




## Article

# Quality and Delivery Costs of Wood Chips by Railway vs. Road Transport

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**Abstract:** Forests are the main sources of wood chips delivered to the end customers by road or railway. This research analysed the impact of the quarter of the year: Q1 (January–March), Q2 (April–June), Q3 (July–September), Q4 (October–December) when wood chips were obtained over two consecutive years (2019–2020) and the type of transport used (railway and road) on the thermophysical properties of wood chips and the cost of their delivery. The mean moisture content in the wood chips was 38.28% and it was the highest (45.55%) in Q1, while in Q2 and Q3, this parameter was 8 and 17 percentage points (p.p.) lower. The mean lower heating value (LHV) of the chips was 10.46 GJ Mg<sup>-1</sup>. The chips delivered by road transport had a 4% higher LHV compared to those shipped by railway transport. The wood chips contained 3.42% d.m. of ash. The road transport at a distance of 200 km was found to be approximately 10% cheaper compared to the transport by rail for most of the study period, both with respect to 1 Mg of fresh or dry mass and 1 GJ of energy in the chips. The railway transport was cheaper in the winter (Q1).

**Keywords:** forest biomass; wood chips; thermophysical properties; transport costs; railway transport; road transport



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## 1. Introduction

Biomass has become an important renewable energy source (RES) throughout the European Union (EU), as it accounted for the greatest part (40.1%) of the primary energy production in 2019 [1]. Solid biofuels are a particularly important RES in northern European countries, such as Estonia (94.5%), Latvia (87.3%) and Finland (74.0%). Biomass has also become the most important RES in Poland, accounting for 65.6% of renewable energy production in 2019. For comparison, wind energy, the second-largest energy source in Poland, accounted for 13.7% of the total primary energy production from RES. Solid biomass in the form of wood chips is mainly consumed by power plants, combined heat and power plants (CHP) and industrial heating plants, with the demand for this fuel rising continuously. They produced 56,414 TJ of energy from solid biofuels in 2017, 58,484 TJ in 2018 and 71,201 TJ in 2019 [2].

Solid wood biomass is derived mainly from forests and the wood processing industry [3,4]. Wood biomass can also be obtained from short rotation coppice (SRC) plantations, such as willow, poplar, black locust or eucalyptus [5–7]. Fruit orchards can be another source of wood biomass, where it is obtained from tree pruning or when an orchard is liquidated when no longer in use. Wood biomass can also be obtained through the maintenance of roadsides, traffic routes and parks. Many projects are underway to restore land to its agricultural use by eliminating self-sown trees, which also yields wood biomass [8–10].

Since wood is obtained from forests virtually all year round, logging residue is also always available. Moreover, since wood is also processed continuously, different kinds of waste are produced without interruption [3]. Therefore, forest and wood processing plant residues must be collected and transported as wood chips to the end consumers of solid biomass such as heating plants, power plants and CHP. However, the demand for fuel is higher in winter, when the need for energy is higher [11]. In consequence, companies transporting wood biomass accumulate it periodically in stacks near the cutting sites or at their logistical sites and subsequently process them into chips immediately before transporting them to the end consumers. This is particularly important as storing large-volume logging residue and post-processing waste results in lower dry matter loss compared to storing wood chips.

Moreover, more intensive use of machines and devices for grinding, loading and transport reduces the unit operating costs if the residues are chopped immediately before shipment [3,12]. Various studies have been conducted to increase the efficiency of delivering wood chips to the end consumer [13–15]. The unit costs of wood chip supply can be significantly reduced by increasing the overall equipment effectiveness (OEE). The means of transport can play a key role in terms of the volume, flexibility and stability of wood chip supply as it is a solid biofuel with a low bulk density.

Wood chips can be delivered to the end customers by road, railway or sea, depending on the scale and logistical capabilities. Road transport is usually used for wood chip biomass from forests in Poland. It still dominates even though the share of railway transport is increasing due to the use of dedicated freight systems (e.g., Innofreight) and to the technical adaptation of CHP to receiving railway deliveries. The advantages of road transport are its flexibility and speed and the possibility of delivering smaller volumes than is the case with deliveries by rail [16]. Due to the geographic features of Poland, wood biomass is not shipped by water routes as this would necessitate intermodal or multimodal transport because major domestic biofuel consumers are located away from river or sea routes.

The type of transport can affect the wood chip transport costs and the solid biofuel quality. For example, the cargo is not covered with tarpaulins in railway transport due to the specific container construction, making the biomass susceptible to soaking if the weather conditions change (rain or snowfall). In such cases, the biomass physicochemical parameters change. For deliveries settled based on energy units (e.g., GJ Mg<sup>-1</sup>), a change in these parameters has a significant economic impact. If deliveries involve truck trailers of the “walking floor” type, a securing tarpaulin is used, protecting the fuel from the weather factors, so it arrives at the consumer’s site with the same physicochemical parameters as when it left the production process. However, the tree species and the part of it that is used (wood, bark, branches, shavings, etc.) and the processing and production conditions are known to be of key importance for biofuel quality [3,17,18].

The novel aspects of the current study include a comparative analysis of the road and rail freight logistics for wood chip transport from a supplier to an end consumer over a period of two consecutive years. The study analysed the effect of dendromass acquisition season and the type of transport on the chips’ thermophysical properties and the cost of their transport to the end consumer. The research hypothesis assumes that the period and type of transport cause a significant differentiation in wood chips’ quality and delivery costs. Therefore, the present study aimed to determine the impact of (1) the year (years 2019–2020); (2) period of dendromass harvest (four quarters: Q1, Q2, Q3, Q4) and (3) type of transport used (railway vs road transport) on thermophysical properties of wood chips and the costs of their transportation to an end consumer.

## 2. Materials and Methods

### 2.1. Characteristics of the Analysed Logistical Chains

The analyses in this study were based on the real-world data obtained from Quercus sp. z o. o.—a company which produces and transports wood chips as energy feed-

stock. The company is located in Pasy in north-eastern Poland (GPS 53.631501814037634, 20.76411808418108). Wood chips were transported from this location to a CHP owned by the consumer—a domestic power supply company located in Warsaw, Poland (GPS 52.229490605191444, 21.0124351854053). The study covered two years: 2019 and 2020. Moreover, each year was divided into four quarters: Q1 (January–March, winter), Q2 (April–June, spring), Q3 (July–September, summer), Q4 (October–December, autumn). Wood chips were transported in two different logistics chains. (1) Innofreight container railway transport, (2) road transport with truck tractors and self-unloading trailers (Figure 1). The transport distance of the wood chips from the producer to the consumer was similar in both variants—approximately 200 km.



**Figure 1.** Diagram of wood chip preparation from various types of wood biomass stored at the Quercus site and the logistics of wood chip transport to the end consumer.

The Innofreight railway transport system, used for the train deliveries of wood chips, is intended to transport energy feedstock, such as biomass and coal. Containers are placed in threes on dedicated platform cars. The whole train comprised 29 SGS dedicated platforms. There were three containers on each platform, 87 containers in one train, with a total cargo capacity of 3915 loose cubic meters (LCM). Since the dimensions of each container were  $2.9 \text{ m} \times 2.9 \text{ m} \times 6.05 \text{ m}$  and the total cubic capacity was  $45.2 \text{ m}^3$ , a total of 45 LCM of chips could be loaded into each container. There were two holes in the bottom part of each container, which could be used to unload the cargo with a forklift truck with a turntable. Unloading a container with fuel can be very efficient with this system regardless of its bulk density and can take as little as 2.5 min [19]. In practice, due to specific conditions at the consumer's site, it can take from 3–5 min. In consequence, unloading a train can last from 4–7 h, including the time of moving a forklift truck to the next container and moving the pendulum to gain access to all platforms.

Road deliveries were completed with truck sets with Kraker and Stas self-unloading trailers with the same loading capacity of  $92 \text{ m}^3$ . Due to the gross vehicle weight (GVW max = 40 Mg), each trailer carried 85 LCM of wood chips. Self-unloading trailers, also known as “walking floors”, are intended for fast and effective unloading of loose materials, including wood chips. Its main parts include metal strips movable in the horizontal plane and the mobile wall, which push the cargo towards the unloading point. Removing the cargo from such a self-unloading trailer took about 10–15 min. This means that the same volume of wood chips (equivalent to the load of one train) can be unloaded in about 11 h from trucks, while the cargo from a train can be unloaded in only seven hours. However, it

should be considered that two trailers can be unloaded simultaneously when the biomass unloading chutes are large enough.

The wood chips used in this study were obtained from an area owned by the State Forests, mainly from logging residue, M2E wood—wood residue [20] and from post-production residue from wood processing plants, such as sawmills, in the proportion of 50/50%. Pine, which is the major forest-forming species in this part of Europe, was predominant in the M2E wood and the post-production residue. It accounted for about 70% of the wood residue. The other species in the chips produced at the Quercus company site included fir, birch, beech and alder, and traces of other species. The whole biomass from these sources was brought to the company storage yard, equipped with a railway siding and truck scales. It was subsequently chopped down to wood chips required under the contract between the company and the consumer and loaded onto the chosen means of transport. Notably, all of the biomass covered by the research (wood chips), regardless of the form of transport, was obtained from one source and was prepared and loaded onto vehicles within one production site.

## 2.2. Thermophysical Properties of Wood Chips

The thermophysical properties of the wood chips were determined in accordance with the formal standards outlined in [21,22], which may be summarised as follows. Biomass samples were collected from each wood chip batch delivered to the CHP. One whole-train delivery constituted one batch, whereas one batch comprised all deliveries completed during one working day in the road transport. Wood chip samples were collected automatically with a dedicated device—a sample collector situated under the unloading chute. This technology made the sample collection procedure regular and fully random.

The laboratory tests of chips delivered by railway and road transport included determination of total moisture content (%), ash content (% DM—dry matter) and lower heating value—LHV ( $\text{GJ Mg}^{-1}$ ). The wood chip moisture content was determined by drying to a constant weight and weighing as per PN-EN ISO 18134-2 [23]. The ash content was determined by the gravimetric method as per PN-EN ISO 18122 [24]. The LHV was calculated as per PN-EN ISO 18125 [25].

As mentioned above, these tests were performed with data obtained from wood chip delivery by railway and road transport in 2019–2020, broken down into four quarters. Six railway deliveries (replicates) were selected randomly from each quarter and, similarly, six road deliveries, which gave 48 deliveries by each of the means of transport under analysis and 96 deliveries altogether over two years. Moreover, the amount of chips delivered (kg) and the train container and vehicle trailer capacity (LCM) was used to calculate the chip bulk density ( $\text{kg LCM}^{-1}$ ).

## 2.3. Cost of Wood Chip Delivery by Railway and Road Transport

Data from the Quercus company (a supplier of biomass as energy feedstock) concerning the cost structure of individual operations were used to analyse the wood chip logistic chain in the two transport systems—by railway and by road. A diagram was presented showing the machines and devices used to prepare wood chips and their loading onto the dedicated means of transport (Figure 1). The analyses included the calculation of the total cost of railway and road transport. Subsequently, the cost of a fresh biomass unit (FM), which was used to settle the deliveries ( $\text{€ Mg}^{-1}$  FM), was calculated as the ratio of the total transport cost (€) and the quantity of delivered biomass (Mg). Moreover, the transport cost for a dry biomass unit ( $\text{€ Mg}^{-1}$  DM) was calculated. The delivery cost for 1 GJ of energy in chips ( $\text{€ GJ}^{-1}$ ) was calculated as the ratio of the total transport cost (€) and the LHV of the chips delivered to the CHP (GJ). The cost was converted from PLN to € according to the average PLN/€ conversion rate for 2019/2020, i.e., 4.3714 PLN for 1 €. The cost analysis accounted for inflation, which in Poland in 2020 reached 3.4% compared to 2109. It should be noted that the costs of wood chip transport and shipping from the Quercus company

to end customers were based on long-term contracts, and the COVID-19 pandemic did not vary them. Therefore, the effect of the COVID-19 pandemic was not considered in the transport cost analysis.

#### 2.4. Statistical Analysis

The Shapiro–Wilk test was applied to verify the normality of the attributes under study before the ANOVA analysis was performed. The statistical analysis of all of the data was based on a three-way analysis of variance ANOVA, using the year (2019 and 2020), quarter (Q1, Q2, Q3, Q4) and type of transport (by railway and by road) as main attributes. Arithmetic means, lower quartile, upper quartile, standard deviation and the coefficients of variation (%) were calculated for all of the studied attributes. Homogeneous groups were identified with Tukey’s honestly significant difference (HSD) test at the significance level of  $p < 0.05$ . The Pearson correlation coefficient between the attributes was also determined. All statistical analyses were conducted with STATISTICA PL software (TIBCO Software Inc., Palo Alto, CA, USA).

### 3. Results and Discussion

#### 3.1. Thermophysical Properties of Biomass

Table 1 presents selected indicators of statistical analysis, including the number of observations, mean, lower and upper quartile and standard deviation for the studied attributes. The moisture content, LHV and ash content in the chips were significantly differentiated by the main source of variation (year, quarter, type of transport) and by the various interactions between them (Table 2).

**Table 1.** Selected statistical analysis indicators for the studied attributes \*.

Attribute	Unit	Mean	Lower Quartile	Upper Quartile	Standard Deviation
Moisture content	%	10.46	9.40	11.61	1.45
Lower heating value	GJ Mg <sup>-1</sup>	38.28	32.65	43.15	7.11
Ash content	% DM	3.42	2.40	4.35	1.35
Bulk density	kg LCM <sup>-1</sup>	305.97	285.96	324.08	27.99
Cost	€ Mg <sup>-1</sup> FM	11.37	10.72	11.79	1.15
Cost	€ Mg <sup>-1</sup> DM	18.55	17.15	19.79	1.83
Cost	€ GJ <sup>-1</sup>	1.10	1.01	1.19	0.13

\* number of observations for all attributes = 96.

**Table 2.** Results of analysis of variance (ANOVA)— $p$  values for the studied attributes.

Source of Variation	Moisture Content	Lower Heating Value	Ash Content	Bulk Density	Cost (€ Mg <sup>-1</sup> FM)	Cost (€ Mg <sup>-1</sup> DM)	Cost (€ GJ <sup>-1</sup> )
Year (Y)	0.000 *	0.000 *	0.046 *	0.129	0.904	0.000 *	0.000 *
Quarter (Q)	0.000 *	0.000 *	0.010 *	0.000 *	0.000 *	0.000 *	0.000 *
Type of transport (T)	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *
Y × Q	0.124	0.080	0.039 *	0.395	0.639	0.978	0.864
Y × T	0.886	0.078	0.000 *	0.001 *	0.357	0.944	0.151
Q × T	0.000 *	0.000 *	0.221	0.000 *	0.000 *	0.000 *	0.000 *
Y × Q × T	0.000 *	0.000 *	0.893	0.027 *	0.006 *	0.000 *	0.000 *

\* significant values ( $p < 0.05$ ).

The mean moisture content in the chips was 38.28%, with a coefficient of variation of 18.6% (Table 3). Its level in 2019 was significantly higher (by 3 p.p.) compared to 2020. Consequently, the moisture content in chips in each quarter of 2019 was higher than the same quarter in 2020. Notably, the period (quarter) in which the chips were produced affected their moisture content. The wood chips produced in Q1 in the winter, had the highest moisture content. It decreased in spring (Q2) and summer (Q3), by 8 and 17 p.p., respectively, compared to the Q1 mean. After that, the moisture content in the chips increased to reach nearly 41% in autumn (Q4).

**Table 3.** The moisture content and the lower heating value of wood chips delivered to the end consumer depending on the year, quarter and type of transport.

Source of Variation	Item	Moisture Content (%)	Lower Heating Value (GJ Mg <sup>-1</sup> )
Year (Y)	2019	39.96 <sup>a</sup> (17.4)	10.22 <sup>b</sup> (14.0)
	2020	36.59 <sup>b</sup> (19.0)	10.69 <sup>a</sup> (13.5)
Quarter (Q)	Q1	45.55 <sup>a</sup> (10.2)	8.90 <sup>d</sup> (10.0)
	Q2	37.80 <sup>c</sup> (10.7)	10.62 <sup>b</sup> (7.7)
	Q3	28.93 <sup>d</sup> (9.2)	12.35 <sup>a</sup> (4.4)
	Q4	40.84 <sup>b</sup> (7.9)	9.95 <sup>c</sup> (6.2)
Type of transport (T)	Railway transport	39.70 <sup>a</sup> (19.6)	10.25 <sup>b</sup> (15.4)
	Road transport	36.86 <sup>b</sup> (16.7)	10.67 <sup>a</sup> (12.1)
Y × Q	2019_Q1	46.82 (12.4)	8.80 (14.0)
	2019_Q2	40.36 (8.9)	10.21 (8.0)
	2019_Q3	30.78 (6.9)	12.03 (3.9)
	2019_Q4	41.89 (6.4)	9.86 (6.9)
	2020_Q1	44.28 (6.3)	9.00 (3.5)
	2020_Q2	35.24 (7.4)	11.03 (5.4)
	2020_Q3	27.08 (6.0)	12.68 (3.2)
	2020_Q4	39.78 (8.9)	10.05 (5.6)
Y × T	2019_Railway	41.42 (18.0)	9.92 (15.4)
	2019_Road	38.51 (16.1)	10.52 (12.3)
	2020_Railway	37.98 (20.7)	10.57 (15.1)
	2020_Road	35.21 (16.3)	10.81 (12.0)
Q × T	Q1_Railway	49.04 <sup>a</sup> (6.7)	8.34 <sup>d</sup> (8.0)
	Q1_Road	42.05 <sup>b</sup> (6.6)	9.46 <sup>c</sup> (7.7)
	Q2_Railway	39.08 <sup>c</sup> (10.3)	10.32 <sup>b</sup> (8.4)
	Q2_Road	36.52 <sup>c</sup> (10.3)	10.93 <sup>b</sup> (6.0)
	Q3_Railway	29.34 <sup>d</sup> (11.8)	12.33 <sup>a</sup> (5.5)
	Q3_Road	28.52 <sup>d</sup> (5.5)	12.37 <sup>a</sup> (3.2)
	Q4_Railway	41.33 <sup>b</sup> (4.4)	10.01 <sup>b</sup> (5.2)
	Q4_Road	40.35 <sup>b</sup> (10.6)	9.90 <sup>b</sup> (7.4)
Mean		38.28 (18.6)	10.46 (13.9)

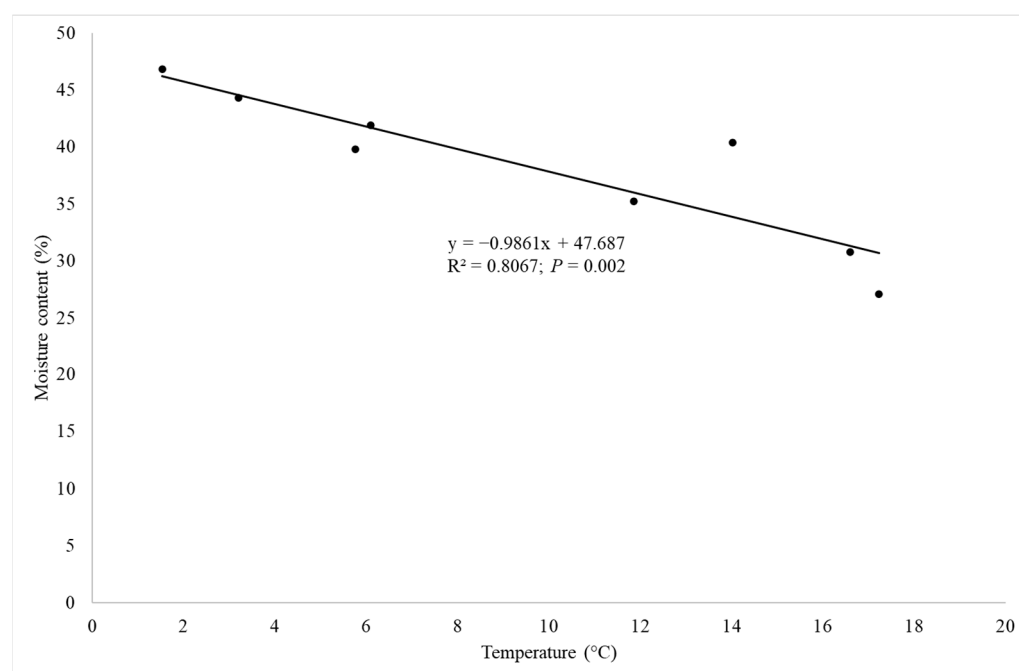
<sup>a,b,c,d</sup> homogenous groups for the main source of variation and their interaction separately for each attribute, no letter denotes an absence of significance; (the coefficients of variation—%).

The variation in wood chip moisture content between years and quarters could be due to different factors such as the length and period of biomass storage at forest clearcuts and wood processing plants. Moreover, atmospheric conditions, mainly precipitation and air temperature, were important factors affecting the biomass moisture content. Table 4 presents selected parameters determining atmospheric conditions for the city of Olsztyn, located approximately 25 km from the Quercus' yard, where the chips were stored and where they were loaded to be shipped to end customer. These data show that the total precipitation in 2019 (672 mm) was slightly higher than in 2020. Furthermore, there were significantly more days with snow cover (44) and days with precipitation (202) in 2019, which may partly explain the higher mean moisture content in wood chips in 2019. However, when analysing the variation in wood chip moisture content between quarters, it should be noted that, apart from the number of days with precipitation or snow cover, it was mainly air temperature that had the greatest and significant influence on the wood chip moisture content. The lowest average air temperatures (on average 1.5–3.2 °C) and the highest number of days with precipitation (64–70) and snow cover (5–43) always occurred in Q1, i.e., winter and then in Q4, i.e., autumn. In contrast, in Q3, i.e., summer, air temperatures were always the highest (on average 16.6–17.2 °C) and the number of days with precipitation was lower compared to Q1 or Q4 and it was in this period where the

wood chip moisture content was the lowest. A significant negative correlation between wood chip moisture content and air temperature was demonstrated, for which  $R^2$  was 0.81 (Figure 2). For the type of transport, chips delivered by road had lower moisture content (by 3 p.p.) compared to those transported by rail (Table 3). These relationships were confirmed in each year and quarter of the study. The moisture content of the wood chips delivered to the CHP throughout the experiment ranged widely from 26.7–51.6%, in summer (Q3) 2020 and in winter (Q1) 2019, respectively (Table S1—Supplementary Materials).

**Table 4.** Selected parameters of weather conditions in the study period.

Item	Average Temperature (°C)	Total Precipitation (mm)	Number of Days with Snow Cover	Number of Days with Precipitation
2019	9.6	672.2	44	202
2020	9.5	667.4	10	194
Q1	2.4	144.5	24	67
Q2	13.0	219.5	1	38
Q3	16.9	185.9	0	41
Q4	5.9	120.0	3	53
2019_Q1	1.5	139.6	43	70
2019_Q2	14.0	227.8	0	31
2019_Q3	16.6	204.3	0	45
2019_Q4	6.1	100.5	1	56
2020_Q1	3.2	149.3	5	64
2020_Q2	11.9	211.1	1	44
2020_Q3	17.2	167.5	0	37
2020_Q4	5.8	139.5	4	49



**Figure 2.** Relationship between the wood chip moisture content and air temperature in the study period.

In another study, the moisture content in forest wood chips was 36.3%, which was similar to the mean value measured in the current study [9]. The moisture content level in wood chips from logging residues (branches and tops) as measured in Sweden was higher

and was 50.6% immediately after collection and decreased with the time of storage [3]. However, this is not surprising, as the value lay within typical ranges for this type of solid biofuel, and the moisture content in chips also exceeded 50% in winter in the current research. In a different study in Estonia, the moisture content in logging residues of various tree species left at the logging site to dry in summer was much lower in autumn and ranged from 23–36% for Norway spruce and Black alder, respectively [26].

The moisture content in wood chips was inversely proportionally correlated ( $-0.98$ ) and directly impacted their LHV (Table 5). Therefore, the relationship between the attributes under study concerning the chips' LHV was inverse compared to their moisture content. The mean chip LHV was  $10.46 \text{ GJ Mg}^{-1}$  with a coefficient of variation of nearly 14% (Table 3). It was significantly higher (by 4%) in 2020 compared to the mean level in 2019. Consequently, the LHV of the chips in each quarter of 2020 was 2% to 7% higher than the same quarter of 2019. Notably, the period (quarter) in which the chips were produced significantly affected their LHV. The significantly highest LHV ( $12.35 \text{ GJ Mg}^{-1}$ ) was calculated for the chips from Q3, i.e., a summer quarter, with the lowest moisture content. It decreased significantly in spring (Q2), autumn (Q4) and winter (Q1) by 14%, 19% and 28%, respectively, compared to the mean value for Q3.

**Table 5.** Simple correlation coefficient between the analysed attributes.

Item	Lower Heating Value	Moisture Content	Ash Content	Bulk Density	Cost (€ Mg <sup>-1</sup> FM)	Cost (€ Mg <sup>-1</sup> DM)
Moisture content	$-0.98^*$					
Ash content	$0.22^*$	$-0.35^*$				
Bulk density	$-0.68^*$	$0.73^*$	$-0.35^*$			
Cost (€ Mg <sup>-1</sup> FM)	$0.57^*$	$-0.57^*$	$-0.02$	$-0.73^*$		
Cost (€ Mg <sup>-1</sup> DM)	$-0.57^*$	$0.60^*$	$-0.41^*$	$0.12$	$0.31^*$	
Cost (€ GJ <sup>-1</sup> )	$-0.72^*$	$0.69^*$	$-0.26^*$	$0.20$	$0.14$	$0.95^*$

\* significant values ( $p < 0.05$ ).

Regarding the type of transport, chips delivered by road featured 4% higher LHV compared to railway transport. These relationships were confirmed in each year and quarter of the study, except for Q4 2020, when the LHV of chips delivered by rail was slightly higher. It should be emphasised that the LHV of the chips transported by truck was higher because their moisture content was lower. The conditions of chip transport may have caused the difference in the chip moisture content and, consequently, the lower heating values between the transport types. The loading process lasted up to more than 10 h because of the logistics of the railway transport, and the rail transport of chips was conducted in open containers that could not be covered and lasted for up to 24 h. Also, the rail containers may have contained rainwater, which could not be removed before the loading.

In contrast, loading one truck in road transport lasted ca. 5 min, the chips were protected against precipitation and the whole transport operation lasted for up to 4 h. These factors could have resulted in higher moisture content of chips delivered by rail transport and, consequently, in their lower LHV compared to road transport. Throughout the experiment, the chip LHV ranged widely from  $7.8$  to  $12.9 \text{ GJ Mg}^{-1}$ , in winter (Q1) 2019 and summer (Q3) 2020, respectively (Table S1—Supplementary Materials).

In a different study, the LHV of forest wood chips was  $11.9 \text{ GJ Mg}^{-1}$  [9] and higher than the mean in the current study. However, the LHV of chips in the current study was higher in summer (Q3) compared to the cited value, as it exceeded  $12 \text{ GJ Mg}^{-1}$ . The LHV of wood chips in a Swedish study, with a moisture content at harvest of 50.6%, was lower ( $8.35 \text{ GJ Mg}^{-1}$ ), although it increased to  $9.00 \text{ GJ Mg}^{-1}$  after 4 months of storage [3]. These values lay within the ranges of results in the current study, especially for chips delivered in winter and late autumn. In a different study in Estonia, the LHV of logging residues of various tree species left at the logging site to dry in summer was higher in late autumn and



was 14 GJ Mg<sup>-1</sup> for Norway spruce and Scots pine. The LHV was lower for Black alder (11.3 GJ Mg<sup>-1</sup>) and Silver birch (12.5 GJ Mg<sup>-1</sup>) [26].

The wood chips contained 3.42% DM of ash, with a high variability coefficient of 39.6% (Table 6). The ash content in chips was significantly higher (by 0.5 p.p.) in 2020, with the variation higher than in 2019. The ash content in chips was significantly higher in Q3 in summer than in the other quarters. It was significantly higher (by 1 p.p.) when wood chips were carried by truck compared to the railway transport. These relationships were confirmed in each year and quarter of the study. Throughout the experiment, the ash content in wood chips ranged widely from 2.05% DM (Q1 2019) to 4.75% DM (Q1 2020) (Table S1—Supplementary Materials).

**Table 6.** Ash content and the bulk density of wood chips delivered to the end consumer depending on the year, quarter and type of transport.

Source of Variation	Item	Ash Content (% DM)	Bulk Density (kg LCM <sup>-1</sup> )
Year (Y)	2019	3.19 <sup>b</sup> (36.7)	308.56 (9.2)
	2020	3.64 <sup>a</sup> (40.9)	303.39 (9.2)
Quarter (Q)	Q1	3.13 <sup>b</sup> (41.8)	323.69 <sup>a</sup> (10.2)
	Q2	3.13 <sup>b</sup> (32.7)	302.28 <sup>b</sup> (6.7)
	Q3	4.06 <sup>a</sup> (30.0)	281.31 <sup>c</sup> (4.6)
	Q4	3.35 <sup>b</sup> (49.1)	316.60 <sup>a</sup> (7.0)
Type of transport (T)	Railway transport	2.91 <sup>b</sup> (28.7)	313.14 <sup>a</sup> (10.3)
	Road transport	3.93 <sup>a</sup> (40.1)	298.81 <sup>b</sup> (7.0)
Y × Q	2019_Q1	2.34 <sup>c</sup> (29.5)	329.07 (10.1)
	2019_Q2	3.14 <sup>b</sup> (25.2)	307.84 (8.4)
	2019_Q3	4.01 <sup>a</sup> (25.9)	281.78 (5.0)
	2019_Q4	3.28 <sup>b</sup> (44.9)	315.55 (4.0)
	2020_Q1	3.92 <sup>a</sup> (33.7)	318.31 (10.4)
	2020_Q2	3.11 <sup>b</sup> (40.1)	296.73 (3.8)
	2020_Q3	4.12 <sup>a</sup> (34.6)	280.84 (4.3)
	2020_Q4	3.42 <sup>b</sup> (54.5)	317.66 (9.3)
Y × T	2019_Railway	3.13 <sup>b</sup> (25.4)	309.61 <sup>a</sup> (10.1)
	2019_Road	3.25 <sup>b</sup> (45.3)	307.51 <sup>a</sup> (8.3)
	2020_Railway	2.68 <sup>b</sup> (30.7)	316.67 <sup>a</sup> (10.5)
	2020_Road	4.60 <sup>a</sup> (30.2)	290.10 <sup>b</sup> (3.5)
Q × T	Q1_Railway	2.86 (26.2)	348.91 <sup>a</sup> (5.3)
	Q1_Road	3.4 (49.7)	298.48 <sup>c</sup> (7.7)
	Q2_Railway	2.76 (29.7)	303.05 <sup>c</sup> (4.3)
	Q2_Road	3.49 (31.6)	301.52 <sup>c</sup> (8.7)
	Q3_Railway	3.55 (26.4)	273.13 <sup>d</sup> (4.7)
	Q3_Road	4.58 (28.2)	289.49 <sup>c</sup> (1.9)
	Q4_Railway	2.46 (16.3)	327.47 <sup>b</sup> (5.0)
	Q4_Road	4.23 (45.8)	305.74 <sup>c</sup> (7.3)
Mean		3.42 (39.6)	305.97 (9.1)

<sup>a,b,c,d</sup> homogenous groups for the main source of variation and their interaction separately for each attribute, no letter denotes an absence of significance; (the coefficients of variation—%).

Nearly a three-fold lower ash content in forest wood chips (0.85% DM) was found in a different study, which may indicate that they were obtained from pure wood stripped from bark [9]. Moreover, they may have been collected directly from a chipping operation, so they did not contain potential natural admixtures, such as sand or dust, which become natural parts of the biofuel during large-scale logistic operations, such as in the current study.

Wood chips examined in research in Sweden contained 2.88% DM of ash [3]. Its content ranged from 3.07% to 3.74% DM depending on the storage method, i.e., it was similar to the results in the current study. The ash content in forest biomass is significantly

differentiated by the species and the part and fraction of the tree from which the biomass is derived. It has been shown to range from 0.24–7.80% DM depending on these factors, for pure wood of Norway spruce and bark of European beech, respectively [17]. A study using *Pinus sylvestris* also showed the ash content to be highly diverse depending on the tree part and was 0.22%, 0.48%, 1.56% and 1.78% DM, in stem wood, branch base, branch twigs and stem bark, respectively [18]. Similar findings were observed in a study of various parts of *Picea Abies*, which contained 0.28%, 2.32% and 3.22% DM of ash, in wood, bark and needles, respectively [27]. The ash content in the wood and bark of this species determined in a different study was slightly higher—0.38% and 3.88% DM, respectively [28]. It was determined to be even higher in the branches and bark of the Greek spruce (*Picea Abies*)—16% and 9.51% DM, respectively [29].

The mean bulk density of the chips was  $306 \text{ kg LCM}^{-1}$ , with a low coefficient of variation of 9.1% (Table 6). The study year did not significantly differentiate the chip bulk density, although it was slightly higher in 2019 than in 2020. It was significantly affected by the period (quarter) of chip production. It was significantly higher (approximately  $320 \text{ kg LCM}^{-1}$ ) for chips produced in Q1 and Q3, i.e., in autumn and winter. The chips bulk density was lower in spring (Q2,  $302 \text{ kg LCM}^{-1}$ ) and in summer (Q3,  $281 \text{ kg LCM}^{-1}$ ). The bulk density of the chips delivered by rail was approximately  $14 \text{ kg LCM}^{-1}$  higher than road transport. A particularly large difference was observed in 2020 when the bulk density was nearly  $27 \text{ kg LCM}^{-1}$  higher in railway transport. It varied during the study period and ranged from 273 to  $350 \text{ kg LCM}^{-1}$  (Table S1—Supplementary Materials).

A study in Finland found that it was similar to the current study from 273 to  $363 \text{ kg LCM}^{-1}$  [30]. The chip bulk density in a study of grapevine biomass logistics in Spain was much lower, i.e.,  $150 \text{ kg LCM}^{-1}$  [31]. This may have resulted from a different type of material and the warmer climate, resulting in a lower moisture content.

### 3.2. Cost of Wood Chip Delivery to the End Consumer

The transport cost for 1 Mg of fresh (FM) and dry (DM) biomass was significantly differentiated by the quarter and transport type and by some interactions between the main attributes (Table 2). The mean transport cost for fresh (moist) chips amounted to  $11.37 \text{ € Mg}^{-1}$  FM, with a low coefficient of variation of 10% (Table 7). This value was almost the same in 2020 and 2019. Notably, the period (quarter) of chip production affected the cost of transport. It was significantly higher in Q3 for fresh chips ( $12.37 \text{ € Mg}^{-1}$  FM) and 14–11% lower in Q1 and Q4, i.e., in autumn and winter. This resulted from the fact that it was negatively correlated with the moisture content ( $-0.57$ ) and density ( $-0.73$ ), which were lower in summer and higher in autumn and winter (Table 5). Regarding the type of transport, it was 8% cheaper for moist chips carried by truck ( $10.94 \text{ € Mg}^{-1}$  FM) than railway transport (Table 7). These relationships were confirmed in nearly every quarter of the study except for Q1 when the transport by rail was cheaper than by road. The cost of fresh chip transport to a CHP situated 200 km away ranged from  $10.06$ – $13.88 \text{ € Mg}^{-1}$  FM, for Q1 and Q3 2020, respectively, for the railway transport (Table S1—Supplementary Materials).

**Table 7.** Transport costs of wood chips delivered to the end consumer depending on the year, quarter and type of transport.

Source of Variation	Item	Cost (€ Mg <sup>-1</sup> FM)	Cost (€ Mg <sup>-1</sup> DM)	Cost (€ GJ <sup>-1</sup> )
Year (Y)	2019	11.38 (9.6)	19.08 <sup>a</sup> (9.2)	1.13 <sup>a</sup> (11.5)
	2020	11.37 (10.7)	18.02 <sup>b</sup> (9.8)	1.07 <sup>b</sup> (11.3)
Quarter (Q)	Q1	10.66 <sup>c</sup> (7.4)	19.66 <sup>a</sup> (8.2)	1.21 <sup>a</sup> (9.6)
	Q2	11.50 <sup>b</sup> (8.4)	18.55 <sup>b</sup> (10.0)	1.09 <sup>b</sup> (11.2)
	Q3	12.37 <sup>a</sup> (10.9)	17.43 <sup>c</sup> (11.5)	1.00 <sup>c</sup> (11.3)
	Q4	10.96 <sup>c</sup> (5.2)	18.56 <sup>b</sup> (6.0)	1.10 <sup>b</sup> (6.3)
Type of transport (T)	Railway transport	11.81 <sup>a</sup> (11.5)	19.64 <sup>a</sup> (5.7)	1.16 <sup>a</sup> (7.9)
	Road transport	10.94 <sup>b</sup> (6.0)	17.46 <sup>b</sup> (10.1)	1.04 <sup>b</sup> (12.5)
Y × Q	2019_Q1	10.66 (8.2)	20.19 (9.4)	1.23 (11.5)
	2019_Q2	11.39 (9.0)	19.14 (10.0)	1.12 (11.9)
	2019_Q3	12.41 (8.1)	17.95 (9.4)	1.03 (10.1)
	2019_Q4	11.06 (6.0)	19.03 (3.7)	1.12 (5.1)
	2020_Q1	10.65 (6.8)	19.13 (5.7)	1.18 (7.3)
	2020_Q2	11.61 (8.1)	17.96 (9.4)	1.06 (9.9)
	2020_Q3	12.34 (13.5)	16.91 (13.1)	0.97 (12.1)
	2020_Q4	10.86 (4.3)	18.09 (7.0)	1.08 (7.1)
Y × T	2019_Railway	11.76 (10.2)	20.16 (5.5)	1.20 (8.6)
	2019_Road	11.00 (7.6)	18.00 (9.1)	1.06 (10.9)
	2020_Railway	11.85 (13.0)	19.12 (4.6)	1.13 (5.6)
	2020_Road	10.88 (3.7)	16.93 (10.4)	1.02 (14.1)
Q × T	Q1_Railway	10.19 <sup>d</sup> (5.6)	20.07 <sup>a</sup> (8.4)	1.23 <sup>a</sup> (10.0)
	Q1_Road	11.13 <sup>c</sup> (6.3)	19.24 <sup>a</sup> (7.7)	1.18 <sup>a</sup> (9.2)
	Q2_Railway	12.20 <sup>b</sup> (4.8)	20.06 <sup>a</sup> (3.8)	1.19 <sup>a</sup> (5.4)
	Q2_Road	10.80 <sup>c</sup> (6.7)	17.04 <sup>b</sup> (7.7)	0.99 <sup>c</sup> (7.5)
	Q3_Railway	13.55 <sup>a</sup> (5.5)	19.19 <sup>a</sup> (4.7)	1.10 <sup>b</sup> (5.5)
	Q3_Road	11.20 <sup>c</sup> (4.2)	15.68 <sup>c</sup> (5.7)	0.91 <sup>d</sup> (5.6)
	Q4_Railway	11.29 <sup>c</sup> (2.7)	19.25 <sup>a</sup> (2.7)	1.13 <sup>b</sup> (4.1)
	Q4_Road	10.63 <sup>c</sup> (5.6)	17.88 <sup>b</sup> (6.4)	1.08 <sup>b</sup> (7.5)
Mean		11.37 (10.1)	18.55 (9.9)	1.10 (11.6)

<sup>a,b,c,d</sup> homogenous groups for the main source of variation and their interaction separately for each attribute, no letter denotes an absence of significance; (the coefficients of variation—%).

The transport cost was higher for grapevine chips in Spain, ranging from 10.15–11.05 € Mg<sup>-1</sup> FM for a distance of 100 km [31]. A study conducted in Finland found that the cost of biomass transport by truck trailer at a distance of 193 km amounted to 5.30 € LCM<sup>-1</sup> FM [30]. Considering mean bulk densities (273–363 kg LCM<sup>-1</sup>), it can be estimated that the transport cost for 1 Mg of chips in the cited studies ranged from 14.6–19.4 € Mg<sup>-1</sup> FM. Therefore, the cost was up to 40% higher compared to the current study. However, it should be noted that the data concerned biomass deliveries in Finland. A different study demonstrated diversity in the chip transport cost in trailers with a capacity of 95–110 m<sup>3</sup>, depending on the transport distance [32]. It amounted to only 0.7 € LCM<sup>-1</sup> FM for a distance of 25 km, whereas an increase in the distance to 50 and 200 km resulted in a considerable cost increase (to 2.7 and 7.0 € LCM<sup>-1</sup> FM, respectively).

In terms of dry matter (€ Mg<sup>-1</sup> DM), the chip transport cost was much higher than that for fresh chips (Mg FM). The mean transport cost for the dry matter of chips amounted to 18.55 € Mg<sup>-1</sup> DM (Table 7). It was significantly higher (by 5.9%) in 2019 compared to the mean value for 2020. The opposite relationships than those for FM were observed in a cost analysis for individual quarters, as the lowest dry matter transport cost (17.43 € Mg<sup>-1</sup> DM) was found in Q3, when their moisture content was the lowest. The transport cost was the

highest (19.66 € Mg<sup>-1</sup> DM) in Q1 in winter, when the moisture content was the highest. The cost was 13% higher compared to the cost in summer.

Regarding the type of transport, chip transport by road was found to be 12% cheaper (17.46 € Mg<sup>-1</sup> FM) compared to railway transport. These relationships were confirmed in each year and quarter of the study. The dry chip transport cost ranged from 14.89–21.33 € Mg<sup>-1</sup> DM throughout the experiment, in Q3 2020 for road transport and Q1 2019 for railway transport, respectively (Table S1—Supplementary Materials).

As determined in a different study, the cost of wood chip transport ranged from 23.0–39.0 CHF Mg<sup>-1</sup> DM [33]. When converted to Euros at the average €/CHF exchange rate as of 1 January 2021, the cost ranged from 21.4–36.3 € Mg<sup>-1</sup> DM. Therefore, these figures were 70% higher than those in the current study.

Apart from determining the transport cost for 1 Mg of dry and fresh chips, it is especially important from an energy-related perspective to determine it per 1 GJ of energy in this solid fuel. The mean transport cost for energy in chips amounted to 1.10 € GJ<sup>-1</sup> with a low coefficient of variation of 12% (Table 7). This cost was significantly higher (by almost 5%) in 2019 compared to 2020. It was differentiated significantly by the period (quarter) of wood chip transportation. In terms of the energy contained in them (1.00 € GJ<sup>-1</sup>), the significantly lowest chip transport cost was observed in summer (Q3). The transport cost was the highest (1.21 € GJ<sup>-1</sup> DM) in Q1 in winter, and it was 20% higher than in summer. Like the transport cost for 1 Mg DM, road transport in terms of the energy contained in chips was 12% cheaper (1.04 € Mg<sup>-1</sup> DM) than the railway transport. These relationships were confirmed in each year and quarter of the study. As referred to the energy contained in them, the chip transport cost ranged from 0.87 to 1.32 € GJ<sup>-1</sup> throughout the experiment, in Q3 2020 for the road transport and in Q1 2019 for the railway transport, respectively (Table S1—Supplementary Materials).

In general, road transport was cheaper compared to railway transport for most of the study period, per 1 Mg FM, 1 Mg DM and 1 GJ of energy (Figure 3). Notably, the difference between the transport types per 1 Mg FM was lower than the differences referred to 1 Mg DM or 1 GJ of energy in chips. However, railway transport was cheaper than road transport in winter (Q1 2019 and 2020) per 1 Mg FM (Figure 3a). It was also cheaper than road transport per 1 Mg DM, but only in winter (Q1 2020). (Figure 3b). Per 1 GJ of energy in chips, railway transport was also cheaper than road transport in winter (Q1) 2020 and in late autumn (Q4) 2019 (Figure 3c). According to these data, the railway transport of chips was competitive compared to the road transport under specific conditions, especially in winter, when the largest amounts of chips are transported to biomass conversion plants. The current study only concerned the cost of chip transport under specific conditions and which was actually incurred. If the costs were increased by costs associated with the environmental burden arising from the difference between the number of shipments necessary to carry the same amount of cargo as in one train, the relationship would probably be different. However, additional studies based on a life cycle analysis are required, which will be the object of future research. It is particularly important concerning sustainable biomass use, which considers the carbon footprint and environmental burden.



**Figure 3.** Cost of wood chip transport depending on the year, quarter and transport type concerning (a) 1 Mg FM (fresh biomass), (b) 1 Mg DM (dry biomass), (c) 1 GJ of energy in this solid biofuel.

#### 4. Practical Implication of the Study

Road transport is used in wood chip freight as it is readily available, affordable and flexible. Moreover, small batches of chips can be transported in specific time windows, and the unloading process does not require involvement from the buyer. No large biomass warehouses are necessary, and if plant failure occurs, the deliveries can be stopped at any time. This solution seems to have only advantages, but this is true only for plants with a daily biomass consumption under 1000 Mg. Handling truck deliveries of this volume requires one-shift work at the biomass receipt site, where each delivery is registered, and its quality is controlled. There is another OSH-related limitation for road transport: each site has limits regarding the maximum number of trucks allowed on the premises at a time. The number of biomass unloading stands is usually the “bottleneck” in wood chip deliveries. Due to these factors, it is often impossible to complete the task during one work shift, even though in theory it takes just four hours longer to unload a truck. One also has to consider that wood chip transport can be organised only when the delivery distance is small. The risk of delivery desynchronisation increases with the transport distance, simultaneously decreasing the truck use effectiveness and, consequently, the driver’s work time. This, in turn, will have a direct impact on the biomass delivery cost.

Producers of energy from large amounts of biomass are often forced to purchase biomass at long distances in large, preferably uniform batches, to make the quality control, quantity registering and unloading as low labour-intensive as possible while observing the required diligence and accuracy. In such cases, the railway transport of wood chips in dedicated systems for transporting loose products seems to be the best solution. The logistics are much simpler, as only one train shipment is required for one 1200 Mg batch of material rather than 50 batches (24 Mg each) by truck.

It must be stressed that railway transport is not so sensitive to loading capacity limitations as truck transport. There was never a situation in the railway transport during the experiment that the loading capacity was exceeded before the transport unit was full. The risk of the ineffective use of a train can be minimised much more easily than in the case of a truck. The advantage of railway transport over truck transport increases with distance, which directly impacts the unit biomass transport costs. The unit cost of railway transport at an average distance of 350 km can be up to three times lower than the truck transport cost [16].

The transport distance was 200 km in the current study, which is where it is economically justified to carry wood chips by rail. The price of the delivered biomass in this experiment depended on its LHV. The optimal solution for a wood chip supplier is to deliver fuel while maximising the use of the truck GVW and the means of transport loading capacity. This creates an opportunity for the optimal use of the vehicle and for keeping the unit transport cost at an acceptable level. The results indicate that the road transport costs were lower nearly throughout the analysed period. The difference was smaller in Q1 and Q4, and the railway transport cost during this period of 2019 was lower than for truck transport. This was associated with the high moisture content in biomass in this period, with a lower amount of energy transported per single truck transport. Moreover, railway transport does not respond dynamically to an increase in fossil fuel prices or labour costs, making it a more stable transport option than road transport [34].

#### 5. Conclusions

The current two-year experiment demonstrated the significant impact of the type of transport, year and period of occurrence on the wood chip quality and cost of delivery to an end consumer. Wood chips transported by truck contained less moisture (with a consequently higher LHV), but they contained more ash compared to wood chips transported by rail. As assumed, higher air temperatures in summer (Q3) reduced the biomass moisture content and increased its LHV, but they also increased the ash content compared to the other periods/quarters, especially to winter (Q1). In general, road transport at a distance of 200 km was approximately 10% cheaper than railway transport for most of the study

period. Nevertheless, the research also showed that road and railway transport differences periodically decreased or even disappeared. This happened especially in Q1 and Q4, when the weather conditions and the biomass parameters increased the chip moisture content, with a consequent decrease in the LHV and an increase in the bulk density.

This is an important observation, especially since the demand for wood chips increases rapidly in the first and the fourth quarters and their bulk density and low LHV have a significant impact on the amount of energy carried per shipment. This is particularly noticeable in biomass produced directly in the forest, where the weather conditions are of key importance for the final biomass parameters. Moreover, longer storage of this type of biomass may result in the initiation of composting and further biofuel degradation. In such cases, the transport cost per unit of energy in biomass increases significantly, but only for road transport. A truck with its cargo will reach the maximum GVW before the loading space is full. In contrast, such a situation did not occur in 2 years of the study, and the railway transport cost did not depend on the transported mass and was fixed for a specific shipment.

Moreover, this 2-year study and observations indicated also other non-economic factors with a significant impact on the choice of the means of transport for wood chips. These factors include transport infrastructure accessibility to the consumer and to the supplier. Road traffic restrictions, both permanent and periodical, make road traffic intensity an important criterion, particularly near residential quarters. Moreover, temporary restrictions of the road traffic in summer should be included in an in-depth analysis, especially because of the holiday period and high temperatures, which cause excessive road pavement wear. The fact that traffic density directly affects road traffic safety and greenhouse gas emissions also require further consideration. Many of the elements mentioned above will be studied in future research as they require further analyses.

**Supplementary Materials:** The following are available online at <https://www.mdpi.com/article/10.3390/en14216877/s1>, Table S1: Supplementary data. Thermophysical properties and transport costs of wood chips delivered to the end consumer depending on the year, quarter and type of transport.

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