OBERNBERGER Ingwald, SUPANCIC Klaus, 2009: Possibilities of Ash Utilisation from Biomass Combustion Plants.
In: Proceedings of the 17th European Biomass Conference, June 2009, Hamburg, Germany, ISBN 978-88-89407-57-3, pp. 2373-2384, ETA-Renewable Energies (Ed.), Florence, Italy

POSSIBILITIES OF ASH UTILISATION FROM BIOMASS COMBUSTION PLANTS

Obernberger I.[1,2,3], Supancic K.[1]
[1]BIOS BIOENERGIESYSTEME GmbH, Inffeldgasse 21b, A-8010 Graz, Austria
Tel.: +43 (0)316 481300 12, Fax: +43 (0)316 481300 4; E-mail: obernberger@bios-bioenergy.at
[2]Institute for Process and Particle Engineering, Inffeldgasse 21b, A-8010 Graz, Austria
[3]BIOENERGY2020+ GmbH, Inffeldgasse 21b, A-8010 Graz, Austria

ABSTRACT: In recent years the thermal utilisation of solid biomass for heat and electricity production has increased substantially in Austria and the European Union. The promotion of energy production from biomass has also led to a strong increase in the amount of combustion residues, i.e. ashes. At present, a large fraction of the biomass ashes produced is disposed of in landfills.

Ash from natural solid biomass fuels contains valuable plant nutrients such as K, P, Mg and Ca, but also contains significant amounts of heavy metals, which have to be considered for the utilisation strategy applied. Therefore, only the nutrient rich and rather heavy metal poor fractions (bottom ash and coarse fly ash) shall be used for fertilising and soil improvement purposes. The heavy metal rich fine fly ash fraction, which represents the smallest fraction, must be industrially utilised or disposed of. Apart from the sustainable recycling of biomass ash to the soil other promising ash utilisation methods like the use in road and civil construction, the use in landscaping or the use as an additive in industrial processes like cement production exist today.

Some of these ash utilisation strategies are already implemented to some extent in European countries (e.g. Sweden, Finland, Austria and Germany). However, their widespread application is currently impeded by missing or insufficient legal regulations, logistic, technical and economic problems as well as a lack of knowledge and training of the plant operators and farmers.

As a conclusion, legal regulations need to be revised based on the research results available in order to establish framework conditions for the environmentally compatible, economically efficient and practicable utilisation of wood ash. In addition, more research is needed into alternative ash utilisation strategies (e.g. use of ash in short rotation coppice plantations, in forest road construction, utilisation of the fly ash fraction) in order to extend the paths of possible ash utilisation and thus decrease the amount of biomass ash disposed of in the future.

Keywords: ashes, biomass, heavy metals, sustainability.

1 INTRODUCTION AND OBJECTIVES

In recent years the thermal utilisation of solid biomass for heat and electricity production has increased substantially in Austria and the European Union. The promotion of energy production from biomass has also led to a strong increase in the amount of combustion residues, i.e. ashes. At present, a large fraction of the wood ashes produced are disposed of in landfills. Finding ways to utilise these ashes in an environmentally and economically efficient manner is thus an important goal throughout Europe, considering their content of valuable nutrients and their physical properties, which makes ash utilisation in agriculture, forestry and in the construction industry an interesting option.

A limiting factor for the use of wood ash is its content of heavy metals and, to a lesser extent, organic pollutants. However, several promising strategies for utilising wood ashes have been developed in Austria and several other European countries in recent years but have scarcely been implemented in practice. This is due to the fact that not all ecological, logistic, technical, and economic aspects have been covered and investigated yet and that sufficient legislation is still lacking to a large extent.

The main purpose of the work presented in this paper was on the one hand the evaluation of strategies currently available for wood and other biomass ash utilisation and the identification of current barriers for increased implementation of these strategies, and on the other hand the specification of necessary further R&D activities and changes in the legal and economical constraints required to increase the implementation of environmentally compatible, economically efficient and practicable strategies for ash utilisation in Austria and the European Union.

2 METHODOLOGY

A comprehensive investigation of research already performed on ash characterisation and utilisation in Austria and other European countries has been carried out in order to summarise and evaluate the state-of-the-art and science concerning existing strategies for biomass ash utilisation. In addition, interviews with experts and plant operators have been performed with the aim to identify the current state of the implementation of ash utilisation strategies. Based on the results of this investigation, ecological, logistic, technical, economic and legal problems which currently impede an increased implementation of ash utilisation in practice and measures to improve the current situation were identified.

3 RESULTS

3.1 General Overview

In 2007 the primary energy demand of solid biomass in Austria amounted to approx. 213 PJ [1]. Close to 80% of the total demand (169 PJ) were mainly covered by ligneous (forest residues, residues from the wood processing industry, short rotation coppice) and to a small extent also from herbaceous (straw, grass, energy crops) biomass fuels. The thermal utilisation of these fractions resulted in 350,000 tons of ash, whereas 295,000 tons were generated in large-scale applications (district heating plants, process heating plants, combined heat and power plants). According to the latest statistics [2] almost 50% (170,000 tons) of the ash were disposed of in landfills in 2007. Since the ash from small-scale applications (ovens, residential heating units) is usually disposed of together with municipal waste, the total amount of ash which is disposed of might be even higher.

In comparison, the total amount of solid biomass (including municipal waste and sewage sludge) used for energy production in the EU-27 amounted to 3,410 PJ in 2005 [3]. Assuming a share of ligneous and herbaceous biomass in the total primary renewable energy demand similar to Austrian conditions (about 80%), the annual amount of ash from biomass combustion plants in the EU-27 would amount to approx. 5.6 million tons.

In the EU, several political measures have been initiated with the aim of supporting the utilisation of renewable energies with the new directive on the promotion of the use of energy from renewable sources (June 2009) as the latest and most important example. The ambitious targets set in the directive are:

- 20% renewables by 2020
- 20% reduction of greenhouse gas emissions by 2020
- 20% increase of energy efficiency
- 10% increase in biofuels by 2020

The binding target of 20% renewables by 2020 will further increase the utilisation of biomass fuels. Assuming that the EU 2020 targets will be achieved, the primary energy consumption from biomass should be more than doubled in 2020 to some 7,540 PJ. This would lead to an annual amount of biomass ash in the EU-27 of approx. 15.5 million tons in 2020. These values underline the importance to promote ecologically and economically efficient ash utilisation paths in Austria and Europe.

It's commonly known from several studies performed in different European countries [4, 5, 6, 7, 8, 9, 10] that ash from the combustion of natural solid biomass contains valuable plant nutrients such as K, P, Mg and Ca.

Ash recycling to agricultural or forest land can therefore help to reduce the use of artificial fertilisers and to close the natural mineral cycle. However, biomass ash also contains significant amounts of heavy metals (due to environmental pollution by heavy metal depositions on the agricultural and forest ecosystem by air and rain), which have to be considered for the utilisation strategy applied. Tables I, II and III show the typical contents of nutrients and heavy metals in ash from the combustion of different biomass fuels in fixed bed furnaces in Austria.

Table I: Nutrient and heavy metal contents of ash from the combustion of bark in fixed bed furnaces in Austria [7]

Explanations: BA… bottom ash, CFA coarse fly-ash, FFA … fine fly ash

Parameter		BA	CFA	FFA
CaO	[% TS]	42.5	42.9	26.4
MgO	[% TS]	6.3	6.1	4.5
K_2O	[% TS]	5.7	6.1	22.7
P_2O_5	[% TS]	2.1	2.4	1.2
Cu	[mg/kg]	125.3	161.6	151.9
Zn	[mg/kg]	422.5	3,024.1	6,828.3
As	[mg/kg]	6.4	10.6	31.2
Ni	[mg/kg]	62.8	65.6	72.7
Cr	[mg/kg]	82.4	91.2	87.1
Pb	[mg/kg]	10.9	62.7	218.5
Cd	[mg/kg]	1.8	21.3	36.7

Table II: Nutrient and heavy metal contents of ash from the combustion of wood chips in fixed bed furnaces in Austria [7]

Explanations: BA… bottom ash, CFA coarse fly-ash, FFA … fine fly ash

Parameter		BA	CFA	FFA
CaO	[% TS]	46.0	46.8	18.1
MgO	[% TS]	7.6	7.1	2.8
K_2O	[% TS]	6.1	6.2	22.0
P_2O_5	[% TS]	2.2	2.5	0.4
Cu	[mg/kg]	147.7	195.4	174.6
Zn	[mg/kg]	452.9	2,464.3	5,849.8
As	[mg/kg]	5.8	9.2	31.5
Ni	[mg/kg]	56.6	89.1	67.8
Cr	[mg/kg]	168.3	140.7	116.0
Pb	[mg/kg]	15.4	70.5	258.8
Cd	[mg/kg]	2.0	20.9	32.9

Table III: Nutrient and heavy metal contents of ash from the combustion of straw in fixed bed furnaces in Austria [5]

Explanations: BA… bottom ash, CFA coarse fly-ash, FFA … fine fly ash

Parameter		BA	CFA	FFA
CaO	[% TS]	7.9	3.7	1.2
MgO	[% TS]	4.4	1.9	0.7
K_2O	[% TS]	14.3	10.1	48.2
P_2O_5	[% TS]	2.2	1.4	1.2
Cu	[mg/kg]	17.0	13.6	44.0
Zn	[mg/kg]	75.0	77.0	520.0
As	[mg/kg]	<5.0	27.9	22.0
Ni	[mg/kg]	4.0	11.9	<2.5
Cr	[mg/kg]	13.5	9.1	6.8
Pb	[mg/kg]	5.1	11.4	80.0
Cd	[mg/kg]	0.2	0.8	5.2

The tables show significant differences in the nutrient and heavy metal content between bottom ash (from the combustion chamber), coarse fly ash (fly ash from the boiler and fly ash precipitated in multi-cyclones or other precipitators based on gravitational forces) and fine fly ash (fly ash precipitated in electrostatic precipitators or baghouse filters).

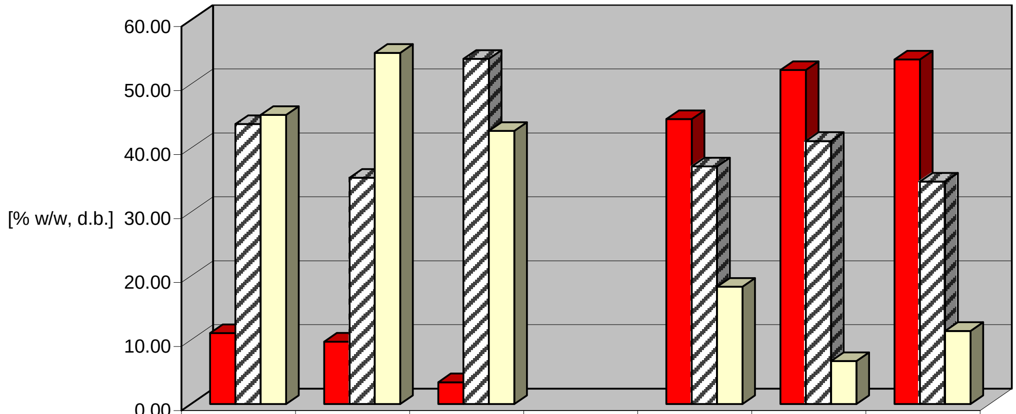
Especially the content of volatile heavy metals such as Zn, Pb and Cd increases with decreasing particle size. Table IV shows the weight distribution of the individual biomass ash fractions from fixed bed furnaces.

Table IV: Average weight distribution of the individual biomass ash fractions from fixed bed furnaces [4, 5]

Fuel/Ash fraction	Bark	Wood chips	Straw
		% w/w, d.b.	
Bottom ash	65 – 85	60 – 90	80 – 90
Coarse fly ash	10 – 25	10 – 30	2 – 5
Fine fly ash	2 – 10	2 – 10	5 – 15

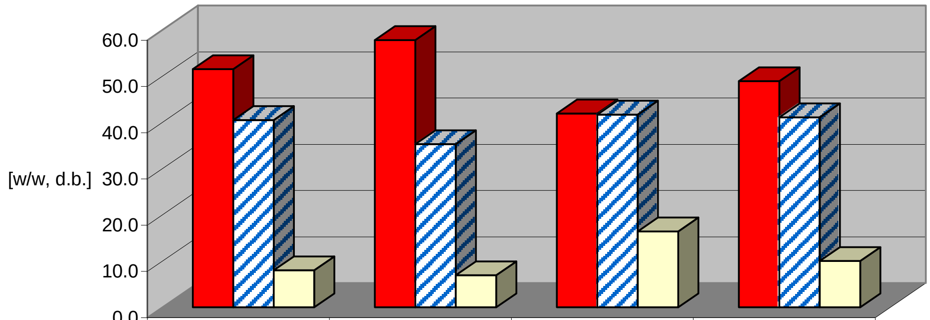
The bottom ash usually accounts for 60 to 90% and the coarse fly ash for 2 to 20% of the total ash generated, whereas the fine fly ash fraction amounts only to 2 to 15%. Considering the heavy metal contents and the weight distribution of the individual ash fractions, it is obvious that volatile heavy metals are concentrated in the fine fly ash fractions (see Figure 1).

Figure 1: Average distribution of selected highly volatile (left) and least volatile (right) heavy metals among the individual ash fractions from the combustion of ligneous biomass in fixed bed furnaces [11]



	Zn	Pb	Cd		Cu	Ni	Cr
Bottom ash	11.1	9.7	3.4		44.5	52.2	53.8
Coarse fly ash	43.7	35.4	53.9		37.1	41.1	34.8
Fine fly ash	45.2	54.9	42.7		18.3	6.7	11.4

Figure 2: Average distribution of nutrients among the individual ash fractions from the combustion of ligneous biomass in fixed bed furnaces [11]



	Ca	Mg	K	P
Bottom ash	51.5	57.8	41.9	48.9
Coarse fly ash	40.5	35.3	41.7	41.1
Fine fly ash	8.0	6.9	16.4	10.0

The contents of Cadmium (Cd) and to a lesser extent Zink (Zn) are usually the most problematic in terms of environmental impacts. Based on the current state-of-the-art about 35 to 65% of the total amount of Cd and 35 to 55% of Zn in the ash is concentrated in the fine fly ash fraction.

Under consideration of the nutrient and heavy metal concentrations and distributions among the different ash fractions (see Figure 1 and Figure 2) it seems reasonable to recycle the bottom ash or a mixture of bottom and coarse fly ash (proportional to the actual amount generated at the combustion/CHP plant) to soils. The utilisation of bottom ash only has the advantage of lower heavy metal concentrations but the disadvantage of higher nutrient losses (due to the cut-off of both fly ash fractions only about 40 to 60% of K, P and Mg can be used sustainably). If a mixture of bottom ash and coarse fly ash is utilised, a better closure of the nutrient cycle can be achieved but the heavy metal concentrations in the ash utilised rise, too.

In Austria, the average heavy metal content of bottom ash or a mixture of bottom ash and coarse fly ash usually complies with the limits set in the Austrian guidelines for the appropriate application of biomass ash on agricultural and forest land [16, 17] (see Table V).

The values in Figure 1 show that an efficient fractionation of the environmentally most relevant heavy metals in biomass ashes is possible by separating the fine fly ash fraction or both fly ash fractions from the other ash. The heavy metal rich fine fly ash fraction shall be collected separately and used in industrial processes or disposed of in landfills in any case.

Apart from the type of ash, the chemical composition of the ash is also determined by the fuel type. Straw ashes generally feature lower heavy metal contents (due to significantly shorter rotations periods, higher pH values of and lower heavy metal depositions on agricultural soils, a lower heavy metal uptake occurs) and higher contents of K_2O. Furthermore, in contrast to ashes from ligneous fuels, where Ca is the main ash forming element, straw ashes mainly consist of Si (not shown in the tables).

The high amount of Ca in wood and bark ashes leads to a high pH-level of the ash (usually > pH 12), which makes it a suitable material for liming.

Furthermore, the high Ca content makes bottom ashes from ligneous biomass a suitable alternative for marlstone in the cement production process. Fly ash fractions, which have similar Ca contents, contain higher amounts of Cl and are therefore less suitable for the cement production process, since Cl causes corrosion of steel beams in reinforced concrete.

Table V: Average heavy metal contents of bottom ash and a mixture of bottom and coarse fly ash in comparison with Austrian guiding values for biomass ash application on agricultural and forest soils [5, 7]
Explanations: WC … wood chips; Limits … limits according to the Austrian guidelines for appropriate biomass ash application on agricultural and forest soils [15, 16]

Parameter		Bark	WC	Straw	Limits
		Bottom ash			
Cu	[mg/kg]	125.3	147.7	17.0	250
Zn	[mg/kg]	422.5	452.9	75.0	1,500
As	[mg/kg]	6.4	5.8	<5.0	20
Ni	[mg/kg]	62.8	56.6	4.0	100
Cr	[mg/kg]	82.4	168.3	13.5	250
Pb	[mg/kg]	10.9	15.4	5.1	100
Cd	[mg/kg]	1.8	2.0	0.2	8
		Mixture of bottom ash and coarse fly ash			
Cu	[mg/kg]	133.2	161.9	16.9	250
Zn	[mg/kg]	991.3	1,049.7	75.1	1,500
As	[mg/kg]	7.3	6.8	5.9	20
Ni	[mg/kg]	63.4	66.2	4.3	100
Cr	[mg/kg]	84.3	160.1	13.3	250
Pb	[mg/kg]	22.3	31.8	5.4	100
Cd	[mg/kg]	6.0	7.6	0.2	8

Ashes from fluidised bed furnaces usually show lower contents of nutrients and heavy metals, since the ash is diluted by the bed material (usually SiO_2), which is to some extent discharged with the ash.

Independent from the fuel source, the fertilising value of the ash is considerable [12]. Based on actual fertiliser prices [13, 14] and the average nutrient contents the fertilising value of biomass ashes is between 216 (straw) and 241 €/t (wood chips). Considering only the nutrient fraction available for plants in the short term [4], the value is still between 148 €/t for straw and 164 €/t for wood chips (see Table VI).

The possibilities to utilise biomass ash in an ecologically and economically reasonable way as well as the current legal framework conditions and still existing barriers for increased ash utilisation are discussed in the following section.

3.2 Possibilities of Ash Utilisation from Biomass Combustion Plants – Current State of Development

Based on the chemical and physical properties of biomass ashes, different utilisation paths are possible, which can be classified in sustainable and other options.

Sustainable ash utilisation

- Utilisation as a secondary raw material for fertilising and soil improving measures on agricultural and forest land (direct or indirect application).

Other ash utilisation options

- Utilisation in road construction.
- Utilisation in landscaping.
- Utilisation in industrial processes.
- Disposal (not discussed).

3.2.1 Ash Utilisation on Agricultural and Forest Land

Since a sustainable utilisation of biomass ashes should be the first priority, this paper mainly focuses on the possible ways to recycle the ash to agricultural or forest land in order to reduce the use of artificial fertilisers and to close the natural mineral cycle as good as possible.

Figure 3 gives an overview of possible sustainable ash utilisation paths.

Comprehensive research has been performed in Austria on the utilisation of biomass ash since the early 1990's [4, 5, 6, 7, 15]. The research activities focused on the characterisation of the different ash fractions (bottom ash, coarse fly ash, usually collected in cyclones, and fine fly ash, usually collected in electrostatic precipitators or baghouse filters) as well as on their environmentally compatible, economically efficient and practicable utilisation on agricultural and forest land. In this respect, direct and indirect application methods (direct application with spreading devices, indirect application via compost production) as well as the ash treatment technologies required for the individual applications were investigated in detail.

The following general principles for a sustainable ash utilisation arise from the results of the research activities already performed in Austria:

- Bottom ash or a mixture of bottom and coarse fly ash proportional to the actual amount generated at the combustion plant shall be recycled to agricultural or forest land in order to contribute to a closure of the mineral cycle. Since the combustion of straw and other herbaceous fuels leads to ashes with high nutrient and low heavy metal contents (compared to ash from ligneous fuels), a mixture of bottom ash and coarse fly ash shall be used in any case. If possible, the ash should be returned to the soil where the fuel has been cultivated (i.e. wood ash to forest land, ash from straw and other herbaceous fuels to grass or agricultural land).

Table VI: Nutrient value of biomass ash (mixture of bottom ash and coarse fly ash) based on current fertiliser prices
Explanations: sources: nutrient contents [5, 7], plant availability [4], fertiliser prices [13, 14]; PAN ... related to plant available nutrients

	Content (% w/w)								Value [€/t]	
Fuel source	P_2O_5	avail.	K_2O	avail.	MgO	avail.	CaO	avail.	total	PAN
Bark	2.1	10%	5.8	95%	6.3	60%	42.6	100%	216	148
Wood chips	2.3	10%	6.1	95%	7.3	60%	46.2	100%	241	164
Straw	2.2	10%	14.4	95%	4.3	60%	7.7	100%	217	154
Price [€/t] (Jan. '09) pure nutrient	1,790.0		791.0		1,270.0		124.0			

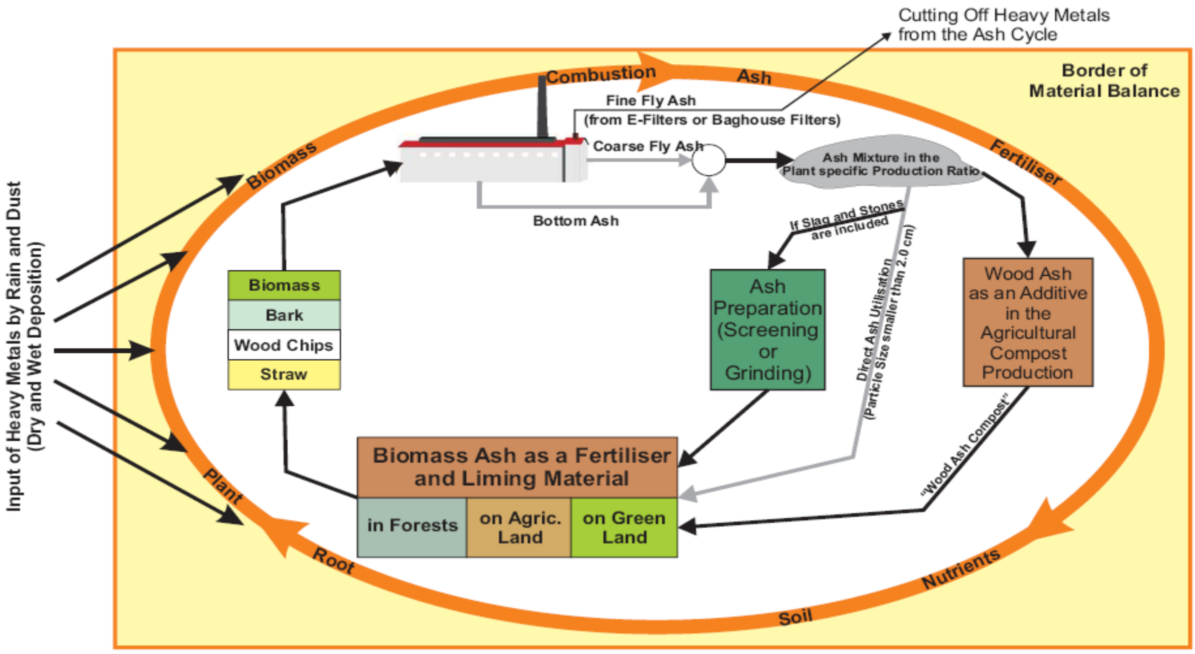


Figure 3: Principle of sustainable ash utilisation paths for ashes from biomass combustion plants

- Fine fly ash, which represents the smallest and heavy metal richest ash fraction, shall be utilised in industrial processes (e.g. heavy metal recovery) or disposed of.
- The cut between coarse and fine fly ash is the ecologically and economically most efficient. Therefore, modern biomass combustion/CHP plants shall be equipped with a two-stage dust precipitation system (cyclone and filter) and an applicable ash handling system to allow the separate collection of the different fly ash fractions.
- Only ash from the combustion of natural biomass fuel sources can be used for fertilising and soil improvement purposes. Ashes from the combustion of waste wood or chemically treated wood must not be applied on soils due to their high heavy metal contents.
- In the late 1990's, based on 4 year application trials performed on agricultural and forest soils [4], the expert advisory committee for soil fertility and soil protection of the Austrian Ministry of Agriculture, Forest, Environment and Water issued guidelines for the appropriate ash application on agricultural and forest land [16, 17], which define limits for heavy metals, quantity limits for ash application as well as general requirements and recommendations for an appropriate ash utilisation (see chapter 3.2.1.2 for more details).

In other countries like Germany, Sweden and Finland the utilisation of biomass ash mainly focuses on the application on forest soils. Increased whole tree processing, where also harvesting residues and the crown foliage (containing the highest nutrient concentrations) are removed from the forest, makes compensation fertilising with wood ash a reasonable way to avoid nutrient depletion in forest soils.

In Germany, the forest research agency of Baden-Württemberg (Forstliche Versuchs- und Forschungsanstalt Baden-Württemberg, FVA) developed in cooperation with the University of Freiburg a concept to recycle wood ash to forest soils ("Holzaschekreislaufkonzept") based on the liming and fertilising requirements of individual forest areas [8]. In this concept, areas for wood ash application are selected based on the information available from a state-wide model predicting the base saturation and other relevant parameters of forest soils. Ash is applied on forest soils with low base saturation in order to increase the pH-level. Only bottom ash in a mixture with lime (30% w/w ash) in order to reduce the reactivity of the ash, is used (see chapter 3.2.1.1 for more details).

Since 1998, the Swedish Forest Agency has recommended ash recycling after extraction of forest fuels. According to the Swedish Forest Agency, until 2010 the total area being treated with wood ash shall be at least as large as the area from which harvest residues (forest fuels) are collected in connection with clear cutting. Nevertheless, most wood fuel ash is still disposed of in landfills [18].

Lack of knowledge and training of plant operators were identified as the main barriers for regular ash recycling to forest land. In addition, many ash utilisation strategies have not been evaluated in detail yet and sufficient legal and technical guidelines are missing.

Two large research programs, the RecAsh-Project (2003-2006, Finland and Sweden) and the Askprogrammet (since 2002 in Sweden), were therefore carried out within the last few years. The RecAsh project [18] demonstrated the economically and ecologically sustainable wood ash utilisation on forest land. The results show that the application of properly treated ash (see next chapter for details), which meets the recommendations of the Swedish Forest Agency regarding minimum nutrient and maximum heavy metal contents, on forest soils can improve forest growth and contributes to the recycling of forest nutrients (except for Nitrogen). The project findings resulted in the preparation of an ash recycling handbook, which shall help plant operators and forest owners to select the appropriate ash treatment and application methods for ash recycling on forest lands.

Askprogrammet [19] deals with other possible options for an environmentally friendly utilisation of non-coal ashes (see below for more details).

3.2.1.1 Ash Treatment

The application of ashes on agricultural or forest land requires an appropriate ash treatment in order to meet the requirements of the ash application process selected. The following tasks have to be considered prior to the application [15]:

- Proper mixture of the usable ash fractions (if a mixture is necessary/planned).
- Preferably dust free ash handling. Avoidance or minimisation of dust formation during ash handling.
- Appropriate dimensioning of the ash storage facilities at intermediate storage sites is usually necessary (the main application period is in spring/summer, so enough storage capacity is needed to store the ash produced during the rest of the year).
- The ash must be provided in a spreadable particle size (i.e. free of slag and other particles larger than 1.5 to 2 cm) if direct ash application on soils is planned. Subsequently, a screening of the ash and also a metal precipitation are usually necessary (except for indirect application).
- Preparation of the treated ash for transport (big bags, silo wagon etc.).
- Decision between direct or indirect ash application.

A successful Austrian approach features ash treatment (screening and metal precipitation) directly at the plant followed by spreading on agricultural land with equipment used for lime spreading (demonstration project in Maria Alm, Salzburg, for more than 10 years ongoing and also replicated in other plants).

Apart from screening and metal precipitation various other treatment methods (e.g. milling, pelletising or elutriation) are performed. In Sweden and Finland the ash is often stabilised in order to make it as homogeneous as possible, to minimise the proportion of fine fractions and to reduce the reactivity of the ash. The wetting and aging of the ash leads to a carbonisation (CaO reacts to $Ca(OH)_2$ and further to $CaCO_3$), which leads to a reduction of the pH-level. Alkaline shock effects on ground vegetation can thus be prevented [18]. Stabilisation is usually performed by mixing the ash with water in a mixer (e.g. cement mixers) to achieve a moisture content of 15 to 40% (w.b.). The wetted ash is spread on a paved surface, where it is allowed to self-harden. After two to four months (depending on the weather conditions and the ash properties) the hardened ash is crushed and screened before being applied to forest land.

In 2008 a research and development project based on the wood ash recycling concept of the FVA started in Germany, where the suitability of a mixture of lime (70% d.b.) and wood ash (30% d.b., bottom ash only) as a liming and fertilising agent for forest soils is tested. The particle size of the ash is first reduced and homogenised by crushing. In a second step the pre-treated ash is mixed with the lime and some water (2 to 10% w/w, w.b.). First results show, that the application of a mixture of lime and wood ash on forest soils is technically feasible and economically and ecologically reasonable [20].

Granulation and pelletising of ash are other ash pre-treatment methods which have been already tested [12, 18]. Both methods yield a more uniform (i.e. easily spreadable) and less reactive product compared to untreated ash. The costs for both methods are, however, higher compared to other treatment methods like screening or stabilisation. So additional research and development is needed in order to optimise the process technology and reduce costs.

3.2.1.2 Direct Ash Application

The methods of direct ash application vary depending on whether the ash is spread on agricultural or forest land and on the topographic conditions of the area to be fertilised.

The direct application on agricultural land can be performed by conventional fertiliser spreading equipment. However, since fertiliser spreaders are not optimised for the application of ash, problems like the erosion of the spreading devices and the generation of dust during application can occur. Therefore, a comprehensive research project was performed in Austria [12] in order to determine suitable ash spreading techniques for biomass ash. Screw spreaders (see Figure 4) and pendulum spout spreaders showed the best results in the comprehensive spreading tests performed and are therefore recommended for ash application on agricultural land.

Figure 4: Ash spreading with a screw spreader [11]

The dissolution of ash in water is not recommended due to high transportation costs (only 10 to 20% w/w, w.b. of ash can be mixed with water in order to keep the mixture spreadable). In addition, the mixture of ash with liquid manure is inadvisable, since the high pH-value of the ash causes N losses (NH_3 emissions).

The direct application of ash on forest land is more difficult since the accessibility to forest roads is often limited. Blowing devices can be used from forest roads but their range is limited to a maximum of 50 m into the forest. In addition, the blowing of ash causes a lot of dust which remains in the air for a long time and thus this application method cannot be used in close proximity to residential areas. In Sweden and Finland [18] as well as in Germany [20] the application of ash to forests is often performed by helicopter (see Figure 5). Global positioning systems (GPS) can be used to determine the route of the helicopter. Based on this system, the pilot can choose the flight route for every spreading trip.

Helicopter spreading is more flexible than ground spreading since it avoids problems concerning the limited accessibility of dense stands or stands with no forest roads as well as the bearing capacity of the soil. Helicopter application can also be a reasonable option on steep slopes or on other rough country conditions where spreading with blowing devices or other ground spreaders is difficult [18]. However, the cost of helicopter spreading is usually higher than for ground spreading. Therefore, further research is necessary to optimise spreading techniques and corresponding logistics in order to make them economically feasible.

Figure 5: Ash spreading by helicopter [17]

The recycling of ash to short rotation coppice plantations is another interesting possibility of direct ash application. International research projects performed in the EU [10, 21] show that the recycling of ash from short rotation coppice to the land where the plants have been grown can be ecologically and economically feasible. However, currently no experience regarding the long term effects of ash application to short rotation coppice plantations is available and not much is known about suitable spreading techniques.

Generally, the installation of easily accessible intermediate storage areas close to the area selected for ash application is recommended [18] in order to reduce transport routes and thus minimising the lag time between filling of the spreading device and ash application.

In addition to the selection of the ash application method, the local regulations regarding ash application need to be considered. As an example, the approach required in Austria for direct ash application based on the current guidelines for ash application on agricultural and forest land [16, 17] is described below:

- Analysis of the nutrient and heavy metal content of the ash prior to the first soil application and repetition of the analysis in regular intervals according to the guideline.
- The maximum quantity of ash applied per ha has to be observed (1,000 kg/ha*a for agricultural land and 750 kg/ha*a for grass land if one or more of the heavy metal limits is reached, respectively higher quantities are allowed if all heavy metal contents are below the limits; 3,000 kg/ha once in 50 years for forest land). The amount of ash to be spread on forest soils was determined by considering the Cadmium balance for the ecosystem wood (since Cd is the most critical heavy metal in biomass ashes) as well as the removal of nutrients after harvesting [22].
- Selection of the appropriate time for ash application.
- Consideration of the ban of ash application for designated areas.
- Selection of areas suitable for ash application (e.g. soils with a low pH-level and/or high nitrogen reservoirs) and consideration of general fertilising guidelines (e.g. determination of the application quantities based on the nutrient demand of the plants to be fertilised).

3.2.1.3 Indirect Ash Application

Besides the direct application of ash on agricultural and forest land, the ash can also be used as an additive in compost production.

Indirect ash application features some advantages compared to a direct application of ash to agricultural and forest land [6]:

- No problems of dust formation.
- No pre-treatment (screening, metal precipitation) of the ash is usually necessary, since these impurities are sorted out during the composting process (turning of compost material at regular intervals).
- The addition of ash can reduce the time required for the composting process and can improve the compost structure.
- An addition of ash to the compost reduces the pH-level of the ash due to the carbonisation process occurring.

The results of research projects performed in Austria [6, 23] show that the addition of 5 to 16 % (w/w, d.b.) of ash is ecologically acceptable depending on the quality of the ash to be utilised. However, according to the Austrian Compost Ordinance the maximum amount of ash to be added is limited to only 2 % (w/w, w.b.), which limits the potential of this utilisation path significantly. Therefore, a change of the regulations, based on the scientific findings mentioned, is urgently necessary.

3.2.2 Ash Utilisation in road construction

Especially bottom ash of wood fuels features latent hydraulic properties (good hydration of wet material in the soil due to pozzolanic properties of the ash) and can therefore be used for road construction (e.g. substitution of gravel), if ash from the combustion of untreated biomass is used. Ash from fluidised bed furnaces with a high SiO_2 content may be used as well.

No specific studies regarding the use of biomass ash in road construction have been performed in Austria yet, but the results from research projects done in Sweden and Finland [19, 24] show that the utilisation of biomass ashes in road construction is possible, considering the following conditions:

- The ash used for road construction must feature respective mechanical and physical (e.g. stability, bearing capacity, frost, mechanical and chemical resistance, permeability) as well as chemical properties (pH-value, leachate behaviour), so regular ash analyses are necessary.
- Depending on the mechanical/physical and

chemical properties, a pre-treatment of the ash might be necessary.

- Bottom and coarse fly ash fractions can be used in road and civil construction (the suitability of fine fly ash fractions has not been analysed in detail yet).

Especially the use of the bottom ash fraction would be beneficial, since bottom ash features good stability, bearing capacity and frost resistance (due to the good latent hydraulic properties). In addition, large particle sizes would not be a problem and therefore crushing and milling of the ash could be avoided.

In practice, the utilisation of biomass ash in road and/or civil construction is not possible in Austria at present, since legal regulations and technical guidelines are missing.

Due to the fact that especially the use of wood and bark ash in the construction of forest roads would bear a great potential for ash utilisation in Austria, research on the ecological impact of the use of wood and bark ash in forest road construction is needed as a basis for appropriate application guidelines.

3.2.3 Ash Utilisation in landscaping

Due to the usually high CaO content of wood and bark ash it can be used instead of lime as a binder for the consolidation of soils [25].

The high pH-level (a consequence of the high CaO content), the relatively high salt content and the high hardness of the ash (bottom or coarse fly ash) yield in combination with other secondary raw materials like sewage sludge an effective barrier for the use of the cover of landfills and mine tailings. This kind of utilisation has already been successfully demonstrated in Sweden [19].

The use of biomass ash in landscaping has not been analysed yet in Austria, and given the currently small potential for this kind of ash utilisation in Austria, it is expected that biomass ash will not be used to a large extent in landscaping in Austria in the near future.

3.2.3 Ash Utilisation in Industrial Processes

The utilisation of biomass ash in industrial processes substitutes materials from non-renewable resources and therefore contributes to their conservation.

However, the utilisation in industrial processes is usually limited to combustion/CHP plants which generate ash in sufficient amounts and relatively constant quality.

There are no results from Austrian research and development projects available on this topic, but there are several examples of biomass bottom ash utilisation in the cement industry. Results of international research activities [19, 26] also show that the utilisation of biomass bottom ash in the cement (e.g. as a substitute for marlstone, which reduces the generation of CO_2 during clinker production) or concrete (as an additive with pozzolanic characteristics) and other construction material industries is technically possible.

The European standard EN 450 (Fly ash for concrete) allows the use of fly ash from coal combustion plants with biomass co-firing. According to EN 450, an addition of biomass up to 20% w/w fuel based and 10% w/w ash based is allowed [27].

3.3 Legal Framework Conditions

Due to the fact that from a legal point of view ash from biomass combustion plants is primarily considered as waste and not as a secondary raw material, the utilisation of biomass ash often implicates legal problems. As an example, the current situation in Austria is briefly described below with a comparison to the situation in other countries in the European Union.

According to the Austrian Waste Management Law, ash from biomass combustion plants is considered as waste with corresponding key numbers for bottom as well as coarse and fine fly ashes in the Austrian Waste Index. In order to classify biomass ash as a secondary raw material, a separate ordinance to the Waste Management Law would be necessary. This has not happened yet and is also not planned in the near future.

Other than the German Fertilising Ordinance, which allows the utilisation of ash as a fertiliser (as long as the rather strict limits for heavy metals shown in Table VII are kept), or the Finish Fertiliser Law, which defines two different types of ashes to be used on agricultural and forest land, respectively (see Table VII), the Austrian Fertiliser Law does not cover any combustion residues and prohibits the use of ash as a fertiliser.

In Denmark, a designated ordinance for the use of biomass ash on agricultural and forest land exists. According to the ordinance, ash from herbaceous fuels shall only be applied on agricultural soils whereas ash from ligneous fuels shall be only applied to forest soils. Mixtures of ash from herbaceous and ligneous fuels can be applied either on agricultural or forest soils (for limits see Table VII). A revision of the ordinance is currently under way.

The Austrian Forest Law and the soil preservation laws of the Austrian Provinces also miss any explicit statements regarding the use of ash as a fertilising or liming agent. However, there is an official comment of the Austrian Ministry of Agriculture, Forest, Environment and Water to the Forest Law, which states that the use of biomass ash according to the guideline for the appropriate use of biomass ash on forest land [16] does not interfere with the regulations of the Austrian Forest Law. Still, local forest authorities may also decide to prohibit the application of biomass ash on forest soils. The Swedish Forest Law contains general guidelines for the application of wood ash on forest soils but there are no legally binding limits for heavy metals.

The current compost ordinance is the only legal regulation in Austria where the use of biomass ash is covered. As already mentioned above, a maximum amount of 2 % (w/w, w.b.) of biomass ash (bottom and coarse fly ash only) can be used as an additive to the compost material. Given the fact that far higher fractions of biomass ash (5 to 16 % w/w, d.b.) are ecologically acceptable, the current situation is not satisfying and needs modification based on R&D results already obtained.

In order to harmonise the application of biomass ashes on agricultural and forest land, the expert advisory committee for soil fertility and soil protection issued two guidelines for the appropriate use of biomass ash on agricultural land [17] as well as on forest land [16] in the late 1990’s. The guidelines contain limits for heavy metals (see Table VII) and individual maximum applicable ash quantities for agricultural and forest land. The guidelines are currently revised and merged to one single guideline. The release of the new guideline for the application of biomass ash on agricultural and forest land is scheduled for the end of 2009.

Table VII: Overview of the limits for heavy metals and nutrients in biomass ash for the application on agricultural and forest lands in Germany, Austria, Denmark, Sweden and Finland

Explanations: Germany: only bottom ash may be used as a fertiliser; limits are not relevant for wood ash which is solely recycled to forest land. Denmark: left Cd limit for straw ash/right Cd limit for wood ash; the limit for Ni is 30 mg/kg, between 30 and 60mg/kg a reduced ash quantity can be applied. Sweden: limits only valid for the application on forest soils. Finland: left values for application on agricultural soils/right values for application on forest soils

	Germany	Austria	Denmark	Sweden	Finland
		in g/kg (nutrients) and mg/kg (heavy metals)			
Nutrients (min.)					
Ca				125	80/60
K				30	K+P 20/10
Mg				15	
P				7	K+P 20/10
Zn				0.5	
Heavy Metals (max.)					
As	40	20		30	25/30
B				800	
Cd	1.5	8	5/15	30	1.5/17.5
$Cr_{(tot.)}$		250	100	100	300
Cu	70	250		400	600/700
Hg	1.0		0.8	3.0	1.0
Ni	80	100	30/60	70	100/150
Pb	150	100	120	300	100/150
Tl	1.0				
V		100		70	
Zn	1,000	1,500		7,000	4,500

In addition to the national guidelines also regional guidelines, which mainly follow the national guidelines exist in some of the Austrian provinces.

The limits for heavy metals and the minimum contents for some nutrients in biomass ashes from selected European countries are listed in Table VII.

Like in Austria, the limits for heavy metals (and minimum contents for some nutrients) in biomass ashes in Sweden are set in a legally non binding guideline (see Table VII).

A comparison of the limits shows that the limits for Cu and Zn of the German Fertiliser Ordinance are rather strict compared to regulations in other countries. Especially the very low limit for Cu prohibits the use of most of the ashes from ligneous fuels (see Table I and II). The low German and Danish limits for Ni would also prohibit the utilisation of ligneous fuels on forest land.

The Swedish limit for Ni may lead to problems for ashes from bark. Another interesting result of the comparison of the guidelines and regulations is the fact that the limits for Zn are significantly lower in Austria and Germany than in Sweden or Finland. The Danish ordinance doesn't even list a limit for Zn. The reason for this difference is based on the fact that Zn is considered rather as a micronutrient than a harmful element in these countries.

3.4 Actual Barriers and Possible Ways to Increase Ash Utilisation

Despite various possible biomass ash utilisation paths analysed and demonstrated in Austria and other European countries, still a large amount of the ash generated in biomass combustion plants is disposed of. In Austria, as already stated above, the fraction of biomass ash which was disposed of in landfills amounted to almost 50% (170,000 tons) in 2007. A similar situation exists in Sweden, where a large fraction of the ash is disposed of or used as a construction material in landfills [28].

This indicates that still problems with the practical implementation of the ash utilisation strategies promoted exist. The comprehensive investigation of the current situation identified the following barriers for wood ash utilisation in Austria, which in large part also apply to other European countries.

3.4.1 Insufficient legislation

Apart from the (legally not binding) guidelines regarding the application of biomass ash on agricultural and forest land, legal guidelines except for the use of biomass ash as an additive in compost production are missing on the federal level in Austria. In addition, legal regulations on provincial levels are also missing or differ from province to province.

Currently biomass ash is not always recognised as a secondary raw material with fertilising and liming properties, which leads to the resistance of authorities to approve biomass ash application on soils.

Only very small fractions (despite the results from several studies indicate otherwise, only 2% of total wet weight are allowed, according to the Austrian compost Ordinance) may be used as an additive in compost production which limits the utilisation potential significantly.

Generally, the lack of sufficient legislation causes uncertainty for plant operators and authorities alike. Furthermore, the guidelines for ash utilisation are too complex and costly (e.g. analyses) for many operators, with the result that often the “easier” way of ash disposal is chosen.

Plant operators in Germany face a different problem. There exists a clear legal regulation with the German Fertiliser Ordinance. But since some of the limits for heavy metals are very strict, especially an utilisation of ligneous biomass ash as a fertiliser is very difficult.

3.4.2 Logistic and technical problems

Usually large storage areas are required since the main part of the ash is often produced during the winter season whereas ash application usually takes place during warmer periods. Therefore, a logistic concept considering intermediate storage sites is necessary.

Differing ash treatment technologies are necessary for individual application technologies so ash treatment and ash utilisation possibilities should already be considered during the design of a biomass combustion/CHP plant.

The lack of application technologies optimised for biomass ash leads to problems at the interface between plant operators and farmers and during application regarding ash logistics and appropriate transport and spreading techniques.

3.4.3 Administrative barriers

In addition to the chemical analysis of the ash a costly soil analysis is required for application on agricultural soils in Austria. In addition, due to the insufficient legislation often a complex approval procedure is required for the application of biomass ash on soils which leads to delays, causing problems with potential users of the ash.

3.4.4 Economic problems

Due to administrative barriers as well as logistic and technical problems ash utilisation is often more expensive than its disposal in landfills.

3.4.5 Lack of knowledge and training of plant operators

Many operators are not aware of the possibilities of ash utilisation and/or lack the knowledge of proper ash treatment necessary for ash utilisation. As a consequence, the ash produced does not meet the requirements for ash utilisation and must therefore be disposed of.

3.4.6 Possible Ways to increase Ash Utilisation

The barriers for widespread ash utilisation discussed above show that improvements and adjustments in different areas are required. Some of them have already been addressed in recent projects like the RecAsh (improvement of the knowledge of plant operators) and the Askprogrammet (diversification of ash utilisation paths, drafting of technical guidelines for the use of ash in construction processes) projects in Sweden or like the wood ash concept of the FVA in Germany (demonstration of the possibility to use wood ash as a fertiliser under the new German Fertilising Ordinance).

Still, especially for Austria but also for many other European countries, several open tasks remain, which need to be addressed as soon as possible in order to further promote the utilisation of biomass ash:

- Performance of further research regarding the utilisation of biomass ash as an additive in compost production in order to define ecologically meaningful ash quantities to be added.
- Ecological evaluation and performance of field tests regarding the utilisation of wood ash on short rotation coppice sites.
- Optimisation of the actual ash spreading techniques of wood ash in forests with regard to economically and technically feasible applications and the necessary logistic concepts.
- Improvement of the process technology and logistics between the operator of the biomass combustion/CHP plant and the user of the ash regarding ash removal, ash treatment, ash storage and ash transport.
- Ecological evaluation and performance of field tests regarding the application of wood ash for the construction of forest roads and other construction related areas (e.g. cement production).
- Revision of existing and initiation of new general legal guidelines for the utilisation of biomass ash on federal and provincial level in order to establish legal certainty for operators and ash users.
- Simplification of the approval process with the introduction of simple analysis procedures, the use of existing data (soil maps) for the approval instead of additional soil analyses as well as standardised web-based monitoring of ash utilisation.
- Intensification of the international exchange of know-how between European countries with the long-term goal to prepare a European guideline for the ecologically and economically feasible use of biomass ash.

A first step towards the intensification of international knowhow exchange has already been taken by organising a workshop in Vienna with international experts from Germany, Sweden and Austria in April 2009. Further exchange of knowledge is planned in the future.

In addition, a large R&D project focussing on the open questions mentioned above towards the achievement of a practicable biomass ash utilisation in the near future is currently under preparation.

4 CONCLUSIONS AND RECOMMENDATIONS

Several promising and ecologically feasible ash utilisation strategies already exist today. The recycling of ash to agricultural and forest land is already implemented to some extend in European countries (e.g. Sweden, Finland, Austria and Germany). However, their widespread application is currently impeded by missing or insufficient legal regulations (leading to a missing legal certainty for plant operators and farmers), logistic, technical and economic problems (complex ash and soil analyses required, large ash storage capacities and ash treatment facilities necessary, lack of ash application technologies optimised for biomass ash) as well as a lack of knowledge and training of the plant operators and farmers.

The use of wood ash as an additive in compost production has been studied since the early 1990's in Austria and seems to be a promising ash utilisation strategy, but the current ecologically and economically unfeasible limiting values for the addition of ash to compost materials in Austria impedes the increased use of ash in this area. Some promising new ash utilisation strategies, like the use of biomass ash as a construction material for roads and covering of mine tailings and landfills have been evaluated recently and bear some potential for biomass ash utilisation. Other new strategies, like the utilisation of ash on short rotation coppice plantations and application technologies like optimised ash application in forests have only insufficiently been investigated yet and need further research.

As a conclusion, legal regulations need to be revised based on the research results available in order to establish framework conditions for the environmentally compatible, economically efficient and practicable utilisation of biomass ash. Furthermore, the international exchange of knowhow between European countries with experience in ash utilisation needs to be intensified. Finally, more research is needed in alternative ash utilisation strategies (e.g. use of ash in short rotation coppice plantations, in forest road construction, utilisation of the fly ash fractions) in order to extend the paths of possible ash utilisation and thus decrease the amount of biomass ash disposed of in the future.

5 REFERENCES

[1] Österreichischer Biomasseverband (Ed.). Das österreichische Energiesystem 2000-2005-2020-2050 (2009). Vienna, Austria

[2] Umweltbundesamt GmbH (Ed.). Die Bestandsaufnahme der Abfallwirtschaft in Österreich, Statusbericht 2008. (2009). Vienna, Austria

[3] European Environment Agency (Ed.). Energy and Environment Report 2008. (2008). Copenhagen, Denmark

[4] P. Ruckenbauer, I. Obernberger, H. Holzner. Erforschung der Verwendungsmöglichkeiten von Aschen aus Hackgut- und Rindenfeuerungen. Endbericht der Projektphase II. (1995). Institut für Pflanzenbau und Pflanzenzüchtung, BOKU Wien, Austria

[5] I. Obernberger, W. Widmann, F. Wurst, M. Wörgetter. Beurteilung der Umweltverträglichkeit des Einsatzes von Einjahresganzpflanzen und Stroh zur Fernwärmeerzeugung; Jahresbericht zum gleichnamigen Forschungsprojekt. (1995). Institut für Prozess- und Partikeltechnik, Technische Universität Graz, Austria

[6] M. Narodoslawsky, I. Obernberger. Die Kompostierung von Holzasche: Erfahrungen und Möglichkeiten. (1994). Tagungsband zum Symposium „Sekundärrohstoff Holzasche – Nachhaltiges Wirtschaften im Zuge der Energiegewinnung aus Biomasse“. Institut für Prozess- und Partikeltechnik, Technische Universität Graz, Austria

[7] I. Obernberger, F. Biedermann, W. Kohlbach. FRACTIO - Fraktionierte Schwermetallabscheidung in Biomasseheizwerken; Jahresbericht zum gleichnamigen ITF-Projekt mit Unterstützung der Bund-Bundesländerkooperation. (1995). Institut für Prozess- und Partikeltechnik, Technische Universität Graz, Austria

[8] Forstwissenschaftliche Fakultät der Universität Freiburg und Forstliche Versuchs- und Forschungsanstalt Baden-Württemberg (Ed.). Holzasche-Ausbringung im Wald, ein Kreislaufkonzept, Berichte Freiburger Forstliche Forschung, Heft 43. (2002). Freiburg, Germany

[9] E. Stahl. Qualität und Verwertungsmöglichkeiten von Holzaschen. Master Thesis. (2006). Lehr- und Forschungsgebiet Abfallwirtschaft, RWTH-Aachen, Germany

[10] M. Johannesson et al. The Market Implication of Integrated Management for Heavy Metals Flows for Bioenergy Use in the European Union, Final Report. (2002). Kalmar University, Kalmar, Schweden

[11] F. Biedermann. Stoffflüsse der Nährstoffe und Scwermetalle in Biomasseheizwerken: Die Bilanzierung Brennstoff- Asche- Rauchgas (1994). Tagungsband zum Symposium „Sekundärrohstoff Holzasche – Nachhaltiges Wirtschaften im Zuge der Energiegewinnung aus Biomasse“. Institut für Prozess- und Partikeltechnik, Technische Universität Graz, Austria

[12] E. Rotheneder. Land- und forstwirtschaftliche Nutzung von Biomasseaschen, Pro Cinis II – Endbericht. (2005) Graz, Austria

[13] AgrarMarkt Austria (Ed.): Marktbericht Getreide und Ölsaaten, Jänner 2009. (2009). Wien, Austria

[14] Hanseatische Umwelt (Ed.): Preisliste für Pholin; http://www.gutshaus-rederank.de/hanse/pdf-dateien/070320_Pholin.pdf, accessed February 19 2009

[15] I. Obernberger, M. Narodoslawsky. Die Bindeglieder Biomasseheizwerk-Bauer-Boden: Aschenaustragung, Aufbereitung und Ausbringung. (1994). Tagungsband zum Symposium „Sekundärrohstoff Holzasche – Nachhaltiges Wirtschaften im Zuge der Energiegewinnung aus Biomasse“. Institut für Prozess- und Partikeltechnik, Technische Universität Graz, Austria

[16] Bundesministerium for Land- und Forstwirtschaft, Fachbeirat für Bodenfruchtbarkeit und Bodenschutz. Der sachgerechte Einsatz von Pflanzenaschen im Wald. (1997). Vienna, Austria

[17] Bundesministerium for Land- und Forstwirtschaft, Fachbeirat für Bodenfruchtbarkeit und Bodenschutz. Der sachgerechte Einsatz von Pflanzenaschen im Acker- und Grünland. (1998). Vienna, Austria

[18] S. Emilsson. International Handbook – From Extraction of Forest Fuels to Ash Recycling. (2006). Swedish Forest Agency, Stockholm, Sweden

[19] C. Ribbing. Environmentally friendly use of non-coal ashes in Sweden; Waste Management 27 (2007)

[20] K. v. Wilpert. Holzasche-Kreislaufkonzept der Forstlichen Forschungs- und Versuchsanstalt Freiberg in Baden.Württemberg. (2009). Presentation at the Workshop „Sinnvolle Nutzung von Holzaschen aus Biomassefeuerungen“ of the FHP Kooperationsplattform Forst Holz Papier, 14th of April 2009 in Vienna, Austria

[21] D. Riddel-Black. et al. Bioremediation and economic renewal of industrially degraded land by biomass fuel crops, Final Report of the EU project BIORENEW. (220). England

[22] M. Narodoslawsky, I. Obernberger. From waste to raw material – the route from biomass to wood ash for cadmium and other heavy metals. Journal of Hazardous Materials 50 (1996) pp. 157-168

[23] T. Kuba. Verwertung von Holzasche als Zuschlagsstoff zu Kompost, Diplomarbeit. (2007). Leopold-Franzens Universität Innsbruck, Austria

[24] P. Lahtinen. Fly Ash Mixtures as Flexible Structural Materials for Low-Volume Roads. (2001). Finnish Road Administration, Helsinki, Finland

[25] S. Hottenroth, B. Hartleitner, W. Rommel, S. Kögl, J. Steinemann. Verwertung von Aschen aus der Biomasseverbrennung – Bioasche als Kalkersatz? (2003). Bayrisches Institut für Angewandte Umweltforschung und Technik GmbH, Augsburg, Germany

[26] S. Wang, L. Baxter. Comprehensive study of biomass fly ash in concrete: strength, microscopy,

kinetics and durability. Fuel Processing Technology 88 (2007)
[27] ÖNORM EN 450, 2005: Flugasche für Beton (Fly ash in concrete). Österreichisches Normungsinstitut (Ed.), Vienna, Austria
[28] C. Ribbing. Environmentally friendly use of non-coal ashes – research and use in Sweden. (2009). Presentation at the Workshop „Sinnvolle Nutzung von Holzaschen aus Biomassefeuerungen" of the FHP Kooperationsplattform Forst Holz Papier, 14th of April 2009 in Vienna, Austria

6 ACKNOWLEDGEMENTS

- The Authors are grateful to Christopher Boman, Anders Evald, Christa Müller, Claes Ribbing and Klaus v. Wilpert for the good cooperation and their support regarding the research for data and best practice examples.

7 LOGO SPACE