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Energy Efficiency of Industrial Wood Drying: Comparative Analysis of Convective and Vacuum Drying Based on an Operational Case Study

Energetska učinkovitost industrijskog sušenja drva: komparativna analiza konvektivnoga i vakuumskog sušenja na temelju studije slučaja iz prakse

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ABSTRACT • *Artificial wood drying is an energy-intensive industrial process with major economic and environmental implications. This study evaluates the energy performance of convective and vacuum drying in a Hungarian wood-processing plant, with separate analysis of one summer and one winter convective cycle. For convective drying, measured energy use was compared with literature-based theoretical estimates. The measured thermal demand exceeded the theoretical estimate by approximately 17 % in winter, whereas the summer deviation remained within ± 4 %. Electrical demand was markedly lower in summer; however, as only full-kiln electrical data were available, this difference is interpreted cautiously as the combined effect of fan duty, cycle duration, moisture condition, and seasonal operating context rather than as a direct fan-level effect. On an annual total basis, the vacuum dryer consumed only about one-quarter to one-fifth as much energy as the convective system, but on a specific volume basis it showed substantially higher electrical demand. The results indicate that industrial wood-drying energy performance may be improved through heat recovery, improved thermal insulation, and more adaptive fan-control strategies. As the convective analysis was based on only two industrial cycles, the findings should be interpreted as site-specific evidence rather than generally transferable performance relationships.*

KEYWORDS: *wood drying; energy efficiency; convective drying; vacuum drying; industrial case study*

SAŽETAK • *Umjetno sušenje drva energetski je intenzivan industrijski proces s velikim ekonomskim i ekološkim učincima. U ovoj se studiji procjenjuju energetska svojstva konvektivnoga i vakuumskog sušenja u pogonu za preradu drva u Mađarskoj, s odvojenom analizom jednoga ljetnog i jednoga zimskog konvektivnog ciklusa. Za konvektivno je sušenje izmjerena potrošnja energije uspoređena s teorijskim procjenama utemeljenima na literaturi. Izmjerena po-*

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treba toplinske energije premašila je teorijsku procjenu za otprilike 17 % zimi, dok je ljetno odstupanje ostalo unutar ± 4 %. Potreba za električnom energijom bila je znatno niža ljeti. Međutim, zbog dostupnosti podataka o električnoj energiji samo za punu sušaru, ta se razlika oprezno tumači kao kombinirani učinak rada ventilatora, trajanja ciklusa, sadržaja vode i sezonske prirode rada, a ne kao izravan učinak rada ventilatora. Na godišnjoj razini vakuumska je sušara približno potrošila samo jednu četvrtinu do jednu petinu energije koju je potrošio konvektivni sustav, ali ako se računa na temelju specifičnog volumena, pokazala je znatno veću potrošnju električne energije. Rezultati pokazuju da se energetska učinkovitost industrijskog sušenja drva može poboljšati povratom topline, poboljšanom toplinskom izolacijom i prilagodljivijim strategijama upravljanja ventilatorima. Budući da je konvektivna analiza bila utemeljena samo na dva industrijska ciklusa, rezultate treba shvatiti kao specifične dokaze za istraživanu lokaciju, a ne kao općenito prenosive odnose svojstava konvektivnoga i vakuumskog sušenja drva.

KLJUČNE RIJEČI: *sušenje drva; energetska učinkovitost; konvektivno sušenje; vakuumsko sušenje; studija industrijskog slučaja*

1 INTRODUCTION
1. UVOD

Wood drying is a fundamental prerequisite for the quality of sawn timber, as insufficiently dried wood is prone to warping, cracking, and increased susceptibility to biological degradation (Faipar, n.d.). Although natural air drying requires no direct energy input, it is slow and demands extensive storage space. Consequently, various artificial drying methods have become widespread in modern wood processing, including convective, condensation (heat-pump), vacuum, microwave, and radio-frequency drying. While all technologies aim to reduce wood moisture content to a target level, their energy efficiency and environmental impacts differ substantially. Artificial wood drying is a process with high thermal energy demand. In industrial practice, actual energy consumption is often substantially higher than the theoretical minimum required for water evaporation, due to the high initial moisture content of green wood and additional heat losses associated with kiln operation (Simpson, 1991). Convective dryers remove moisture through continuous air exchange, resulting in considerable energy consumption, whereas heat-pump-based systems can recover a large proportion of heat from circulating air, achieving savings of up to 50–70 % (Faipar, n.d.). Vacuum drying has been widely discussed in the literature as an alternative drying technology that operates under reduced pressure and may provide shorter drying times and gentler treatment, particularly for hardwoods and higher value-added products (Espinoza and Bond, 2016). At the same time, commercial implementation requires careful consideration of equipment costs, electricity demand, and process applicability under industrial conditions (Espinoza and Bond, 2016; Lyon *et al.*, 2021). The annual drying volume of the Hungarian sawmilling industry is estimated at approximately 1.1 – 1.3 million m³/year (KSH, 2023; FAGOSZ, 2023). Since about 90 – 95 % of industrial drying relies on convective technology, an average volume of 1.2 million m³/year was considered for national-scale evaluation. Based on operational experience, the average specific energy demand is approximately 2000 MJ/m³ of thermal energy and 112 kWh/m³ of electrical energy (≈ 403 MJ/m³), corresponding at national scale to roughly 2400 TJ/year of heat and 134.4 GWh/year (≈ 484 TJ/year) of electricity consumption. Approximately two-thirds of the thermal demand is typically covered by wood-based by-products, while the remaining share is supplied by natural gas. Assuming an emission factor of 56.26 kg carbon dioxide equivalent (CO_2eq)/GJ for natural gas (IPCC, 2021) and a boiler efficiency of 90 %, emissions related to heat production amount to approximately 50 kt CO_2 eq/year. Electricity consumption, calculated using the Hungarian annual average grid carbon intensity of 0.243 kg CO_2 eq/kWh for 2024, based on Electricity Maps yearly data (Electricity Maps, n.d.), contributes an additional ~32.7 kt CO_2 eq/year. The applied factor was used as an attributional average electricity-emission indicator rather than as a marginal emission factor. Accordingly, total annual emissions from wood drying in Hungary are estimated at approximately 82.5 kt CO_2 eq, corresponding to about 69 kg CO_2 eq/m³. Energy demand in wood drying is influenced by factors such as wood species, thickness, initial and target moisture content, and equipment design. In conventional convective kiln drying, seasonal ambient conditions can substantially influence thermal energy demand. This is because total kiln energy consumption is not limited to moisture evaporation but also includes the heating of kiln structures and incoming air, ventilation-related losses, thermal transmission through the kiln envelope, and air leakage losses (Elustondo and Oliveira, 2009). Accordingly, colder winter operation generally requires more heat than summer operation due to the larger temperature difference between kiln and ambient air. Experimental observations by Meng *et al.* (2019) showed that, although less fresh air may be needed in winter, more energy is required to heat the colder incoming air, resulting in higher kiln heating demand under winter conditions. Likewise, annual simulations by Lamrani *et al.* (2021) confirmed that climate has a pronounced effect on wood-dryer energy performance and that cold-climate operation is associated with a stronger thermal-energy penalty than hot-climate operation. This literature background supports the expectation that winter heat demand may substantially exceed summer heat demand under industrial convective drying conditions. Consequently, industrial boiler systems are typically sized to meet peak winter loads.

This study presents an industrial case study based on high-resolution energy measurements in a Hungarian wood-processing plant. It compares one summer and one winter convective drying cycle, evaluates the energy-consumption structure of convective and vacuum drying, and identifies practical opportunities for improving industrial energy efficiency. The focus is on seasonal and technology-related energy-use patterns under real operating conditions rather than on statistically generalized conclusions.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Experimental site and equipment
2.1. Eksperimentalna lokacija i oprema

The investigation was carried out at the drying facility of a Hungarian wood-processing company operating a sawmill; the company name is not disclosed at the operator's request. The plant operates six conventional convective drying chambers and one vacuum dryer under industrial conditions. The convective chambers are Mühlböck ZLSM units, each with an effective stack capacity of approximately 90 – 100 m³. The vacuum dryer is a WTT 151031 system with a net capacity of about 7 – 8 m³, primarily used for drying smaller volumes of higher value-added products. The convective chambers are heated via hot-water heat exchangers supplied by a central boiler system. The vacuum dryer also uses a water-based heating system; however, during winter operation, capacity limitations of the central boiler require periodic support from a local auxiliary boiler. Any such auxiliary-boiler support was supplied through the same heating circuit and was therefore included in the measured thermal energy delivered to the vacuum dryer. All chambers are equipped with circulation fans driven by variable frequency drives (VFD), enabling automatic adjustment of air-circulation intensity according to process conditions such as temperature and moisture content.

2.2 Description of the applied measurement system
2.2. Opis primijenjenoga mjernog sustava

The supervisory and data acquisition system implemented in the industrial test environment was designed for the continuous monitoring and centralized recording of thermal and electrical energy consumption in the drying chambers (Figure 1). This setup enabled a high time-resolution comparative analysis of convective and vacuum drying technologies under real industrial operating conditions. Thermal energy consumption was measured using LOW USFL-400 Engelmann ultrasonic flow meters combined with SensoStar2C evaluation units. Heat energy was calculated from the mass flow rate of the heating circuit water and the temperature difference between supply and return lines and expressed in MWh. As heat metering was performed at the dryer-side heating circuit, the measured thermal values represent the total heat actually supplied to the chamber, irrespective of whether it originated from the central boiler or from auxiliary winter support. Data transmission was performed via the M-Bus protocol. Electrical energy consumption was recorded using Schneider Electric PM710 power meters with current transformers. Voltage, current, and power parameters of the three-phase system were collected at one-minute intervals via Modbus RTU over an RS-485 communication line. Interoperability between protocols was ensured by an EGX100 Modbus/Ethernet gateway and an M-Bus/RS-232 converter. System control was provided by a Twido PLC, while aggregated data were processed using PowerLogic™ ION Enterprise™ 6.0 software, allowing real-time visualization, archiving, and automated reporting. Energy consumption data from both convective and vacuum chambers were collected by a central acquisition unit, ensuring consistent measurement-based evaluation throughout the investigated period. The reported electrical energy consumption values were based on full-kiln electricity metering. Accordingly, the measured values represent the total electrical consumption registered for the drying chamber within the applied measurement boundary, rather than a fan-only sub-metered value. In practical terms, the dominant electrical load was the kiln air-circulation system, while additional auxiliary electrical loads may also have been included where they were connected within the same chamber-level metering scope. However, detailed sub-metered data for individual consumers such as fans, dampers, pumps, or control units were not available in the processed industrial dataset. For the convective chambers, both the summer and winter cycles were carried out with VFD-controlled circulation fans. Thus, frequency-controlled fan operation was present in both analyzed runs, although the available industrial dataset did not include motor-level time series suitable for a direct reconstruction of phase-specific fan-power demand. To improve interpretability of the chamber-level electrical measurements, the circulation-fan system consisted of six fans with an installed power of approximately 3 – 4 kW per fan, corresponding to a total installed fan power of approximately 18 – 24 kW. These values are re-

Figure 1 Thermal and electrical energy monitoring and data acquisition setup for convective (left) and vacuum (right) drying systems
Slika 1. Instalacija za praćenje potrošnje toplinske i električne energije i prikupljanje podataka za konvektivne (lijevo) i vakuumske (desno) sustave sušenja

ported as engineering boundary conditions to support physical interpretation of the measured electricity demand, rather than as a disclosure of the complete proprietary equipment specification. According to manufacturer specifications, the Schneider Electric PM710 meter used for electrical energy recording conforms to Class 1 active-energy accuracy, while the thermal-energy metering chain was based on industrial ultrasonic heat-metering components designed for standardized heat-accounting applications; therefore, the instrumental uncertainty of measured energy values is expected to be moderate relative to the broader process variability of industrial drying.

2.3 Drying cycles and calculation methods
2.3. Ciklusi sušenja i metode izračuna

In the convective test chamber, one complete summer and one complete winter drying cycle were analyzed under industrial operating conditions. The summer cycle was carried out between 11 July and 30 July 2024, while the winter cycle took place between 26 January and 19 February 2024. In both cases, oak sawn timber (28 mm thickness) was dried from an initial moisture content of approximately 45 % (summer) and 55 % (winter) to a target final moisture content of 10 %. The convective dataset therefore represents a clearly defined product group, namely 28 mm oak sawn timber dried to a target final moisture content of 10 % under routine industrial kiln operation. By contrast, the vacuum-drying evaluation presented later in the paper is based on the annual operating dataset of the vacuum system as used in the investigated plant, where the technology is applied primarily to smaller batches and products with higher quality-related processing requirements. Accordingly, the convective and vacuum results should be interpreted as technology-level industrial reference cases within the same plant, rather than as a strictly matched one-to-one experimental comparison of identical charges. The reported moisture content values used for process characterization were obtained from the kiln control system based on in-kiln moisture probes. In the present study, the initial moisture contents of approximately 45 % in summer and 55 % in winter were therefore interpreted as charge-level operational values derived from kiln monitoring rather than from a separate laboratory-based sampling campaign. The convective cycles were operated under industrial kiln-control schedules in which the control settings changed by process stage. Accordingly, the value of approximately 60 °C should be interpreted as a characteristic temperature level of the main drying phase rather than as a constant set-point applied throughout the entire cycle. Due to a confidentiality agreement with the industrial partner, the complete time-resolved commercial drying schedule, including stage-wise dry-bulb and wet-bulb or EMC/RH set-points, fan-control settings, and end-stage treatments, cannot be disclosed in full. Nevertheless, in order to improve process interpretability, approximate operating ranges are provided for the principal stages of the convective schedule. For the investigated 28 mm oak charges, the schedule started under relatively mild initial conditions, typically with a dry-bulb temperature in the range of approximately 40 – 45 °C and an EMC of approximately 12 – 15 %, followed by a gradual increase in drying intensity as the timber moisture content decreased. The main drying stage was characterized by a temperature level of about 60 °C. In the final drying stage, the operating conditions typically approached approximately 60 – 65 °C with an EMC of approximately 6 – 8 %, consistent with industrial kiln drying of oak to a target final moisture content of 10 %. Equalization and/or mild conditioning were applied at the end of the process as part of routine industrial kiln operation; however, their detailed stepwise parameters also form part of the confidential commercial schedule. For interpretative purposes, these end-stage treatments may be characterized as short final adjustments carried out approximately within the range of 60 – 65 °C and about 8 – 12 % EMC in order to reduce within-charge moisture gradients and residual drying stresses before unloading. These values should be interpreted as approximate industrial operating ranges describing the principal boundary conditions of the analyzed kiln runs rather than as a fully disclosed stage-by-stage drying schedule.

Climatic conditions differed considerably, with an average outdoor temperature of about 22 °C in summer and -12 °C in winter. For each cycle, total thermal energy consumption (MWh) and electrical energy demand (kWh) were determined, together with specific values per unit volume of dried wood (MJ/m³, kWh/m³). The calculations were intentionally simplified in order to obtain an engineering estimate suitable for comparison with measured industrial energy consumption. Accordingly, minor contributions from humidification, air leakage, short transient control phases, and local inhomogeneities of airflow and moisture distribution within the stack were neglected. The simplified theoretical model did not include a separate latent heat of fusion term for possible thawing of frozen water in the wood charge; such effects were implicitly absorbed into the general heating demand and may therefore contribute to underestimation under severe winter conditions. Material properties were taken from literature data representative of oak drying, including an oven-dry density of approximately 650 kg/m³, an effective specific heat capacity of approximately 2.5 kJ/kg·K, and a latent heat of evaporation of approximately 2500 kJ/kg. Correlation-based heat-loss estimation followed the simplified approach reported by Konopka *et al.* (2021), adapted to the measured industrial chamber dimensions and seasonal temperature conditions. Literature on conventional kiln drying consistently shows that total energy demand is dominated by thermal energy, whereas electricity is mainly associated with circulation fans and auxiliary equipment; reported practice-based proportions can be expressed approximately as 80 – 90 % thermal and 10 – 20 % electrical energy (Elustondo and Oliveira, 2009; Andersson, 2014; Konopka *et al*., 2021; Lamrani *et al*., 2021). Therefore, the 88 % thermal and 12 % electrical split applied in this study should be interpreted as a practical engineering assumption within that range, in accordance with Hungarian industrial experience and expert consultation.

Vacuum drying was also evaluated under the same industrial conditions. The vacuum dryer is mainly used for rapid drying of smaller volumes of high value-added products, processing approximately 200 – 300 m³ annually (2 – 3 cycles per month, 7 – 8 m³ per cycle). For comparability, the same wood species and thickness (oak, 28 mm) were analyzed for both technologies. Vacuum dryer energy demand was assessed exclusively from continuous measurement data, as no generally accepted theoretical correlation is available in the literature; therefore, the analysis focused on the measured energy consumption structure (thermal versus electrical share). Time-resolved chamber-pressure data were not available in the processed project database; therefore, vacuum drying was evaluated here on the basis of measured thermal and electrical energy consumption rather than by correlating energy demand with detailed pressure profiles. For consistency throughout the manuscript, thermal energy is reported primarily in MJ (or MJ/m³), while electrical energy is reported primarily in kWh (or kWh/m³), where direct comparison between energy forms is relevant, and electrical values are additionally expressed in MJ using the conversion 1 kWh = 3.6 MJ.

2.3.1 Calculation framework for theoretical thermal energy demand

2.3.1. Okvir za izračun teorijske potrebe za toplinskom energijom

The theoretical thermal energy demand of the convective drying cycles was estimated by a simplified charge-level heat balance. The calculation was structured around three main components: (i) sensible heat required to increase the temperature of the wood substance and its moisture content, (ii) latent heat required for water evaporation, and (iii) heat losses associated with kiln operation. In this way, the total theoretical thermal energy demand was expressed as:

$$Q_{\text{th,total}} = Q_{\text{heat}} + Q_{\text{evap}} + Q_{\text{loss}} \tag{1}$$

Where $Q_{\text{th,total}}$ is the total theoretical thermal energy demand (MJ), Q_{heat} is the sensible heat demand for heating the wood-water system (MJ), Q_{evap} is the latent heat demand of moisture removal (MJ), and Q_{loss} represents the estimated heat losses of the kiln system (MJ). The oven-dry wood mass was determined from the loaded timber volume and the oven-dry density of oak:

$$m_0 = V \cdot \rho_0 \tag{2}$$

Where m_0 is the oven-dry wood mass (kg), V is the timber volume loaded into the kiln (m³), and ρ_0 is the oven-dry density of oak (kg/m³).

The initial and final water masses in the charge were determined from the corresponding moisture contents on a dry basis:

$$m_{\text{w,i}} = m_0 \cdot MC_{\text{i}} \tag{3}$$

$$m_{\text{w,f}} = m_0 \cdot MC_{\text{f}} \tag{4}$$

Where $m_{\text{w,i}}$ and $m_{\text{w,f}}$ are the initial and final water masses (kg), and MC_{i} and MC_{f} are the initial and final moisture contents expressed on a dry basis (kg water/kg oven-dry wood). Accordingly, the mass of removed water was calculated as:

$$m_{evap} = m_{w,i} - m_{w,f} \tag{5}$$

For comparability, the energy results were expressed using multiple functional units. In addition to the conventional volume-based indicator (MJ/m³ of dried timber), the study also used moisture-normalized and dry-matter-normalized indicators, namely MJ/kg of removed water and MJ/kg of oven-dry wood. These were calculated as:

$$SEC_V = Q / V \tag{6}$$

$$SEC_W = Q / m_{evap} \tag{7}$$

$$SEC_{OD} = Q / m_0 \tag{8}$$

Where SEC_V is the specific energy consumption per unit volume of dried timber, SEC_W is the specific energy consumption per kilogram of removed water, SEC_{OD} is the specific energy consumption per kilogram of oven-dry wood, Q is the relevant measured or calculated energy value, m_{evap} is the mass of removed water. The sensible heat demand was estimated as:

$$Q_{heat} = m_0 \cdot c_{wd} \cdot (T_d - T_0) + m_{w,avg} \cdot c_w \cdot (T_d - T_0) \tag{9}$$

Where c_{wd} is the specific heat capacity of oven-dry wood, c_w is the specific heat capacity of water, T_0 is the initial timber temperature, T_d is the characteristic drying temperature, and $m_{w,avg}$ is the average water mass considered during heating.

The latent heat demand of evaporation was estimated as:

$$Q_{evap} = m_{evap} \cdot h_{fg} \tag{10}$$

Where h_{fg} is the latent heat of evaporation of water at the applied drying-temperature range. The heat-loss term was treated as an aggregate operational loss term that includes, in simplified form, the effects of heat transmission through the kiln envelope and other process-related thermal losses during the cycle:

$$Q_{loss} = Q_{trans} + Q_{other} \tag{11}$$

Where Q_{trans} represents conductive heat loss through the kiln structure and Q_{other} represents additional operational losses not explicitly resolved in the available industrial documentation. As the full time-resolved kiln schedule and ventilation history were confidential, the calculation was intentionally formulated as a simplified cycle-level engineering estimate using the same structure for both seasonal cases, rather than as a transient stage-resolved process model.

2.4 Nature, limitations and uncertainties of the measurement database

2.4. Priroda, ograničenja i nesigurnosti baze podataka mjerenja

The present study is an industrial case study based on the energy analysis of two complete convective drying cycles (one summer and one winter) and on the continuous annual operational measurement database of the investigated drying facility collected during the 2024 project period. The effective monitoring period was limited to one year, because the preceding project phase focused on installation and commissioning of the industrial test environment, while the subsequent phase was dedicated to data processing and evaluation.

The convective-drying analysis was intentionally restricted to two complete industrial cycles representing contrasting seasonal conditions. The aim was not to derive statistically averaged values from repeated runs, but to evaluate seasonal differences in energy demand under real industrial conditions and to compare measured convective energy consumption with simplified literature-based theoretical estimates. Representativeness is partially supported by the use of typical production material (oak, 28 mm thickness), a target final moisture content of 10 %, and routine industrial kiln operation. However, as the complete time-resolved industrial drying schedule is subject to confidentiality restrictions, detailed process-level comparability remains limited. To improve interpretability, the revised manuscript reports approximate operating ranges for the principal initial, main, and final stages of the convective drying schedule, including the general presence of end-stage equalization/conditioning treatments. Since replicated convective cycles under identical conditions were not available, repeatability-based statistical descriptors such as coefficients of variation were not considered methodologically robust. The conclusions should therefore be interpreted primarily within the context of the investigated equipment, operating conditions, raw material, and measurement period. Electrical parameters were recorded at one-minute intervals, providing tens of thousands of data points per cycle and enabling high time-resolution analysis. However, the available electrical dataset represented total chamber electricity consumption and did not permit separate reconstruction of fan-specific duty cycles, full-load operating fractions, or other component-level load profiles. Electrical energy was measured with Schneider Electric PM710 meters, specified by the manufacturer as Class 1 active-energy instruments. Thermal energy was recorded by an ultrasonic heat-metering chain; although the exact calibration certificate of the installed configuration was not evaluated in this paper, comparable Engelmann ultrasonic heat-metering systems are designed for standardized industrial heat accounting. Accordingly, direct metering uncertainty is unlikely to be the dominant source of deviation.

A more important source of uncertainty is associated with moisture-content determination and model simplification. The initial moisture contents used in the theoretical calculations were derived from in-kiln moisture-probe readings and interpreted as charge-level average operational values rather than as results of a separate destructive laboratory sampling campaign. Consequently, within-stack moisture heterogeneity, particularly in the winter charge, may have influenced the calculated heat demand through both the estimated evaporated water mass and the assumed heating requirement. The differences between calculated and measured values should therefore be interpreted as the combined effect of metering uncertainty, sampling uncertainty, and simplifying assumptions in the theoretical model, rather than as a single-source discrepancy.

No dedicated comparative dataset was available on drying quality, defect formation, or internal stress development for the two technologies. Quality-related statements in this paper should therefore be interpreted as technology-related practical considerations rather than as directly measured comparative results. The observed trends, particularly the higher winter thermal demand and the potentially lower electrical demand under VFD-controlled summer operation, are consistent with broader industrial expectations, but the present dataset is not sufficient for broad quantitative generalization.

The vacuum-drying evaluation was based on a complete annual measurement dataset. No theoretical energy calculation was applied, because no uniformly accepted correlation for vacuum-drying energy demand is available in the literature. Vacuum-related results should therefore be interpreted primarily as a measurement-based comparison and as an illustration of energy-consumption structure (thermal versus electrical share). In addition, time-resolved vacuum-pressure data were not available in the analyzed dataset; therefore, the present study does not establish a direct relationship between chamber pressure and energy demand, but rather provides a measurement-based comparison of the overall thermal and electrical consumption structure.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Energy demand of summer and winter convective drying cycles
3.1. Potrošnja energije konvektivnog sušenja u ljetnim i zimskim ciklusima

During the summer convective drying cycle (11 July – 30 July 2024), thermal energy consumption amounted to 25.60 MWh (92160 MJ) for drying 84.66 m^3 of oak timber, corresponding to a specific demand of approximately 1089 MJ/m^3. Electrical energy consumption was 905.7 kWh (3260 MJ), i.e. about 10.7 kWh/m^3 (≈38.5 MJ/m^3). In the winter cycle (26 January – 19 February 2024), 90 m^3 of oak timber was dried with a measured thermal energy consumption of 57.80 MWh (208080 MJ), corresponding to about 2312 MJ/m^3. Electrical demand reached 5045 kWh (18162 MJ), corresponding to approximately 56.1 kWh/m^3 (≈ 202 MJ/m^3). The total summer cycle duration was 20 days according to production records, referring to the full industrial kiln cycle. The corresponding winter cycle duration was 25 days, likewise referring to the full industrial cycle rather than only to a selected active drying sub-phase. Measured energy data were compared with theoretical heat balance estimates. For the summer cycle, the calculated thermal demand was 95711 MJ, exceeding measurements by only 3.7 %, indicating close agreement. In contrast, the winter cycle showed a calculated demand of 173000 MJ versus a measured value of 208080 MJ, corresponding to an approximately 17 % higher real industrial energy requirement. For electrical energy, the summer cycle exhibited a major deviation from the literature-based benchmark estimate (≈ 3190 kWh), with a measured value of only 905.7 kWh. In the winter cycle, measured electricity demand was 5045 kWh. This corresponds to an approximately 5.6-fold difference between the two analyzed industrial cycles, whereas the cycle duration differed only from 20 to 25 days. Accordingly, the seasonal gap in measured electricity use cannot be interpreted as a simple consequence of cycle length alone. The large seasonal difference observed in chamber-level electricity demand should therefore be interpreted with caution. The applied electrical measurement boundary covered the full kiln electrical consumption rather than a fan-only sub-metered load. Within this boundary, the dominant consumer was the air-circulation system; however, detailed sub-metered records for individual fans and other auxiliary electrical components were not available. Consequently, the present dataset does not permit a direct fan-level decomposition or a time-resolved verification of fan-duty profiles. In both analyzed convective cycles, the circulation fans were operated by variable-frequency drives. Thus, a difference in fan-control strategy or duty profile between summer and winter is a technically plausible contributor to the observed electricity gap, but it cannot be isolated quantitatively from the available data. The convective chamber was equipped with six circulation fans rated at approximately 3 – 4 kW each, corresponding to a total installed fan power of approximately 18 – 24 kW. Relative to this installed capacity, the measured chamber-level electricity demand corresponds to an average equivalent electrical load of about 1.9 kW over the 20-day summer cycle and about 8.4 kW over the 25-day winter cycle. Although these average values cannot be interpreted as direct fan-only power levels, they indicate that the seasonal difference is physically consistent with markedly different effective fan-duty conditions within a VFD-controlled kiln system. Although exact time-resolved fan-frequency data cannot be published, the operating concept in both cycles can be described indicatively as follows: higher fan frequencies were used in the earlier, wetter stages of drying, while reduced frequencies were applied in later stages as the timber moisture content decreased and the required circulation intensity was lower. In this sense, the summer cycle can be interpreted as having operated for a larger share of the process under reduced effective fan-speed conditions, whereas the winter cycle likely required a higher average effective circulation level over a longer fraction of the cycle. Therefore, the more appropriate interpretation is that the winter – summer difference in measured electricity use was most likely the combined result of several interacting factors: different fan-duty conditions under VFD control, a longer cycle duration, a higher initial moisture content in winter, and the overall harsher winter operating context. As the present dataset does not contain motor-level time series, these results should not be interpreted as a direct quantitative proof of fan-specific optimization performance, but rather as an industrial case-based indication that chamber-level electricity demand can vary substantially between seasonal operating conditions. In conventional kiln drying, total process demand includes not only moisture evaporation but also the heating of the wood charge and kiln structure, heat losses through the kiln envelope, and ventilation- and air-leakage-related losses. Under winter conditions, the larger temperature gradient between the kiln and ambient air increases transmission and infiltration losses, while colder incoming air requires more heat input during operation. In addition, the winter charge had a higher average initial stack moisture content (≈ 55 % vs. ≈ 45 % in summer), implying a greater moisture removal requirement. Frozen water may also have been present in part of the load during the initial phase, which would further increase the thermal burden associated with thawing and subsequent heating. To separate, at least partly, the effect of differing initial moisture contents from that of seasonal operating conditions, the energy results were also interpreted per kilogram of removed water. On this basis, the measured thermal energy demand for evaporation-related drying was approximately 4.3 MJ/kg of removed water in the summer cycle and 6.9 MJ/kg in the winter cycle. As the winter cycle remained more energy-intensive even after normalization by removed water mass, the difference between the two cycles cannot be attributed solely to the higher initial moisture content of the winter charge. Instead, the results suggest that the larger moisture removal requirement and the more severe winter heat-loss conditions acted simultaneously. Overall, thermal energy closely matched theoretical expectations in summer, whereas winter operation resulted in significantly higher measured heat consumption. Electrical energy demand remained below calculated estimates in both cycles, particularly during summer operation. The comparison of measured and calculated energy consumption values is summarized in Table 1. In addition to the conventional volume-specific indicators (MJ/m³, kWh/m³), Table 1 also presents the thermal energy demand per kilogram of removed water, which provides a more moisture-normalized basis for comparing the summer and winter convective cycles. Additionally, the table includes the specific thermal energy demand per kilogram of oven-dry wood, providing a dry-matter-based normalization of the measured and calculated thermal demand. In the summer cycle, thermal energy demand deviated from the theoretical estimate by only 3.7 %, while electrical consumption was approximately 72 % lower than the literature-based proportion. In the winter cycle, meas-

Table 1 Comparison of calculated and measured energy demands for summer and winter convective drying cycles (oak, 28 mm; MC: 45 – 55 % → 10 %; characteristic main-phase temperature ≈ 60 °C)
Tablica 1. Usporedba izračunanih i izmjerenih energetskih potreba za ljetni i zimski ciklus konvektivnog sušenja (hrast, 28 mm; MC: 45 – 55 % → 10 %; karakteristična temperatura glavne faze ≈ 60 °C)

Energy parameter *Energetski parametar*	**Summer cycle (calculated)** *Ljetni ciklus (izračunano)*	**Summer cycle (measured)** *Ljetni ciklus (izmjereno)*	**Winter cycle (calculated)** *Zimski ciklus (izračunano)*	**Winter cycle (measured)** *Zimski ciklus (izmjereno)*
Total thermal energy demand for drying, MJ *ukupna potrebna toplinska energija za sušenje,* MJ	95711	92160	173000	208080
Total electrical energy demand for drying, kWh *ukupna potrebna električna energija za sušenje,* kWh	3190 (11484 MJ)	905.7 (3260 MJ)	5767 (20762 MJ)	5045 (18162 MJ)
Total energy demand (thermal + electrical), MJ *ukupna potrebna energija (toplinska + električna),* MJ	107195	95420	193762	226242
Specific drying energy demand, MJ/m³ *specifična potrebna energija za sušenje,* MJ/m³	1266	1127	2153	2514
Thermal energy demand for evaporation of 1 kg of water, MJ/kg / *potrebna toplinska energija za isparavanje 1* kg *vode,* MJ/kg	4.5	4.3	5.7	6.9
Specific thermal energy demand per kg oven-dry wood, MJ/kg / *specifična potrebna toplinska energija po* kg *suhog drva,* MJ/kg	1.6	1.5	2.6	3.1
Electrical-to-thermal energy ratio, % *omjer električne i toplinske energije,* %	12 %	3.5 %	12 %	8.7 %

ured heat demand exceeded the theoretical value by about 17 %, whereas electrical energy consumption remained around 12 % below the calculated estimate. Accordingly, the electrical share of total energy demand was only 3.5 % in summer and 8.7 % in winter, compared with the assumed ~12 % proportion. These findings indicate that under real industrial operating conditions, the relative contribution of electrical energy may be lower than expected from general literature estimates, as further discussed in the Conclusions section.

Based on the summer cycle, about half of the total thermal energy demand was related to moisture evaporation, while the remaining share originated from system heating and heat losses (air exchange and transmission). In winter, losses were considerably higher: transmission losses were estimated to approach 20 %, compared with approximately 11 % in summer. Consequently, total measured energy consumption in the winter cycle was about 2.23.

3.2 Energy demand of vacuum drying and comparison with convective drying

3.2. Potrošnja energije vakuumskog sušenja i usporedba s konvektivnim sušenjem

In the investigated plant, vacuum drying is mainly applied for smaller volumes of high value-added products with increased quality requirements (e.g., oak parquet or ash decking). Its main practical advantage is faster and potentially gentler moisture removal, which according to industrial experience and literature may reduce internal stresses and improve product quality; however, the present study did not include a separate quantitative evaluation of drying quality or defect formation for the two technologies. The plant produces approximately 200–300 m³ of vacuum-dried timber annually. The six convective chambers have an installed maximum capacity of about 8000 m³/year, while the actual measured annual processed volume of the test chamber considered in the present 2024 energy evaluation was approximately 1000–1200 m³. Based on measured operational data from 2024, the annual thermal energy demand of the vacuum dryer was approximately 250000 MJ/year, while electrical consumption reached about 44000 kWh/year (158400 MJ/year). The reported annual thermal-energy value for the vacuum dryer includes all measured heat supplied through its heating circuit, including the periodic auxiliary-boiler support required during winter operation. In comparison, the convective system exhibited an annual thermal demand of around 1717560 MJ/year and electrical consumption of about 50000 kWh/year (180000 MJ/year). As the annual processed wood volume differed substantially between the two technologies, the comparison should primarily be interpreted on a specific energy basis rather than from absolute annual totals. Convective drying showed a specific electrical demand of about 45 kWh/m³ (≈ 162 MJ/m³), while the vacuum dryer required about 176 kWh/m³ (≈ 634 MJ/m³), i.e. approximately four times more electrical energy per unit volume of dried wood. This distinction is crucial, because the apparent advantage of vacuum drying in annual total energy use merely reflects its much lower processed volume, not superior overall energy efficiency. In the present comparison, CO_2 eq emissions related to electricity use were calculated using a Hungarian annual average grid carbon intensity factor of 0.243 kg CO_2 eq/kWh for 2024, obtained from Electricity Maps yearly data. This factor was interpreted as an average attributional indicator of the electricity mix available on the grid, not as a marginal emission factor. As vacuum drying is much more electricity-intensive, its operating cost is expected to be more sensitive to electricity prices. By contrast, the economic performance of convective drying depends more strongly on the cost of process heat, which may vary substantially depending on whether the thermal energy is supplied by natural gas, biomass, or a mixed heat system. In European non-household energy markets, electricity is generally priced higher per unit of delivered energy than natural gas, while the competitiveness of biomass-based heat depends strongly on local fuel availability, transport distance, and site-specific fuel handling conditions. Therefore, the economic ranking of vacuum and convective drying cannot be assessed solely from energy quantities; it is also influenced by the local energy-price structure and plant-specific infrastructure. Overall, vacuum drying energy use is largely associated with maintaining vacuum conditions and internal heat transfer, whereas convective drying mainly consumes heat for air heating and circulation. Although detailed chamber-pressure profiles were not available for direct analysis, the measured energy pattern suggests that the high electrical intensity of vacuum drying was related to the continuous demand of vacuum generation and auxiliary equipment throughout the cycle. For completeness, annual total energy use is also reported in Table 2; however, these totals mainly reflect the strongly different annual throughput of the two technologies and should not be interpreted as direct indicators of relative process efficiency.

Within the technological and energy-supply context of the investigated plant, shifting the approximately 250 m³/year currently processed by vacuum drying toward convective drying would be associated with lower calculated electricity-related CO_2 eq emissions under the applied Hungarian average grid-mix assumption. On this indicative basis, convective drying showed a specific CO_2eq value approximately 31.73 kg CO_2 eq/m³ lower than vacuum drying, corresponding to about 7.93 t CO_2 eq/year for the currently vacuum-

Table 2 Comparison of specific and annual energy consumption and CO_2eq emissions of convective and vacuum drying systems based on 2024 industrial operating data
Tablica 2. Usporedba specifične i godišnje potrošnje energije i emisija CO_2eq konvektivnih i vakuumskih sustava sušenja na temelju industrijskih operativnih podataka iz 2024.

Parameter *Parametar*	**Convective drying** *Konvektivno sušenje*	**Vacuum drying** *Vakuumsko sušenje*	**Remarks** *Napomena*
Specific indicators / *Specifični pokazatelji*			
Specific thermal energy demand, MJ/m^3 *specifična potreba za toplinskom energijom,* MJ/m^3	~ 1560	~ 1000	Calculated using average annual processed volume *izračunano na temelju prosječnoga godišnjeg obrađenog volumena*
Specific electrical energy demand, kWh/m^3 *specifična potreba za električnom energijom,* kWh/m^3	45	176	Calculated using average annual processed volume *izračunano na temelju prosječnoga godišnjeg obrađenog volumena*
Specific electrical energy demand, MJ/m^3 *specifična potreba za električnom energijom,* MJ/m^3	162	633.6	Electrical energy converted using 1 kWh = 3.6 MJ *električna energija pretvorena primjenom odnosa* 1 kWh = 3,6 MJ
Specific total energy demand, MJ/m^3 *specifična ukupna potreba za energijom,* MJ/m^3	~ 1600 – 1900	~ 1400 – 2000	Calculated based on the minimum and maximum annual quantities *izračunano na temelju minimalnih i maksimalnih godišnjih količina*
Specific CO_2 eq emissions (kg/m^3) from electricity consumption *specifične emisije* CO_2 *eq* (kg/m^3) *iz potrošnje električne energije*	11.04	42.77	0.243 kgCO_2 eq/kWh (Electricity Maps, n.d.)
Difference (vacuum − convective) *razlika (vakuumsko − konvektivno)*			+31.73 kgCO_2 eq/m^3
Annual totals / *Godišnji iznosi*			
Annual volume of dried wood, m^3/year *godišnji volumen osušenog drva,* m^3/god.	1000 – 1200	200 – 300	
Annual thermal energy consumption, MJ/year *godišnja potrošnja toplinske energije,* MJ/god.	1717560	250000	
Annual electrical energy consumption, kWh/year *godišnja potrošnja električne energije,* kWh/god.	50000	44000	
Annual electrical energy consumption, MJ/year *godišnja potrošnja električne energije,* MJ/god.	180000	158400	
Annual total energy consumption, MJ/year *ukupna godišnja potrošnja energije,* MJ/god.	1897560	408400	
Average share of electrical energy in total drying energy, % *prosječni udio električne energije u ukupnoj energiji sušenja, %*	~ 10%	~ 39%	
Annual CO_2 eq emissions (t/year) from electricity consumption *godišnje emisije* CO_2 *eq* (t/god.) *od potrošnje električne energije*	12.15	10.69	0.243 kgCO_2 eq/kWh (Electricity Maps, n.d.)

Note: Electrical energy was converted using 1 kWh = 3.6 MJ. CO_2eq values related to electricity consumption were calculated using the Hungarian annual average grid carbon intensity of 0.243 kg CO_2 eq/kWh for 2024, based on Electricity Maps yearly data. The applied factor represents an average attributional electricity-mix indicator rather than a marginal emission factor. Biogenic CO_2 from biomass combustion was excluded, in line with common greenhouse gas accounting practice, under which biomass-combustion CO_2 is treated separately from fossil-energy-related emissions (IPCC, 2021). The reported CO_2 eq values therefore mainly reflect differences in electrical intensity.

Napomena: Električna energija pretvorena je primjenom odnosa 1 kWh = 3,6 MJ. Vrijednosti CO_2 *eq povezane s potrošnjom električne energije izračunane su korištenjem prosječnoga godišnjeg intenziteta ugljika u mađarskoj mreži od 0,243 kg* CO_2 *eq/kWh za 2024. godinu, na temelju godišnjih podataka objavljenih u Electricity Maps. Primijenjeni faktor prosječni je pokazatelj atribucijskog miksa električne energije, a ne granični faktor emisije. Biogeni* CO_2 *iz izgaranja biomase isključen je u skladu s uobičajenom računovodstvenom praksom stakleničkih plinova, prema kojoj se* CO_2 *iz izgaranja biomase tretira odvojeno od emisija povezanih s fosilnom energijom (IPCC, 2021.). Stoga prijavljene vrijednosti* CO_2 *eq uglavnom odražavaju razlike u električnom intenzitetu.*

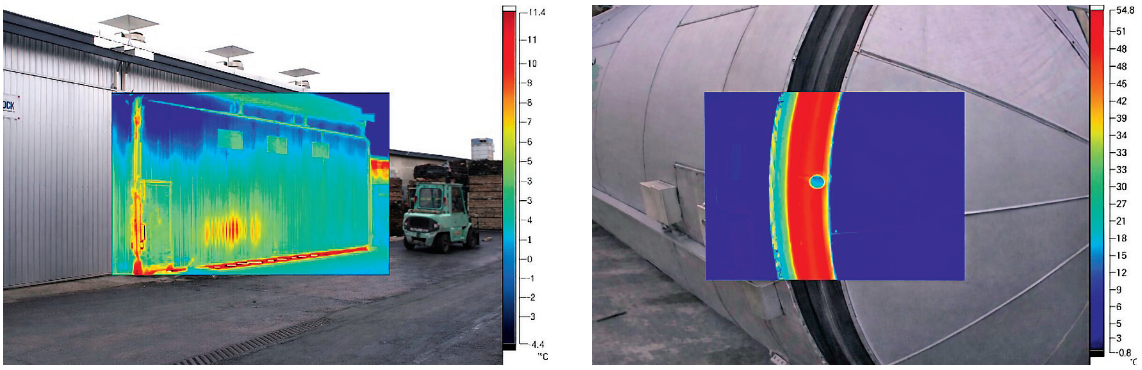

Figure 2 Thermographic visualization of winter heat transfer losses in the convective dryer (left) and vacuum dryer (right)
Slika 2. Termografska vizualizacija gubitaka topline zimi u konvektivnoj sušari (lijevo) i u vakuumskoj sušari (desno)

dried volume. However, this comparison should be interpreted strictly as case-study evidence, because it reflects the measured operating conditions, throughput structure, and energy supply of the investigated plant rather than a universally applicable technology ranking. The relative environmental outcome would also change under different electricity carbon intensities, alternative heat-supply configurations, or different product-quality requirements. If the grid carbon intensity decreases in the future due to a higher share of low-carbon generation, the CO_2 eq disadvantage associated with the higher electricity demand of vacuum drying will also decrease; conversely, under a more carbon-intensive electricity mix, the relative carbon burden of vacuum drying would become even more pronounced. The thermal energy demand of the summer drying cycle was well described by the theoretical model, with only ~ 4 % deviation between calculated and measured values. In contrast, winter heat consumption exceeded the theoretical estimate by approximately 17 %, likely due to combined industrial factors. Moisture content in certain zones of the winter load may have been higher than assumed, and drying control is typically adjusted to the wettest stack sections. In addition, the large winter temperature gradient (≈ 60–70 °C) increased transmission heat losses through chamber walls and structural interfaces, as confirmed by thermographic inspections (Figure 2). The color scale indicates transmission heat losses. The redder the color, the greater the transmission heat loss directed outward from the chamber. A further contributing factor may have been the colder, and possibly partly frozen, condition of the winter wood charge at the beginning of drying; since the latent heat of fusion was not treated as a separate term in the simplified model, this effect may also have contributed to the underestimation of measured winter heat demand.

Operational factors may also have influenced actual energy consumption, including suboptimal boiler performance or additional heating phases. Therefore, the ~17 % deviation between calculated and measured winter heat demand may partly reflect the safety margins and control reserves typical of industrial operation. Measured electrical energy consumption in the summer cycle was significantly lower than the benchmark estimate. This difference is consistent with the expected effect of VFD-controlled fan operation under favorable summer climatic conditions, when reduced air circulation may be sufficient for maintaining the required drying performance. However, as the present study did not include a separate time-resolved analysis of fan-specific power profiles, this interpretation should be regarded as an operationally plausible explanation rather than a direct component-level verification. Under favorable summer climatic conditions, the measured electrical share accounted for only ~ 3.5 % of total energy demand, compared with the assumed benchmark value of 12 %, which suggests that actual air-circulation demand in this cycle was substantially lower than indicated by the general literature-based proportion. In winter, measured electrical consumption remained about 12 % below the benchmark estimate. This may also reflect reduced fan speeds during certain drying phases; however, the present dataset does not allow direct decomposition of the total electrical demand into fan-level operating profiles. Vacuum drying offers substantially shorter process times (4 – 5 days versus 20 – 25 days for convective drying), but requires a much higher electrical input. Although thermal energy demand scales with processed volume (vacuum: ~ 250000 MJ vs. convective: ~ 1717560 MJ annually), electrical consumption remains of similar magnitude in both systems due to the continuous power requirement of vacuum pumps and auxiliary equipment. In contrast, fan energy demand in convective drying can be reduced as drying progresses. From the perspective of the present case study, the higher electrical intensity of vacuum drying resulted in a less favorable electricity-related CO_2 eq profile under the applied Hungarian grid-mix assumption. This observation should, however, be interpreted as conditional on the plant configuration and energy context investigated, not as a generally valid conclusion for all industrial drying applications.

4 CONCLUSIONS
4. ZAKLJUČAK

This study evaluated the energy efficiency of industrial wood drying in a Hungarian facility, focusing on seasonal differences in convective drying and on the comparison between convective and vacuum technologies. The main conclusions are:

- Seasonal effect: Winter operation required about 2.23 times more total energy than summer drying, mainly due to higher heating demand and increased transmission heat losses. Thus, winter peak-load conditions are decisive for dryer and boiler system dimensioning.
- Measured vs. calculated demand: Thermal energy estimates matched measurements closely in summer, while an approximately 17 % deviation was observed in winter. Electrical consumption was substantially lower than literature-based benchmark expectations in the summer cycle and remained moderately below the benchmark range in winter. However, as the available electrical data were recorded at full-kiln level and did not include fan-level sub-metering or time-resolved motor-power records, the observed seasonal difference in electricity use cannot be attributed quantitatively to fan control alone. Rather, the results indicate that chamber-level electrical demand in industrial convective drying can vary strongly between seasonal operating conditions, most likely due to the combined influence of VFD-controlled air-circulation duty, cycle duration, product moisture condition, and winter-related operational load.
- Convective vs. vacuum drying: In the investigated industrial case, vacuum drying was substantially faster (4 – 5 days vs. 20 – 25 days), but exhibited a markedly higher specific electrical demand (176 kWh/m³ compared to 45 kWh/m³ for convective drying). At the same time, the specific thermal energy requirement of vacuum drying was lower by approximately 30 – 35 % under the analyzed operating conditions. Accordingly, the present results suggest that in this case study the main difference between the two technologies lies in their energy structure: vacuum drying reduced thermal demand but required substantially higher electrical intensity. Under the applied Hungarian average electricity-mix assumption, this led to a less favorable electricity-related carbon profile for vacuum drying in the investigated plant. However, these findings should be interpreted as indicative evidence from a site-specific industrial case study rather than as a universally applicable comparison between drying technologies, particularly because only two convective drying cycles were analyzed and no direct quantitative quality comparison was included.
- Efficiency improvement potential: Literature on industrial kiln operation indicates that fan-speed optimization by variable-frequency control can reduce electrical energy consumption substantially under appropriate operating conditions. In the present case study, however, the analyzed chamber-level electricity data do not permit a direct quantitative optimization assessment at fan level. Therefore, any further electricity-saving potential related to fan-control optimization should be interpreted as a literature-supported technological opportunity rather than as a directly verified numerical result of the two analyzed seasonal cycles. In addition, heat recovery, condensation-based systems, and improved chamber insulation could significantly reduce thermal demand, especially in winter. Renewable energy integration (PV, wind, biomass by-products) may further decrease emissions and improve energy independence.
- Environmental impact: Under the investigated Hungarian electricity mix and the applied annual average grid-emission assumption, in this case study the convective system showed lower calculated electricity-related specific CO_2 eq emissions than the vacuum system by approximately 31.73 t CO_2 eq per 1000 m³. For the currently vacuum-dried annual volume in the investigated plant, this corresponds to an indicative difference of about 8 t CO_2 eq/year. This result should not be generalized without caution, because it depends on the analyzed throughput, the local energy mix, and the plant-specific technological configuration.

4.1 Practical recommendations
4.1. Praktične preporuke

- In convective kiln drying, priority should be given to reducing winter heat losses through improved insulation of chamber walls, doors, and structural thermal bridges, because seasonal heat demand is strongly influenced by ambient temperature conditions.
- Retrofitting or optimizing variable frequency drive (VFD) control of circulation fans may be considered a high-priority measure, because literature and the present chamber-level observations together suggest that favorable operating conditions may allow lower electrical demand; however, the current dataset does not permit a direct fan-level quantification of this effect.
- When evaluating heat-recovery systems, selection should be based on the expected seasonal temperature regime, because the highest thermal savings are likely to be achieved under winter operation with large kiln-to-ambient temperature differences.
- Technology selection between convective and vacuum drying should not be based solely on annual total

energy use or on simplified cross-technology comparison of non-identical product groups. Specific energy demand, electricity intensity, product quality requirements, target moisture content, batch strategy, and the local energy-price structure should all be considered simultaneously.

- Vacuum drying may remain justified for high value-added products with strict quality requirements, whereas convective drying may offer advantages where lower electricity intensity and biomass-based heat integration are available.
- For industrial plants planning modernization, measurement-based energy monitoring at high time resolution is recommended before major investment decisions, as simplified benchmark assumptions may not accurately reflect actual fan operation, seasonal effects, or dryer-specific energy structure.

Overall, the present results provide indicative industrial evidence that wood-drying energy performance can be improved through technological development and operational optimization. However, broader generalization would require analysis of a larger number of drying cycles under more diverse conditions. The study also shows that volume-based indicators alone are insufficient for comparing cycles with different moisture loads; moisture-normalized indicators, especially per kilogram of removed water, provide a more robust basis for interpretation. In the investigated plant, the combined evaluation of measured and calculated data proved useful for identifying potentially more energy-efficient drying strategies. Future development may also include RF–vacuum drying.

5 NOMENCLATURE
5. NOMENKLATURA

Symbols and variables – Simboli i varijable

$Q_{\mathrm{th,total}}$ – total theoretical thermal energy demand
Q_{heat} – sensible heat demand for heating the wood-water system
Q_{evap} – latent heat demand of moisture removal
Q_{loss} – estimated total heat losses during kiln operation
Q_{trans} – conductive heat loss through the kiln structure
Q_{other} – additional operational heat losses not explicitly resolved in the simplified model
m_0 – oven-dry wood mass
$m_{\mathrm{w,i}}$ – initial water mass in the wood charge
$m_{\mathrm{w,f}}$ – final water mass in the wood charge
$m_{\mathrm{w,avg}}$ – average water mass considered during heating
m_{evap} – mass of removed water
V – timber volume loaded into the kiln
ρ_0 – oven-dry density of wood
MC_{i} – initial moisture content on a dry basis
MC_{f} – final moisture content on a dry basis
c_{wd} – specific heat capacity of oven-dry wood
c_{w} – specific heat capacity of water
T_0 – initial timber temperature
T_{d} – characteristic drying temperature
h_{fg} – latent heat of evaporation of water
Q – relevant measured or calculated energy value
SEC_{V} – specific energy consumption per unit volume of dried timber
SEC_{W} – specific energy consumption per kilogram of removed water
SEC_{OD} – specific energy consumption per kilogram of oven-dry wood

Abbreviations – Kratice

VFD – variable frequency drive
CO_2 eq – carbon dioxide equivalent
MC – moisture content

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