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THE IMPACT OF STORAGE DURATION ON CHANGES IN THE QUALITY OF ENERGY WOOD IN LATVIA

***Santa Kaleja, Agris Zimelis, Gints Spalva**
Latvian State Forest Research Institute 'Silava', Latvia
*Corresponding author's email: santa.kaleja@silava.lv

Abstract
Energy wood is a key component of Latvia's renewable energy sector, contributing 76.2% of total renewable energy consumption in 2023. Although energy wood is harvested year-round, its demand and quality vary seasonally, influenced by storage duration, weather conditions, and storage practices. This study aimed to assess how storage duration and weather conditions impact the quality and value of energy wood stored in windrows. To achieve this, 10 deciduous stands managed by JSC 'Latvia's State Forests' (LVM) were selected. Ten windrows of energy wood were created for long-term storage. Monthly laboratory analyses were conducted on wood samples from the windrows and during chipping to measure moisture and ash content, and calorific value. The findings reveal notable seasonal fluctuations in the relative moisture content of energy wood, driven by meteorological conditions. Intensive drying during spring and summer reduced the average moisture content from 39.58% in spring to 33.57% in summer. Conversely, autumn and winter showed an increase in moisture content, rising from 42.20% in autumn to 49.52% in winter. The study also confirmed that the net calorific value of energy wood improves as its moisture content decreases. These findings emphasize the importance of selecting optimal storage locations and planning appropriate drying durations to maximize the energy efficiency of energy wood. By addressing moisture content monitoring and storage challenges, Latvia can further enhance the sustainability and efficiency of its energy wood production processes.
Keywords: energy wood, moisture content, ash content, calorific value, windrows.

Introduction
Energy wood is primarily sourced from less productive trees, undergrowth, and logging residues (Lazdāns et al., 2008a; Lazdiņš, 2012; IRENA, 2018). Its efficiency is influenced by quality factors such as moisture content, calorific value, and ash content, which change during storage (Pettersson & Nordfjell, 2007; Routa et al., 2016). Moisture content, the key determinant of quality, affects calorific value, storage duration, and transportation costs. Freshly prepared energy wood typically contains 50-60% moisture, decreasing to 20-30% in warm seasons but rising again in autumn and winter due to hygroscopic properties (Gautam et al., 2012; Routa et al., 2015, 2016; Eliasson et al., 2019). Optimizing drying and minimizing reabsorption are essential for maintaining quality (Routa et al., 2015, 2016). Ash content varies by tree species, site conditions, and age. Younger trees and hardwoods tend to have higher ash content, ranging from 1.0% to 3.0% (Thörnqvist, 1985; Pettersson & Nordfjell, 2007). Calorific value is also species-dependent, with softwood generally having higher energy content (Thörnqvist, 1985; Būmanis, 2008). In Latvia, energy wood production primarily involves logging residues and small-diameter wood from thinning and regeneration fellings (Iwarsson Wide et al., 2008; Lazdāns et al., 2008b; Kalēja et al., 2014). JSC 'Latvia's State Forests' (LVM) manages 50% of state-owned forests, promoting energy wood production to enhance energy independence. Given Latvia's climatic conditions, LVM has developed guidelines for optimal production and storage, including stacking logging residues along forest roads for efficient transport (Latvian State Forests, 2016, 2021). The LVM guidelines specify a maximum energy wood length of 4 m, with partial delimbing for easier chipping (Latvian State Forests, 2016). Storage occurs in three stages: initial piling in the felling area (1–6 months), roadside stacking with optional covering for conifer-rich wood (Latvian State Forests, 2021), and windrow storage (3–12 months) with at least three months in spring or summer to facilitate drying. The final step involves chipping and delivery to consumers. A key challenge remains the lack of systematic moisture content monitoring during storage. Addressing this requires predictive modelling based on empirical data on moisture content, ash content, and calorific value changes over time. This study aims to evaluate the impact of storage duration and weather conditions on energy wood quality.

Materials and Methods
To obtain the empirical data necessary for achieving the study aim, 10 stands were selected in areas managed by LVM, where overgrowth removal and energy wood preparation had been carried out. For the trials, deciduous stands were selected (with a conifer admixture not exceeding 20%) where the average diameter of dominant trees did not exceed 12 cm, or where thicker trees had been felled and removed either before or after the preparation of energy wood from small-diameter trees.
In planning the trial sites, areas were selected where storage yards could accommodate multiple energy wood piles, each containing 60–80 LV m³ (loose cubic meters) of deciduous energy wood. The piles were positioned to ensure similar exposure to the forest edge, prevailing winds, and terrain. According to guidelines developed by LVM (Latvian State Forests, 2021), the planned width of the unloading area was up to 5 m.
Harvesting was conducted in September 2021 using a mid-sized harvester, John Deere 1070D, equipped with a Bracke C16 harvesting head. At the trial sites, harvesting involved preparing whole, unbranched stems, with the option to cut the trunks into multiple

segments as needed. Energy wood was forwarded in September–October 2021 using a mid-sized forwarder, John Deere 1010D, equipped with Intermercato grapple scales XW 50 PS, immediately after material preparation.

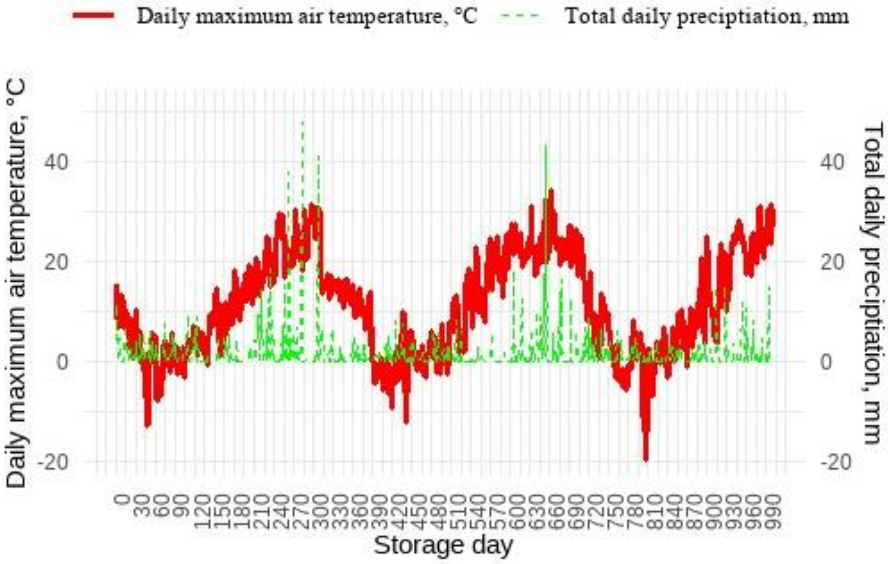
The trial design specified that the windrows of energy wood would have a maximum length of 18 m (with actual lengths ranging from 12 to 16 m), a maximum width of 8 m, and a maximum height of 4 m. In total, 10 windrows of energy wood (coordinates for windrows 1–5: 56.35184° N, 24.0751° E; coordinates for windrows 6–10: 56.36618° N, 24.05872° E) were created for long-term storage as part of the trial. To assess energy wood residues after chipping and enhance moisture control, the designated areas for energy wood stacks were covered with a paper-based laminate before the formation of windrows (Eliasson et al., 2019). The methodology involves chipping one pile every three months.

The storage period of energy wood was divided into three phases. The first phase began on the first day of storage (October 2021) and lasted for 343 days (until September 30, 2022). The second phase started on the 344th day of storage (October 1, 2022) and lasted for 364 days (until the 708th day of storage, September 30, 2023). The third storage phase began on the 709th day of storage and lasted for 297 days (until the 1006th day of storage, July 23, 2024).

Weather data ʻFigure 1ʼ were collected from the nearest meteorological station in Bauska (coordinates 56.3791° N, 24.2217° E), approximately 20 km from the trial site (LVĢMC, 2024).

Figure 1

Changes in daily maximum air temperatures and total precipitation during the storage of energy wood



To more accurately characterize the impact of meteorological conditions on changes in the quality of energy wood during storage, the Forest Fire Weather Index (FWI) system was utilized, which is widely applied for assessing forest fire risks (Van Wagner & Pickett, 1985; Miller, 2020). The FWI system relies on daily meteorological data (LVĢMC, 2024) including maximum daily air temperature (°C), minimum daily relative humidity (%), average daily wind speed (km h^{-1}), and total daily precipitation (mm). It models how weather conditions influence the moisture content of forest biomass and the potential for fire spread. To predict changes in the moisture content of energy wood, the components of the FWI system were calculated using Canadian FWI formulas (Van Wagner & Pickett, 1985; Miller, 2020). These formulas are used to compute the Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC), and Drought Code (DC). A higher FFMC value, on a scale from 0 to 101 (representing very dry material), indicates lower moisture content in energy wood (Van Wagner & Pickett, 1985).

After the formation of the energy wood windrow, as well as during the survey and measurement of windrows, wood samples were collected from each windrow for laboratory analysis. Samples were taken from six locations: two at the ends, two from the top, and two from the front section of each windrow. The wood samples were collected to ensure representation of different wood diameter groups. Industrially processed chip samples were collected from multiple locations within the chip pile. The samples, primarily consisting of branches and a few stem sections, were processed using a gardening chipper. The resulting chips were thoroughly mixed, and a single sample was collected from each windrow. Moisture and ash content, as well as the calorific value, were determined in the laboratory for wood samples taken from energy wood windrows once a month and for samples collected during energy wood chipping.

The data from continuous measurements were prepared for analysis. As part of the study, ISO standard methods and CEN technical specifications adapted to Latvian standards were used in the laboratory to test wood samples obtained from energy wood windrows and crushed under laboratory conditions, as well as industrially crushed (chipped) wood samples. The LVS EN ISO 18134-2:2024 standard (LVS EN ISO 18134-2:2024, 2024) was used to determine the moisture content of the wood. Wood samples were dried using the oven dry method in the atmosphere at a temperature of 105 °C until a constant mass was reached, and the percentage moisture content was calculated based on the mass loss of the samples. The relative moisture content (W_0, %) of the wood samples was calculated using Equation 1.

$$W_0 = \frac{m_{moist} - m_{dry}}{m_{moist}} \times 100\% \quad (1)$$

where:
W_0 – relative moisture content of wood, %;
m_{moist} – weight of naturally moist wood, g;
m_{dry} – weight of dry matter, g.

The LVS EN ISO 18122:2022 standard (LVS EN ISO 18122:2022, 2022) was used to determine the ash content. Wood samples (air-dried ground wood materials) were ashed in a muffle furnace at a temperature of 550 °C, following the muffle furnace manufacturer instructions and pre-set programs. The ash content (P, %) of the analysed sample was calculated using Equation 2.

$$P_{\%} = \frac{a \times 100}{b} \times K_m \quad (2)$$

where:
a – mass of ashes, g;
b – weight of air-dry sample, g;
100 – conversion coefficient;
K_m – moisture coefficient.

The LVS EN ISO 18125:2017 specification (LVS EN ISO 18125:2017, 2017) was used to determine the gross calorific value (MJ kg^{-1}) of energy wood. The test samples were burned in a high-pressure constant volume oxygen bomb calorimeter. A system calibration procedure was performed before processing each sample to ensure the reliability of the results. The gross calorific value of the test sample was calculated by considering the calorific value of the calorimeter, determined during the calibration process, and the temperature change caused by the combustion of the test sample, including corrections for ignition energy, burner efficiency, and thermal by-products such as nitric acid and sulfuric acid. The PARR Instrument 6200 calorimeter used in the tests automatically calculates the gross calorific value (Equation 3), applying the correction factors specified by the equipment manufacturer to adjust the results.

$$H_c = \frac{WT - e_1 - e_2 - e_3}{m} \quad (3)$$

where:
H_c – gross calorific value, MJ kg^{-1};
T – observed temperature rise;
W – effective heat capacity of a calorimeter;
e_1 – heat of combustion of air in the combustion tank forming nitric acid;
e_2 – heat generated by the reaction of sulfur dioxide, water and nitrogen to form nitric acid;
e_3 – heat generated by the burner;
m – mass of the sample, g.

For statistical calculations, data analysis, and visualization, the R software was used. As the data follow normal distribution, one-way analysis of variance (One-way ANOVA) was applied to compare the mean values obtained in the calculations and to determine significant differences. Tukey's Honestly Significant Difference test (Tukey HSD) was used to identify which group means are statistically significantly different.

Results and Discussion

Moisture content

The energy wood was prepared in September 2021, with the first storage period beginning upon its delivery in October 2021. Data on the relative moisture content (MC) from 10 piles of energy wood indicate that the initial MC of the delivered material ranged from 41.1% to 50.2%.

Assessing changes in the relative MC of energy wood over storage seasons, the average relative MC increased during winter (December–February) compared to autumn (September–November) by 5.06% (1st storage period) to 8.55% (2nd storage period), depending on the storage period. During winter, the highest average relative MC (50.34±0.92%) was observed in the 1st storage period, while the lowest (48.55±2.74%) was recorded in the 2nd storage period.

In spring (March–May) and summer (June–August), the drying of the material becomes more intensive, significantly influenced by higher maximum daily air temperatures and lower total daily precipitation. Comparing the average relative MC recorded in spring to that in winter, the spring values were 8.84% (2nd storage period) to 10.09% (1st storage period) lower. During spring, the highest average relative MC (40.29±1.64%) was observed in the 1st storage period, while the lowest (38.75±0.38%) was recorded in the 3rd storage period.

As the drying process continues in summer, the average relative MC of energy wood further decreases. Comparing the winter values to those recorded in summer, a reduction of 13.69% (1st storage period) to 17.24% (3rd storage period) was observed. During summer, the highest average relative MC (36.69±2.51%) was found in the 1st storage period, while the lowest (31.64±2.78%) was recorded in the 2nd storage period.

Compared to summer, the average moisture content in autumn increased by 8.36% (2nd storage period) to 8.90% (3rd storage period). During autumn (excluding the 1st storage period when the material was initially transported), the highest average relative moisture content (41.30±2.17%) was observed in the 3rd storage period, while the lowest (39.99±1.93%) was recorded in the 2nd storage period.

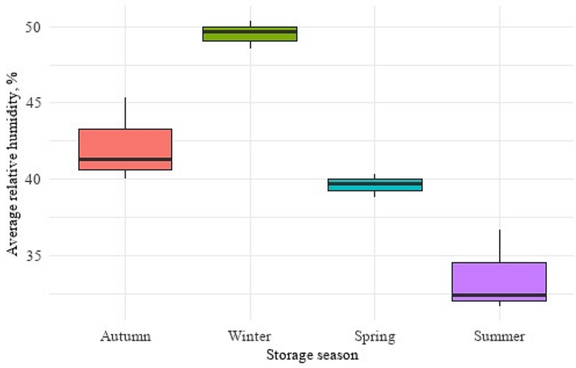
'Figure 2' reflects the changes in average relative MC of energy wood depending on the storage season, with quartile distribution used to characterize the data. From the presented data, it is evident that relative MC is highest during the winter season, with a median of 49.6%. The values are concentrated within the range of 49.1% to 50.0%, indicating low variability. In the summer season, MC is the lowest, with a median of 32.4% and a wider range of fluctuations (Q1–Q3: 32.0–34.5%), indicating greater variability. During the autumn season, relative MC is relatively high, with a median of 41.3%, and a greater spread in the data is observed (Q1–Q3: 40.6–43.3%). The spring season does not differ significantly, with a median of 39.7% and a small spread (Q1–Q3: 39.2–40.0%). The created diagram effectively illustrates the relative MC trends, variability, and central values for each season, which may be significant when selecting appropriate storage conditions for energy wood.

In deciduous stands, the average MC of energy wood prepared in September and stacked in fresh windrows in October was 47.29±1.37%.

To more precisely characterize changes in the relative MC of energy wood during storage, the FWI index 'Figure 3' was applied, incorporating meteorological observations for the respective period (LVĢMC, 2024) and data from the FWI system (Van Wagner & Pickett, 1985; Miller, 2020). The results show that during the 1st storage period, the average relative MC increased to 52.56% by the 101st storage day (January 2022), attributed to a low FWI index indicating unfavorable drying conditions. From the 102nd to the 190th storage day (February 2022), the MC decreased to 32.90%, driven by a rising FWI index, indicating favorable drying conditions starting in April (approximately six months after storage began).

Between the 191st and 251st storage days (May 2022), the MC increased to 42.16%, coinciding with a period of a relatively low FWI index. Subsequently, from the 252nd to the 313th storage day (July, August 2022), the MC decreased to 34.94%, explained by seasonal effects reflected in the FWI index. At the onset of autumn (314th storage day, September 2022), the MC increased again, reaching 37.54% by the end of the 1st storage period (343rd storage day, September 2022).

Figure 2
The seasonal variations of the average relative MC of energy wood during storage



At the start of the 2nd storage period, seasonal effects led to repeated moisture absorption, continuing until the 466th storage day (January 2023), with the moisture content reaching 53.1% due to a low FWI index. Between the 467th and 494th storage days (February 2023), the average MC decreased to 50.9% as the FWI index gradually increased. From the 526th to 647th storage days (April – July 2023), intense drying occurred, with the average MC dropping to 24.1%, explained by the high FWI index characteristic of summer. During the latter half of summer (647th–678th storage days, July, August 2023), the FWI index decreased, causing the MC to rise to 35.37%. At the end of the 2nd storage period (708th storage day, September 2023), the MC was 30.75%.

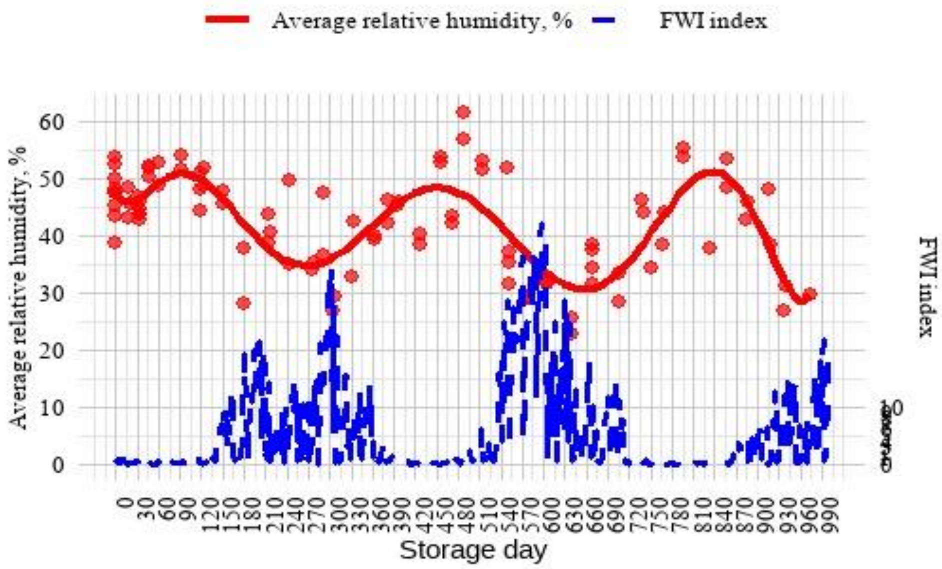
At the beginning of the 3rd storage period, the MC increased rapidly due to seasonal effects, reaching 54.5% by the 831st day (January, 2024). From the 832nd storage day (February, 2024), the moisture content began to decline, reaching 43.1% by the 921st day (April, 2024) and further decreasing to 28.9% by the 952nd storage day (May, 2024), driven by an increasing FWI index. From the 953rd storage day (Jun, 2024), the MC increased again, reaching 33.85% by the 1006th storage day (July, 2024).

The drying process of energy wood intensifies in spring and summer due to higher temperatures, lower precipitation, solar radiation, and wind, accelerating water evaporation from wood fibers. Routa et al. (2016) noted that drier conditions in these seasons can reduce wood moisture content (MC) by 20–30%, especially in well-stacked, ventilated materials.

In summer, higher temperatures and lower humidity further increase evaporation, making it the most effective period for MC reduction (Pettersson & Nordfjell, 2007). Previous studies (Pettersson & Nordfjell, 2007; Gautam et al., 2012; Routa et al., 2016; Eliasson et al., 2019) confirm these trends, aligning with this study's findings.

Conversely, in autumn and winter, energy wood absorbs moisture due to its hygroscopic properties, increased humidity, and lower temperatures (Gautam et al., 2012). Afzal et al. (2010) explained that low temperatures reduce evaporation, leading to moisture retention, increased weight, and lower net calorific value. Seasonal climatic variations significantly impact wood MC (Eliasson et al., 2019).

Figure 3
Changes in the average relative moisture content of energy wood during storage



Effective storage and drying planning are crucial for optimizing energy efficiency. Gautam et al. (2012) and Eliasson et al. (2019) highlighted that proper storage location and drying duration can enhance drying rates. The initial MC of freshly prepared energy wood varies by region and is influenced by stand location, species composition, and preparation time.

This study found an initial MC of 47.29±1.37%, similar to Canadian (45.5±5%) findings (Afzal et al., 2010) but differing from Swedish (Nilsson et al., 2013) data (25.6±4.3% to 43.8±6.5%) and Finnish (Nurmi, 1999) data (56%). Regional climate conditions during preparation and stacking significantly affect initial MC, with higher values observed in wetter climates (Afzal et al., 2010; Nilsson et al., 2013). Species composition also plays a role, as coniferous residues retain more moisture due to needle structure (Nurmi, 1999).

For a more accurate assessment of energy wood MC during storage, multiple influencing factors should be considered. The FWI index (Van Wagner & Pickett, 1985; Miller, 2020) used in this study helps evaluate drying dynamics under varying climatic conditions and the long-term impact on wood quality (LVĢMC, 2024).

Ash content

Changes in the ash content (AC) of energy wood during storage are presented in 'Figure 4' and can be attributed to changes in energy wood quality and the influence of the surrounding environment.

Overall, the ash content (AC) of energy wood during storage is variable, with observed fluctuations in AC throughout the material improvement process ranging from approximately 1% to 2%. Although differences in AC of energy wood during storage exist, they are not statistically significant.

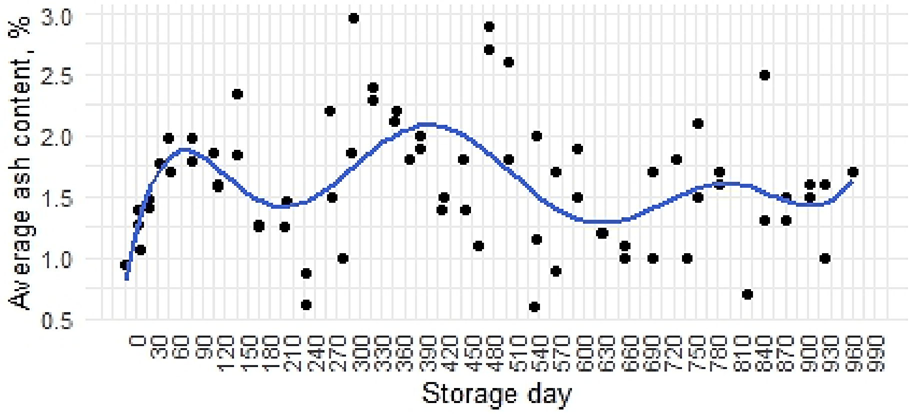
The obtained results show that the average AC of freshly prepared deciduous energy wood is 0.97%. Following the transportation of the material, an increase in ash content is observed by the 160th storage day (March 2022), reaching an average of 2.10%. The intensive drying of energy wood affects its quality, resulting in a decrease in average AC from the 161st storage day (April 2022), reaching an average of 0.75% by the 251st storage day (June 2022). An increase in the average AC of energy wood is observed again starting from the 252nd storage day (July 2022), and by the end of the first storage period (343rd storage day, September 2022), the average AC reaches 2.35%.

The second storage period begins with a gradual decrease in AC, reaching an average of 1.45% by the 435th storage day (December 2022). A repeated increase in AC is observed starting from the 436th storage day (January 2023), reaching an average AC of 2.20% by the 525th storage day (March 2023). This corresponds to the trends observed in AC changes during the first storage period (an increase in AC from January to March). Starting from the 526th storage day (April 2023), the average AC of the material ranged from 1.07% to 1.70%, and by the end of the second storage period (708th storage day, September 2023), the average AC was approximately 1.35%.

Overall, during the third storage period, the average AC of energy wood ranged from 1.20% (983rd–1006th storage day, July 2024) to 1.80% (709th–739th storage day, October 2023).

The study found that the average ash content (AC) of deciduous energy wood ranged from 1.48±0.54% to 1.58±0.57% across three storage periods, consistent with previous research (Thörnqvist, 1985; Pettersson & Nordfjell, 2007), which attributes higher AC in deciduous wood to its greater bark content.

Figure 4
Changes in the average AC of energy wood during storage



No significant AC changes were observed over 1,006 days, though the highest AC appeared in the second storage period, similar to findings from Sweden and Canada (Pettersson & Nordfjell, 2007; Afzal et al., 2010; Gautam et al., 2012). A slight increase may result from dust and soil deposition during extended drying (Lehtikangas, 2001). While seasonal effects and drying duration can slightly raise AC, proper storage can help minimize these changes.

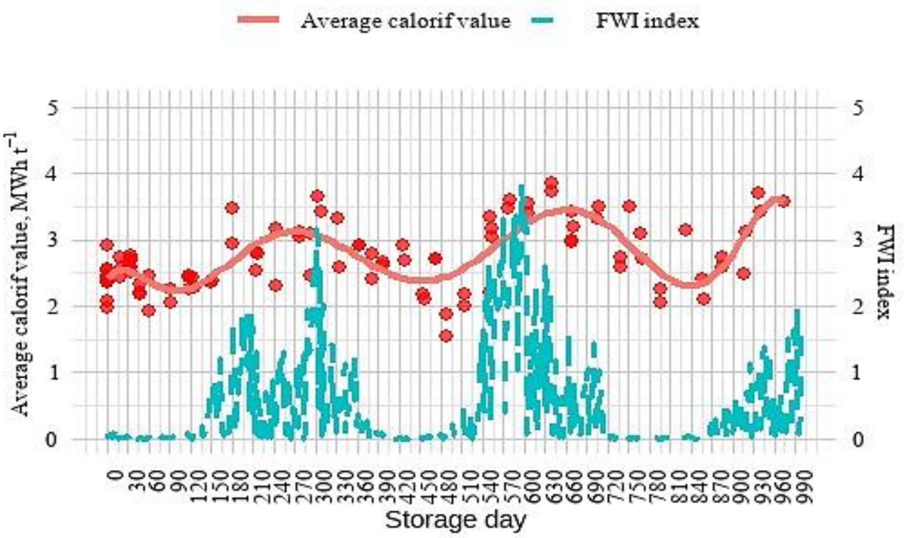
Calorific value

Changes in the net calorific value (CV) of energy wood during storage are shown in 'Figure 5' and can be explained by the influence of favorable or unfavorable conditions for wood drying, as indicated by changes in the FWI index during the respective period.

The obtained results show that the net CV of freshly prepared deciduous energy wood is on average 2.38 MWh t^{-1}.

During the 1st storage period, until the 160th storage day (March 2022), the average CV of energy wood ranged from 2.15 MWh t^{-1} (72nd–101st storage day, January 2022) to 2.62 MWh t^{-1} (10th–40th storage day, November 2021). Starting from the 161st storage day (April 2022), an increase in the CV of energy wood was observed, ranging from 2.71 MWh t^{-1} (191st–221st storage day, May 2022) to 3.20 MWh t^{-1} (161st–190th storage day, April 2022). By the end of the 1st storage period (343rd storage day, September 2022), the average CV of energy wood reached 2.95 MWh t^{-1}.

Figure 5
Changes in the net calorific value of energy wood during storage



The 2nd storage period (beginning on the 344th storage day, October 2022) started with a gradual decrease in CV until the 525th storage day (March 2023), with observed average CV values ranging from 2.09 MWh t^{-1} (495th–525th storage day, March 2023) to 2.90 MWh t^{-1} (344th–374th storage day, October 2022).

A repeated increase in the CV of energy wood was observed starting from the 526th storage day (April 2023) and continued until the end of the 2nd storage period (708th storage day, September 2023), with the average CV values ranging from 2.94 MWh t^{-1} (526th–555th storage day, April 2023) to 3.78 MWh t^{-1} (617th–647th storage day, July 2023). By the end of the 2nd storage period (708th storage day, September 2023), the average CV of energy wood was 3.40 MWh t^{-1}.

Overall, during the 3rd storage period (beginning on the 709th storage day, October 2023), the average CV of energy wood ranged from 2.14 MWh t^{-1} (770th–800th storage day, December 2023) to 3.57 MWh t^{-1} (709th–739th storage day, May 2024).

The results indicate that during the 1st storage period, the net CV of energy wood (with the following average parameters: relative MC of 44.43±6.79%, AC of 1.48±0.54%, and HC of 19.04±0.56 MJ kg^{-1}) was 2.59±0.39 MWh t^{-1}.

An increase in the net calorific value was observed during the 2nd storage period (with the following average parameters: relative MC of 39.97±9.73%, AC of 1.58±0.57%, and HC of 19.13±0.42 MJ kg^{-1}), reaching 2.87±0.59 MWh t^{-1}.

A further increase in the net CV was observed during the 3rd storage period (with the following average parameters: relative MC of 41.28±8.53%, AC of 1.51±0.41%, and HC of 19.69 ± 0.40 MJ kg^{-1}), reaching 2.88 ± 0.51 MWh t^{-1}.

Conclusions

1. The study results confirm significant seasonal changes in the relative MC of energy wood influenced by meteorological conditions. During spring and summer, as intensive drying occurs, the relative MC can decrease from an average of 39.58% (spring) to 33.57% (summer). In autumn and winter, an increase in the relative MC is observed, rising from an average of 42.20% (autumn) to 49.52% (winter), largely influenced by the hygroscopic properties of the material.
2. The average AC of deciduous energy wood during storage ranged from 1.48% to 1.58%. However, changes in the average AC values are not statistically significant and could be explained by the deposition of dust and mineral soil particles on the stored material.
3. When planning the storage of energy wood, seasonal fluctuations should be considered. Also, the obtained results show that the average net CV of energy wood increases during storage, and the relative MC of the material is one of the main factors influencing the net CV of energy wood.
4. The findings highlight that the effective selection of storage locations and appropriate drying durations can significantly improve the energy efficiency of energy wood. To provide recommendations for the optimal storage duration of energy wood, it is also necessary to evaluate the impact of mass loss on the quality of energy wood.

Acknowledgements

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