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Suitability of semi-natural grassland biomass for bioenergy production through combustion

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SUITABILITY OF SEMI-NATURAL GRASSLAND BIOMASS FOR BIOENERGY PRODUCTION THROUGH COMBUSTION

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AMDG

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Abbreviations, acronyms and symbols

1. BImSchV	Erste Verordnung zur Durchführung des Bundes-Immissionsschutzgesetzes
ASTM	American Society for Testing and Materials
BMU	Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit
C.A.R.M.E.N.	Centrales Agrar-Rohstoff-Marketing- und Entwicklungsnetzwerk e.V.
CEN	European Committee for Standardization
CHP	combined heat and power
DBFZ	Deutsches Biomasseforschungszentrum
DM	dry matter
EEA	European Environment Agency
EEG	Erneuerbare Energien Gesetz
EIONET	European Environment Information and Observation Network
ENE	east northeast
EU	European Union
EU-25	European Union member states up to 2006
EUE	energy use efficiency
FNR	Fachagentur Nachwachsende Rohstoffe
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
KTBL	Kuratorium für Technik und Bauwesen in der Landwirtschaft
kW_{el}	electrical capacity (kW)
kW_{th}	thermal capacity (kW)
LCA	life cycle analysis / life cycle assessment
MW_{el}	electrical capacity (MW)
MW_{th}	thermal capacity (MW)
m^3_0	cubic meter under normal conditions (pressure of 101.3 kPa, temperature of 273 K)
NO_x	mono-nitrogen oxides: nitric oxide (NO) and nitrogen dioxide (NO_2)
ns	not significant
PCDD	polychlorinated dibenzo-p-dioxins
PCDF	polychlorinated dibenzofurans

SCR	selective catalytic reduction
SNCR	selective non-catalytic reduction
SO_x	sulphur dioxide (SO_2) and sulphur trioxide (SO_3)
TA Luft	Technische Anleitung zur Reinhaltung der Luft
UNEP	United Nations Environment Programme
VDLUFA	Verband Deutscher Landwirtschaftlicher Untersuchungs- und Forschungsanstalten
WSW	west southwest
*	significant at α=0.05
**	significant at α=0.01
***	significant at α=0.001
°N	degrees north latitude
°W	degrees west longitude

1 Introduction

1.1 Bioenergy production as an alternative utilization of semi-natural grassland biomass

Semi-natural grasslands are man-made habitats of high biodiversity. For their conservation they depend on a continued low-intensity agricultural management, but both intensification and abandonment of management threaten their existence in many parts of Europe (Bignal and McCracken, 1996; Ostermann, 1998). In many European regions, they are restricted to marginal sites that are characterized either by hydrological extremes or by difficulties in mechanization, for example small-structured, steep, rocky or tree-covered sites. While many semi-natural grassland communities are low-intensity pastures, others have their origin in hay-making and rely on mowing, rather than grazing, for the preservation of their specific botanical composition (Ostermann, 1998).

Both the high ecological value of semi-natural grasslands and their need for special conservation efforts have been recognized on a European level by including the majority of semi-natural grassland communities as 'habitat types of community interest' in Annex I of the European Habitats Directive (European Council, 1992). The directive places legal obligation on the member states to prevent loss or deterioration of Annex I habitats within designated special areas of conservation, and to report on the total area and conservation status of these habitats in regular intervals. Table 1.1 shows the reported areas for the period of 2001-2006 of those habitat types that are considered to have their origin either exclusively or partly in haymaking, or to be threatened by the abandonment of this practice. In total, they make up about 3.4 million hectares in the EU-25, nearly half of which are situated in the Continental biogeographic region (EIONET, no date). With few exceptions, the future prospects of these habitats were evaluated as 'inadequate' or 'bad' according to the three-category EIONET classification.

One major limitation for an economically viable use of the biomass produced on these grasslands as an animal forage lies in the comparatively late cutting dates that are necessary for preserving their botanical composition. Increasing maturity of grassland biomass leads to increasing fibre contents and decreasing protein contents and digestibility. As nutritional requirements of high-performing ruminants have strongly increased over the last decades, the opportunities of using late-cut grassland herbage as a forage have become severely limited, and alternative uses for this biomass have to be found.

Table 1.1 Reported areas of grassland habitats listed in Annex 1 of the European Habitats Directive in the EU-25.

Habitat type		Habitat area in the EU-25 (km²) (1)							Origin (2)	Threat (3)
		ALP	ATL	BOR	CON	MED	PAN	Sum		
1630	Boreal baltic coastal meadows	–	–	214	15	–	–	229	G, H	–
6210	Semi-natural dry calcerous grasslands / scrubland	1850	2320	228	2065	>2567	134	>9164	G, H	AG
6270	Fennoscandian lowland dry to mesic grasslands	–	–	406	43	–	–	449	G, H	AG
6410	Molinia meadows on calcareous, peaty or clayey-silt-laden soils	214	>389	255	508	>86	83	>1535	H	AG, AH
6420	Mediterranean tall humid grasslands	2	–	–	13	>2456	–	>2471	H	AG
6430	Hydrophilous tall herb fringe communities	>532	>452	130	>672	>539	19	>2344	H	–
6440	Alluvial meadows of river valleys	–	–	–	86	–	553	639	H	–
6450	Northern boreal alluvial meadows	27	–	427	–	–	–	454	H	AH
6510	Lowland hay meadows	1601	>579	196	11154	>883	323	>14736	G, H	AH, AG
6520	Mountain hay meadows	543	11	3	1642	50	8	2257	G, H	AH, AG
6530	Fennoscandian wooded meadows	–	–	53	–	–	–	53	G	AG, AH
Sum		>4769	>3751	1912	>16199	>6581	1120	>34332		

(1) Assessments on the conservation status of habitat types and species of Community interest carried out in the EU-25 for the period 2001-2006, compiled as part of the Habitats Directive - Article 17 reporting process. (EIONET, no date); Biogeographic regions - ALP: Alpine; ATL: Atlantic; BOR: Boreal; CON: Continental; MED: Mediterranean; PAN: Pannonic.

(2) adapted from Ostermann (1998); G: origin in grazing; H: origin in haymaking; C: origin in crops.

(3) adapted from Ostermann (1998); AG: threatened by abandonment of grazing; AH: threatened by abadonment of hay-making; other threats not considered here

With the now widely acknowledged need to reduce greenhouse gas emissions and fossil fuel consumption, and ambitious targets for increasing the share of renewable energy in the EU (European Parliament and European Council, 2009), bioenergy generation emerges as a promising new utilization for semi-natural grassland biomass. Using grassland biomass not currently needed as a forage, this strategy has the advantage of avoiding competition between bioenergy and food production. In contrast to many other bioenergy options, it also does not lead to a conflict, but rather to a synergy with nature conservation aims. However, it first has to be established that the bioenergy use of semi-natural grassland biomass actually leads to net energy production and net greenhouse gas savings. While semi-natural grassland biomass production involves low inputs compared to many dedicated bioenergy crops, biomass yields are also much lower. Hay moreover has a low energy density, which may lead to high energy costs if transport is necessary. A life cycle assessment (LCA) quantifying energy inputs and outputs as well as greenhouse gas emission savings is therefore the first step in evaluating the suitability of semi-natural grassland biomass for bioenergy generation.

1.2 Potential conversion technologies for semi-natural grassland biomass

A suitable conversion technology for semi-natural grassland biomass must be adapted to deal with the biomass quality that results from low-intensity management, notably the high proportion of the lignocellulosic cell wall fraction. As the low energy density leads to high transportation costs, and the often scattered occurrence of semi-natural grasslands poses considerable logistic challenges, small-scale and decentralized technologies should also be preferred.

In Germany and Austria, anaerobic fermentation for biogas generation is currently the quantitatively most important conversion technology for grassland biomass. However, the majority of currently existing biogas plants are not particularly well adapted to the utilization of more mature grassland biomass. Not only does a larger fibre content lead to reduced substrate-specific methane yields, it also has negative effects on the technical process. High fibre contents necessitate more stirring and thus lead to higher electricity use; they also increase abrasions of the feeding and stirring equipment (Prochnow *et al*., 2009b). These effects limit the proportion of fibre-rich substrates that can be used in conventional agricultural biogas plants. An additional problem exists in the difficulty of ensiling very mature grassland herbage.

Technologies more suitable for converting lignocellulosic biomass include combustion, thermochemical gasification, pyrolysis and generation of lignocellulosic ethanol (Faaij, 2006;

Sims *et al*., 2010). Gasification allows the generation of heat and electricity, or the production of hydrogen, methanol, Fischer-Tropsch liquids or synthetic natural gas from the syngas. Due to the lack of efficient small-scale gas cleaning equipment and consequently high fuel quality requirements of smaller-scale gasifiers, only large-scale plants of capacities well exceeding 10 MW_{th} are currently of practical relevance. Pyrolysis consist in converting biomass to charcoal, liquid and gaseous fractions at temperatures of about 500 °C in the absence of oxygen. Like hydrolysis of lignocellulosic biomass for ethanol production, it has as yet not been practically implemented on a meaningful scale (Faaij, 2006; Sims *et al*., 2010). Combustion, on the other hand, is a comparatively well established technology with a wide range of capacities being available. Herbaceous biomass of similar properties as semi-natural grassland, such as cereal straw and perennial energy grasses, is already extensively being used as fuels. From the general suitability for using lignocellulosic fuels, the advanced stage of technical development and the availability of small-scale facilities, combustion seems currently the most promising bioenergy conversion technology for semi-natural grassland biomass, and therefore is the focus of this thesis.

1.3 Combustion technology for semi-natural grassland biomass

The basic layout of a combustion appliance is determined by the physical dimension, the form and size distribution, the bulk and particle density, as well as the moisture and ash content of the intended fuel (van Loo and Koppejan, 2008). In all these properties, grassland biomass is very similar to other herbaceous biofuels. Technologies for small- to medium-scale combustion of herbaceous biofuels in the range of some few kW_{th} to about 20 MW_{th} include pellet-fired systems, whole-bale combustion furnaces and grate furnaces.

Pellet-fired systems for residential use are available in capacities starting at 2.5 kW_{th} and offer a high degree of user convenience (Hartmann *et al*., 2009ab). Though wood pellets are at present the most common fuel used, pelletizing is an attractive option for herbaceous biofuels as well, as it increases energy density, lowers transportation costs and facilitates fuel feeding into the burner. It is, however associated with additional monetary and energy costs (Hartmann and Witt, 2009). Thek and Obernberger (2004) calculated the production costs of wood pellets from sawdust in a large-scale pellet production plant to be 79.6-94.6 € per tonne pellets, at an energy expenditure of 460-617 MJ per tonne, or about 2.6-3.6% of the gross calorific value. Whole-bale combustion furnaces are semi-continuous systems, into which bales are fed manually. Their batch-wise operation presents a problem as it results in temperature and CO emission peaks which cannot be adequately controlled by current process control systems (Hartmann *et al*., 2009b). Grate furnaces are suitable for fuels with varying particle sizes and high moisture or ash contents. Although small appliances starting at about 50 kW_{th} exist, grate furnaces are also used in combustion plants of 20 MW_{th} or more (van Loo and Koppejan, 2008; Hartmann *et al*., 2009b). Most commonly used for fuels like wood chips or bark, grate furnaces have also been adapted for herbaceous fuels. These can be automatically fed either as briquettes or loose, with a preceding bale cutter or shredder.

Pulverized fuel and fluidized bed combustion are further technologies, which only become relevant at larger plant sizes for economic reasons. In pulverized fuel combustion, fuel of maximum particles sizes of 10-20 mm is pneumatically injected into the furnace together with the primary combustion air. Capacities range from 1 MW_{th} to several hundred MW_{th}. The upper range is represented by pulverized coal-fired boilers, in which co-combustion of biomass fuels is possible. In fluidized bed combustion systems, starting at about 20 MW_{th}, the fuel is mixed with an inert, granular bed material. The bed is fluidized by the primary combustion air that enters the furnace from below. Mixtures of fuels can be burned, but particle size should not exceed 40-100 mm (van Loo and Koppejan, 2008; Hartmann *et al*., 2009).

Production of electricity as well as heat from biomass is possible in combined heat and power (CHP) plants. Stirling engines for small-scale power production are currently in the pilot and development phase, but as they require very clean flue gas, they are not suitable for herbaceous biofuels. Among proven technologies, steam piston engines are available for smaller CHP plants, starting at capacities of 25 kW_{el} with electrical efficiencies of 4-7%. Steam turbines are typically used in large-scale CHP plants of 500 kW_{el} to 500 MW_{el}. Electrical efficiencies rise from <15% in small steam turbines to up to 40% in large ones. High electrical efficiencies, however, are linked to high steam pressure and temperature, which can lead to substantial superheater corrosion and fouling problems in biomass-fired plants (Baxter *et al*., 1998; Faaj, 2006; van Loo and Koppejan, 2008).

In general, all the described combustion technologies are well suited to deal with the physical characteristics of herbaceous biofuels, in the case of fluidized bed and pulverized combustion