual variations of nutrient concentrations in botanical fractions from extensively managed grasslands. Anim. Feed Sci. Tech. 66, 257-269.

Graß, R., Reulein, J., Scheffer, K., Stülpnagel, R., Wachendorf, M., 2009. Die integrierte Biogas- und Festbrennstofferzeugung aus Ganzpflanzensilage. Berichte über Landwirtschaft 87 , 43-64.

Hadders, G., Olsson, R. 1997. Harvest of grass for combustion in late summer and in spring. Biomass Bioenergy 12, 171-175.

Hahn, H., Krautkremer, B., Hartmann, K., Wachendorf, M., 2014. Review of concepts for a demand-driven biogas supply for flexible power generation. Renewable and Sustainable Energy Reviews 29, 383-393.

Halada, L., Evans, D., Romão, C., Petersen, J.E., 2011. Which habitats of European importance depend on agricultural practices? Biodiversity and Conservation 20, 2365-2378.

Hartmann, H., Böhm, T., Maier, L., 2000. Naturbelassene biogene Festbrennstoffe - umweltrelevante Eigenschaften und Einflussmöglichkeiten. In: Bayerisches Staatsministerium für Landesentwicklung und Umweltfragen (Eds.): Umwelt und Entwicklung Bayern, 154, Munich.

Hartmann, H., 2009. Brennstoffzusammensetzung und -eigenschaften. In: Kaltschmitt, M., Hartmann, H., Hofbauer, H. (Eds.), Energie aus Biomasse: Grundlagen, Techniken und Verfahren. Springer-Verlag, Berlin, 333-376.

Heinrichs, H., Brumsack, H.-J., Loftfield, N., König, N., 1986. Verbessertes Druckaufschlußsystem für biologische und anorganische Materialien. Z. Pflanzenernaehr. Bodenk. 149, 350-353.

Heinsoo, K., Melts, I., Sammul, M., Holm, B., 2010. The potential of Estonian semi-natural grasslands for bioenergy production. Agric. Ecosyst. Environ. 137, 86-92.

Hensgen, F., Richter, F., Wachendorf, M., 2011. Integrated generation of solid fuel and biogas from green cut material from landscape conservation and private households. Bioresour. Technol. 102, 10441-10450.

Hensgen, F., Bühle, L., Donnison, I., Fraser, M., Vale, J., Corton, J., Heinsoo, K., Melts, I., Wachendorf, M., 2012. Mineral concentrations in solid fuels from European semi-natural grasslands after hydrothermal conditioning and subsequent mechanical dehydration. Bioresour. Technol. 118, 332-342.

Herrmann, A., 2013. Biogas production from maize: current state, challenges and prospects. 2. Agronomic and environmental aspects. Bioenergy Research 6, 372-387.

Hidaka, T., Arai, S., Okamoto, S., Uchida, T., 2013. Anaerobic co-digestion of sewage sludge with shredded grass from public green spaces. Bioresour. Technol. 130, 667-672.

Hoogwijk, M., Faai, J. A., Van Den Broek, R., Berndes, G., Gielen, D., Turkenburg, W., 2003. Exploration of the ranges of the global potential of biomass for energy. Biomass Bioenergy 25, 119-133.

Isselstein, J., Jeangros, B., Pavlu, V., 2005. Agronomic aspects of biodiversity targeted management of temperate grasslands in Europe- a review. Agron. Res. 3, 139-151.

IUSS (IUSS Working Group WRB), 2007. World Reference Base for Soil Resources 2006, first update 2007, World Soil Resources Reports No. 103, FAO, Rome.

Jenkins, B.M., Baxter, L.L., Miles Jr., T.R., Miles, T.R., 1998. Combustion properties of biomass. Fuel Process. Technol. 54, 17–46.

Johansson, D., Azar, C., 2007. A scenario based analysis of land competition between food and bioenergy production in the US. Clim. Change 82, 267-91.

Kern, M., Raussen, T., Funda, K., Lootsma, A., Hofmann, H., 2010. Efforts and returns of an optimized organic waste recycling with special emphasis on energy efficiency as well as climate and resource protection. Federal Environment Agency, Dessau, Germany. http://www.uba.de/uba-info-medien/4010.html [04.03.2011].

King, C., McEniry, J., O'Kiely, P., Richardson, M., 2012. The effects of hydrothermal conditioning, detergent and mechanical pressing on the isolation of the fibre-rich press-cake fraction from a range of grass silages. Biomass Bioenergy 42, 179-188.

Kolár, L., Kuzel, S., Peterka, J., Borová-Batt, J., 2010. Agrochemical value of the liquid phase of wastes from fermenters during biogas production. Plant Soil Environ. 56, 23-27.

Kranert, M., Gottschall, R., Bruns, C., Hafner, G., 2010. Energy or compost from green waste? -A $CO_2$-Based assessment. Waste Manage. 30, (4), 697-701.

Landström, S., Lomakka, L., Anderssson, S., 1996. Harvest in spring improves yield and quality of reed canary grass as a bioenergy crop. Biomass Bioenergy 11, 333-341.

Londo, G., 1975. Dezimalskala für die vegetationskundliche Aufnahme von Dauerquadraten in: Tüxen, R., (ed.), Sukzessionsforschung, Ber. int. Symp. IVV., Vaduz, 613-617.

Lootsma, A., 2006. Energiepflanzenanbau und Biogaserzeugung - eine energetische Betrachtung im Bioenergiedorf Jühnde [diploma thesis]. Witzenhausen: University of Kassel.

Lootsma, A., Raussen, T.,. 2008. Aktuelle Verfahren zur Aufbereitung und Verwertung von Gärresten. In: Wiemer K. and Kern M. (eds) Bio- und Sekundärrohstoffverwertung III. Witzenhausen, Germany: Witzenhausen-Institut, 559–576.

Love, B.J., Einheuser, M.D., Nejadhashemi, A.P., 2011. Effects on aquatic and human health due to large scale bioenergy crop expansion. Science of the Total Environment 409, 3215-3229.

Manas, E., Bravo, L., Saura-Calixto, F., 1994. Sources of error in dietary fibre analysis. Food Chemistry 50, 331-342.

Mattson, W.J., 1980. Herbivory in relation to plant nitrogen content. Ann. Rev. Ecol. Syst. 11, 119-161.

Nayono, S. E., Winter, J., Gallert, C., 2010. Anaerobic digestion of pressed of leachate from the organic fraction of municipal solid waste. Waste Management 30, 1828-1833.

Nelder, J.A., Lane, P.W., 1995. The computer analysis of factorial experiments. In memoriam: Frank Yates. Amer. Stat. 49, 382-385

Nussbaumer, T., 2003. Combustion and Co-combustion of Biomass: Fundamentals, Technologies, and Primary Measures for Emission Reduction. Energy Fuels 17, 1510-1521.

Obernberger, I., Brunner, T., Bärnthaler, G., 2006. Chemical properties of solid biofuels – significance and impact. Biomass Bioenergy 30, 973–982.

Ostermann, O.P., 1998. The need for management of nature conservation sites designated under Natura 2000. J. Appl. Ecol. 35, 968-973.

PIK, 2009. Protected Areas in Germany under Global Change - Risks and Policy Options. Potsdam Institute for Climate Impact Researchl. http://www.pik-potsdam.de/~wrobel/sg-klima-3/landk/Vogelsbergkreis.html [24.11.2011].

Poschlod, P., Bakker, J.P., Kahmen, S., 2005. Changing land use and its impact on biodiversity. Basic Appl. Ecol. 6, 93–98.

Porter, M.G., Murray, R.S., 2001. The volatility of components of grass silage on oven drying and the inter-relationship between dry-matter content estimated by different analytical methods. Grass Forage Sci. 65, 405-411.

Prochnow, A., Heiermann, M., Plöchl, M., Linke, B., Idler, C., Amon, T., Hobbs, P.J., 2009a. Bioenergy from permanent grassland - A review: 1. Biogas. Bioresour. Technol. 100, 4931-4944.

Prochnow, A., Heiermann, M., Plöchl, M., Amon, T., Hobbs, P.J., 2009b. Bioenergy from permanent grassland – A review: 2. Combustion. Bioresour. Technol. 100, 4945-4954.

R Development Core Team, 2011. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org/.

Richter, F., Graß, R., Fricke, T., Zerr, W., Wachendorf, M., 2009. Utilization of semi-natural grassland through integrated generation of solid fuel and biogas from biomass. II. Effects of hydrothermal conditioning and mechanical dehydration on anaerobic digestion of press fluids. Grass Forage Sci. 64, 354-363.

Richter, F., Fricke, T., Wachendorf, M., 2010. Utilization of semi-natural grassland through integrated generation of solid fuel and biogas from biomass. III. Effects of hydrothermal conditioning and mechanical dehydration on solid fuel properties and on energy and greenhouse gas balances. Grass Forage Sci. 65, 185-199.

Richter, F., Fricke, T., Wachendorf, M., 2011 a. Influence of sward maturity and pre-conditioning temperature on the energy production from grass silage through integrated generation of solid fuel and biogas from biomass (IFBB): 1. The fate of mineral compounds. Bioresour. Technol. 102, 4855-4865.

Richter, F., Fricke, T., Wachendorf, M., 2011 b. Influence of sward maturity and pre-conditioning temperature on the energy production from grass silage through integrated generation of solid fuel and biogas from biomass (IFBB): 2. Properties of energy carriers and energy yield. Bioresour. Technol. 102, 4866-4875.

Rieckmann, C., 2006. Grünland. In: Kuratorium für Technik und Bauwesen in der Landwirtschaft (Eds.), Energiepflanzen. Darmstadt, 263-273.

Rösch, C., Skarka, J., Raab, K., Stelzer, V., 2009. Energy production from grassland – Assessing the sustainability of different process chains under German conditions. Biomass Bioenerg. 33, 689-700.

Ruano-Ramos, A., Garcia-Ciudad, A., Garcia-Criado, B., 1999. Near infrared spectroscopy prediction of mineral content in botanical fractions from semi-arid grasslands. Anim. Feed Sci. Tech. 77, 331-343.

Shiralipour, A., Smith, P.H., 1984. Conversion of biomass into methane gas. Biomass 6, 85-92.

Scholwin, F., Weidele, T., Gattermann, H., 2006. Gasaufbereitung und Verwertungsmöglichkeiten. In: Fachagentur. Nachwachsende Rohstoffe e.V. (Eds.) Handreichung Biogasgewinnung und -nutzung. Fachagentur Nachwachsende Rohstoffe e.V., Gülzow, 97–116.

Soil Survey Division Staff. 1993. Soil survey manual. Soil Conservation Service. U.S. Department of Agriculture Handbook 18.

Sokhansanj, S., Fenton, J., 2006. Cost benefit of biomass supply and pre-processing. BIOCAP Canada Foundation, Ottawa.

Steenari, B.M., Lundberg, A., Pettersson, H., Wilewska-Bien, M., Andersson, D., 2009. Investigation of ash sintering during combustion of agricultural residues and the effect of additives. Energy Fuels 23, 5655-5662.

Tilman, D., Socolow, R., Foley, J. A., Hill, J., Larson, E., Lynd, L., et al., 2009. Beneficial biofuels - The food, energy and environment trilemma. Science 325, 270-271.

Tahir, M.H.N., Casler, M.D., Moore, K.J., Brummer, E.C., 2011. Biomass Yield and Quality of Reed Canarygrass under Five Harvest Management Systems for Bioenergy Production. Bioenergy Res. 4, 111-119.

Tallowin, J.R.B., Jefferson, R.G., 1999. Hay production from lowland semi-natural grasslands: a review of implications for ruminant livestock systems. Grass Forage Sci. 54, 99-115.

Tonini, D., Hamelin, L, Wenzel, H., Astrup, T., 2012. Bioenergy production from perennial energy crops: A consequential LCA of 12 Bioenergy Scenarios including land use changes. Environmental Science & Technology 46, 13521-13530.

Tonn, B., Thumm, U., Claupein, W., 2010. Semi-natural grassland biomass for combustion: influence of botanical composition, harvest date and site conditions on fuel composition. Grass Forage Sci. 65, 383-397.

Tonn, B., Thumm, U., Lewandowski, I., Claupein, W., 2012. Leaching of biomass from semi-natural grasslands - Effects on chemical composition and ash high-temperature behaviour. Biomass Bioenergy 63, 390-403.

United Kingdom Meteorological Office, 2011. UK climate averages. http://www.metoffice.gov.uk/climate/uk/averages/19611990/sites/trawscoed.html [25.11.2011].

University of Hohenheim (eds.), 1997. DLG-Futterwerttabellen Wiederkäuer (DLG nutrition value tables for ruminants). Frankfurt, Germany: DLG-Verlag.

Van Soest, P.J., Wine, R.H., 1967. Use of detergents in the analysis of fibrous feeds IV. Determination of plant cell-wall constituents. Journal of Association of Official Analytical Chemists 28, 50-59.

Van Loo, S., Koppejan, J., 2008. The Handbook of Combustion and Co-Firing. Earthscan, London.

VDI 4630, 2004. Vergärung organischer Stoffe. Verein Deutscher Ingenieure, Düsseldorf.

Weißbach, F., Strubelt, C., 2008. Die Korrektur des Trockensubstanzgehaltes von Grassilagen als Substrat für Biogasanlagen. Landtechnik 63, Vol. 4, 210-211.

Wachendorf, M., Richter, F., Fricke, T., Graß, R., Neff, R., 2009. Utilization of semi-natural grassland through integrated generation of solid fuel and biogas from biomass. I. Effects of hydrothermal conditioning and mechanical dehydration on mass flows of organic and mineral plant compounds, and nutrient balances. Grass Forage Sci. 64, 132-143.

Zah, R., Böni, H., Gauch, M., Hischier, R., Lehmann, M., Wäger, P., 2007. Ökobilanz von Energieprodukten – Ökologische Bewertung von Biotreibstoffen. Studie des EMPA im Auftrag der Bundesämter für Umwelt, Landwirtschaft und Energie der Schweiz, EMPA Materials Science & Technology, Zurich/St. Gallen/Dübendorf. http://www.news.admin.ch/NSBSubscriber/message/attachments/8514.pdf [04.03.2011].

Zerr, W., 2006. Versuchsanlage zur energetischen Beurteilung von Substraten und Kofermentaten für Biogasanlagen. Z. Umweltchem. Ökotox. 18, (4), 219-227.

# 11 List of other publications

## In reviewed journals

Bühle, L., Hensgen, F., Donnison, I., Heinsoo, K., 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.

Bühle, L., Dürl, G., Hensgen, F., Urban, A., 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.

Hensgen, F, Albrecht, C., Donath, T. W., Otte, A., Eckstein, R.L., 2011. Distribution of gastropods in floodplain compartments and feeding preferences for river corridor plant species: is there an effect of gastropod herbivory on the distribution of river corridor plants? Flora 206, 534-543.

## Other publications

Bühle, L., Hensgen, F., Donnison, I., Heinsoo, K., Wachendorf, M., 2011. Evaluation of fuel and biogas production on typical semi-natural grasslands in Germany, Wales and Estonia. Grassland Science in Europe 16, 398-400.

Bühle, L., Hensgen, F., Donnison, I., Heinsoo, K., Wachendorf M., 2011. Improving combustion performance of European grassland biomass through water mashing and subsequent dehydration. Grassland Science in Europe 16, 401-403.

Bühle, L., Urban, A., Hensgen, F., Donnison, I., Heinsoo, K., Wachendorf, M., 2011. Technische und ökologische Aspekte der Produktion und Verwertung von Festbrennstoff aus Biomasse von Extensivgrünland. Mitteilungen der Gesellschaft für Pflanzenbauwissenschaften 23, 85-86.

Bühle, L., Hensgen, F., Donnison, I., Heinsoo, K., Wachendorf, M., 2012. Balance of energy production from high-biodiversity grasslands. Grassland Science in Europe 17, 454-456.

Bühle, L., Hensgen, F., Donnison, I., Heinsoo, K., Wachendorf, M., 2012. Energie- und Emissionsbilanz verschiedener Bewirtschaftungsformen des Extensivgrünlands. Mitteilungen der Arbeitsgemeinschaft Grünland und Futterbau 13, 45-50.

Bühle, L., Urban, A., Dürl, G., Hensgen, F., Wachendorf, M., 2013. Ascheerweichungsverhalten bei der Verbrennung von Grünlandbrennstoffen. In: Mitteilungen der Gesellschaft für Pflanzenbauwissenschaften 25, 267-268.

Hensgen, F., Bühle, L., Wachendorf, M., 2011. Assessment of productivity of semi-natural grasslands under different fertilisation and cutting treatments. Grassland Science in Europe 16, 550-552.

Hensgen, F., Bühle, L., Donnison, I., Heinsoo, K., Wachendorf, M., 2011. Verbesserung der Brennstoffeigenschaften von Grünlandbrennstoffen durch Maischung und mechanische Entwässerung. Mitteilungen der Gesellschaft für Pflanzenbauwissenschaften 23, 83-84.

Hensgen, F., Richter, F., Wachendorf, M., 2011. Towards an efficient energetic conversion of landscape conservation material. In: Grassland Farming and Land Management Systems in Mountainous Regions. Eds. Erich M. Pötsch, Bernhard Krautzer and Alan Hopkins. Grassland Science in Europe 16, 338-340

Hensgen, F., Bühle, L., Wachendorf, M., 2012. Erhalt der Biodiversität von Naturschutzgrünland durch eine dezentrale energetische Verwertung der Biomasse. Mitteilung der Gesellschaft für Pflanzenbauwissenschaften 24, 218-219.

Hensgen, F., Bühle, L., Donnison, I., Heinsoo, K., Wachendorf, M., 2012. Chemische und botanische Determinanten der Mineralstoffgehalte in Brennstoffen von extensiv genutztem Grünland in Europa. Mitteilungen der Arbeitsgemeinschaft Grünland und Futterbau 13, 94-97.

Hensgen, F., Bühle, L., Donnison, I., Heinsoo, K., Wachendorf, M., 2012. Reduction of mineral concentration of semi-natural grassland biomass used as biofuel through mashing and dewatering. Grassland Science in Europe 17, 466-468.

Hensgen, F., Bühle, L., Khalsa, J., Wachendorf, M., 2013. Energetische Verwertung des Laubes städtischer Bäume. In: Mitteilungen der Gesellschaft für Pflanzenbauwissenschaften 25, 259-260.

Hensgen, F., Bühle, L., Wachendorf, M., 2013. Biogasertrag von Presssäften europäischen Extensivgrünlands nach hydrothermaler Konditionierung und mechanischer Entwässerung. In: Mitteilungen der Gesellschaft für Pflanzenbauwissenschaften 25, 52-53.

Wachendorf, M., Möller, D., Bühle, L., Hensgen, F., Blumenstein, B., 2011. Erhalt von Naturschutzgrünland durch eine dezentrale energetische Verwertung - Zwischenergebnisse des Modellprojekts PROGRASS. In: Solarzeitalter - Politik, Kultur und Ökonomie erneuerbarer Energien, 02/2011, EUROSOLAR e.V. Bonn, 28-34.

# Appendix

Table A1: Detailed results of the eighteen European semi-natural grassland sites concerning yield and fuel quality, arithmetic mean value of two year data

| Site[a] | | NATURA 2000 habitat type | Yield [t DM$^{-1}$ yr$^{-1}$] | Silage [g kg$^{-1}$ DM] | | | | PC [g kg$^{-1}$ DM] | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | N | S | Cl | K | N | S | Cl | K |
| DE | I | Lowland hay meadow (6510) | 3.16 | 15.55 | 1.70 | 2.88 | 7.03 | 14.99 | 1.07 | 0.42 | 1.53 |
| | II | Lowland hay meadow (6510) | 2.93 | 17.42 | 1.85 | 1.95 | 6.47 | 14.29 | 1.07 | 0.35 | 138 |
| | III | Mountain hay meadow (6520) | 2.92 | 14.77 | 1.77 | 2.50 | 7.88 | 13.40 | 0.98 | 0.45 | 2.13 |
| | IV | Species-rich Nardus grasslands (6230) | 3.58 | 15.43 | 1.98 | 2.92 | 9.55 | 12.09 | 1.08 | 0.78 | 3.18 |
| | V | Molinia meadow (6410) | 4.35 | 15.12 | 1.73 | 6.35 | 12.65 | 12.29 | 1.08 | 0.90 | 3.07 |
| | VI | Humid tall herb fringes of watercourses and woodlands (6431) | 6.44 | 14.14 | 1.92 | 4.28 | 9.05 | 12.47 | 1.17 | 0.50 | 1.85 |
| UK | I | Degraded raised bogs still capable of natural regeneration (7120) | 3.49 | 12.74 | 1.53 | 7.93 | 9.27 | 8.99 | 0.93 | 1.22 | 2.08 |
| | II | Degraded raised bogs still capable of natural regeneration (7120) | 3.63 | 13.47 | 1.48 | 3.88 | 5.52 | 10.85 | 1.12 | 0.52 | 1.35 |
| | III | Degraded raised bogs still capable of natural regeneration (7120) | 4.84 | 13.20 | 1.47 | 4.30 | 5.50 | 10.33 | 1.05 | 0.60 | 1.17 |
| | IV | European dry heaths (4030) | 4.95 | 14.64 | 1.25 | 1.25 | 4.63 | 11.75 | 1.00 | 0.37 | 1.20 |
| | V | Not classifiable | 3.69 | 15.70 | 1.78 | 4.92 | 10.87 | 14.98 | 1.20 | 0.88 | 4.08 |
| | VI | Blanket bogs (7130) | 1.97 | 14.40 | 1.37 | 4.38 | 10.37 | 10.52 | 0.90 | 0.87 | 3.02 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| EST | I | Northern boreal alluvial meadows (6450) | 3.10 | 15.13 | 1.41 | 5.02 | 16.90 | 12.90 | 0.96 | 0.97 | 4.57 |
| | II | Fennoscandian lowland species-rich dry to mesic grasslands (6270) | 3.39 | 15.03 | 1.32 | 2.23 | 10.24 | 11.14 | 0.91 | 0.54 | 2.82 |
| | III | Fennoscandian wooded meadows (6530) | 1.63 | 15.35 | 1.45 | 3.80 | 21.05 | 11.91 | 0.94 | 0.77 | 6.04 |
| | IV | Northern boreal alluvial meadows (6450) | 3.79 | 16.48 | 1.86 | 4.21 | 13.20 | 13.41 | 1.18 | 0.86 | 3.71 |
| | V | Fennoscandian lowland species-rich dry to mesic grasslands (6270) | 3.17 | 14.40 | 1.34 | 2.38 | 9.46 | 12.60 | 0.97 | 0.51 | 2.53 |
| | VI | Fennoscandian wooded meadows (6530) | 2.41 | 16.94 | 1.66 | 3.38 | 15.58 | 14.18 | 1.02 | 0.73 | 4.43 |

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To act against the negative effects of climate change, the European Union (EU) has increased its efforts in the field of renewable energies. This led to the definition of national and EU wide targets for the share of energy from renewable sources in gross final consumption of energy by the year 2020 for each EU-Member state and the Union as a whole. To reach these aims without jeopardising other important aims like food security and nature conservation, sustainable systems of recovery of renewable energy have to be developed. One possibility is the "integrated generation of solid fuel and biogas from biomass" (IFBB). Its core element is the mechanical separation of the biomass into a solid fuel for combustion and a liquid for anaerobic digestion.

This study investigated the technology on a prototype scale for a variety of European semi natural grasslands and urban green cut biomasses. The quality of the derived energy carriers and the parameters influencing these qualities were in the research focus. In addition, the IFBB system was compared to other energy recovery systems.