Ash Content *vs.* the Economics of Using Wood Chips for Energy: Model Based on Data from Central Europe

Martin Lieskovský,[a] Martin Jankovský,[b,]* Marek Trenčiansky,[c] Ján Merganič,[d] and Jiří Dvořák [b]

Biomass utilization is vital for developing sustainability in the bioenergy sector. In this work the effects of high ash content on the heating properties of wood chips were evaluated. In an analysis of 450 wood chips samples, the ash content, moisture content, and gross calorific value were determined, and a generalized linear model was created to identify the relationship between the gross calorific value and the ash content of the wood chips. The mean ash content of the analyzed wood chips samples was 2.64%, the mean moisture content was 38.8%, and the mean gross calorific value was 19.43 MJ kg^{-1}. Statistical analyses showed that 49% of the gross calorific value variability was due to the ash content variability. A one percent increase in ash content resulted in a 0.11 MJ kg^{-1} decrease of gross calorific value. The estimated costs of ash disposal at various ash contents were calculated. Burning wood chips with 5% ash content would lead to depositing an extra 5.6 megatons in the US or 21.2 megatons in the EU, compared to burning wood chips with 2.5% ash content.

Keywords: Ash content; Wood chips; Gross calorific value; Bioenergy

Contact information: a: Department of Forest Harvesting, Logistics and Ameliorations, Faculty of Forestry, Technical University in Zvolen, T.G. Masaryka 24, 960 53, Zvolen, Slovakia; b: Department of Forestry Technologies and Construction, Faculty of Forestry and Wood Sciences, Czech University of Life Sciences in Prague, Kamýcká 129, 165 21 Prague 6 – Suchdol, Czech Republic; c: Department of Economics and Management of Forestry, Faculty of Forestry, Technical University in Zvolen, T.G. Masaryka 24, 960 53, Zvolen, Slovakia; d: Department of Forest Management and Geodesy, Faculty of Forestry, Technical University in Zvolen, T.G. Masaryka 24, 960 53, Zvolen, Slovakia;
** Corresponding author: jankovskym@fld.czu.cz*

INTRODUCTION

Current reliance of the global economy on using fossil fuels negatively affects it in multiple ways, *e.g.* by creating fuel crises (Núñez-Regueira *et al.* 2001), or by contributing to climate change — by reducing crop yields and increasing the probability of weather extreme, thus increasing the costs of recovery from natural disasters (Lin and Jia 2012). Accordingly, we need new energy sources, with smaller environmental impacts and competitive prices. Overall, biomass has a potential to supply 200 to 400 EJ per year by 2050, mostly through intensive agriculture dedicated to producing biomass (IEA Bioenergy 2007). Surplus forest growth could supply from 59 EJ yr^{-1} (a low plantation scenario) to 103 EJ yr^{-1} (a high plantation scenario) of energy by 2050 (Smeets *et al.* 2007) or even 115 EJ yr^{-1} (Hämäläinen *et al.* 2011). Biomass now covers about 14% of the world's annual energy consumption (Rosua and Pasadas 2012). In the European Union (EU) alone, the annual consumption of wood for energy was 1 billion m^{3} (8.5 EJ), 70% of which came from forests and 30% from other sources (Mantau *et al.* 2010).

Not all regions generate as much energy from wood, however. In the United States of America (USA) the amount of energy generated from wood and wood residues was considerably lower in the USA — 2.04 quadrillion BTU (2.15 EJ) (EIA 2012). According to Pleguezuelo *et al*. (2014), three times more electricity will come from renewable energy sources in 2035 than in 2008, this is largely due to biomass.

Forestry produces biomass for energy use primarily in the form of wood chips. Wood chips were among the first renewable fuels used to substitute fossil fuels, as they are similar to solid fossil fuels in many ways, such that thermal energy plants can be relatively easily adapted for their use. Wood chips are a product of chipping wood with a size up to 120 mm (STN 48 0057 2004; STN 48 0058 2004) with a varying calorific value, moisture content, bark content, and impurities content. The moisture content affects the lower calorific value of the wood chips (Lestander and Rhen 2005) and other properties of the wood chips, which then affects their storage management and handling properties (Mattsson 1990; Evald and Jacobsen 1993; Jensen *et al*. 2004, 2006; Jirjis 2005). The content of the impurities in the wood chips (such as dirt, mineral matter, or foreign material) is difficult to determine before combustion, but relatively easy to determine afterwards, as they are mostly non-combustible and increase the amount of ash after combustion. Increased ash content negatively affects the economics of the whole conversion process by decreasing the calorific value of the wood chips, and increasing the handling and processing costs (McKendry 2002). In order to increase the competitiveness of the energy production from wood chips, compared to the energy production from solid fossil fuels, wood chips need to have high energy yields (affected by moisture and ash content) and low production of residue (affected by ash content).

Energy yield is a parameter that interests all energy producers when it comes to fuels, and many models have been developed to estimate the gross or net calorific value of wood chips. The precision of their predictions depends on the used analytic method. Erol *et al*. (2010) proposed 13 equations, based on parameters of the wood chips measured by proximate analyses. Everard *et al*. (2012) and Fagan *et al*. (2011) used either visible or near infrared spectroscopy to estimate the gross calorific value. Friedl *et al*. (2005) and Kumar and Pratt (1996) estimated the gross calorific value of the wood chips based on the elemental composition of the fuel. Sheng and Azevedo (2005) summarized 19 models based on the proximate, ultimate, or chemical analysis of biomass based fuels. Out of the models based on the proximate analysis, the model with the ash content as a predictor offers the best results; however, an even better estimation can be achieved when predictors from an ultimate analysis are used.

As renewable energy sources gain popularity and their share on energy production increases, land use will be considerably influenced (Banse *et al*. 2011); 105 million ha of land will be needed to produce biofuels alone by the year 2050 (IEA 2011). To reduce the influence, higher quality fuels are needed with greater energy content. At present, heat and power producers frequently use lower grade fuels with a varying share of non-combustible matter, which increases the amount of ash after burning.

The objective of this paper was to estimate the economic and environmental effects of using wood chips with various ash contents on the bioenergy sectors of the EU and USA, based on a model of the relationship between gross calorific value and ash content in wood chips. The model was created on wood chip samples collected from Slovak heat and power plants.

EXPERIMENTAL

Materials

Wood chips used during the research were sampled in two combined heat and power (CHP) plants. The CHP plants were located in Bardejov (GPS coordinates 49°17'59.09"N 21°14'57.83"E) and Topoľčany (48°34'1.83"N 18°11'27.96"E). Each CHP plant consumed about 100 000 m^3 of wood chips per year. Wood chips were produced from biomass grown in a radius of 60 km from that particular plant. Almost all of the timber came from hardwoods (90 to 95%) (*Fagus sylvatica*, *Quercus robur*, *Quercus cerris*, *Carpinus betulus*, *Populus tremula*, *Salix*, *etc*.). Softwoods (*Pinus sylvestris*, *Picea abies*, *Larix decidua*) accounted for the remaining 5 to 10% of timber used for chipping.

All timber used in this research was harvested manually and skidded from the forest stands by skidders. Approximately 50% of the timber was chipped by contractors at the roadside, using mobile drum chippers. Timber was not cleaned of any debris or other dirt, and wood chips were stored temporarily in piles on unpaved surfaces at the roadside. The remaining part of the timber was transported to the timber storage of the CHP plants as logs. There it was chipped using stationary disk chippers and transported to the main wood chip storage. All storages of the CHP plants are paved; the main wood chip storage was partially sheltered. Because the authors sampled the wood chips at the feeding conveyors of the boilers, it was not possible to distinguish between wood chips that were chipped at the road side and wood chips that were chipped at the main storage.

The relative moisture content, gross calorific value, net calorific value, and ash content were determined on 450 analytical samples collected from April 2010 until October 2015. Each analytical sample consisted of seven subsamples. One 200 g subsample was collected each day of the week. Immediately after collection, the subsamples were sealed and stored in polyethylene bags to prevent loss of material and moisture. After seven subsamples were collected, they were mixed together, creating the analytical sample. After mixing, the analytical sample was sealed in a polyethylene bag and transported to the laboratory located at the Technical University in Zvolen.

Methods

The gross calorific value of the analytical samples was determined according to STN ISO 1928(2003). Ground and homogenized analytical samples were pressed into 0.8 to 1.5 g pellets and combusted in an IKA C200 oxygen bomb calorimeter (IKA Werke, GmbH&CO.KG, Staufen, Germany). After combusting the samples, their ash content was determined as the gravimetric percent of the dry mineral residue after combustion of the fuel, according to STN EN 14775:2010.

For statistical analyses and model creation, the R statistical software (R Development Core Team 2016) was used. First the normality of data distribution was tested through the Shapiro-Wilk test. Then a generalized linear model with a Gaussian family type and an “identity” link function was created. The model served for prediction of the GCV of the wood chips based on their AC. The quality of the created model was assessed through the Akaike information criterion (AIC) and the predictors selected through the variance inflation factor (VIF), t-test, and ANOVA.

To estimate the effect of using wood and wooden residue with various ash contents on wood consumption, ash production, and costs of ash disposal, the created model was used to calculate the net calorific value of wood chips. Net calorific value was calculated according to Eq. 1 (STN ISO 1928(2003)).

$$NCV = \frac{(GCV * 1000 - 206 * HC) * (1 - 0{,}01 * MC) - 23 * MC}{1000} \quad (1)$$

where *NCV* is net calorific value (MJ kg^{-1}), *GCV* is gross calorific value (MJ kg^{-1}), *HC* is hydrogen content (%), and *MC* is moisture content (%).

The consumption of wood and wooden residues was estimated according to Eq. 2.

$$m = \frac{E}{NCV} \quad (2)$$

where *m* is the weight of the wood and wooden residues used for energy production (t), *E* is the energy currently produced from wood and wood residues in the EU and the US (MJ), and *NCV* is the net calorific value of wood and wood residues determined according to Eq. 1 (MJ kg^{-1}).

To estimate the weight of ash produced from wood and wooden residues in energy production, the weight of wood and wooden residues from Eq. 2, and ash content (%) were multiplied. The costs of ash disposal were estimated by multiplying the price of ash disposal (USD t^{-1}) and the weight of ash produced from wood and wooden residues (t) in the EU and the US.

RESULTS AND DISCUSSION

When assessing the quality of various renewable energy sources, it is better to use the gross calorific value, rather than the net calorific value. The reason is that water does not participate in the reaction itself and only absorbs heat energy as it evaporates (Nyström and Dahlquist 2004), biasing the results of analyses in favor of drier fuels. The gross calorific value refers to the heat released from fuel combustion with the original and generated water in a condensed state. In this study, the gross calorific value ranged from 14.81 MJ kg^{-1} to 20.92 MJ kg^{-1}, with a mean of 19.43 MJ kg^{-1}. Woody biomass typically has a mean gross calorific value in the range of circa 17 MJ kg^{-1} to circa 20 MJ kg^{-1} (Friedl *et al.* 2005; Núñez-Regueira *et al.* 2001; Erol *et al.* 2010; Everard *et al.* 2012), and it depends on multiple factors, such as tree species. Fagan *et al.* (2011) found that short rotation willows have GCV about 17.02 MJ kg^{-1}, part of tree that was chipped; Núñez-Regueira *et al.* (2001) found that eucalyptus leaves have GCV of about 21 MJ kg^{-1}, thin branches of eucalyptus have GCV of 18.5 MJ kg^{-1}, and thick branches have 18.3 MJ kg^{-1}. Friedl *et al.* (2005) analyzed the GCV of wood chips from mixed woody material and found they had GCV of 19.6 MJ kg^{-1}, which is similar to the present findings.

The ash content (in a dried state) varied from 0.42% to 22.43%, with a mean of 2.64% of the mass of the input material. The mean ash content was similar to previously reported values in woody biomass, where the ash content typically ranges from 0.3% to about 6% (mean values) (Núñez-Regueira *et al.* 2001; Friedl *et al.* 2005; Erol *et al.* 2010; Everard *et al.* 2012; Todaro *et al.* 2015). Figure 1 shows that the gross calorific value changed in the individual months (Fig. 1b). The monthly fluctuation was partially attributed to the season of the harvest, as concluded also by Pettersson and Nordfjell (2007) and Picchio *et al.* (2012). Forest harvesting is typically carried out by chainsaws and skidders in Slovakia (Ambrušová *et al.* 2013; Forests of the Slovak Republic 2015). This was also the case in our study. In these conditions, the timber was more likely to collect mineral matter when extracted and skidded from the forest to the forest landing in unfavorable conditions. Similar observations were made by McKendry (2002).

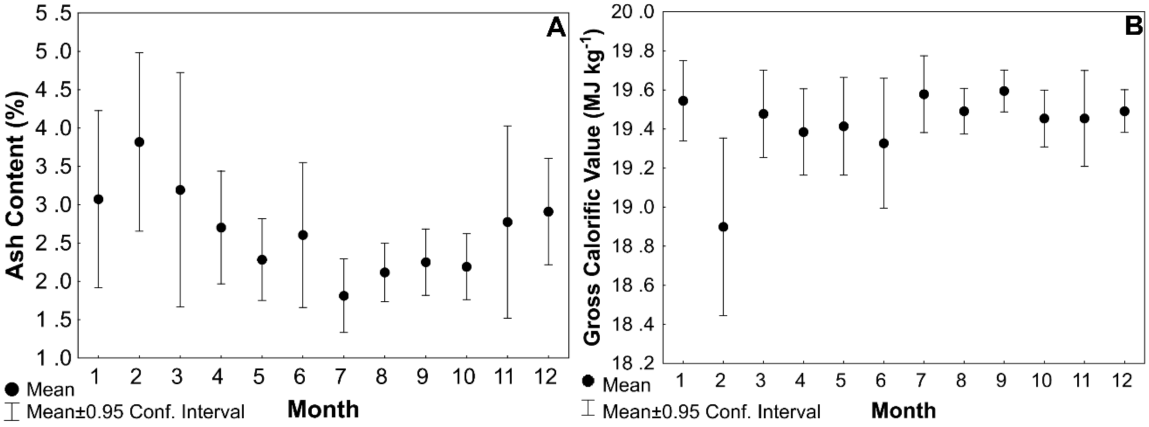

Fig. 1. The mean ash content in the wood chip samples measured in the particular months (A); the mean gross calorific value measured in the particular months (B)

Figure 1b shows that the gross calorific value fluctuated and that the fluctuation was more-or-less proportional to the ash content of the wood chips (Fig. 1a). However, this representation of the data provides only a limited view on the relationship between ash content and the gross calorific value of wood chips. To show the quality of the correlation, gross calorific value was plotted as a function of the ash content in a scatterplot (Fig. 2). Figure 2 shows a clear trend that the gross calorific value decreased with the increase of ash content in the wood chips. After the visual analysis, a generalized linear model was created in order to quantify the effects of ash content on the gross calorific value. This model was chosen, because the data were not normally distributed, as determined through the Shapiro-Wilk test. The regression equation for the estimate of gross calorific value through the ash content of wood chips is shown in Eq. 2. Other characteristics of the model are shown in Table 1,

$$GCV = 19.944863 - 0.198124\,AC \tag{2}$$

where GCV is the gross calorific value of wood chips (MJ kg^{-1}), AC is the ash content of wood chips in dried state (%).

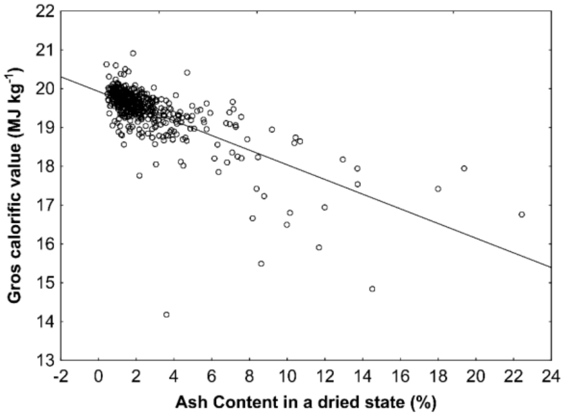

Fig. 2. The relationship between ash content of wood chips in dried state and gross calorific value of wood chips plotted in a scatterplot

Table 1. Characteristics of the Generalized Linear Model for the Estimation of the Gross Calorific Value of the Wood Chips through their Ash Content

	Estimate	Std. Error	t value	Pr(>|t|)
Intercept	19.944863	0.034814	572.90	<2e-16 *
Ash Content	-0.198124	0.009702	-20.42	<2e-16 *
* p-value: 0.000				

The relationship between the gross calorific value and the ash content was moderately strong, with the coefficient of correlation equal to -0.7. The model explained 49% of the variability of the gross calorific value based on the content of the ash in the particular samples. Sheng and Azevedo (2005) were able to explain about 62.5% of the variability of gross calorific value through the ash content of the samples, using databases of samples from the open literature. García *et al.* (2014) proposed another model, based on the ash content with an average absolute error of 5.80%. Most authors used multiple variables to estimate the gross calorific value though, such as the share of free carbon or the share of volatile matter besides ash content. However, using multiple variables does not automatically mean a greater determination of the variability; Phichai *et al.* (2013) used volatile matter content and free carbon content in their model and were only able to explain about 41% of the variability, Jiménez and Gonzáles (1991) were able to determine about 53% of the variability of gross calorific value through volatile matter and free carbon content. On the other hand, Ghugare *et al.* (2014) developed a model with more than 96% determination using genetic programing on proximate analysis data, and Akkaya (2016) achieved 88% determination of gross calorific value through proximate analysis data with an adaptive neuro-fuzzy inference system model. Most models are built around material collected from one locality, harvested by one technology, from one tree species, *etc*. This is also true for the models created on data from the open literature, as the resulting database is aggregated from these "homogenous" samples. The proportion of the variability of gross calorific value explained by the present model is lower compared to models by Ghugare *et al.* (2014) or Akkaya (2016); however, this was partially caused by the nature of the empirical material used during the research, which was mixed wood chips commonly used in the industrial energy generation. Our goal was to create a model that represented real conditions in the energy industry.

The relative moisture content of the samples varied between 17 and 58%, with the mean at 38.8%, a typical moisture content range for biomass feedstocks (Prokkola *et al.* 2014). Throughout the year, the moisture content of the samples either increased or decreased, based on the precipitation, outside temperature and the season of the harvest (Pettersson and Nordfjell 2007; Lenz *et al.* 2015). The largest difference was recorded between the samples from March (45%) and July (32%). The largest gradient between two consecutive months was a *circa* 5% loss of moisture between June and July (Fig. 3). The moisture content in the wood chips has a very strong negative relationship with their net calorific value. As shown in Fig. 4a and Fig 3., the development of the calorific value was inversely related to the development of the relative moisture content in the samples throughout the year. The relationship was clearer when the data were represented in a scatterplot, as in Fig. 4b. Overall, the net calorific value ranged from 4.92 MJ kg^{-1} to 14.92 MJ kg^{-1}, with a mean of 10.32 MJ kg^{-1}.

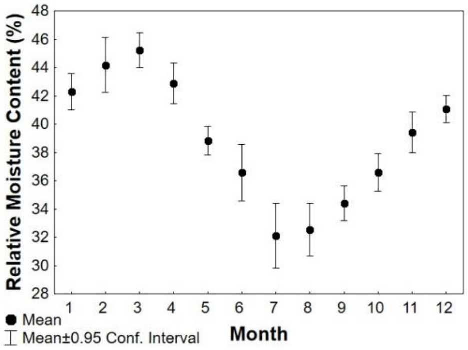

Fig. 3. The relative moisture content of the wood chip samples collected weekly based on the month of collection

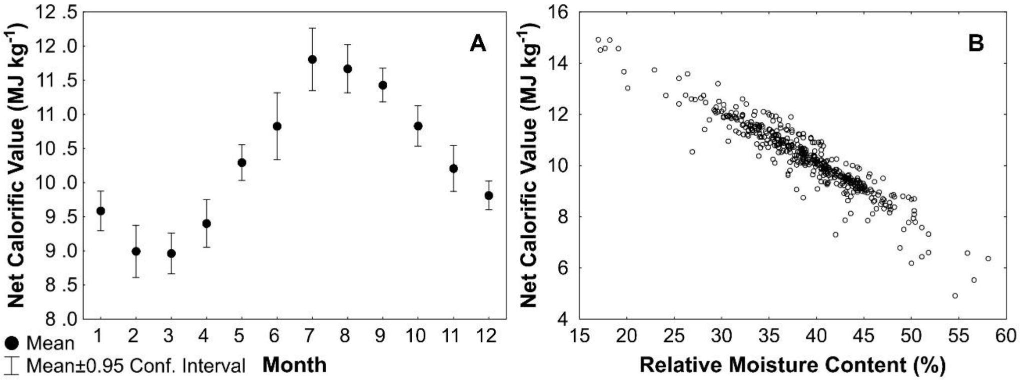

Fig. 4. The mean net calorific value of the wood chips according to the month of the sample collection (A); the relationship between the relative moisture content of the wood chips and their net calorific value (B)

Energy yielded from fuel by its combustion is reflected in its net calorific value. The increment of the amount of fuel needed to generate a particular amount of energy is proportional to the reduction of its net calorific value. Ash content decreases the net calorific value by substituting the share of combustible matter for incombustible matter in fuels. Overall, a 1% increase of ash content lead to a 1.18% increase of fuel consumption (Table 2) based on use of the present model to estimate the wood and wood residues combustion. Using Sheng and Azevedo's (2005) model provided similar results, with an even more elastic relationship — a 1% increase of ash content results in 1.39% increase of wood and wood residue consumption. Given the amount of energy generated from wood and wood residues, the mass of material needed to cover it would be about 205 million t in the USA or about 781 million t in the EU, if the wood and wood residues contained 0.5% of ash — the lower end of the typical ash content interval of woody materials (Núñez-Regueira *et al.* 2001; Friedl *et al.* 2005; Erol *et al.* 2010; Everard *et al.* 2012; Todaro *et al.* 2015). Combusting wood and wood residues with ash content considered high for woody material (5%) would lead to the need to secure an additional 11 million t of wood and wood residues in the USA or 43 million t in the EU. The additional demand for energy wood could be covered by establishing about 100 000 ha of short rotation willow plantations in the USA or about 381 000 ha in the EU (estimated with mean annual yield of 12.5 t of dry matter per ha according to Labrecque and Teodorescu (2005) and McElroy and Dawson (1986).

Table 2. Estimated Wood and Wood Residue Demand, Ash Production, and Costs of Ash Disposal at a Particular Ash Content in Energy Wood and Wood Residues in the USA and EU

Ash content (%)	GCV[a] (MJ kg^{-1})	EWC[b] USA (Mt y^{-1})	EWC[b] EU (Mt y^{-1})	Ash production USA (Mt y^{-1})	Ash production EU (Mt y^{-1})	ADC[c] USA (mil.$ y^{-1})[d]	ADC[c] EU (mil.$ y^{-1})[d]
0.5	19.85	205	781	1.03	3.91	3-41	12-156
1.0	19.75	206	786	2.06	7.86	6-82	2.4-314
1.5	19.65	207	790	3.11	11.85	9-124	3.6-474
2.0	19.55	209	795	4.17	15.90	13-167	4.8-636
2.5	19.45	210	800	5.25	19.99	16-210	6.0-800
3.0	19.35	211	804	6.33	24.13	19-253	7.2-965
3.5	19.25	212	809	7.43	28.32	22-297	85-1133
4.0	19.15	214	814	8.55	32.56	26-342	98-1303
4.5	19.5	215	819	9.67	36.86	29-387	111-1474
5.0	18.95	216	824	10.81	41.20	32-433	124-1648

[a]GCF: Gross Calorific Value; [b]EWC: Energy Wood Consumption; [c]ADC: Ash Disposal Costs; [d]Costs are calculated based on the mean ash disposal costs at $3 to $40 per metric ton; Mt: Megaton

Besides the effect of ash content on the consumption of wood and wood residues, it also affects the amount of ash that needs to be disposed after the combustion. According to our estimates, combusting woody material with typical ash content would lead to production from about 2 Mt of ash (0.5% ash content) to about 11 Mt of ash (5% ash content) in the USA, and from 8 Mt of ash (0.5% ash content) to 41 Mt of ash (5% ash content) in the EU (Table 2). The increase of ash production consisted of two components — the direct increase of ash content, and the ash produced from the increased amount of fuel that needed to be combusted to generate the same amount of energy. One percent increase of ash content in the fuel therefore resulted in a 1.02% mean increase of ash production. However, combusting wood and wood residues with ash contents that are considered high for this type of fuel produce significantly less ash than combusting *e.g.* brown coal with typical ash content of 4.2% to 33% (Arkhipov and Dorogoi 2011; Rafezi *et al.* 2011; Kermer *et al.* 2016; Loginov *et al.* 2016).

There are several ways to dispose of ash. Wood ash contains a number of macro- and micronutrients, important for plant growth. These include calcium, potassium, and magnesium, as well as phosphorus and manganese (Blander *et al.* 1995). Based on the source of the combusted biomass and the conditions of combustion, ash also may contain trace amounts of heavy metals, such as lead, cadmium, mercury, nickel and others, which are hazardous, when ash is used as a mineral soil additive. European and US legislation (Council Directive 1999; Walker *et al.* 1994) sets limits of maximal permissible concentrations of hazardous elements in fertilizers and other soil additives (Otepka and Tóthová 2011). When considering application of fresh wood ash, especially to forest soils, one must keep in mind that doing so could lead to increase of the soil's pH levels, thus damaging the tissue of plants in direct contact with the ash (Arvidsson and Lundkvist

2002). Wood ash should therefore be treated before adding it to soils. Another form of ash disposal is in civil construction, *e.g.* as a filler in road embankments, or bedding for pipes and cables (Hinojosa *et al.* 2014; Pavšič *et al.* 2014), or landfilling it.

Ash that is to be landfilled has to meet certain ecological standards, such as the concentration of hazardous elements. In the USA, the requirements are set in federal standard n. 40 CFR, part 503 (Walker *et al.* 1994) and are higher than in the EU, especially the mercury and lead concentrations. EU regulates the permissible concentrations of such elements through the EU Landfill directive 1999/31/EC (Council Directive, 1999). Though landfilling is viewed by some as the most economically feasible way of ash disposal (DiGioia *et al.* 1995), both USA and EU encourage the ash producers to minimize the amount of ash that is landfilled and to find different ways to dispose of ash. In fact, Heidrich *et al.* (2013) states that about 91% of the 52 Mt of coal combustion products (*i.e.* ash) were reused in EU during 2010, whereas in the US coal combustion producers reused about 42% of the 118 Mt of ash in the same year. Taking the mean ash content of the analyzed wood chips (2.64%) into account, the total costs of landfilling ash would range from $16.65 to $222.02 million per year in the USA and from $63.44 to $845.85 million per year in the EU. The estimated total costs of ash disposal for the lowest and highest unit costs were $3 to $40 per metric ton, as shown in Table 2. The costs of landfilling ash depend on the produced quantity and factors such as the specific type of ash, location, transportation mode, climate, terrain, regulatory requirements, and the potential for future use (Heidrich *et al.* 2013). The lowest costs are achieved when a disposal site is located near the power plant and the ash being disposed can be easily handled. Under these conditions, costs may be as low as $3 to $5 per metric ton. If the ash has to be transported over large distances, and it must be handled several times due to its moisture content or volume, costs range from $20 to $40 per metric ton (ACAA, 2016). Butalia *et al.* (2001) state that the total costs of landfilling ash, without transportation costs outside the landfill, are $16.33 per metric ton. The substantial costs of landfilling ash, and the fact that it is a non-beneficial utilization strategy, make it an economic burden to the producer. It is therefore desirable to minimize the quantity of landfilled ash by reusing it or, preferably, by preventing its generation through the selection of higher grade wood chips with lower share of impurities and mineral matter.

CONCLUSIONS

1. Forty-nine percent of the gross calorific value was explained by the ash content of the wood chips. Increasing the ash content by 1% resulted in a 0.11 MJ kg^{-1} decrease of the gross calorific value. For comparison, increasing the relative moisture content by 1% resulted in a 0.20 MJ kg^{-1} decrease in the net calorific value.
2. Minimizing the ash content in the wood chips significantly affects the economics of the heat and power generation. Because the fuel with a greater ash content has a smaller calorific value, more fuel is needed for the same amount of energy to be generated. However, greater ash production increases the costs of ash management.
3. Taking the growth rate of the bioenergy sector in developed countries into account, minimizing the ash content in the wood chips is important from an environmental point of view. Using the current heat and power generated from wood and wood residue in the US and EU, by burning wood chips with 5% ash content, the US would have to

deposit an additional 5.6 Mt or an additional 21.2 Mt in the EU, compared to burning wood chips with a 2.5% ash content.

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