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Influence of Tree Species, Harvesting Method and Storage on Energy Demand and Wood Chip Quality When Chipping Poplar, Willow and Black Locust

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Abstract: The cultivation of fast-growing wood (e.g., poplar, willow or black locust) in short rotation coppices and agroforestry systems presents an opportunity for producing biomass sustainably in the agricultural sector. Cost-efficient agricultural wood production requires the availability of high-performance machinery and methods with which high-quality wood chips can be produced at low cost. It is known from harvesting short rotation coppices in practice that both the wood chip quality and the performance of the harvesting machinery depend on a variety of factors (e.g., harvesting method, weather conditions, tree species). That is why this study examines in detail the influence of the tree species (different varieties of poplar, willow, black locust) and the wood condition (fresh, stored or dried, frozen) on the specific energy demand for comminution in a stationary drum chipper and on the particle size distribution of the wood chips produced. For all the tree species examined, the chipping of dried as well as frozen stems was connected with a significant increase in the specific energy demand for comminution. An increase of 31% has been measured if poplar stems are chipped in frozen conditions (max. 6.31 kWh t^{-1}). Drying led to an increase of 59% for dried willow stems (max. 6.67 kWh t^{-1}). Drying and frost had also an influence on the size and quality of the wood chips, but no globally significant connection could be established for the examined tree varieties.

Keywords: agroforestry; short rotation coppice; poplar; willow; black locust; wood chips; comminution; energy demand; drying

1. Introduction

Trees planted on agricultural land present an opportunity for producing biomass sustainably and at the same time improving farm income. Fast-growing tree species such as poplar, willow and black locust cultivated in short rotation coppices (SRC) or agroforestry systems (AFS) offer not only considerable potential for producing plant biomass, but can also at the same time withdraw carbon from the atmosphere and store it in their biomass [1–6]. To be successful in competition with wood products from the forestry sector, various obstacles need to be overcome when expanding the cultivation of fast-growing agricultural timber crops. Such expansion is desirable for ecological reasons. The agricultural timber produced on farm land has so far preferably been used as a source of renewable energy for producing heat and electricity in regional cogeneration and power stations. For this, the harvested trees have to be converted to wood chips and frequently stored for relatively long periods [7–10]. Short rotation coppices are harvested in winter with moisture contents of

50–60 wt%. Demand for the material continues throughout the year, however, and thus makes storage absolutely necessary. Dry matter losses of up to 30% can result from the hitherto customary method of storing and drying wood chips in naturally ventilated large outdoor piles for periods of more than 6 months [6,8,11–13].

In addition to the necessary expertise concerning site-appropriate process design, in order to make agricultural wood production profitable it is also necessary to have efficient machinery available with which high-quality wood chips can be produced at low cost and easily handled during storage and transport [14–17]. It was established that depending on the biomass yields, the cultivation methods applied and the selection of the harvesting machinery, harvesting alone accounts for 35–60% of the total costs of biomass production in short rotation coppices [7,18–20]. In the past thirty years there have been many machinery-based attempts to make mechanical harvesting of short rotation coppices more efficient, but only few of these have achieved market maturity. Looking at the coupling of the individual process steps necessary for SRC harvesting, it is possible to differentiate basically between single-step and two-step methods (Figure 1) [21–23]. While in single-step harvesting (Figure 1, Systems A and B) the trees are cut directly from the stump and chipped, in two-step harvesting comminution generally only takes place after relatively long storage and natural drying of the wood in the log deck (Figure 1, Systems C–E) [24–26].

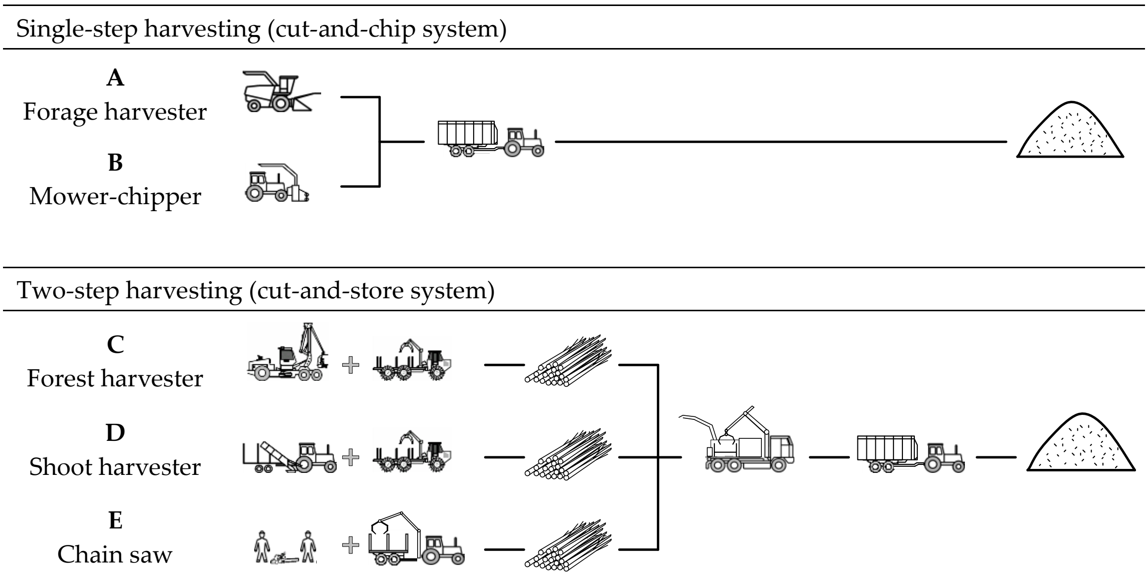

Figure 1. Single-step (A–B) and two-step (C–E) harvesting lines of agricultural wood and processing to wood chips.

In all methods, comminution of the trees to wood chips is the central process step, involving a high energy demand. Depending on the selection of the comminution machinery and the properties of the trees at the time of chipping—influenced for instance by variety, trunk diameter, age of the root stocks and shoots, water content, modification of the wood strength due to storage processes or frost—the quality of the wood chips is largely determined in this process. For cost-efficient production and marketing of high-grade wood chips, not only must the requirements of the valid standards be met, for instance as regards the fines fraction and the water and ash contents [27–29], but also the losses and the energy input along the entire process chain of wood chip production should be as low as possible [10,30–33]. The drying processes and losses during storage of the wood are crucially influenced by the nature of the wood conditioning and/or comminution during harvesting [8,34,35].

To date, given the frequent lack of availability of suitable harvesting machinery in many cultivation regions, the selection of harvesting time and harvesting technology has frequently not been based on process engineering requirements. Instead, the harvest is mainly carried out by service providers who harvest the land in accordance with a fixed time schedule as soon as the soil is fit for driving on in the winter. As a general recommendation, wherever possible, it is best to harvest when the soil is frozen in order to avoid excessive loads on the soil together with the formation of deep furrows in the field by the machines [9,10,36]. However, as a consequence of adopting this practice, the trees can be frozen at this point in time. In our own trials, the chipping unit of the harvesting machinery frequently sustained damage particularly when harvesting during prolonged periods of severe frost. To what extent this is attributable to possibly different behavior of frozen trees from SRC during chipping has not been investigated sufficiently. However, it is known that sugar dissolved in the wood leads to a reduction in the freezing point of the water in the wood [37]. At temperatures below −5 to −10 °C, however, the water freezes in the wood too. Furthermore, it is known from the use of modified forage harvesters for harvesting SRCs and from the forestry sector that both the design of the chipping units and the condition of the blades and counter blades (degree of wear) exert substantial influence not only on the energy demand during chipping, but also on the quality of the wood chips [35,38–44].

The goal of this study was therefore to conduct a detailed analysis of the connection between tree species, the condition of the trees at the time of chipping (fresh, stored, frozen), the energy demand for comminution, and the quality of the wood chips produced.

2. Materials and Methods

2.1. Test Stand for Determining the Specific Energy Demand

The test stand shown in Figure 2 was used to determine the specific energy demand during comminution of wood logs and shoots from short rotation coppices. The core component of the test stand is a drum chipper (HE100 500 STA, JENZ, Petershagen, Germany), the basic structure of which corresponds to the mobile chippers generally used in forestry. On this test stand a defined mass flow of timber could be fed to the chipping drum via a conveyor belt. The electric drive (power rating 22 kW) was controlled via a frequency inverter (SJ 300, Hitachi, Tokyo, Japan). With this it was possible to record the power consumption of the chipper during the comminution process and to store this on a connected measuring computer for detailed analysis (Hitachi ProDrive v1.9.1.1, sampling rate: 11 measurements per second, Hitachi, Tokyo, Japan). The knives of the chipper were sharpened before the trials in order to rule out any influencing of the results by wear of the blades. The chipper was equipped with a screen with rectangular holes (5 cm screen width).

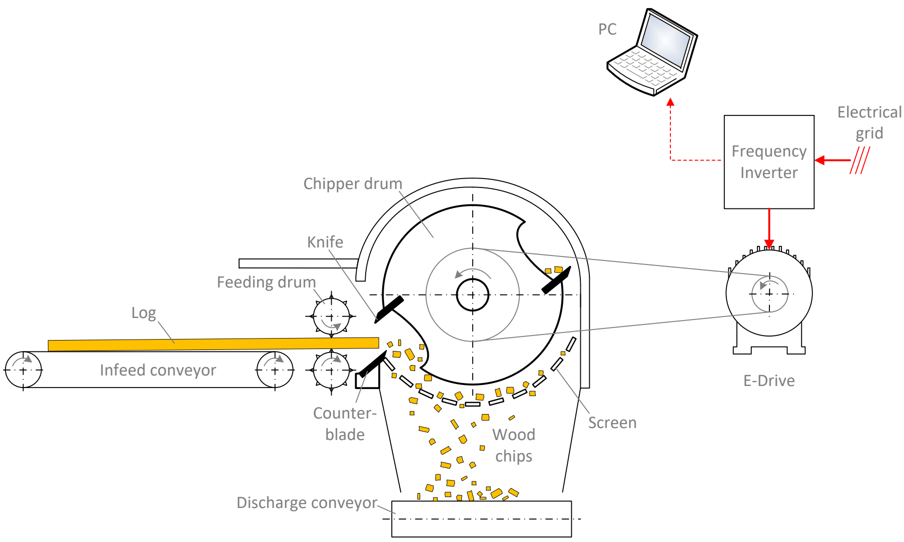

Figure 2. Test stand for determining the specific chipping energy demand.

2.2. Raw Material Properties, Sample Preparation and Performance of Trials

Trunks of different poplar, willow and black locust varieties were examined in the trials for their comminution behaviour. In some measurements we additionally varied the condition of the raw timber material (fresh, stored, frozen) as an essential parameter for the energy demand and wood chip quality. The parameters investigated here for different raw material conditions of the stems during chipping were:

(a) Freshly harvested wood: the trees were harvested in February/March and chipped immediately.
(b) Dried wood: the trees were harvested in February/March, then stored out in the open for several months and at the same time dried naturally. Chipping was only carried out following this roughly nine-month storage period.
(c) Frozen wood: the trees were harvested in February/March and cut into logs of 2 m length. These logs were put into a freezing chamber and stored at minus 18 °C for seven days. After this freezing treatment the logs were chipped immediately in frozen condition.

As it was assumed that the size of the trees also influences the chipping process, the tree diameters were also varied in some trials. Table 1 provides an overview of the various wood ranges and timber conditions used for the comminution trials. The majority of all material samples have been collected at the research plantations of the Leibniz Institute for Agricultural Engineering and Bioeconomy (ATB) in Potsdam. In addition, three willow samples have been provided by Rothamsted Research, Harpenden/England (Willow SV E, Table 1).

Table 1. Characteristics of poplar, willow and black locust used for comminution experiments.

Variety	Stem Diameter [cm]	Number of Shoots per Trial	Condition	Label [1]
Poplar Max [2]	3.5 ... 4	4	wet	P-M-w-4
	3.5 ... 4	4	dried	P-M-d-4
	3.5 ... 4	4	frozen	P-M-f-4
	5 ... 6	2	wet	P-M-w-2
Poplar AF2	5 ... 6	2	wet	P-A-w-2
Poplar H275	5 ... 6	2	wet	P-H-w-2
	7.9	1	frozen	P-H-f-1
	3.5 ... 4	4	frozen	P-H-f-4
	3.5 ... 4	4	wet	P-H-w-4
Black Locust [3]	3.5 ... 4	4	wet	B-L-w-4
Willow Inger	3.0 ... 4	5	wet	W-I-w-4
Willow SV G [4]	2.5 ... 3	9	dried	W-S-d-9
	2.5 ... 3	9	wet	W-S-w-9
Willow Tordis	3.5 ... 4	4	frozen	W-T-f-4
	3.5 ... 4	4	wet	W-T-w-4
Willow SV E [5]	2.9 ... 3	7	dried	W-S-d-7
	2.5 ... 2.8	7	wet	W-S-w-7
	1.8 ... 2	15	dried	W-S-d-15

[1] Labelling: Variety-Clone-Condition-No of shoots per trial. Example for labelling: W-S-d-15 = **W**illow, clone ***S**alix viminalis*, **d**ried shoots, **15** shoots per chipping trial. [2] Poplar Max1 and Max4. [3] Black Locust 1jS1/0. [4] *Salix viminalis* 12 from Leibniz Institute of Agricultural Engineering and Bio-economy (ATB), Germany. [5] *Salix viminalis* from Rothamsted Research, England.

The mass of the wood samples fed in and the moisture content had to be determined to investigate the specific energy demand. The stems and shoots used for the measurements were therefore weighed separately before comminution for each round of the experiment (fresh mass, Satorius BP12000S balance, Goettingen, Germany, d = 0.1 g). The wood moisture content was determined with the help of three samples of the wood chips produced in the respective trial round (Oven-Dry-Method, EN ISO 18134-2 [45]). The particle size analysis and the classification into size categories were carried out on the basis of EN ISO 17827-1 and EN ISO17225-1 [27,46] using three further samples of the wood chips in each case. The median value (d_{50}) of the particle size distribution curves (shown as cumulative frequency of wood particles passing screens with different sizes according to EN ISO 17827-1 [46,47]) has been used to evaluate the influence of different treatments on the average size of the produced wood chips. The d_{50} was determined as the intersection between the horizontal 50% line (d_{50}) and the rectilinear connection of the measurement points closest to this 50% line. All the comminution experiments were repeated four times. Feeding of the chipper while ensuring comparable comminution conditions for samples with greatly differing stem diameters turned out to be a particular problem. In order to ensure the same conditions as far as possible, the samples were bundled for each round of the trials in such a way that the mean stem diameter of the wood samples selected only varied slightly (max. 10%) and the total of the cross-section areas of the selected stems for a trial round was always 48 to 50 cm^2 (Figure 3; Figure 4). This made it possible to guarantee a constant filling degree of the chipper and hence uniform framework conditions for all comminution experiments. Depending on the timber variety, the weight of a chipping sample was between 7.5 and 10 kg for the fresh samples, and between 4.9 and 5.6 kg for the dried samples. In addition, all the branches were removed from the logs prior to chipping and the logs were cut to a length of 2 m.

Figure 3. Bundling of the chipping samples and setup of the experimental stand (chipper HE 100 500, JENZ, Petershagen, Germany).

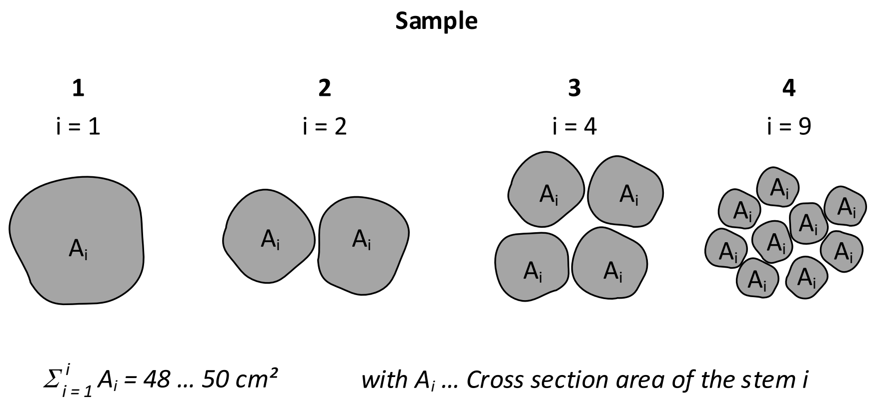

Figure 4. Method for arranging chipping samples with the same cross section area.

2.3. Specific Energy Demand

The specific energy demand W_{spec} for the chipping process was determined on the basis of the average power recorded in the measuring curves during the chipping process as shown in Figure 5.

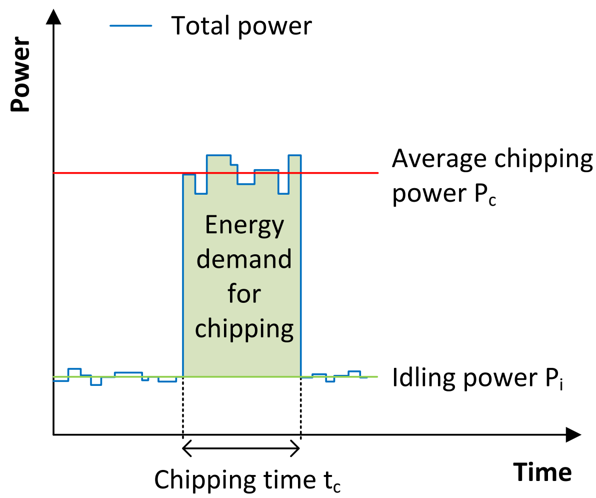

Figure 5. Determining the mean energy demand for comminution of wood in a drum chipper, taking idling power into account (P_c average chipping power; P_i Idling power; t_c chipping time).

Taking into account the dry wood matter comminuted during the measurement, it was than possible to calculate the specific energy demand for chipping a wood sample as follows (Equation (1)) [44]:

$$W_{spec} = \frac{(P_c - P_i) \times t_c}{3600 \times m_d} \times 1000 \tag{1}$$

W_{spec}, specific energy demand for chipping on dry matter basis [kWh t^{-1}]; P_c, average power consumption during chipping [kW]; P_i, average power consumption during idling [kW]; t_c, time required for chipping of one sample [h]; m_d, dry matter of the processed sample [t].

2.4. Statistical Analysis

The results were evaluated by the statistical software SAS v9.4 (SAS Institute Inc., Cary, NC, USA). For evaluation of the data the procedure GLIMMIX was used in order to carry out a two factorial ANOVA. The GLIMMIX procedure adapts statistical models to data with correlations or non-constant variability, homogeneous or non-homogeneous variances where the response is not necessarily normally distributed. Due to the interactions between the two factors only the twofold effect was considered. In the following figures, treatments labelled by different letters are different according to GLIMMIX procedure with $p \leq 0.05$.

3. Results

3.1. Specific Energy Demand

Table 2 provides an overview of the results of the specific energy demand measurements and the mean particle size produced when chipping different timber ranges. The results show that there are relatively large differences in the specific energy demand, not only depending on the variety, but also depending on the condition of the stems (freshly harvested, dried or frozen). Chipping of thin willow shoots (seven freshly harvested stems per trial) required the least energy, displaying a specific energy demand of 4.03 kWh t^{-1} (Trial No. W-S-w-7). A comparison of the comminution experiments that were conducted with four fresh and distinctly thicker stems in each case reveals that the chipping of poplar of the Max variety requires the least energy at 4.81 kWh t^{-1}, followed by willow (Tordis 5.63 kWh t^{-1}, Inger 5.87 kWh t^{-1}), black locust (6.28 kWh t^{-1}) and the poplar Hybrid 275 (6.50 kWh t^{-1}), see also Figure 6.

Table 2. Specific energy demand and median particle size of the wood chips produced for different tree species.

Variety	Trial No. [1]	Moisture Content [%]	Particle Size d_{50} [2] [mm]	Content of Fines [3] [%]	Specific Energy Demand [4] [kWh t^{-1}]
Poplar Max	P-M-w-4	54.5	12.7	3.2 (0.07)	4.81 (0.31)
	P-M-d-4	34.8	10.9	5.1 (0.11)	5.44 (0.26)
	P-M-f-4	57.0	11.9	4.0 (0.83)	6.31 (0.41)
	P-M-w-2	59.4	12.0	3.6 (0.09)	6.37 (0.03)
Poplar AF2	P-A-w-2	61.1	11.4	4.3 (0.08)	6.44 (0.21)
Poplar H275	P-H-w-2	51.6	14.8	4.0 (0.12)	7.87 (0.10)
	P-H-f-1	55.8	12.0	4.3 (0.07)	9.16 (1.20)
	P-H-f-4	51.5	12.2	4.9 (0.14)	7.93 (0.25)
	P-H-w-4	50.5	13.8	2.1 (0.12)	6.50 (0.16)
Black Locust	B-L-w-4	40.8	12.2	4.2 (0.11)	6.28 (0.18)
Willow Inger	W-I-w-4	46.8	11.1	5.7 (0.15)	5.87 (0.28)
Willow SV G	W-S-d-9	24.6	10.4	8.6 (0.05)	6.67 (0.52)
	W-S-w-9	40.5	12.9	3.7 (0.08)	4.21 (0.15)
Willow Tordis	W-T-f-4	48.4	12.1	3.8 (0.04)	6.46 (0.51)
	W-T-w-4	50.4	11.5	3.9 (0.06)	5.63 (0.17)
Willow SV E	W-S-d-7	26.8	13.3	2.0 (0.23)	5.35 (0.21)
	W-S-w-7	45.6	12.6	3.5 (0.14)	4.03 (0.14)
	W-S-d-15	23.7	14.6	2.7 (0.21)	5.84 (0.26)

[1] Labelling: Variety-Clone-Condition-No of shoots per trial. Example for labelling: W-S-d-15 = **W**illow, clone ***S**alix viminalis*, **d**ried shoots, **15** shoots per chipping trial. [2] Median value of the particle size distribution. [3] Dry matter mass fraction smaller than 3.15 mm (EN ISO 17225-1), standard deviation in brackets. [4] On dry matter basis, standard deviation in brackets.

For the poplar varieties Max and Hybrid 275, the influence of the stem diameter on the energy demand during chipping was examined in detail. It was shown that an increase in the stem diameter of both poplar varieties also led to a significant increase in the energy demand for comminution. In the same way, in all trials significantly more energy was required for chipping frozen stems—the energy demand increased by 15% to 31% depending on the variety (four stems per trial, Figure 7). An additional increase in the stem diameter led to a considerable but statistically non-significant rise in the energy demand for frozen trees. As a consequence, chipping of a single, frozen, very thick log with a cross section area equivalent to four stems displayed the highest specific energy demand (9.16kWht^{-1}, trial P-H-f-1) measured in all the trials.

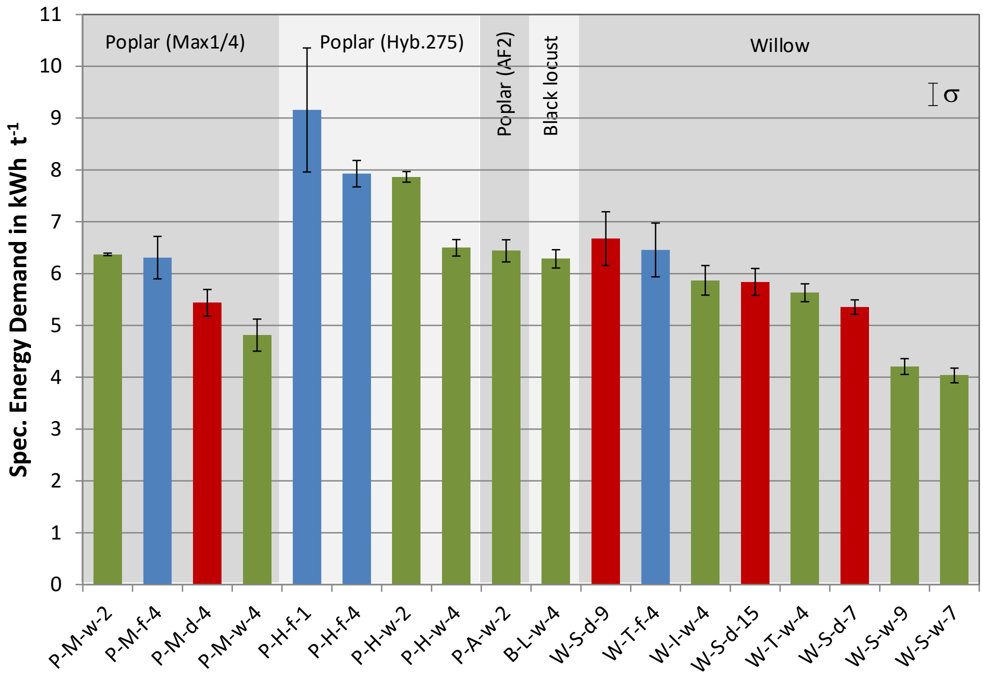

Figure 6. Overview of the specific energy demand for chipping poplars, willows and black locusts from short rotation coppices (SRCs) in fresh, dried and frozen conditions (colors: green = fresh, dried = red, blue = frozen); Labelling of trials on x-axis: Variety-Clone-Condition-No of shoots per trial. Example for labelling: W-S-d-15 = **W**illow, clone ***S****alix viminalis*, **d**ried shoots, **15** shoots per chipping trial, see Table 1.

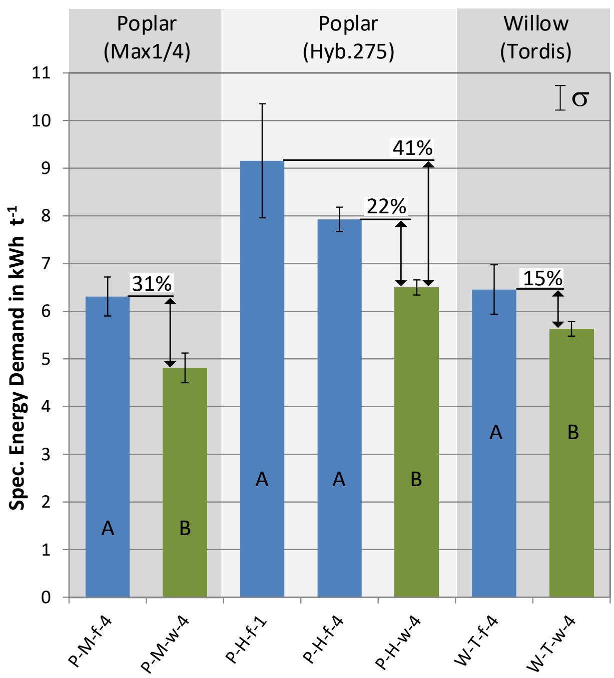

Figure 7. Comparison of the specific energy demand for chipping fresh and frozen poplars and willows from SRCs (colors: green = fresh, blue = frozen; different letters indicate significant differences between trials ($p \leq 0.05$)); Labelling of trials on x-axis: see Table 1.

In addition, more energy is also required for chipping dried trees from SRCs (Figure 8). Accordingly, the specific energy demand for chipping dried poplars (variety Max) increased significantly by approx. 13% and for dried willows (variety *Salix viminalis* from England) by as much as 33%. The chipping of bundles of very thin, dried willow shoots (diameter of the individual shoots 1.8 to 2 cm, trial W-S-d-15) required approx. 9% more energy by comparison with thicker dried shoots of the same variety (diameter 2.9 to 3 cm, trial W-S-d-7).

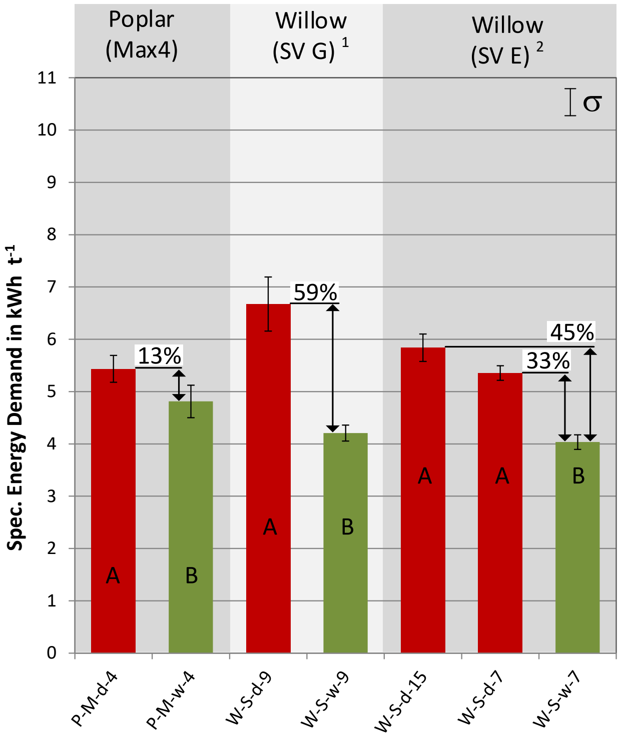

Figure 8. Comparison of the specific energy demand for chipping fresh and dried poplars and willows from SRCs (colors: green = fresh, red = dried; different letters indicate significant differences between trials ($p \leq 0.05$)). [1] *Salix viminalis* from ATB, Germany. [2] *Salix viminalis* from Rothamsted Research, England; Labelling of trials on x-axis: see Table 1.

3.2. Particle Analysis

Figures 9–11 show the results of the particle size analysis for the different wood varieties. The median values of the particle size (d_{50}) are additionally listed in Table 2 for a better comparison of the trial results.

Figure 9 shows the connection between the particle size distribution and variety for the trials with freshly harvested samples (four stems per chipping trial). It is evident from this that the willow varieties examined supply the finest wood chips, followed by black locust and poplar. If the results obtained with fresh trees and four stems in each case are compared, the poplar variety Hybrid 275 with a median value d_{50} of approx. 13.8 mm produces the coarsest wood chips, and willow of the Inger variety with a median value of 11.1 produces the finest wood chips. When a smaller number of thicker trees were chipped, the trials with the poplar variety Hybrid 275 showed a rise of approx. 7% in the median value of the particle size distribution (d_{50} = 14.8 for two trees, Table 2, trial P-H-w-2).

Figure 10 shows the effect of frost and drying on the particle size distribution of poplar wood chips. The chipping of both frozen and dried stems led to a reduction in the particle sizes (see the median values in Table 2). For poplar stems (variety Max) the median value of the particle size distribution was reduced from 12.7 mm to 11.9 mm for frozen stems and to 10.9 mm for dried stems (reduction by 5% and 13% respectively). If one considers the screen fraction relevant for classification of the wood chips into different quality and fines fraction classes up to 3.15 mm screen aperture diameter, the mass fraction in these classes grew as a result of drying and frost. Wood chips from freshly chipped poplar (trial P-M-w-4) contained a fines fraction of only 3.2%, while wood chips from poplars of the same variety and diameter chipped after drying contained a fines fraction of 5.1% (trial P-M-d-4) and wood chips from frozen poplars contained a fines fraction of 4.0% (trial P-M-f-4). The comparison between different wood species chipped under comparable conditions (wet, 4 shoots) shows, that the content of fines in chips from willow and black locust is higher (3.9–5.7%) than in chips from poplar (2.1–3.2%).

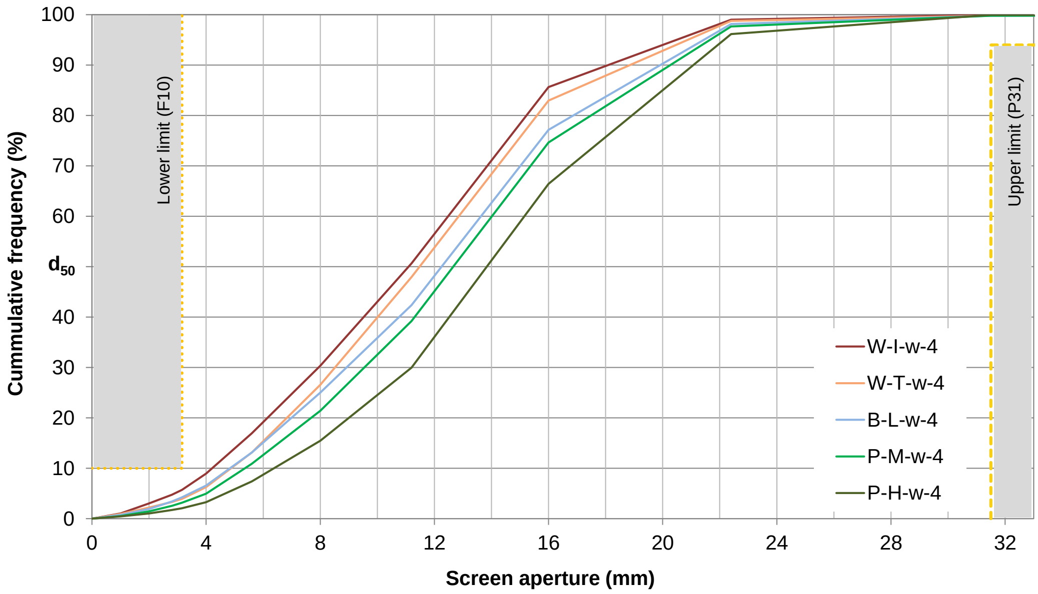

Figure 9. Particle size distribution for fine wood chips from poplar, willow and black locust and standard ranges according to EN ISO 17225-1; Labelling of trials: see Table 1.

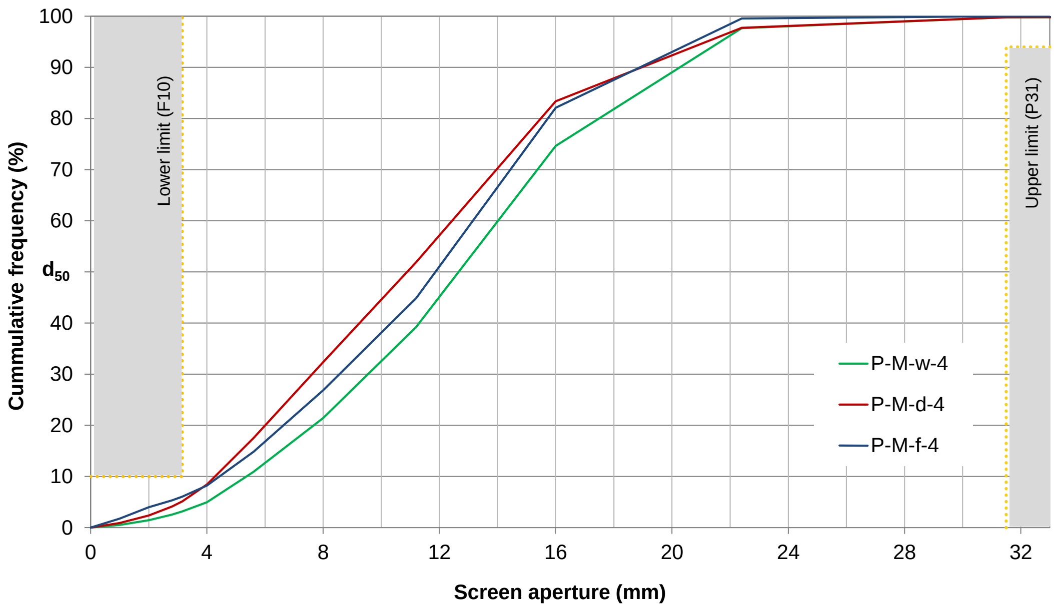

Figure 10. Particle size distribution for fine wood chips from fresh, dried and frozen poplars (variety Max) and standard ranges according to EN ISO 17225-1; Labelling of trials: see Table 1.

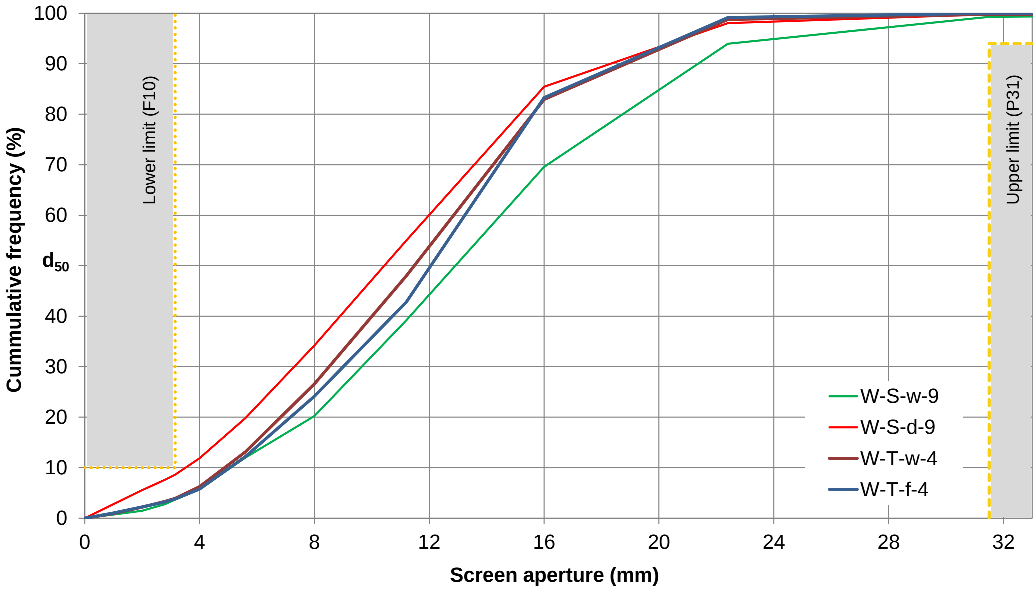

Figure 11. Particle size distribution for fine wood chips from fresh, dried and frozen willows and standard ranges according to EN ISO 17225-1; Labelling of trials: see Table 1.

Figure 11 shows the connection between drying, frost and particle size distribution for willow. While for the *Salix viminalis* from Germany drying led to a reduction of 19% in the median value of the particle size after chipping, this value was increased distinctly by 10% for the *Salix viminalis* harvested in England (W-S-w-7 and W-S-d-7, see Table 2). It was possible to examine the influence of frost on the particle size for the variety Tordis. Here the median value for wood chips from frozen willow shoots rose by approx. 5% (Table 2, trial W-T-w-4 and W-T-f-4). The willows of the *Salix viminalis* species examined form a large number of very thin shoots per stump by comparison with the Tordis variety. Therefore, bundles of nine shoots always had to be chipped to obtain a representative trial round. As can be seen from Figure 11, chipping of these shoots in dried condition lead to a distinctly higher fines fraction of 8.6%.

4. Discussion

4.1. Energy Demand

The investigations conducted have shown that substantially more energy is required for chipping frozen or dried poplars and willows from short rotation coppices than for chipping fresh trees. This may have been an essential cause of the damage to the harvesting machine observed during harvesting within prolonged frost periods at temperatures well below −5 °C. If we compare the specific energy demand required for chipping the approx. 4 cm thick non-frozen poplar trees (4.81 kWh t^{-1}) with the demand required for approx. 8 cm thick frozen trees (9.16 kWh t^{-1}), it is evident that here nearly twice as much comminution energy is needed—along with correspondingly higher mechanical stress upon the chipping unit of the harvesting machine. Despite being the same age, by nature the trees within a short rotation coppice plantation do not have a uniform trunk diameter. On the grounds of natural fluctuations of essential growth factors, such as for example the availability of nutrients, water and light in an SRC plantation, there is always a scatter of diameters in the tree population. Especially in edge rows and in areas adjacent to gaps among the trees, there are often considerably thicker trees [48–50]. In order to avoid damage to machinery during heavy frost periods, particular care must therefore be taken when harvesting these parts of the field. The driving speed should be reduced and with it the specific mass flow of wood to the chipping unit. One essential cause of the higher energy demand when chipping frozen trees will be the water frozen to ice inside the trees at temperatures lower than −5 °C [37], that now additionally has to be comminuted. At the same time the stems—as the particle size analysis has shown—are comminuted rather more finely. On the other hand, harvesting in frosty conditions also offers advantages, such as better trafficability of the fields. Hence, harvesting in frost can be further recommended, but outdoor temperatures lower than −5 °C should be avoided, and machine operators should work with special care at lower temperatures.

It was also established that chipping dried trees can be disadvantageous in energy terms as well. This was shown by the trials with the thicker stems of the poplar Max and willow (from England) varieties. Only chipping of the very thin shoots of the willow from Germany showed a reduction in the specific energy demand.

If the condition-dependent changes in the energy demand for chipping are set in relation to the energy content of the harvested material and the total energy outlay of the harvesting machines used, it becomes clear that this is, however, very slight. Taking the energy content of the poplar wood chips harvested on one hectare after four years as a basis (gross calorific value 18.5 MJ kg^{-1}, yield 10 t dry matter per year [5,51]), then the extra energy outlay is less than 0.1%, even under the most unfavorable harvesting conditions. Based on the results obtained by Scholz et. al. 2011 [5] and Schweier et. al. 2016 [20] for the fuel demand of the forage harvesters frequently used for SRC harvesting (80 to 90 l ha^{-1}), the fuel requirement of a forage harvester for harvesting would rise by up to 17 L per hectare—combined with a simultaneous increase in the harvesting costs. If the harvesting of frozen trees of relatively large diameter is additionally combined with higher malfunction times or damage to the machines, this can also lead to a substantial rise in the harvesting costs.

4.2. Particle Size

A comparison of the particle sizes obtained from chipping poplars of the same diameter makes it clear that chipping both frozen and dried stems leads to a distinct reduction of the mean wood chip size and, in connection with this, to a distinct increase in the fines fraction. Depending on the tree species, the stock and storage of the trees, this can in practice lead to a substantial reduction of the wood chip quality. Despite the quality differences determined, all the wood chips examined met the requirements of Standard EN ISO 17225-1 for the fines fraction category F10 [27]. In practice the rise in the fines fraction when chipping dried stems can at the same time be connected with an additional loss of mass in chipping. The mobile chippers used here are normally equipped with a discharge chute, via which the wood chips are blown onto a transport trailer. When producing wood chips with a high fines fraction, this leads on the one hand to high dust loads in the environment, while at the same time a larger share of the fines is lost via the airflow. These possible losses become clearest in the example of chipping the willow shoots of the *Salix viminalis* variety (trials W-S-w-9 and W-S-d-9). The increase in the fines fraction/the losses caused by drying amounted to 5 percentage points of the dry matter here. In this connection the dust emissions caused during chipping can also be particularly significant. Particles that have passed through the screen with an aperture width of 1 mm can potentially be discharged as dust during chipping [47]. As a consequence, when chipping one metric ton of dried willow shoots (*Salix viminalis*), up to 28 kg dust can be discharged. In a freshly harvested condition at most only 7 kg dust would result (calculated on the dry matter basis).

5. Conclusions

The chipping of dried or frozen poplars and willows from short rotation coppices with the usual stem diameters of more than 3 cm leads to a higher energy demand of 13–59% for comminution coupled with a rise in the fines fraction in the wood chips. Although harvest during frost in winter can be recommended due to improved trafficability of the fields, special care should be taken if very thick frozen trees have to be harvested with modified forage harvesters or tractor-mounted mower-chippers. Under these conditions the highest specific energy demand of all trials (9.16 kWh t^{-1}, an increase of 41%) has been measured—along with correspondingly higher mechanical stress for the chipping unit. However, the rise in energy demand is negligibly low by comparison with the yield of an SRC area and the energy demand for the entire process chain.

Looking at the particle sizes produced and in particular the fines fraction, the quality of the wood chips rises when trees with larger trunk diameters are chipped. Therefore, the development of machinery for single-step harvesting of SRCs with relatively large stem diameters is recommended, but special attention needs to be paid to the increase of the mechanical stress of the chipping unit at low temperatures in winter. Furthermore, our results have shown that the fines fraction in the wood chips grows, especially when chipping thin dried stems (max. 8.9%, willow). To what extent this affects the balance of the mass losses along the overall process chain needs to be examined in future studies. One advantage of the two-step harvesting of SRC with storage of the harvested stems can be seen in the reduced mass losses during storage and drying. To what extent this advantage is in turn relativized by process-related losses during handling of the trees during harvesting and at the storage site as well as by further losses during chipping has not so far been investigated sufficiently.

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