Suitability of Bamboo as an Energy Resource: Analysis of Bamboo Combustion Values Dependent on the Culm's Age

Benjamin Engler
Siegmar Schoenherr
Zheke Zhong
Gero Becker

Abstract

Bamboo has gained increasing attention, especially due to its fast growth and its versatile utilization. It is used by millions of people in their daily lives and is a resource for timber, pulp and paper, and for food industries—not only in Asia. So far, the bioenergy sector has shown only marginal interest in bamboo, whose energetic properties are less intensively studied than its physical properties. This paper presents physical and chemical properties of two bamboo species—*Phyllostachys pubescens* and *Bambusa emeiensis*—for energy recovery. Both species were tested on calorific value, moisture, ash and chloride content in dependence on the culm's age, and the sample's position along the culm. Furthermore, the sustainable biomass potential from bamboo stands for energetic utilization of *Phyllostachys pubescens* was assessed. The obtained results show that both bamboo species have a potential for energy recovery and are essentially suitable to be used as an energy source for combustion. Compared to woody biomass, both species show similar calorific values and only slightly higher chloride and ash contents.

Keywords: bamboo, bioenergy, combustion, *Phyllostachys pubescens*, *Bambusa emeiensis*, calorific value, China.
Received 7 July 2011, Revised 21 June 2012, Accepted 4 July 2012.

Introduction

Over the past few decades, bamboo has received ever more attention as a renewable, fast-growing resource. Research has increased rapidly due to its wide availability and material characteristics comparable to wood. Non-timber forest products (NTFP) like bamboo play a major role in mitigating the pressure on slow-growing forest resources and the growing demand for qualitative timber (Van der Lugt et al. 2009).

The collective term "bamboo" comprises a subfamily of all arboreal or shrub-like true grasses—*Pocaceae*—that have a lignifying, perennial and branched stem. They are most abundant in the tropics and subtropics between the latitudes of 46°N to 47°S (Scurlock et al. 2000). Culms are produced vegetatively on an annual basis, and after cutting, no replanting is needed, which is a sustainable yield characteristic (Ueda 1960). Bamboo belongs to the monocotyledons and does not exhibit secondary growth; however, the xylem-like lignification of bamboo tissue results in many of its properties being similar to wood.

Bamboo is used widely as a household material, but due to advanced processing technology and increased market demand, it has extended to industrial applications—for example, pulp and paper, furniture and construction. Past research focused mainly on the physical, mechanical and nutritional properties of different bamboo species and less on energy recovery. Use of bamboo as an energy feedstock is not new (especially in millions of rural households); yet it has been neglected by the bioenergy industry as a sustainable energy alternative.

The energetic properties and energy recovery potential of bamboo have been reviewed by several studies, partly referred to as the *net calorific value* (NCV, also called H_i and *lower heating value* (LHV)) and sometimes referred to the *gross calorific value* (GCV, also called H_s, *higher heating value* (HHV) or *upper heating value* (UHV)). NCV is the energy quantity where the latent heat of vaporization of water in reaction products is not recovered—whereas GCV is the energy quantity where the latent heat of vaporization of water in the combustion products is taken into account. Sinha and Bajpai (2009) reported on feasibility studies for small-scale power generation through gasification of bamboo in India. Gielis (2000) described a net calorific value (NCV) of 18.3–

Author information: Benjamin Engler (corresponding author), Siegmar Schoenherr and Gero Becker, Institute of Forest Utilization and Forest Work Science, University of Freiburg, Werthmannstr. 6, 79085 Freiburg, Germany.benjamin.engler@fobawi.uni-freiburg.de, siegmar.schoenherr@fobawi.uni-freiburg.de, Zheke Zhong; China National Bamboo Research Center, Wenyi Rd 310, 310012, Hangzhou China. zhekez@yahoo.com.cn.

International Journal of Forest Engineering
ISSN 1494-2119 (print) and 1913-2220 (online)

19.7 Megajoule (MJ) kg $^{-1}$ and conducted gasification and carbonization trials for several bamboo species. In a study on the use of *Phyllostachys pubescens* from less managed forests for district heating, the bamboo pellets were analyzed to have gross calorific values (GCV) of 19.3–20 MJ kg^{-1} and ash content between 0.3% and 0.8% (Nagano et al. 2009). Lan et al. (1999) derived a similar gross calorific value of 20.1 MJ kg^{-1} for *Ph. pubescens* culms. Experiments about biomass productivity and fuel characteristics of different *Phyllostachys* species have been carried out by Scurlock et al. (2000). Furthermore, Isagi et al. (1997) reported on the net production of *Ph. pubescens* stands in Japan, which was summarized in an International Network for Bamboo and Rattan (INBAR) working paper together with other bamboo species in Asia (Hunter and Junqi 2002). Li (2004) and Li et al. (2007) reported physical and chemical properties of *Ph. pubescens* in different age classes and culm positions, but micro-structural and chemical changes with increasing age and their effects on generation of energy from bamboo are less well described (Li 2004, Van der Lugt et al. 2009, Janssen et al. 1988).

To develop a management system with optimized rotation periods, with reference to bioenergy purposes, and to point out possible tradeoffs between alternative material uses and energy recovery, the aim of this study is to determine conclusive combustion characteristics of bamboo in relation to the culm's age and the position of the tissue along the culm. Calorific value, moisture content, ash content and chloride content were analyzed to give characteristic values for the suitability of bamboo for the production of bioenergy through combustion. Based on a randomized stand inventory, the potential amount of energy from sustainable managed bamboo stands is calculated.

Materials and Methods

Study Site

The study was composed of two different parts, although both made use of bamboo samples from China. In a first study by Dietenberger (2009), *Bambusa emeiensis* was analyzed, obtained from Shaoping village, Pingxiang city in Guangxi province, China. Guangxi is one of the southern provinces and belongs to the tropical climate zone in the south and to the subtropical climate zone in the central and northern part of the province. Its average annual precipitation reaches 1,000 mm to 2,000 mm, with an average annual temperature of 17°C to 23°C. The study site is situated in the lateritic red earths of the Chinese red soil classification, whose intensive weathering is favored by high temperatures and high annual precipitation rates (He et al. 2004). Intensive agriculture is dominating the land use in this province, and forested areas are found only on the upper steep slopes, where agricultural production is not feasible.

The samples of *Phyllostachys pubescens* for the second part of Dietenberger (2009) and the study of Schoenherr (2010) were obtained from Nanjin village, Xin Deng town, Fuyang city in Zhejiang province, China. Zhejiang is located at the coastline of China's southeast and is characterized mainly by mountain ranges. The climate is humid subtropical, with an average annual temperature of 15°C to 19°C and an annual precipitation of 1,200 mm to 1,800 mm. Zhejiang is situated in the region of the red earths, which are characterized by a seasonal dry and wet season and are deep weathered (He et al. 2004).

Sampling and analysis of chemical and physical characteristics

Two studies carried out by Dietenberger (2009) and Schoenherr (2010) are summarized within this paper. In the first study (Dietenberger 2009), for the analysis of *Bambusa emeiensis*, 96 samples from 11 culms of different ages (1, 1.5, 2.5, 5, 5.5, 9, 10 years) were collected at the heights of 1.5 m (bottom), 5.0 m (middle) and 10.0 m (top) in March 2009. Furthermore, 27 samples from 1-, 2- and 3-year-old culms of *Phyllostachys pubescens* obtained in March 2009 from Zhejiang province were analyzed. All samples were transported to Germany and were analyzed in cooperation with the Agriculture Technology Centre (LTZ), Forchheim.

Figure 1. *Selective harvest of bamboo culms* of Phyllostachys pubescens *in Zhejiang province (above) and transportation of the culms using a pushcart (below). Photos: Benjamin Engler.*

The second study focused on biomass growth, gross calorific value and energetic characteristics of *Ph. pubescens* as well and was carried out in October 2009, also in Zhejiang province (Schoenherr 2010). The bamboo stand of *Ph. pubescens* in Zhejiang province is managed by a kind of selective cutting (Figure 1), where all culms of a specific age are harvested every second year, leaving younger culms and keeping the closed canopy required for new culms to sprout. Due to the management of the bamboo stand, only three age classes—divided into young (0.5 years, shooting year 2009), middle age (2.5 years, 2007) and old (4.5 years, 2005)—were available. For sample collection, five plots were randomly distributed within the bamboo stand, each with a size of 10 m × 10 m. Within a full inventory on these plots, the age, diameter at breast height (1.3 m; $d_{1.3}$) and number of culms were noted and measured, resulting in 196 culms. For the laboratory analysis, nine culms of all three available ages (0.5, 2.5, 4.5 years) were selected, resulting in 27 sampled culms. After felling, the trunk and leaves were weighted separately of each culm. Similar to the study of Dietenberger (2009), the culms were separated into bottom (1.5 m), middle (6 m) and a top part (10 m), and a cylindrical sample piece of 15 cm to 20 cm was removed at each height. These culm samples were splinted into two sub-samples, to get additional control samples (A and B). The testing was carried out in the laboratory of the China National Bamboo Research Center (CNBRC) in Hangzhou and the Zhejiang Forest Academy. In total, 162 samples were analyzed.

Table 1. *Number of samples of Phyllostachys pubescens and Bambusa emeiensis available for laboratory analysis.*

Age (year)	Phyllostachys pubescens		Bambusa emeiensis	
	n of samples	*n of culms*	*n of samples*	*n of culms*
0.5	54	9	-	-
1.0	9	1	15	2
1.5	-	-	9	1
2.0	9	1	-	-
2.5	54	9	27	3
3.0	9	1	-	-
4.5	54	9	-	-
5.0	-	-	9	1
5.5	-	-	18	2
9.0	-	-	9	1
10.0	-	-	9	1
Ages pooled	189	30	96	11

Measurements of moisture content on a dry basis (u) were conducted only for the trunks, and not the branches and leaves. Consequently, calculations of biomass production and gross calorific value of the dry mass refer only to the trunk. The branches and leaves are left out of consideration, also for ecological reasons.

The samples were dried at only 40°C until constant weight, as bamboo contains pyroligneous acids and some samples were additionally tested on fiber characteristics. The culm sections were cut into small pieces and ground with a mill, while avoiding high temperatures. Table 1 gives an overview on the number of samples used for laboratory analysis.

All laboratory measurements on chemical and physical characteristics were conducted according to international standards for wood analysis. The standards used within both studies are listed in Table 2.

Table 2. *Standards used for chemical analysis and testing of physical characteristics.*

Parameter	*Standard*	
	used by Dietenberger (2009)	*used by Schoenherr (2010)*
Moisture content u	DIN 52 183 Nov 1977[a]	DIN 52 183 Nov 1977
Ash content	ASTM D 1102 -84	ASTM D 1102 -84
Gross calorific value H_s	DIN 51 900 – 2: 2003-05	DIN 51 900 – 2: 2003-05
Chloride	EN ISO 15682: 2001	According to Chinese standard

[a] *In addition to the standard, samples had been dried at 40°C to avoid modifications in fiber structure, to be able to conduct continuous experiments at the macro-molecule level.*

Growth measurements of *Ph. Pubescens*

Growth measurements took place on the five study plots in the same bamboo stand of *Ph. pubescens* in Zhejiang province, mentioned above (Schoenherr 2010). To learn age distribution and growing parameters, a full inventory on $d_{1.3}$, age and number of culms, as well as selected height measurements, was done on the plots.

Results and Discussion

Moisture content

Although the calorific value decreases significantly with increasing moisture content (u), the moisture content has a significant influence on the gross calorific value (Kaltschmitt et al. 2009). In both studies, Dietenberger (2009) and Schoenherr

(2010), the youngest measured culms of both species show higher moisture content than the older ones. For *Ph. pubescens*, a strong decrease from 125.6% to 71.8% moisture content (arithmetic mean) between the culms of 0.5 years and 2.5 years was determined, followed by a smooth decrease from 71.8% to 64.5% in the next period between 2.5 years and 4.5 years (Table 4). The same trend could be observed for *B. emeiensis*. The 1-year-old culms had an average moisture content of 243.0%, which decreased to 63.0% for the 10-year-old culms (Table 4). Until the age of 5 years, the moisture content continued to decrease rapidly, compared with the marginal decrease from 5-to-10-year-old culms.

Also on a single culm level, large differences of the moisture content could be observed for both species. For *Ph. Pubescens*, the average (arithmetic mean) moisture content of the bottom section was 113.7%, decreasing to only 61.4% at the 10 m top position (Table 3). For *B. emeiensis*, the difference is not as pronounced as for *Ph. pubescens* (Figure 2). The lower culm part, with an average of 150.3% moisture content, had on average a 10% higher moisture content than the upper culm part (Table 3).

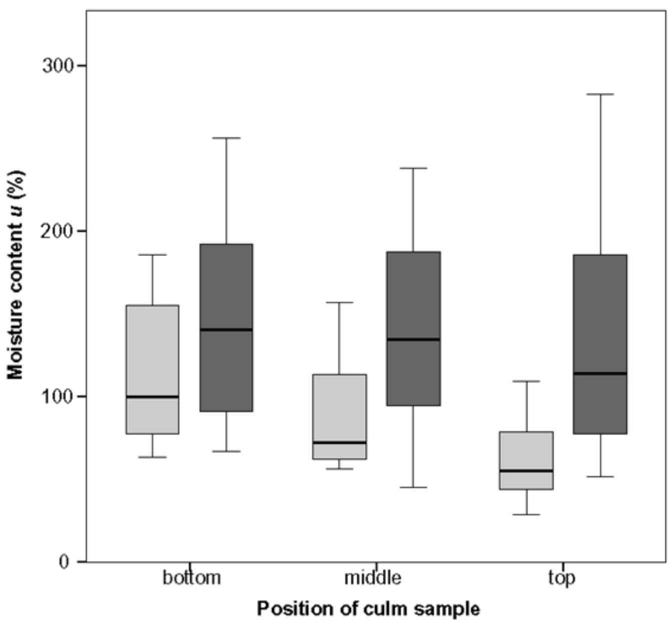

Figure 2. *Boxplot-diagram on moisture content u (%) against the position of the culm pieces (Phyllostachys pubescens: light gray; Bambusa emeiensis: dark gray). Median values are indicated by the horizontal line in the boxes, quartiles are indicated by bottom and top ends of boxes, and the data intervals are indicated by the vertical bars.*

Gross calorific value

The mean gross calorific value (H_s) of *Ph. pubescens* and *B. emeiensis* against the culm age is shown in Figure 3. In comparison, the measurements of Schoenherr (2010) show higher mean values than those of Dietenberger (2009), but also higher variations. This might be due to smaller sample sizes. Within *Ph. Pubescens*, the 4.5-year-old culms have the highest gross calorific value, with an arithmetic mean of 19.62 MJ kg^{-1} (Table 4). The analyzed values for *Ph. pubescens* are similar to those obtained in other publications (e.g., Gielis 2000, Nagano 2009, Scurlock 2000). *B. emeiensis* shows a slight increase in gross calorific value until the age of 5. Samples from culms older than 5 years show a decrease of the gross calorific value again, while in general the older culms show a higher variation than the young culms. Overall, *Ph. pubescens* shows a higher mean gross calorific value, with 19.44 MJ kg^{-1}, than *B. emeiensis*, with 18.32 MJ kg^{-1} (Figure 3). Among the three different positions of the samples within the culm, both species show no distinct differences.

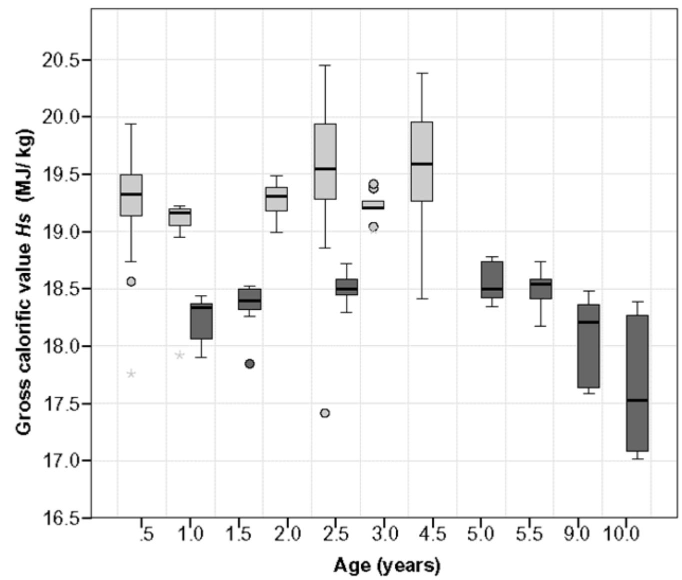

Figure 3. *Boxplot-diagram on the mean gross calorific value of Phyllostachys pubescens and Bambusa emeiensis against the culm age (Phyllostachys pubescens: light gray; Bambusa emeiensis: dark gray). Median values are indicated by the horizontal line in the boxes, quartiles are indicated by bottom and top ends of boxes, and the data intervals are indicated by the vertical bars.*

Chloride content

The chloride content is of high interest for thermochemical-conversion, especially for industrial combustion processes. It is a naturally abundant element occurring as loosely bound chloride or as free anion and is a non-favorable element in biomass for energy purposes, because it causes corrosion in combustion furnaces. The results of *Ph. pubescens* do not necessarily show a correlation between the chloride content and the culm's age, while *B. emeiensis* has a slightly negative trend of chloride content with increasing age (Table 4). On average, the chloride content was 0.068% for *Ph. pubescens* and 0.074% for *B. emeiensis*, both based on absolute dry matter. In comparison, both values are higher than the chloride content of spruce (0.005%) or poplar (0.004%), but less compared to agricultural crops or other perennial grasses (0.19% for wheat straw or 0.22% for Miscanthus) (Kaltschmitt et al. 2009).

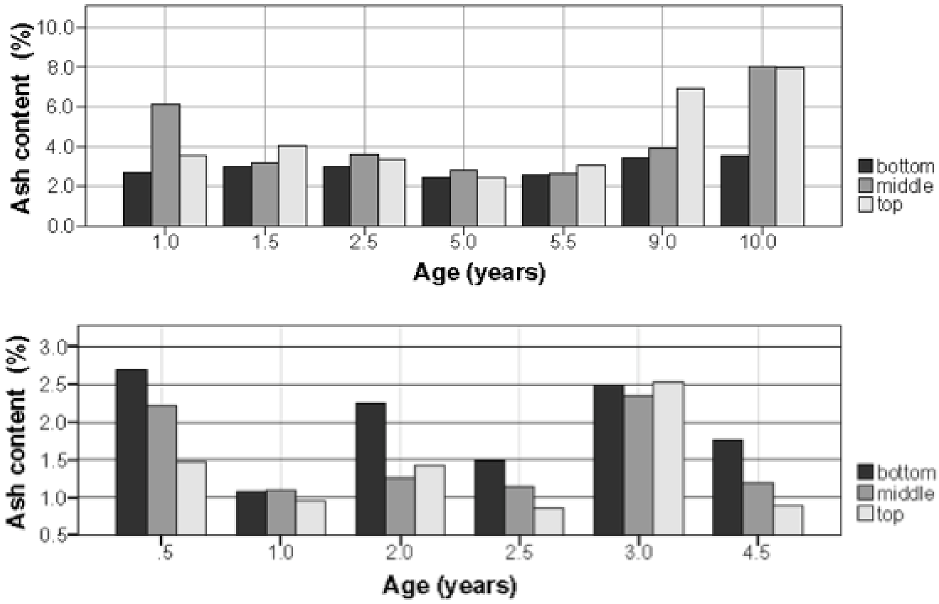

Figure 4. *Ash content of absolute dry matter (%) of Bambusa emeiensis (top pane) and Phyllostachys pubescens (bottom pane) against the culm's age (for B. emeiensis, all data originate from Dietenberger 2009; for Ph. pubescens, data from Dietenberger 2009 (age 1.0; 2.0; 3.0) was pooled with data from Schoenherr 2010 (age 0.5; 2.5; 4.5)).*

Ash content

When comparing both species, *Ph. pubescen*s shows a lower mean ash content of absolute dry matter (1.6%) than *B. emeiensis* (3.7%) for all ages (Figure 3). Even *Ph. pubescens* has lower values than poplar (1.9%) or willow (2.0%) (Hartmann et al. 2000). A correlation between the ash content and the culm's age could not be found for *Ph. pubescens*. The ash content of *B. emeiensis* is decreasing until the age of 5 and remains on a stable level afterwards. Beginning at an age of 9 years, the ash content of *B. emeiensis* seems to increase again, up to 8.1% for the middle and top part of the culm (Figure 4). While *B. emeiensis* has no clear correlation between the ash content and the position of the sample along the culm, the analysis of *Ph. pubescens* shows different results.

In general, the ash content of *Ph. pubescens* decreases from the bottom to the top in all three measured ages by Schoenherr (2010); however, this tendency could not be found clearly in the analysis of first-, second- and third-year culms by Dietenberger (2009).

Ash fusibility

Analysis concerning ash fusibility could not be performed within this study. However, literature gives some rare information on this, but authors are not consistent in this point. Bahwan (2007) resulted in ash deformation temperatures (DT) between 1,300°C and 1,350°C and ash fusion temperatures (FT) between 1,400°C and 1,450°C, being similar to poplar and willow (Kaltschmitt 2009). In contrast, Xiang (2012) stated DT of 1,002°C and FT of 1,113°C. These results might limit the use of bamboo for combustion.

Growth characteristics and biomass production

The overall culm density of *Ph. pubescens* at the stands in Zhejiang province was determined to an average of 3,920 culms per hectare (culms ha^{-1}) (Table 5). While the culms of 0.5 years held a slightly higher percentage share, the age distribution can be seen as closely equal.

Of the 196 culms of *Ph. pubescens* that have been included in the five plots of Schoenherr (2010), the measured $d_{1.3}$ ranges from 9.3 cm to 12.8 cm. As the growth patterns of

Table 3. *Sample arithmetic means of analysis of Phyllostachys pubescens and Bambusa emeiensis dependent on the position of the samples along the culm's height (all data for B. emeiensis originate from Dietenberger 2009; for Ph. Pubescens, the moisture content is based on data of Schoenherr 2010, whereas gross calorific value, chloride content and ash content consists of the pooled data from Dietenberger 2009 and Schoenherr 2010).*

Species	Position of the sample	Moisture content u (%)	n	Gross calorific value ($MJ\ kg^{-1}$)	n	Chloride content (%)	n	Ash content (%)	n
Phyllostachys pubescens	Bottom	113.7	54	19.435	63	0.062	63	1.98	63
	Middle	86.8	54	19.413	63	0.061	63	1.53	63
	Top	61.4	54	19.486	61	0.078	63	1.15	63
Bambusa emeiensis	Bottom	140.3	22	18.507	33	0.072	33	2.91	33
	Middle	139.4	21	18.291	33	0.083	33	4.20	33
	Top	130.7	20	18.158	30	0.065	30	4.12	30

Table 4. *Sample arithmetic mean of analysis of Phyllostachys pubescens and Bambusa emeiensis dependent on the culm's age (all data for B. emeiensis originate from Dietenberger 2009, whereas data for Ph. Pubescens consist of pooled data from Dietenberger 2009 (age 1.0; 2.0; 3.0) and Schoenherr 2010 (age 0.5; 2.5; 4.5)).*

Species	Age (years)	Moisture content u (%)	n	Gross calorific value (MJ kg^{-1})	n	Chloride content (%)	n	Ash content (%)	n
Phyllostachys pubescens	0.5	125.6	54	19.297	54	0.079	54	2.13	54
	1.0	--	--	19.003	9	0.029	9	1.04	9
	2.0	--	--	19.281	9	0.022	9	1.65	9
	2.5	71.8	54	19.564	54	0.059	54	1.16	54
	3.0	--	--	19.218	9	0.029	9	2.46	9
	4.5	64.5	54	19.616	52	0.015	54	2.84	54
Bambusa emeiensis	1.0	243.8	9	18.236	15	0.097	15	4.2	15
	1.5	190.7	6	18.348	9	0.087	9	3.4	9
	2.5	151.9	18	18.499	27	0.097	27	3.3	27
	5.0	85.7	6	18.545	9	0.045	9	2.57	9
	5.5	96.5	12	18.493	18	0.061	18	2.75	18
	9.0	83.4	6	18.063	9	0.053	9	4.7	9
	10.0	63.7	6	17.618	9	0.026	9	6.5	9

bamboo imply, the $d_{1.3}$ is not influenced by the age of the culms. The overall mean $d_{1.3}$ of all ages (all plots pooled) was 11.0 cm, while the 0.5-year-old culms (11.3 cm) and the 2.5-year-old culms (11.4 cm) were slightly bigger than the 4.5-year-old culms (10.3 cm). This might be due to modified fertilizing practices during the last years but could not be stated definitively.

In total, 27 culms were harvested, while only 26 culms could be analyzed completely. The mean oven-dry mass of the bamboo trunk (bamboo culm excluding branches and leaves) was 15.0 kg culm$^{-1,}$ representing 85.5% of the total culm mass, while the rest is shared by branches and leaves.

Based on the stand density of the culms and the oven-dry mass, the amount of above-ground dry biomass was calculated. In total, trunks comprise an above-ground biomass of 57.7 oven dry tonnes per hectare (odt ha^{-1}) (1 tonne = 1000 kg). Based on the age distribution mentioned above, a mean annual increment of 19.2 odt ha^{-1} yr^{-1} of trunk biomass was calculated. Assuming a mean gross calorific value of 19.44 MJ kg^{-1} (see results of the cross calorific value analysis), the mean annual increment equates to a theoretical annual energy yield of 373,322 MJ ha^{-1} yr^{-1} of the trunks (Table 6).

Taking alternative material uses into account, it might be more achievable not to use all the available bamboo biomass, to release competition. Therefore, it is recommended to use the top part of the culm that shows higher calorific values and less wood moisture for energy purposes, and to leave the bottom part that is favored by the wood processing industry for material uses.

Table 5. *Arithmetic mean diameter at 1.3 m and standing culm density over age distribution of Phyllostachys pubescens for all plots in the Zhejiang province pooled.*

Age (years)	*Mean $d_{1.3}$ (cm)*	*Culms analyzed (n)*	*Stand density (culms ha^{-1})*	*Relative share of total stand density (%)*
0.5	11.3	76	1,520	38.8
2.5	11.4	61	1,220	31.1
4.5	10.3	59	1,180	30.1
Ages pooled	11.0	196	3,920	100.0

Table 6. *Biomass density and its energy content for Phyllostachys pubescens trunks by culm age.*

Age	*Oven dry trunk mass*	*Oven dry trunk mass density*	*Energy content*	
(years)	*(kg culm^{-1})*	*(odt ha^{-1})*	*(MJ ha^{-1})*	*(kWh ha^{-1})*
0.5	11.88	18.05	351,020	97,505
2.5	18.50	22.20	431,576	119,882
4.5	14.51	17.42	338,673	94,075
Ages pooled	14.96	57,67	1,121,269	311,462

Conclusions

The studies show that both tested bamboo species, *Bambusa emeiensis* and *Phyllostachys pubescens*, are potentially suitable to be used as a fuel in biomass-fed combustion plants. Bamboo shares desirable fuel characteristics with other wooden biomass, with the (possible) exception of ash fusibility (DT, FT). Taking only the calorific value into account, even young culms of 1 year are suited for combustion. However, with regard to energy efficiency, low-moisture ash and chloride content are preferred. The moisture content of bamboo is in general higher, compared to wood species, but it decreases with maturation time at a given age. The lower parts of the culms generally have higher moisture content than the upper parts. The ash content of both species is comparable to wood, while *Ph. pubescens* shows lower values than *B. emeiensis*. The chloride content of the bamboo is higher compared to wood, but lower than agricultural crops.

B. emeiensis showed the most favorable results at 5 years, where the calorific value is highest and the ash and chloride content are comparatively low. For *Ph. Pubescens*, a harvesting time for energy purposes is suggested to be between 2 to 3 years. This age is also required for material use of bamboo (e.g., flooring, panel boards). For both species, the top parts of the culms are lower in moisture and ash content and show a higher calorific value. Considering competing material interests from other industries in which the bottom parts are usually used, especially the top and middle parts could be of interest for the bioenergy sector. How to implement this into an efficient concept of silviculture treatment and biomass supply might be part of additional research.

Given the widespread abundance of bamboo, biomass from bamboo might contribute significantly to more sustainable and environmentally friendly alternatives for energy production in China.

Acknowledgments

This paper was originally submitted to the Journal of Forest Energy, which instead of fully launching was merged with the International Journal of Forest Engineering. The Journal of Forest Energy initiative was a joint effort between COST Action FP0902 "Development and Harmonization of New Operational and Forest Assessment Procedures of Sustainable Forest Biomass Supply" and IEA Bioenergy Task 43 "Biomass Feedstocks for Energy Markets."

The studies presented in this paper were done by Ralph Dietenberger and Siegmar Schoenherr under supervision of Benjamin Engler. The studies were performed in the framework of the German-Chinese research project "ValWood: Innovative Sustainable Land Use," a cooperation between the University of Freiburg, the Technical University of Dresden and the Chinese Academy of Forestry, Beijing. The project was funded by the Federal Ministry of Education and Research (BMBF) on the German side and the Ministry of Science and Technology (MOST) on the Chinese side. The authors would like to express their thanks for this financial support. As well, the partnering research institutes, which had been involved in the analysis work, have to be thankfully mentioned. This is especially the Agricultural Technology Centre (LTZ) in Forchheim, Germany, the China National Bamboo Research Center in Hangzhou, China, and the Zhejiang Forest Academy in Hangzhou, China.

Literature Cited

Bahwan, V. & Marg, S.J.S. 2007. *Gasification of bamboo*. Info sheet 04 05/07. National Mission on Bamboo Applications, Department of Science and Technology, Government of India.

Dietenberger R. 2009. *Eigenschaftsuntersuchungen von Bambus zur energetischen Verwertung* [*Analysis of bamboo characteristics for energy recovery*]. Diploma thesis, University of Freiburg, Germany.

Gielis, J. 2000. Future possibilities for bamboo in European agriculture. Rijkevorsel, Oprins Plant. Retrieved January 8, 2013, from www.bamboonetwork.org/downloads/gielis01.pdf.

Hartmann, H., Böhm, T. & Maier, L. 2000. *Naturbelassene biogene Festbrennstoffe—Umweltrelevante Eigenschaften und Einflussmöglichkeiten* [*Natural state biogene solid fuels—relevant characteristics and influences on the environment*]. Bayerisches Staatsministerium für Landesentwicklung und Umweltfragen, Material Series 154, Munich.

He, Z., Zhang, M. & Wilson, M.J. 2004. *Distribution and classification of red soils in China*. In: Wilson, M.J. (ed.) 2004. The Red Soils of China: Their Nature, Management, and Utilization. Dordrecht, The Netherlands: Kluwer Academic Publishers. p. 29-33.

Hunter, I.R. & Junqi, W. 2002. *Bamboo biomass*. INBAR working paper 36: 1-11.

Isagi, Y., Kawahara, T., Kamo, K. & Ito, H. 1997. Net production and carbon cycling in a bamboo *Phyllostachys pubescens* stand. *Plant Ecology* 130:41-52.

Janssen, J., Boughton, G., Adkoli, N.S., Ranjan, M.P. & Sastry, C.B. 1988. Bamboo as an Engineering Material: An Annotated Bibliography. Singapore: IDRC Bamboo and Rattan Research Network.

Kaltschmitt, M., Hartmann, H. & Hofbauer, H. 2009. Energie aus Biomasse—Grundlagen, Techniken und Verfahren [Energy from Biomass—Basics, Technology and Processes]. Berlin-Heidelberg-New York: Springer-Verlag.

Lan, B., Hong, W., Wu, C.Z., Xu, W.B. & Zeng, S.T. 1999. A study on the energy structure of *Phyllostachys pubescens* stand. *Journal of Fujian College of Forestry* 19:20-2.

Li, X. 2004. Physical, chemical, and mechanical properties of bamboo and its utilization potential for fiberboard manufacturing. Master of Applied Science thesis, Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College.

Li, X., Shupe, T., Peter, G., Hse, C. & Eberhardt T. 2007. Chemical changes with maturation of the bamboo species *Phyllostachys pubescens*. *Journal of Tropical Forest Science* 19:6-12.

Nagano, M., Nagano, M. & Mabuchi, Y. 2009. Utilization of bamboo forest for a district energy resource: an example of *Phyllostachys pubescens*. *Social Society for Social Management for Social Management* 09-125:1-7.

Schoenherr S. 2010. The energetic properties of *Phyllostachys pubescens* and its potential use for thermochemical biomass conversion. Bachelor of Science thesis, University of Applied Sciences Eberswalde, Germany.

Scurlock, J.M.O., Dayton, D.C. & Hames, B. 2000. Bamboo: an overlooked biomass resource? *Biomass & Bioenergy* 19:229-44.

Sinha, P. & Bajpai, R. 2009. Plant it—bring good luck to people, energy, and environment. *Akshay Urja (Renewable Energy)* 2:18-21.

Ueda, K. 1960. Studies on the physiology of bamboo. *Bulletin of the Kyoto University Forests* 30:1-69.

Van der Lugt, P., Vogtländer, J. & Brezet, H. 2009. *Bamboo, a sustainable solution for Western Europe—design cases, LCAs and land-use*. INBAR technical report 30. Beijing: INBAR.

Xiang, F. & Li, J. 2012. Experimental study on ash fusion characteristics of biomass. *Bioresource Technology* 104:769-774.