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Technical, Energy, and Environmental Performance Evaluation of an Industrial-Scale Solar–Steam Hybrid Wood Drying System in Tropical Climate of Vietnam

Evaluacija tehničkih, energetskih i ekoloških performansi hibridnoga solarno-parnog industrijskog sustava za sušenje drva u tropskoj klimi Vijetnama

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ABSTRACT • *This study presents an industrial-scale evaluation of a 100 m³ per batch solar–steam hybrid wood drying system operating under tropical climate conditions in Vietnam. A full drying cycle of approximately 480 hours was performed on 13-mm Acacia mangium lumber using a multi-point monitoring system that recorded dry- and wet-bulb temperatures, relative humidity, air velocity, solar irradiance, and the thermal and electrical energy inputs at 10-minute intervals. The integrated roof collector achieved an average thermal efficiency of ~46 % (peaking at ~52 %), delivering 15,687 kWh of useful heat and supplying 40 – 52 % of the daytime thermal demand. Compared with a conventional steam kiln, the hybrid system reduced biomass consumption by 50 %, electricity use by 34.3 %, and total energy input by 45.2 %. The Specific Energy Consumption (SEC) decreased from 1.99 to 1.09 kWh/kg of water removed (- 45.2 %), confirming hypothesis H1. The solar fraction reached 44.3 % (thermal basis) and 33.8 % (total basis), supporting hypothesis H3. Wood quality assessments following TCVN 8929/8930 showed that the hybrid kiln maintained comparable levels of product quality, with surface and internal check rates of 2.8 % and 1.0 %, respectively. The average warping was 2.2 mm, exhibiting an improving trend compared with the control kiln (p = 0.054), thereby further supporting hypothesis H2. Environmental analysis following IPCC 2006/2019 guidelines indicated that the hybrid system reduced non-biogenic CO_2 emissions by 34.3 %, consistent with hypothesis H4. Overall energy costs decreased by 38.7 % per batch, resulting in a payback period of approximately 3.04 years, which remained below 4 years under CAPEX variations of ± 20 %. Collectively, the findings demonstrate that the solar–steam hybrid system is an efficient, stable, and economically viable solution for industrial wood drying under tropical conditions, contributing to reduced fossil-based CO_2 emissions and supporting sustainable production pathways.*

KEYWORDS: *solar-steam hybrid wood drying; solar-assisted drying; specific energy consumption (SEC); solar fraction; industrial-scale experiment; acacia mangium; energy efficiency; CO_2 emissions; hygrothermal performance*

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SAŽETAK • *Studija donosi evaluaciju hibridnoga solarno-parnoga industrijskog sustava za sušenje drva kapaciteta 100 m³ po seriji, kakav radi u tropskim klimatskim uvjetima u Vijetnamu. Za potrebe istraživanja proveden je puni ciklus sušenja drva Acacia mangium debljine 13 mm u trajanju od približno 480 sati. Primjenom sustava mjerenja u više je točaka bilježena temperatura suhoga i vlažnog termometra, relativna vlažnost, brzina zraka, Sunčevo zračenje te potrošnja toplinske i električne energije u intervalima od deset minuta. Integrirani krovni kolektor postigao je prosječnu toplinsku učinkovitost od 46 % (s vrhuncem od 52 %), isporučujući 15 687 kWh korisne topline i osiguravajući 40 – 52 % dnevno potrebne topline. U usporedbi s konvencionalnom parnom sušarom, hibridni sustav smanjio je potrošnju biomase za 50 %, potrošnju električne energije za 34,3 %, a ukupnu potrošnju energije za 45,2 %. Specifična potrošnja energije (SEC) smanjila se s 1,99 na 1,09 kWh/kg uklonjene vode (–45,2%), potvrđujući hipotezu H1. Solarni udio dosegnuo je 44,3 % (toplinska osnova) i 33,8 % (ukupna osnova), što potvrđuje hipotezu H3. Procjene kvalitete drva prema TCVN 8929/8930 pokazale su da hibridna sušara osigurava usporedive razine kvalitete proizvoda, uz ocjenu pojave površinskih i unutarnjih pukotina od 2,8 % odnosno 1,0 %. Prosječna deformacija bila je 2,2 mm, što pokazuje trend poboljšanja u usporedbi s kontrolnom sušarom (p = 0,054), čime se dodatno potkrepljuje hipoteza H2. Analiza okoliša prema smjernicama IPCC-a 2006/2019 pokazala je da je hibridni sustav smanjio nebiogene emisije CO_2 za 34,3 %, što je u skladu s hipotezom H4. Ukupni troškovi energije smanjili su se za 38,7 % po seriji, što je rezultiralo razdobljem povrata od približno 3,04 godine, dakle manje od 4 godine, uz varijacije CAPEX-a od ± 20 %. Zaključno, rezultati pokazuju da je hibridni solarno-parni sustav učinkovito, stabilno i ekonomski isplativo rješenje za industrijsko sušenje drva u tropskim uvjetima i da pridonosi smanjenju emisija CO_2 iz fosilnih goriva te podupire održive proizvodne procese.*

KLJUČNE RIJEČI: *hibridno sušenje drva solarno-parnim sustavom; sušenje uz pomoć solarne energije; specifična potrošnja energije (SEC); solarni udio; pogonsko ispitivanje; Acacia mangium; energetska učinkovitost; emisije CO_2; higrotermalna svojstva*

1 INTRODUCTION

1. UVOD

1.1 Background

1.1. Dosadašnje spoznaje

Wood drying is one of the most energy-intensive stages in the timber processing chain, typically accounting for 50 – 70 % of the total energy consumption in sawmills and furniture manufacturing facilities (Ya Meng *et al.,* 2019). In Vietnam and most Southeast Asian countries, conventional steam kilns fueled by biomass – such as sawdust, bark, and wood chips – remain the dominant technology. While compatible with local production practices, these systems exhibit substantial limitations, including low thermal efficiency, significant heat losses due to non-uniform stacking, high fuel costs, and considerable emissions of biogenic CO_2 and particulate matter resulting from biomass combustion.

Vietnam's tropical monsoon climate, characterized by high solar irradiance, long sunshine duration, and pronounced hygrothermal fluctuations, offers strong potential for integrating solar energy into industrial thermal processes such as wood drying (Rahman *et al.,* 2025). Solar-assisted and hybrid drying technologies have been shown to reduce energy consumption and CO_2 emissions while providing milder drying conditions that help mitigate internal stresses within the wood. However, most existing studies on solar-assisted or hybrid wood drying have been limited to laboratory-scale or small pilot-scale experiments. Industrial-scale evaluations (≥ 80 – 100 m³ per batch), which involve more complex influences from weather variability, operational practices, and raw material heterogeneity, remain scarce – particularly under the tropical climate conditions of Southeast Asia.

Therefore, implementing and evaluating a 100 m³ per batch industrial-scale solar–steam hybrid wood drying system at an operational manufacturing facility serving export markets (EU, US) is essential to validate its technical feasibility, energy-saving potential, and impact on product quality under real production conditions.

1.2 Research gaps

1.2. Istraživačke praznine

Although previous studies have contributed meaningfully to the understanding of solar-assisted and hybrid wood drying, several critical scientific gaps remain:

(i) Limited industrial-scale research in tropical climates: Most prior studies have been conducted at laboratory or pilot scales, or in temperate regions with relatively stable solar radiation and humidity patterns, limiting their relevance to the highly dynamic climatic conditions of tropical Southeast Asia (Elustondo *et al.,* 2023).

(ii) Insufficient technical transparency: Many studies lack essential details regarding collector geometry, airflow configuration, insulation design, sensor placement, and control logic-parameters crucial for experimental reproducibility and accurate numerical modeling (Martynenko and Vieira, 2023).

(iii) Lack of multi-dimensional performance assessment: Most research focuses on thermal efficiency or energy savings, while critical dimensions such as CO_2 emissions, energy costs, economic performance, and post-drying wood quality are seldom evaluated concurrently (Khouya, 2022).

(iv) Absence of standardized international metrics: Indicators such as Specific Energy Consumption (*SEC*), Solar Fraction (*SF*), collector efficiency, and system-boundary-based energy balances are often reported inconsistently or incompletely. Notably, no existing study has evaluated CO_2 emissions following IPCC (2006; 2019) guidelines.

(v) Lack of critical hygrothermal measurements: Key determinants of wood drying performance – including relative humidity (RH), wet-bulb temperature (T_{wb}), and the spatial distribution of airflow velocity within the kiln – are frequently overlooked or measured insufficiently.

(vi) Inadequate statistical analysis and uncertainty quantification: Most prior work does not assess measurement uncertainty, fails to report 95 % confidence intervals, and lacks rigorous statistical hypothesis testing, limiting the reliability of conclusions and complicating cross-study comparisons.

These gaps underscore the need for an industrial-scale experimental study employing a multi-dimensional analytical framework supported by a comprehensive, high-resolution dataset collected under Vietnamese tropical climate conditions.

1.3 Research hypotheses

1.3. Istraživačke hipoteze

Building upon the contextual analysis and identified research gaps, this study is structured around four testable hypotheses:

H1: The solar–steam hybrid wood drying system reduces Specific Energy Consumption (SEC) by ≥ 30 % compared with a conventional steam kiln;

H2: The post-drying wood quality produced by the hybrid system exhibits no statistically significant difference compared with the steam kiln at a significance level of $p > 0.05$;

H3: Under the tropical climate of Vietnam's Central Highlands, the hybrid system achieves a Solar Fraction > 0.30;

H4: Non-biogenic CO_2 emissions decrease proportionally with the energy savings achieved, whereas biogenic CO_2 is accounted for separately following IPCC guidelines to ensure international comparability.

1.4 Research objectives

1.4. Ciljevi istraživanja

This study aims to comprehensively evaluate the performance of the industrial-scale hybrid wood drying system in Vietnam, covering technical, hygrothermal, energy, wood quality, economic, and environmental dimensions. The specific objectives are to:

1. Evaluate the operational characteristics, hygrothermal variability, and heat–mass transfer behavior of the 100 m³ per batch hybrid drying system;

2. Establish an energy balance based on clearly defined system boundaries to quantify core performance indicators including Specific Energy Consumption (*SEC*), total Solar Fraction (SF_{total}), and collector efficiency;

3. Compare total energy consumption, electricity consumption, fuel use, drying duration, and the influence of control logic between the hybrid and conventional steam systems;

4. Assess post-drying wood quality in accordance with TCVN 8929/8930, combined with appropriate statistical testing;

5. Analyze economic performance (energy costs, payback period) and conduct sensitivity analysis under ± 20 % variations in major economic parameters;

6. Evaluate CO_2 emissions following IPCC 2006/2019 guidelines, distinguishing clearly between biogenic and non-biogenic CO_2;

7. Identify technical limitations and propose directions for future research.

1.5 Novelty

1.5. Znanstveni doprinos

To the best of the authors' knowledge, this study presents the following novel contributions:

1. First industrial-scale evaluation of a 100 m³ per batch solar–steam hybrid wood drying system in Southeast Asia under tropical climate conditions.

2. A multi-dimensional analytical framework (Technical – Energy – Economic – Environmental – Wood Quality), extending beyond earlier studies that primarily focused on thermal efficiency.

3. Comprehensive technical transparency, detailing collector geometry, airflow pathways, insulation structure, and control logic components often only briefly mentioned in prior research.

4. Application of statistical analysis and measurement uncertainty assessment, improving the reliability and comparability of *SEC*, *SF*, and CO_2 indicators.

5. Proposal of the SF_{total} metric and the separation of biogenic CO_2 following IPCC guidelines, contributing to the standardization of performance assessment for hybrid drying systems.

Compared with previous hybrid-drying studies (Tarigan and Tekasakul, 2005; Lamrani *et al.,* 2021; Ferrari *et al.,* 2024), this study demonstrates three distinctive and verifiable innovations:

- Integrated roof collector (Large-area, Dual-layer Design): Unlike externally mounted collectors in earlier studies, the kiln roof itself functions as a 243.7 m² solar absorber, reducing thermal losses and eliminating ducting inefficiencies;
- 100 m³ Industrial scale (50 × larger than prior laboratory systems): Most previous works were 2 – 10 m³; this study evaluates a fully operational 100 m³

kiln, representing the largest documented hybrid system in tropical Asia;.

- Full hygrothermal instrumentation and uncertainty analysis: This work includes T_{db}, T_{wb}, RH, EMC, airflow 3D mapping, DNI, POA irradiance, and CI95 % – providing a dataset uncommon in prior research.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Study site and experimental design
2.1. Mjesto istraživanja i postavke eksperimenta

2.1.1 Study site and climatic conditions
2.1.1. Mjesto istraživanja i klimatski uvjeti

The study was conducted at a large-scale industrial wood processing facility in Gia Lai Province, Vietnam (13°59′N; 108°00′E), situated within the tropical savanna climate zone (Aw) of the Central Highlands. This region features two distinct seasons: a rainy season (May–November) and a dry season (December–April). During the dry season, high solar irradiance, long sunshine duration, and low relative humidity provide favorable conditions for applying solar thermal technologies to industrial wood drying.

Recent meteorological studies have reported Direct Normal Irradiance (DNI) levels of 1,000 – 1,200 W/m² on clear dry-season days in the Central Highlands (Nguyen *et al*., 2024; Rahman *et al.,* 2025), indicating substantial solar energy potential. To accurately characterize environmental influences on collector performance, an automated meteorological station was installed directly at the collector site. Three key parameters were continuously recorded at 10-minute intervals throughout the 480-hour drying cycle: (i) ambient temperature (°C), (ii) relative humidity (%RH), and (iii) solar irradiance (W/m²).

Solar irradiance was measured using a PCE-SPM1 pyranometer oriented perpendicular to the sun's rays, enabling direct measurement of DNI and providing an accurate representation of usable solar energy reaching the collector. The maximum recorded irradiance reached 1,245 W/m², consistent with typical peak DNI values in the region during intense dry-season conditions. The time-series data collected were subsequently used to determine collector efficiency, calculate the Solar Fraction (SF), and evaluate measurement uncertainty associated with energy indicators.

2.1.2 Experimental design
2.1.2. Postavke eksperimenta

The experiments were carried out at the manufacturing facility of Thanh Tam Wood Processing JSC in Gia Lai Province, Vietnam. Two industrial-scale drying systems, each with a nominal capacity of approximately 100 m³ per batch, were operated simultaneously in parallel: (i) Hybrid Kiln – a solar–steam hybrid drying system, and (ii) Control Kiln – a conventional steam-heated drying system. The experimental objective was to compare the two systems in terms of energy performance, wood quality, environmental emissions, and economic efficiency under actual industrial operating conditions. Detailed technical descriptions of both systems are provided in Section 2.4.

Timing and Experimental Conditions: The experimental campaign was implemented during the dry season (March–April 2025). Two drying batches were operated in parallel under strictly synchronized schedules to ensure comparability across kilns. Each kiln was charged with approximately 90 m³ of sawn timber, corresponding to 80 – 90 % of the system nominal design capacity. This loading rate reflects standard industrial practice at the factory and is known to promote stable airflow distribution and thermal uniformity inside the drying chamber. The characteristics of processed timber are detailed in Section 2.2. The lumber loaded into both kilns had identical cross-sectional dimensions, similar biological and anatomical properties, and was stacked using the same standardized procedures adopted by the factory to minimize variability between batches.

2.2 Timber material
2.2. Drvni materijal

The timber used in this study was *Acacia mangium*, a major plantation species in Vietnam widely utilized for export-oriented furniture manufacturing. *Acacia mangium* is known for its high permeability and substantial variation in initial moisture content, making it particularly prone to drying defects such as checking and warping when exposed to unstable drying conditions. These characteristics make it an appropriate material for evaluating the performance and robustness of the hybrid drying system (Martynenko and Vieira, 2023).

To ensure experimental uniformity, the raw timber was sourced from a single logging batch with consistent stand age, site conditions, and storage history. The sawn boards had standardized dimensions of 13 mm (thickness) × 200 mm (width) × 3,000 mm (length). Lumber stacks were prepared using industrial stacking procedures with 20-mm stickers to facilitate optimal airflow channels, minimize stagnant air pockets, and ensure uniform air velocity distribution within the kiln.

Determination of Initial moisture content (MC_i): The initial moisture content was measured using 30 randomly selected boards (n = 30) assessed with a CEM DT-129 resistance-type moisture meter. These readings were calibrated against 10 samples determined by the gravimetric (oven-dry) method following

Table 1 Complete drying schedule for 13-mm *Acacia mangium*
Tablica 1. Potpuni režim sušenja za drvo *Acacia mangium* debljine 13 mm

Phase *Faza*	**Target *MC*, %** *Ciljani sadržaj vode,* %	T_{db}, °C	T_{wb}, °C	**RH, %**	**EMC, %**	**Air velocity, m/s** *Strujanje zraka,* m/s	**Notes** *Napomene*
Heating *zagrijavanje*	>45	50	48	70 – 75	19.0	1.5 – 2.0	Gradual warm-up *postupno zagrijavanje*
Pre-drying *predsušenje*	45 – 40	50	46	65 – 70	15.5	1.8 – 2.2	RH controlled via venting *regulacija relativne vlažnosti zraka putem ventilacije*
Main drying *glavno sušenje*	35 – 25	55	49	55 – 60	12.0	2.0 – 2.4	Maximum solar utilization *maksimalno iskorištenje solarne energije*
Final drying *završno sušenje*	25 – 15	60	50	50 – 55	9.5	2.0 – 2.3	Reduced vent aperture *uz pritvoren ventilacijski otvor*
Equalizing *izjednačivanje*	15	60	52	60 – 65	10.5	1.5 – 2.0	Stress relief and conditioning *oslobađanje naprezanja i kondicioniranje*

ISO 13061-1: 2014. The results showed an average MC_i of 50.2 % with a standard deviation of 3.1 %, indicating low variability and confirming the homogeneity of the input material – an essential condition for comparing the two drying systems.

The target final moisture content was set at (12 ± 3) %, meeting quality requirements for furniture products destined for EU and US export markets (Elustondo *et al.,* 2023).

2.3 Drying schedule and control strategy
2.3. Režim sušenja drva i način kontrole

The drying schedule plays a critical role in balancing drying efficiency and final product quality. In this study, the schedule for 13-mm *Acacia mangium* lumber was designed by integrating empirical operational experience with heat and mass transfer principles. The goal was to simultaneously regulate the dry-bulb temperature (T_{db}), wet-bulb temperature (T_{wb}), and airflow velocity to maintain an appropriate moisture gradient between the core and the surface, thereby preventing moisture shock and mitigating internal stresses.

Five-Phase Drying Schedule: The drying schedule consists of five distinct phases, each reflecting the evolving moisture behavior of the wood throughout the process.

System Control Logic: A central controller monitored real-time data from a sensor network distributed inside the kiln and continuously adjusted the setpoints. The system controlled: Venting aperture, regulating humidity discharge; Heat source selection, switching between the solar collector and the steam boiler; Circulation fan speed, adjusted via Variable frequency drives (VFDs).

Venting strategy: The controller applied an RH-deviation algorithm whereby: When measured RH exceeded the setpoint → vents opened proportionally. When RH fell → vents gradually closed to conserve thermal energy. This approach minimized abrupt RH fluctuations, a common cause of surface checking.

Airflow distribution: Airflow uniformity was evaluated using 12 anemometers arranged in a three-dimensional grid (three vertical levels × three horizontal positions within the lumber stack). The measured values yielded a mean air velocity of 2.1 m/s with a standard deviation of ± 0.4 m/s, corresponding to a coefficient of variation of approximately 19 %. This level of variability is considered acceptable for industrial kilns, indicating that no major stagnant zones were present.

Energy Integration strategy: The hybrid system followed a “Solar-Priority” operational principle, defined as follows: Daytime with high solar irradiance: The system operated in Solar-only mode, using thermal energy exclusively from the roof collector. Hybrid mode: When solar energy was insufficient to maintain T_{db} setpoints, the system automatically switched to Hybrid mode, supplementing solar heat with steam from the boiler. This adaptive logic optimized energy consumption while maintaining drying stability.

2.4 System description
2.4. Opis sustava

This section provides a complete and detailed description of the drying system to clarify the interactions between the kiln structure, the integrated solar collector, the air circulation subsystems, and the control logic-factors that directly influence energy efficiency, thermal distribution within the lumber load, and final product quality. The system examined in this study is a hybrid configuration in which the arched kiln roof simultaneously acts as an integrated solar air collector, while saturated steam supplied by a biomass-fired boiler serves as the auxiliary heat source when solar energy is insufficient.

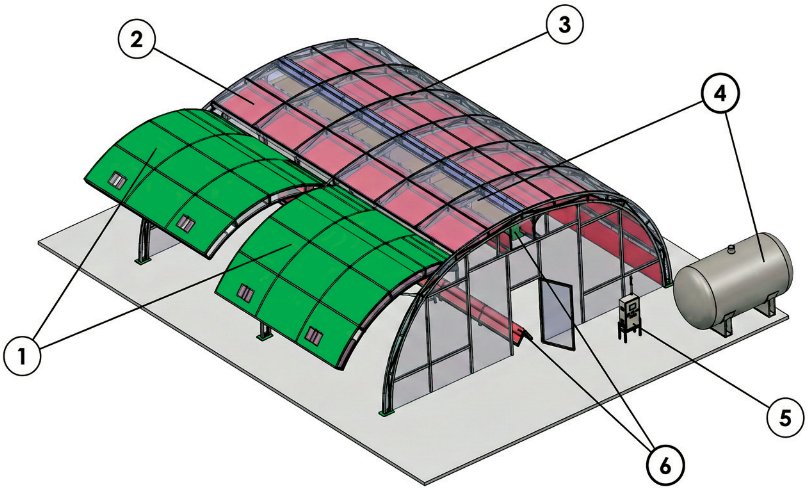
The drying kiln has overall dimensions of 12.6 m (length) × 12 m (width) × 5.1 m (height). It is constructed using a load-bearing steel frame combined

Figure 1 Schematic diagram of the experimental solar–steam hybrid wood drying system: a) Exterior view of the kiln; b) Interior view of the kiln during drying
Slika 1. Prikaz eksperimentalnoga hibridnog solarno-parnog sustava za sušenje drva: a) vanjski pogled na sušaru; b) pogled u unutrašnjost sušare tijekom sušenja

with 50-mm polyurethane (PU) sandwich insulation panels to reduce lateral heat transfer, thereby stabilizing internal kiln temperature against external environmental fluctuations. The interior walls are lined with galvanized steel sheets to improve corrosion resistance, ensuring long-term durability under continuous industrial operation. The combination of a large chamber volume (design capacity 100 m^3, operational capacity 90 m^3) and high-performance insulation is essential for maintaining the required thermal gradient and minimizing heat loss through the walls and floor.

A key design feature that distinguishes this hybrid system is the geometry of the integrated collector. Instead of employing stand-alone flat-plate collectors, the system utilizes the entire dual-layer polycarbonate roof structure as the glazing layer. The roof consists of 10-mm twin-wall polycarbonate panels (solar transmissivity $\tau \geq 0.85$), beneath which a black-chrome coated aluminum absorber plate (solar absorptivity $\alpha \geq 0.95$) is installed. The cavity between the glazing and the absorber, approximately 360 mm wide, serves as the hot-air channel for solar heat collection and transport. With this configuration, the kiln roof becomes a large-area solar collector with a useful absorption area of $A_c \approx 243.7$ m^2.

This integrated collector design shortens the heat transfer path and reduces thermal losses compared with externally mounted collector configurations. During operation, air is drawn from the chamber and circu-



1 – New-generation power-assisted lifting door / *vrata nove generacije s električnim podizanjem*
2 – Absorber unit and insulated kiln shell / *kolektor i izolirani plašt sušare*
3 – Main kiln frame and saturated steam heat supply / *glavni okvir sušare i opskrba zasićenom toplom parom*
4 – Auxiliary steam heating system / *pomoćni sustav grijanja parom*
5 – Dual-source drying control system / *sustav upravljanja sušenjem s dva izvora*
6 – Airflow deflectors / *deflektori protoka zraka*

Figure 2 Overall configuration of the experimental solar–steam hybrid wood drying system, including the integrated roof solar collector, circulation fans, moisture exhaust fans, saturated steam supply, and data acquisition network
Slika 2. Potpuna konfiguracija eksperimentalnoga hibridnog solarno-parnog sustava sušenja drva, uključujući integrirani krovni solarni kolektor, cirkulacijske ventilatore, ventilatore za odvod vlage, dovod zasićene pare i mrežu za prikupljanje podataka

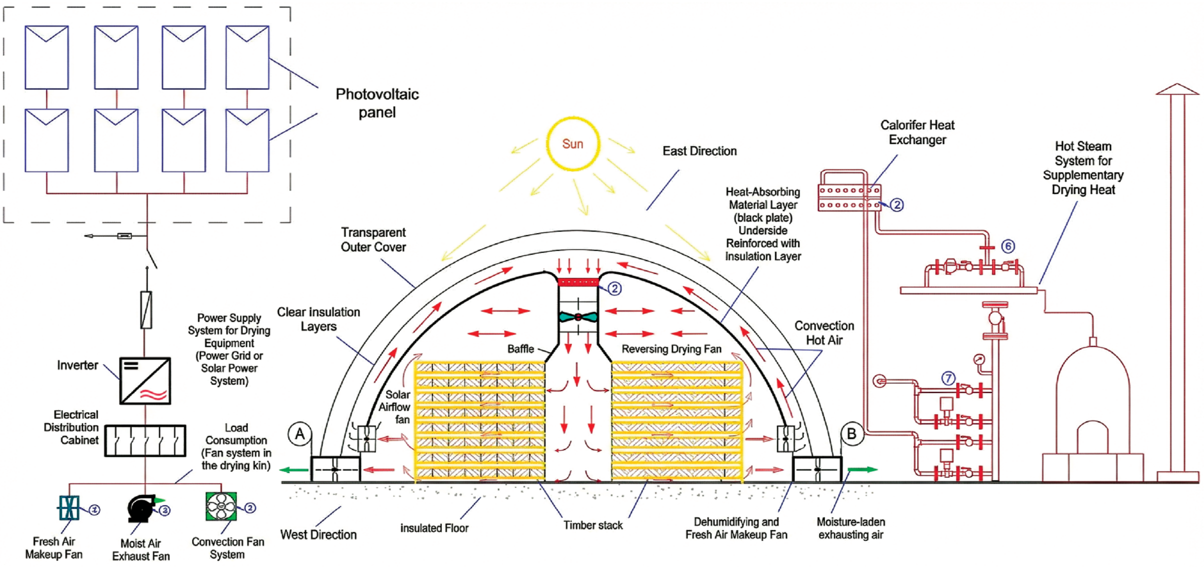


Figure 3 Schematic diagram of the hybrid drying system
Slika 3. Shematski dijagram hibridnog sustava sušenja

lated through the collector channel by the circulation fans, where it absorbs heat from the absorber plate before being blown back into the drying chamber to heat the lumber load. The airflow rate through the collector is regulated according to the thermal requirements of each drying phase: airflow is increased during the constant-rate drying period to maximize heat transfer and reduced during later phases to retain heat or to prevent excessive surface drying. The control system continuously monitors the relationship between collector airflow rate, solar heat gain, and the surface moisture transfer coefficient to optimize collector utilization.

The fan system is functionally stratified: Ten circulation fans (rated at 2.2 kW per fan) generate forced convection within the chamber, ensuring uniform temperature and humidity distribution across the lumber stacks. Seven moisture exhaust fans, installed along the side walls (with balanced intake and exhaust flow), have a combined electrical capacity of approximately 1.2 kW and operate intermittently when humidity removal is required.

During daytime operation, when solar irradiance is high, the circulation fans can operate at high capacity to maximize heat collection. At night, they reduce speed to an "idle mode" (~30 % of rated capacity) via VFDs, conserving electricity while maintaining minimum thermal uniformity. This flexible load modulation strategy is one of the main factors contributing to the reduced total electricity consumption of the hybrid system, even though the drying duration is slightly longer due to the factory's policy of not supplying steam at night.

The heat source control logic follows a Solar-Priority principle. When the irradiance on the Plane of Array (POA) exceeds the safety threshold of 150 W/m², the system switches to Solar-Only Mode. When POA decreases or the chamber temperature remains ≥ 5 °C below the setpoint for 20 consecutive minutes, the system automatically activates the steam valve to transition into Hybrid Mode. The use of a time-dependent temperature deviation algorithm—rather than instantaneous on/off switching – prevents large thermal oscillations and reduces unnecessary boiler activation, thereby conserving energy.

Operational log data from the entire drying batch shows that the temporal ratio between Solar-Only Mode and Hybrid Mode is relatively balanced (≈ 48 – 52 %), indicating that solar energy makes a substantial contribution to the overall thermal demand of the drying process.

For comparison, the Control Kiln is constructed with equivalent dimensions, loading volume, and fan layout. However, as all heat is supplied by saturated steam, the circulation fans must operate continuously at high load to maintain uniform heat distribution. As a result, the Control Kiln consistently exhibits higher electricity consumption compared with the hybrid system, which can dynamically modulate fan load in response to changing solar availability.

2.5 System boundary definition for energy and mass balance

2.5. Definicija granica sustava za bilancu energije i mase

To ensure clarity, consistency, and reproducibility in evaluating system performance, a formal system boundary was established following ASHRAE, 2010 and IPCC (2006; 2019) guidelines. The defined boundaries apply to all energy indicators – Specific Energy Consumption (*SEC*), Solar Fraction (SF_{total}), and useful thermal energy (Q_{solar} and Q_{steam}).

Thermal energy boundary – This boundary includes all useful heat delivered to the drying chamber:

Solar thermal energy (Q_{solar}) collected through the integrated roof absorber; Auxiliary steam heat (Q_{steam}) supplied by the biomass boiler. Excluded from the boundary: Conduction losses through walls, floor, and roof; Fan-induced heat; Heat stored in wood mass.

Electrical Energy Boundary (E_{elec}) – Includes electrical consumption from: Circulation fans (10 × 2.2 kW); Exhaust fans (7 × 0.17 kW); PLC, control system, and data acquisition.

Boundary for Specific Energy Consumption (*SEC*): $SEC = \dfrac{E_{\text{biomass}} + E_{\text{elec}}}{m_{\text{evap}}}$

Where: $E_{\text{biomass}} = m_{\text{biomass}} \cdot 3.89\ \text{kWh}/\text{kg}$ (IPCC 2006), E_{elec} = measured electricity, m_{evap} = evaporated water (kg).

Boundary for Solar Fraction (SF_{total}):

$$SF_{\text{total}} = \frac{Q_{\text{solar}}}{Q_{\text{solar}} + Q_{\text{steam}}}$$

All energy values were computed using 10-minute interval data across 480 hours, capturing full daytime–nighttime variability.

CO_2 Accounting Boundary (IPCC-compliant): Non-biogenic CO_2: derived from grid electricity. Biogenic CO_2: reported separately, not included in net emissions, following IPCC rules

This distinction ensures comparability with international GHG inventories.

2.6 Data acquisition and processing system
2.6. Sustav za prikupljanje i obradu podataka
2.6.1 Data collection
2.6.1. Prikupljanje podataka

To ensure the reliability of the measurements and to support comprehensive energy analysis, the drying system was equipped with a multi-point sensor network integrated with an automated Data Acquisition System (DAS). The system operated continuously throughout the entire drying cycle, recording data at 10-minute intervals. This sampling frequency provides sufficiently high temporal resolution to capture variations in energy, moisture, and temperature, while optimizing the data volume for subsequent statistical analysis and modeling.

Measurement of Dry- and Wet-Bulb Temperatures (T_{db}, T_{wb}): Temperature measurements were obtained using Type-K thermocouples with an accuracy of ± 0.5 °C after calibration. The T_{wb} sensors were equipped with standard cotton wicks and distilled water to maintain strictly saturated wet-bulb conditions. Sensors were positioned at six representative locations inside the chamber: near the air inlet, at the chamber center, at the end of the airflow path, and in the middle layer of the timber stack. Sensors were positioned at six locations representing the inlet, center, outlet, and mid-stack layers, providing spatial coverage of the kiln thermal field.

Measurement of Air Relative Humidity (RH): RH inside the kiln was measured using a Honeywell HIH-4000 capacitive sensor with an accuracy of ± 2.0 % RH. Combined with T_{db} and T_{wb}, RH data were used to determine the Equilibrium Moisture Content (*EMC*) under corresponding psychrometric conditions.

EMC calculation: The Equilibrium Moisture Content (*EMC*) for *Acacia mangium* was computed using the widely accepted Hailwood–Horrobin model:

$$EMC = \frac{1800}{W}\left(K_1 \cdot \frac{h}{1-h} + K_2 \cdot \frac{h}{(1-h)^2}\right) \quad (1)$$

Where: h – relative humidity (decimal), $W = 330 + 0.452T + 0.00415T^2$, $K_1 = 0.791 + 4.63 \cdot 10^{-4}T - 8.44 \cdot$

Table 2 List of measurement instruments used
Tablica 2. Popis upotrijebljenih mjernih uređaja

Measured parameter *Mjerni parametar*	**Instrument** *Uređaj*	**Measurement range** *Raspon mjerenja*	**Accuracy / uncertainty** *Točnost / mjerna nesigurnost*	**Location / quantity** *Položaj / količina*
Solar irradiance *Sunčevo zračenje*	PCE-SPM1 pyranometer	0 – 2,000 W/m²	±10 W/m²	Oriented for DNI / 1 *orijentirano za DNI / 1*
Temperature (T_{db}, T_{wb}) *temperatura* (T_{db}, T_{wb})	Type K Thermocouple	–50 to 200 °C	±0.75 °C	6 positions inside the kiln *6 pozicija unutar sušare*
Ambient RH *relativna vlažnost zraka*	HT-3009 hygrometer	10 – 95 %RH	±3 %RH	Outdoor / 1 *vani / 1*
Wood MC *sadržaj vode u drvu*	Resistance probe	6 – 90 %	±2 %	8 positions within the stack *8 pozicija unutar složaja drva*
Wood MC check *provjera sadržaja vode u drvu*	CEM DT-129	6 – 90 %	±2 %	Manual checks *ručne provjere*
Air velocity *brzina strujanja zraka*	Vane anemometer	0.3 – 30 m/s	±3 %	12 points on the stack *12 mjernih mjesta na složaju*
Electricity *električna energija*	Power meter	–	±1 %	Main electrical cabinet *glavni električni ormar*
Steam flow *protok pare*	Steam flow meter	–	±2.5 %	Steam supply line *dovod pare*

$10^{-7}T^2$, $K^2 = 6.34+7.75 \cdot 10^{-4}T - 9.35 \cdot 10^{-5}T^2$, T – dry-bulb temperature (°C).

This formulation ensures high accuracy for tropical kiln-drying conditions within 40 – 70 °C, consistent with ASHRAE and widely cited wood-drying studies.

Measurement of air velocity: Air velocity was measured using a vane-type anemometer (TSI-9545) with an accuracy of ± 0.03 m/s. A total of 12 measurement points, arranged in a three-dimensional grid, were deployed to evaluate airflow distribution, identify potential dead-air zones, and verify the effectiveness of the circulation-fan system.

Measurement of Solar Irradiance: Solar irradiance was measured using the PCE-SPM1 pyranometer. The sensor head was oriented perpendicular to the sun's rays, allowing the measurement of Direct Normal Irradiance (DNI). DNI was subsequently converted to Plane-of-Array (POA) irradiance based on the 15° roof tilt angle for collector-efficiency calculations.

Measurement of Wood Moisture Content (MC): The moisture content of the timber was monitored using a two-step approach:

- Rapid resistance-type measurements at 30 fixed sampling points;
- Verification by the gravimetric oven-dry method following ISO 13061-1: 2014.

This dual-method approach improves calibration accuracy and enhances data reliability.

Data Logging and Synchronization: All data were recorded via the DAS (Advantech ADAM-6000) synchronized with the central PID. Data were stored in *.CSV* format and visualized in real time, supporting energy-performance analysis and monitoring of deviations from the drying schedule.

2.6.2 Calibration

2.6.2. Kalibracija

All measurement devices – including the pyranometer, hygrometer, thermocouples, moisture meters, steam flow meter, and power meter – were inspected and calibrated prior to the experiment following manufacturer recommendations. Calibration information (reference values, calibration date, and deviation) was documented in the factory's instrument-log records.

2.6.3 Data processing

2.6.3. Obrada podataka

Data preprocessing included removing abnormal points caused by sensor malfunction, cross-checking measurements among identical sensors, and applying a three-point moving average to smooth variables with rapid short-term fluctuations when necessary.

For statistical analysis: Quantitative variables (e.g., warping) were compared using the two-sample independent t-test. Proportional variables (e.g., surface checks, internal checks) were evaluated using the two-sample z-test. The statistical significance threshold was set at $\alpha = 0.05$.

2.6.4 Analysis of measurement uncertainty and data representativeness

2.6.4. Analiza mjerne nesigurnosti i reprezentativnosti podataka

Industrial-scale drying cycles (90 – 100 m³; ~480 h) inherently limit the feasibility of repeated batch experiments. Therefore, the study adopted two methodological approaches to ensure data representativeness: (i) standardized industrial procedures, and (ii) statistical characterization of spatial sensor data. Nevertheless, the reliability and representativeness of the collected data were ensured through the following two methodological approaches:

(1) Industrial Standardization: The experiment was conducted at a large-scale wood-processing factory with extensive experience in supplying export markets such as the United States and the European Union. Therefore, all stages of sample preparation – from raw-material selection (*Acacia mangium*), sawing, to stacking techniques – strictly followed the factory's Standard Operating Procedures (SOPs) and Quality Control (QC) systems. The factory's standardized procedures for sawing, stacking, and QC ensure consistent input conditions across batches, reducing variability associated with material preparation.

(2) Statistical Analysis Using Spatial Sensor Data: Spatial data from the multi-point sensor network were utilized to quantify within-batch variability, serving as an alternative to experimental replicates. Continuous data were collected from 10 wood-MC measurement points and 12 air-velocity points distributed throughout the kiln.

A Bootstrap method with 1,000 resamples (B = 1,000 bootstrap resamples, not physical sample count) was applied to estimate the Standard Deviation (SD) and 95 % Confidence Interval (95 % CI) for key performance indicators such as final MC, Specific Energy Consumption (*SEC*), and Solar Fraction (*SF*). Bootstrap resampling (B = 1,000) was applied to quantify measurement uncertainty for *MC*, *SEC*, and *SF*, following established practices in industrial-scale process monitoring.

2.6.5 Assessment of dried wood quality

2.6.5. Procjena kvalitete osušenog drva

A total of $n = 120$ boards were sampled from each batch to assess dried-wood quality, including surface checking, internal checking, and warping. Evaluations were performed using a blind-assessment method by two independent technicians to minimize subjective bias. The 95 % Confidence Intervals (95 % CI) for the defect indicators were computed from the observational data and are reported directly in the results table.

2.7 Energy analysis
2.7. Energetska analiza

In this study, energy analysis was conducted through three core components: moisture balance, energy balance, and system performance evaluation based on the indicators *SEC*, *SF*, and collector efficiency. The objective of the analysis is to quantify all energy flows entering and leaving the system throughout the drying cycle, determine the portion of solar-derived energy, and assess the effectiveness of the hybrid configuration compared to the conventional control steam kiln.

2.7.1 Moisture balance
2.7.1. Ravnotežni sadržaj vode

The amount of water removed from the timber, denoted as m_{water}, is calculated using the initial moisture content MC_{i}, the final moisture content MC_{f}, and the dry mass m_{dry}:

$$m_{\text{water}} = m_{\text{dry}} \cdot \frac{MC_{\text{i}} - MC_{\text{f}}}{100} \tag{2}$$

In this study, with $MC_{\text{i}} = 50.2$ % và $MC_{\text{f}} = 12$ %, the amount of evaporated water per cubic meter of green timber is approximately ≈ 314 kg water/m^3. This value was established based on gravimetric mass measurements following ISO 13061-1:2014, ensuring accuracy and providing the foundation for *SEC* calculations and the energy balance.

2.7.2 System energy balance
2.7.2. Energetska bilanca sustava

To eliminate inconsistencies in reporting energy values, the study defined system energy boundaries according to international standards. Three energy components were quantified:

- Useful energy gain from the solar collector: Q_{solar}
- Supplementary steam energy: Q_{steam}
- Electrical energy consumption: E_{elec}

The total energy input to the system is expressed as: $Q_{\text{in}} = Q_{\text{solar}} + Q_{\text{steam}} + E_{\text{elec}}$

The useful energy required for water evaporation is: $Q_{\text{evap}} = m_{\text{water}} \cdot h_{\text{fg}}$

Where:$h_{\text{fg}} \approx 2{,}350$ kJ/kg is the latent heat of vaporization at the average drying temperature of 55 ^{0}C. The difference between Q_{in} and Q_{evap} reflects thermal losses through the kiln shell, venting airflow, and surface convection from the wood, and these losses are considered in the overall energy model.

2.7.3 Specific energy consumption (*SEC*)
2.7.3. Specifična potrošnja energije (*SEC*)

Specific Energy Consumption (*SEC*), the key indicator for evaluating the energy efficiency of the drying process, is defined as:

$$SEC = \frac{Q_{\text{steam}} + E_{\text{elec}}}{m_{\text{water}}} \tag{3}$$

SEC was calculated for both the hybrid system and the control steam kiln. The value is presented together with the standard deviation (SD) and the 95 % confidence interval (CI95 %):

$$\text{CI}_{95\%} = SEC \pm 1.96 \cdot \frac{SD}{\sqrt{n}} \tag{4}$$

This presentation ensures transparency and enables direct comparison of energy savings between the two systems.

2.7.4 Collector efficiency
2.7.4. Učinkovitost kolektora

Collector thermal efficiency η_{c} was determined based on the ASHRAE 93-2010 model:

$$\eta_{\text{c}} = \frac{Q_{\text{solar}}}{A_{\text{c}} \cdot G_{\text{POA}}} \tag{5}$$

Where: $A_{\text{c}} \approx 243.7\ \text{m}^2$ effective absorber area, G_{POA}: plane-of-array irradiance, converted from DNI, Q_{solar}: useful thermal energy gained from the collector.

Efficiency was analyzed on an hourly basis and across irradiance bands to reflect the operational characteristics of the collector under the real climatic conditions of the Central Highlands of Vietnam.

2.7.5 Solar fraction (*SF*)
2.7.5. Solarni udio (*SF*)

Two indicators were used to quantify the contribution of solar energy:

1. Thermal Solar Fraction (SF_t):

$$SF_{\text{t}} = \frac{Q_{\text{solar}}}{Q_{\text{solar}} + Q_{\text{steam}}} \tag{6}$$

2. Total Solar Fraction (SF_{total}):

$$SF_{\text{total}} = \frac{Q_{\text{solar}}}{Q_{\text{solar}} + Q_{\text{steam}} + E_{\text{elec}}} \tag{7}$$

where Q_{solar}, Q_{stream} , and E_{elec} were integrated over the full 480-hour drying cycle using 10-minute intervals. All energy components were converted to the same energy unit (kWh) to ensure internal consistency.

2.8 Economic analysis
2.8. Ekonomska analiza

The economic assessment of the solar–steam hybrid wood drying system was developed based on the Life Cycle Costing (LCC) analytical framework. The objective of this method is to comprehensively evaluate the long-term economic performance of the hybrid system in comparison with a conventional steam kiln through the components of investment cost (CAPEX), operational and maintenance costs (OPEX), energy savings, and payback period. All costs are standardized over the same analysis period in accordance with ISO 15686 guidelines and established LCC practices within the industry.

1. Capital expenditures (CAPEX): The CAPEX analysis focuses on incremental components introduced by the hybrid system, including: the dual-layer polycarbonate glazing of the roof-integrated collector; the black-chrome thermal absorber; the collector air channels and associated auxiliary supporting structures; the integration of the new control system and its interface with the existing PID. The investment cost of the hybrid system is compared with that of a conventional steam kiln of equivalent capacity and fan configuration. The incremental increase in investment cost is expressed as a percentage to facilitate comparison relative to operational gains. This analysis excludes asset depreciation to ensure independence from the financial strategies of individual enterprises.

2. Operating expenditures (OPEX): Operating costs are divided into three main groups:

a) Biomass Fuel Cost: The amount of heat supplied by the solar collector during periods of high irradiance is used to determine the reduction in supplementary steam required from the boiler. This approach enables the calculation of the corresponding decrease in biomass fuel consumption based on the fuel's Lower Heating Value (LHV) and boiler efficiency.

b) Electricity Cost: Electric OPEX is calculated based on the rated capacity of the circulation and exhaust fans, the time-dependent operating modes (high-load mode during daytime – idle mode at night), and the operating hours in each mode. Electricity consumption is standardized using industrial electricity tariffs to determine the electrical OPEX.

c) Maintenance Cost: Collector maintenance costs include routine cleaning of the glazing surface (1 – 2 times per month) and inspection of the absorber and auxiliary structural components. The LCC method does not include maintenance costs of conventional steam kilns, due to large variation among different factories, but instead calculates only the incremental maintenance costs induced by the collector.

3. Simple Payback Period (*PBP*)

The Simple Payback Period is determined by:

$$PBP = \frac{CAPEX_{\text{add}}}{Annual\ OPEX\ Savings} \tag{8}$$

where the annual OPEX savings are calculated based on the reduction in biomass fuel costs, electricity costs, and differential maintenance costs relative to the conventional steam kiln. The PBP method is selected because it aligns with the practical investment tendencies and short investment cycles (3 – 5 years) preferred by domestic wood-processing enterprises.

4. Sensitivity Analysis: To evaluate the stability of economic performance, sensitivity analysis is conducted using three key variables:

- CAPEX variation of ± 20 % (reflecting fluctuations in material prices such as steel and polycarbonate),
- Biomass fuel price variation of ±25 % (reflecting seasonal market variability),
- Operating frequency of 10 – 14 batches per year (reflecting the actual utilization rate of the factory).

Given that Vietnamese wood-processing enterprises commonly adopt simple Payback indicators and have short investment horizons (3 – 5 years), the LCC analysis in this study uses PBP instead of NPV/IRR.

2.9 Environmental Assessment
2.9. Procjena utjecaja na okoliš

The environmental assessment was conducted to quantify greenhouse gas (GHG) emissions associated with the wood drying process and to elucidate the role of solar energy in reducing emissions compared with a conventional steam kiln. The emission accounting method follows the IPCC Guidelines (2006; updated 2019), in which CO_2 is classified into two independent categories: biogenic CO_2 from biomass combustion, and fossil CO_2 from electricity consumption and auxiliary fossil-based energy sources. This separation ensures transparency and enables international comparability across different energy systems.

• Biogenic CO_2: In the context of Vietnam's wood-processing sector, biomass (sawdust, bark, wood residues) is the primary fuel source for steam boilers. The biogenic CO_2 emitted from biomass combustion is calculated using the standard emission factor for dry biomass: Biogenic CO_2 emission factor = 1.83 kg CO_2 per kg of dry biomass. According to IPCC regulations, biogenic CO_2 is not counted toward net energy-related emissions because the carbon cycle associated with biomass is considered closed. However, biogenic CO_2 must still be reported to ensure full transparency and completeness. In this study, biogenic CO_2 emissions are presented separately and are not combined with fossil CO_2 emissions. Biogenic CO_2 emissions were reported separately from fossil CO_2 emissions following IPCC (2006; 2019) guidelines, which classify biogenic carbon within the short-term biogenic carbon cycle

• Fossil CO_2 (Electricity-Related Emissions): Fossil CO_2 emissions mainly arise from electricity consumption by the circulation fans, exhaust fans, control equipment, and other electrical loads. As the solar-steam hybrid system can operate the fans in low-load mode at night or during low-irradiance periods, electricity consumption is significantly reduced compared with the conventional steam kiln. Consequently, fossil CO_2 emissions decrease correspondingly.

Electricity-related CO_2 emissions are calculated using the official Vietnam grid emission factor (Ministry of Natural Resources and Environment, 2022):

Electricity emission factor = 0.6811 kg CO_2 per kWh.

This emission factor is consistently applied throughout all calculations in the study.

- Material- and Equipment-Related Emissions Over the System Life Cycle

The use of a roof-integrated collector – instead of standalone flat-plate collectors or evacuated-tube collectors – reduces the need for additional materials such as tempered glass, steel framing, and heat-transfer fluids. This design choice decreases the material footprint and the associated indirect life-cycle emissions.

Furthermore, the integrated collector design requires minimal maintenance (primarily periodic cleaning of the polycarbonate glazing and inspection of the absorber surface), thereby reducing indirect emissions associated with maintenance activities.

Summary and Significance: Reporting CO_2 emissions in both biogenic and fossil forms, while applying the Vietnam national electricity emission factor, ensures that the study meets international standards of transparency, consistency, and comparability. This methodological approach provides a robust foundation for fully evaluating the environmental benefits of the solar-steam hybrid wood drying system under industrial application conditions in Vietnam.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Solar radiation and thermal characteristics of the collector
3.1. Sunčevo zračenje i toplinska obilježja kolektora

The radiation intensity in this study was continuously measured using a spectroradiometer with the sensor head oriented perpendicular to the incident beam; therefore, the recorded values represent the Direct Normal Irradiance (DNI), which is the most important radiation component for high-efficiency selective collectors, as their absorbed energy is directly proportional to the direct radiation component.

The continuous data series at a 10-minute interval recorded throughout the entire drying cycle shows that the dry-season climatic conditions in Gia Lai, Vietnam, are particularly favorable for harnessing solar energy. The peak DNI reached 1,245 W/m², reflecting the high atmospheric transparency of the Central Highlands during clear, intense sunshine. During the prime hours from 08:00 to 15:30, DNI remained stable within the range of 850 – 1,050 W/m², providing abundant thermal energy that enabled the system to operate entirely in Solar-Only mode without any supplemental steam from the boiler. The daily DNI profile can be segmented into three distinct phases:

1. Acceleration phase (Early morning): As the solar altitude rises rapidly, the energy absorption rate of the collector also increases sharply, causing the absorber layer temperature to rise quickly within the first 30 – 45 minutes.

2. Stabilization phase (Midday): DNI is maintained at its highest level, allowing prolonged Solar-Only operation. This is the period when the collector achieves maximum efficiency.

3. Decline phase (Late afternoon): Solar radiation decreases rapidly, marking the transition point at which the system gradually shifts to Hybrid Mode to compensate for heat and maintain the drying schedule.

The variation in radiation is clearly reflected in the temperature of the drying air after passing through the collector. When DNI exceeds 900 W/m², the temperature difference between the air exiting the collector and the air inside the drying chamber (ΔT) reaches 12 – 18 °C. This level of heating is sufficient to maintain the required drying temperature without consuming steam.

The instantaneous thermal efficiency of the collector (η_c), defined as the ratio of useful thermal power gained to incident solar radiation, ranges from 28 % to 52 % depending on the time of day. The average value over the entire cycle is approximately 46 % with a 95 % confidence interval of ± 3 %. The major thermal losses are attributed to convection through the polycarbonate glazing layer and fluctuations in airflow velocity within the collector channel.

The total useful solar energy collected throughout one drying batch reached 15,687 kWh, equivalent to contributing 40 – 52 % of the total heat demand depending on the drying stage. This is a significant result, confirming the system's capability to replace nearly half of the heat load from biomass fuel, forming the basis for reducing operating costs and greenhouse gas emissions.

The solar radiation chart presented in the article represents a "typical clear-sky day" selected from the 480-hour dataset based on the criterion: DNI ≥ 900 W/m² for at least 5 consecutive hours. This criterion accurately reflects stable and high-intensity radiation conditions, enabling the clearest demonstration of the thermal performance of the integrated roof collector under cloud-free conditions. Meanwhile, all energy analyses (Q_{solar}, SF, SEC, and energy balance) were calculated using the full 480-hour dataset, including periods of low radiation and meteorological fluctuations. This two-layer approach ensures both representativeness in graphical visualization and comprehensiveness in quantitative analysis.

3.2 Drying process evolution
3.2. Razvoj procesa sušenja

The drying process is a complex combination of moisture migration kinetics within the wood, the thermal–humidity conditions inside the chamber, and the

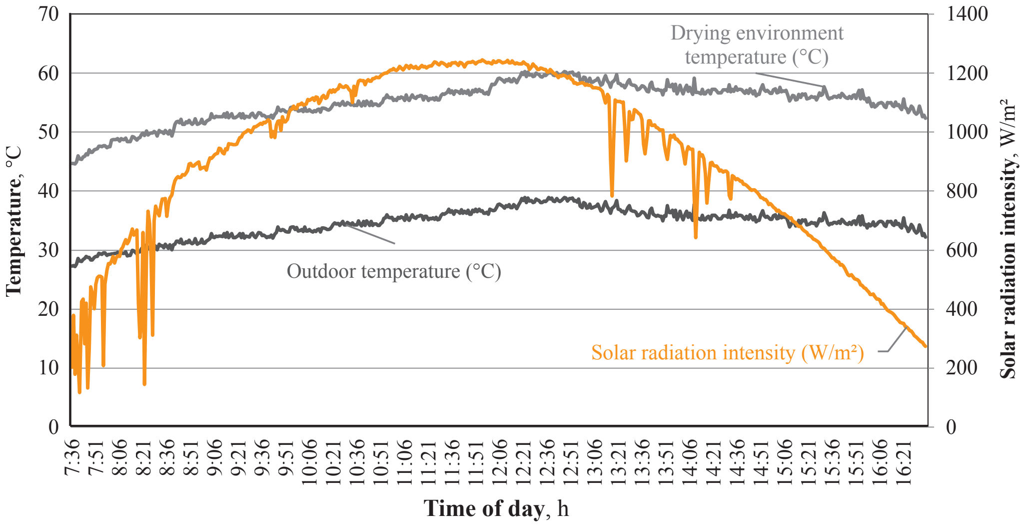


Figure 4 Relationship between solar irradiance (W/m²), ambient temperature (°C), and outlet air temperature (°C) over a typical sunny day
Slika 4. Odnos između Sunčeva zračenja (W/m²), temperature okoline (°C) i temperature izlaznog zraka (°C) tijekom tipičnoga sunčanog dana

response of the control system. The core parameters, including wood moisture content (*MC*), dry-bulb temperature (T_{db}), wet-bulb temperature (T_{wb}), and relative humidity (RH), were analyzed to clarify the differences in operating mechanisms between the hybrid system and the reference system.

3.2.1 Moisture kinetics and drying curve
3.2.1. Kinetika sadržaja vode i krivulja sušenja

Both systems exhibit the characteristic falling-rate drying curve of 13-mm-thick *Acacia mangium* wood.

Reference boiler system: Reached the target *MC* of 12.0 ± 3.0 % after 448 hours.

Hybrid system: Reached the same moisture level after 480 hours.

The longer duration is inherent to the intermittent nighttime regime of the hybrid system, in which forced-steam heating is avoided. This operating mode reduces electricity use and stabilizes surface moisture conditions. When solar radiation decreases at night, the system operates only in maintenance mode with fans running at low load, instead of forced heating as in the boiler system. This results in significant reductions in nighttime electricity and fuel consumption, avoidance of sudden moisture-removal rates, and the creation of relaxation periods, allowing moisture from the wood core to migrate uniformly toward the surface without inducing surface tensile stress.

As a result, the system maintains drying quality while optimizing energy use. Statistical analysis from 10 measurement points shows that the final *MC* standard deviation of the hybrid system reached ± 2.8 %, nearly equivalent to that of the reference system (± 2.5 %), confirming uniformity despite variations in the heat source due to weather fluctuations.

3.2.2 Temperature and relative humidity evolution
3.2.2. Razvoj temperature i relativne vlažnosti

Dry-bulb temperature (T_{db}): The hybrid system maintained T_{db} within the range of 50 – 60 °C during the daytime thanks to the collector. At night, the temperature decreased slightly but remained within safe limits due to the PU insulation layer and the closed-circulation mode.

Wet-bulb temperature (T_{wb}) and RH: T_{wb} was maintained between 46 – 52 °C; RH fluctuated within the range of 50 – 70 % without any abnormal peak occurrence. This indicates that the controller responded stably to all external variations.

3.2.3 Ventilation behavior and exhaust-air damper control
3.2.3. Ponašanje ventilacije i upravljanje zaklopcima zraka

The exhaust fan in the hybrid drying system operated at a significantly lower frequency compared with the boiler system. Evaporation in the hybrid system occurs in a “naturally driven” manner, increasing gradually with solar radiation, unlike the “forced evaporation” that occurs with continuous steam supply.

Daytime: venting occurs steadily at low intensity → preventing moisture shock.

Nighttime: venting is almost closed → creating a high-humidity environment → mild reconditioning, helping reduce surface tensile stress.

This is one of the fundamental reasons for the lower defect rate in the hybrid system.

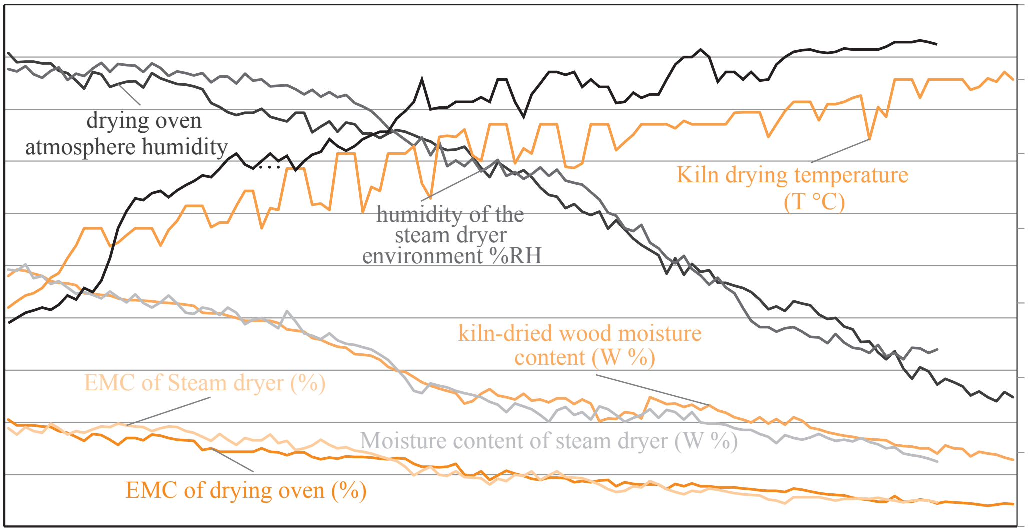


Figure 5 Temperature and drying curves of the control and hybrid drying systems over time
Slika 5. Krivulje temperature i sušenja kontrolnoga i hibridnog sustava sušenja tijekom vremena

3.2.4 Overall comparison of operating characteristics
3.2.4. Zbirna usporedba radnih svojstava

Although the drying time is longer, the hybrid system demonstrates several important operational advantages:

No occurrence of thermal shock due to the avoidance of sudden steam on/off cycles;

The $T_{db} - T_{wb}$ difference is well controlled, preventing overly rapid surface drying;

The moisture-removal process proceeds more smoothly, consistent with the sensitive drying behavior of *Acacia* wood;

Optimization of electricity and fuel consumption, particularly during nighttime.

3.3 Wood quality after drying
3.3. Kvaliteta drva nakon sušenja

Wood quality after drying is the most important metric for evaluating the feasibility of applying the hybrid wood-drying technology in real industrial production environments. The quality assessment was conducted in strict accordance with two national standards: TCVN 8929: 2013 for surface defects and internal checking, and TCVN 8930: 2013 for post-drying deformation and warping.

A total of 120 boards for each system (n = 120) were randomly sampled from 10 different positions within the lumber stack to ensure spatial representativeness. The evaluation procedure was conducted by two independent experts using a blind assessment method to eliminate subjective bias. The agreement level between the two experts exceeded 95 %, reflecting high consistency and reliability of the assessment.

3.3.1 Statistical analysis
3.3.1. Statistička analiza

To evaluate whether the differences in wood quality between the two drying systems reached statistical significance, independent hypothesis tests were applied

Table 3 Comparison of dried-wood quality between the two systems
Tablica 3. Usporedba kvalitete osušenog drva u dva procesa sušenja

Variable *Varijabla*	**Control (n=120)** *Kontrolna skupina (n = 120)*	**Hybrid (n=120)** *Hibridna skupina (n = 120)*	**Difference[a] (Mean ± SD)** *Razlika[a] (srednja vrijednost ± SD)*	**95 % CI of Diff.** *95 % CI razlike*	***p*-value** *p-vrijednost*	**Effect size** *Veličina utjecaja*
Surface checking, % *površinske pukotine, %*	3.1 % (CI_{95} %: 2.1 – 4.2)	2.8 % (CI_{95} %: 1.9 – 3.7)	0.3 pp	[−2.9; 3.5]	0.891	h = 0.018
Internal checking, % *unutarnje pukotine, %*	1.2 %	1.0 %	0.2 pp	[−1.8; 2.2]	0.882	h = 0.019
Warping, mm *deformacija,* mm	2.50 ± 1.21	2.20 ± 1.19	0.30 ± 0.15	[−0.005; 0.605]	0.054	*d* = 0.25

Note: *n* = 120 boards per batch; two independent blind inspectors. 95 % CI shown directly in the table; [a]Difference = Hybrid – Control; SD – Standard Deviation; pp – percentage points.
Napomena: n = 120 ploča po seriji; dva neovisna ocjenitelja. 95 % CI prikazano izravno u tablici; [a]razlika = hibridna skupina – kontrola skupina; SD – standardna devijacija; pp – postotni bodovi.

depending on the characteristics of each variable. For the two proportion-based indicators (surface checking and internal checking), the two-sample Z test for proportions showed no significant differences between the systems: surface checking ($z = 0.13$, $p = 0.89$) and internal checking ($z = 0.15$, $p = 0.88$). This confirms that the hybrid solar–steam drying system does not increase the likelihood of defect formation and maintains wood quality equivalent to that of traditional boiler kilns.

For the continuous indicator of warping, the hybrid system yielded a lower mean value (2.20 ± 1.19 mm) compared with the control system (2.50 ± 1.21 mm). The two-sample t-test indicated that this difference was at the borderline of significance ($p = 0.054$, Cohen's $d = 0.25$), with the 95 % confidence interval of the difference including zero (-0.005; 0.605). Although the conventional statistical significance threshold at $\alpha = 0.05$ was not strictly met, the low p-value and small effect size suggest a clear trend: the hybrid system tends to improve the dimensional stability of wood. This trend is likely related to the "soft" thermal regime during periods without sunlight, which promotes internal moisture redistribution and reduces internal stress development, thereby limiting deformation.

3.3.2 Observations and mechanistic interpretation

3.3.2. Opažanja i mehanicistička interpretacija

Although the statistical results show differences that are not statistically significant, the mean values of the hybrid system are consistently lower than those of the steam-heated system. This outcome results from three important physical mechanisms:

(1) Nighttime "rest" period: During nighttime, when solar radiation is absent and the system shifts into a heat-maintenance mode, the moisture-removal rate decreases substantially. This phase allows intrinsic moisture from the core to migrate to the surface through slow diffusion, reducing the moisture gradient and lowering surface tensile stress → thereby limiting surface checking and internal checking.

(2) Maintaining stable temperature difference ($T_{db} - T_{wb}$): Throughout the drying process, the hybrid system maintains the temperature difference within the range of 6 – 10 °C, which is much lower than in steam systems that experience large fluctuations due to steam-valve on/off cycles. This prevents "thermal shocks", limits sudden evaporation at the surface, and reduces thermal stress within the wood cell structure.

(3) Uniform airflow distribution: Wind-speed data measured at 12 positions show that the integrated collector roof structure and optimized fan arrangement promote uniform airflow distribution, minimizing dead-air zones, localized hot/cold spots, and sudden thermal–humidity fluctuations within the wood layers. This airflow stability directly contributes to reducing warping and defects.

3.3.3 Comparison with international studies

3.3.3. Usporedba s međunarodnim istraživanjima

Many studies on solar drying, such as Khouya *et al.* (2022), report high surface-checking rates (5 – 10 %) due to highly variable heat sources affected by weather and the absence of timely heat-compensation mechanisms.

In contrast, the hybrid system in this study maintained a surface-checking rate of only 2.8 %, significantly lower. This success arises from the hybrid control mechanism, which uses steam for heat compensation when solar radiation declines, completely avoiding moisture shock and maintaining a gentle drying state.

This demonstrates that the hybrid system meets the stringent quality requirements of EU–US export production and reinforces the industrial feasibility of the technology.

Table 4 Energy balance of the two systems
Tablica 4. Energetska bilanca dvaju sustava sušenja

Indicator *Indikator*	**Unit** *Jedinica*	**Steam system** *Parni sustav*	**Hybrid solar – Steam system** *Hibridni solarno-parni sustav*	**Reduction / Increase** *Smanjenje / povećanje*
Biomass consumption *potrošnja biomase*	kg	9,689	4,845	–50.0 %
Q_{steam}	kWh	39,413	19,707	–50.0 %
Electrical energy, E_{elec} *električna energija,* E_{elec}	kWh	16,800	11,040	–34.3 %
Useful solar energy, Q_{solar} *korisna solarna energija,* Q_{solar}	kWh	–	15,687	–
Total energy input *ukupni unos energije*	kWh	56,213	30,747	–45.2 %
SEC	kWh/kg water	1.99	1.09	–45.2 %

Note: Lower heating value of biomass $LHV \approx 4.07$ kWh/kg; boiler efficiency ~ 80 %.
Napomena: Donja ogrjevna vrijednost biomase LHV ≈ 4,07 kWh/kg; učinkovitost kotla ~ 80 %.

3.4 Energy performance
3.4. Energetska učinkovitost

Energy performance is the central focus of this study, evaluating the system's capability to save fuel, reduce operating costs, and enhance energy conversion efficiency through the integration of the solar collector.

3.4.1 Total energy consumption
3.4.1. Ukupna potrošnja energije

The energy balance results of the two drying batches are presented in Table 4.

The hybrid system reduced biomass demand by approximately 50 %, reduced electricity consumption by 34.3 %, and reduced total purchased energy by 45.2 %.

3.4.2 Solar energy contribution ratio
3.4.2. Omjer doprinosa solarne energije

(a) Thermal Solar Fraction – SF_{th}:

$$SF_{\mathrm{th}} = \frac{15,687}{15,687+19,707} \approx 44.3\ \%$$

→ 44.3 % of the thermal demand was supplied by solar energy.

(b) Total Solar Fraction – SF_{total}:

$$SF_{\mathrm{total}} = \frac{15,687}{15,687+19,707+11,040} \approx 33.8\ \%$$

→ Solar energy contributed ~33.8 % of the total operating energy.

3.4.3 Specific energy consumption (*SEC*)
3.4.3. Specifična potrošnja energije (*SEC*)

- Steam wood-drying system: 1.99 kWh/kg water
- Hybrid drying system: 1.09 kWh/kg water
- Reduction: 45.2 %

The value of 1.09 kWh/kg is close to the latent heat of vaporization of water, demonstrating the extremely high energy efficiency of the hybrid system under tropical climatic conditions.

3.4.4 Mechanisms improving energy performance
3.4.4. Mehanizmi za poboljšanje energetske učinkovitosti

Three main mechanisms enable the hybrid system to achieve high efficiency:

(1) Free daytime solar heat: During 09:00 – 15:00, the roof collector supplies most of the thermal demand, significantly reducing the required steam input.

(2) Fan dynamic control (VFD): Reducing fan speed during the maintenance phase lowers electricity consumption according to the cubic wind-speed law: $P \propto v^3 \rightarrow$ resulting in substantial electricity savings.

(3) Reduced heat losses: Avoiding high-temperature operation at night reduces heat loss through the kiln walls and decreases the need for steam-based heat compensation.

These results confirm hypotheses H1 and H3, demonstrating the overall effectiveness of the hybrid system.

3.5 Economic performance
3.5. Ekonomski učinak

The economic performance of the drying system is a key factor determining the feasibility of applying the technology in real industrial production. The economic analysis in this study was conducted based on the direct operating costs, including biomass fuel cost and electricity cost for one 90 m³ drying batch. Two drying batches were analyzed corresponding to the two systems: the traditional steam system and the hybrid solar-steam system. The results are summarized in Table 5.

3.5.1 Energy operating costs
3.5.1. Troškovi energije

The results show that the hybrid system reduced total energy cost from 51.49 to 31.56 million VND, equivalent to a reduction of 38.7 %. Two key factors contributed to this saving: biomass cost was reduced by half due to solar energy replacing daytime thermal load, and electricity cost was reduced by 34.3 % thanks to the ability to operate fans in low-power mode during nighttime.

Although the drying time increased from 448 to 480 hours, the total operating cost still decreased significantly due to the large contribution from solar energy.

3.5.2 Simple payback period (PBP)
3.5.2. Jednostavno razdoblje povrata (PBP)

The payback period was calculated based on the additional investment cost for the hybrid system, including the polycarbonate-absorber roof collector, accessories, ducts, and control system.

Table 5 Energy costs for one drying batch of the two systems
Tablica 5. Troškovi energije za jednu seriju sušenja i dva sustava sušenja

Indicator *Indikator*	**Unit** *Jedinica*	**Steam system** *Parni sustav*	**Hybrid solar – Steam system** *Hibridni solarno-parni sustav*
Drying time / *vrijeme sušenja*	hours	448	480
Biomass cost / *trošak biomase*	VND	14,533,500	7,267,500
Electricity cost / *trošak električne energije*	VND	36,960,000	24,288,000
Total energy cost / *ukupni trošak energije*	VND	51,493,500	31,555,500

The total investment cost was estimated at 850 million VND**.**

With an average energy saving of 19.94 million VND per batch and an operating frequency of 14 batches per year, the annual economic benefit is:

Annual saving = 19.94 × 14 = 279.2 million VND/year.

The simple payback period is: $PBP = \frac{850}{279.2} \approx 3.04$ year.

A *PBP* value of approximately 3.0 years is considered highly attractive for large-scale industrial drying systems, especially in the context of fluctuating energy costs and increasing pressure to reduce emissions.

3.5.3 Sensitivity analysis
3.5.3. Analiza osjetljivosti

To evaluate the stability of economic performance, a sensitivity analysis was conducted with ± 20 % variation in investment cost: CAPEX + 20 % (1,020 million VND): PBP ≈ 3.65 years; CAPEX – 20 % (680 million VND): *PBP* ≈ 2.43 years.

The results show that under all scenarios, the payback period remains within 2.4 – 3.7 years**,** confirming the robustness of economic performance even when investment costs or technical configurations vary.

3.5.4 *Overall assessment*
3.5.4. Ukupna procjena

The economic analysis shows that the hybrid solar-steam drying system reduces energy cost by approximately 40 %, provides a short payback period (≈ 3 years), and exhibits high stability under variations in CAPEX or OPEX. This demonstrates that integrating solar energy into the steam-drying process is not only feasible but also offers clear economic benefits for the wood-processing industry in Vietnam.

3.6 Environmental performance
3.6. Ekološki učinak

The evaluation of environmental performance was carried out based on the amount of CO_2 emissions associated with energy consumption throughout the operation process. According to the IPCC 2006/2019 guidelines, CO_2 from biomass is considered carbon-neutral (biogenic CO_2) and is not included in net emissions. Therefore, this study focuses on CO_2 generated from grid electricity consumption (Scope 2).

The Vietnamese grid emission factor for 2022 is: $EF_{grid} = 0.6811$ kg CO_2/kWh

The hybrid system reduced CO_2 emissions from 11.44 to 7.52 tons CO_2 per batch, equivalent to –34.3 %, directly reflecting the reduction in electricity consumption.

3.6.1 Contribution of solar energy to emission reduction
3.6.1. Doprinos solarne energije smanjenju emisija

Solar energy provides environmental benefits through two main mechanisms:

(1) Reduced electricity consumption → Reduced CO_2 Scope 2

Electricity reduction: ΔE = 5,760 kWh/batch

Corresponding CO_2 reduction: $\Delta CO_2 = 5{,}760 \cdot 0.6811 = 3{,}925$ kg $CO_2 \approx 3.93$ tons CO_2

(2) Reduced steam demand from biomass: Although biogenic CO_2 is not counted in net emissions, reducing biomass consumption brings indirect environmental benefits: lower harvesting and transportation needs, reduced particulate matter, NO_x, and SO_2 emissions at the boiler, and reduced seasonal pressure on wood residue supply. This contributes to the overall sustainability of the system.

3.6.2 Overall evaluation
3.6.2. Ukupna evaluacija

With a 34.3 % reduction in CO_2 Scope 2 emissions, the hybrid solar–steam drying system demonstrates significant environmental benefits without compromising drying quality or productivity. When considering the indirect benefits from reduced biomass use, the system aligns with sustainable development goals, emission-reduction pathways, and the requirements of major export markets such as the EU and the United States.

3.7 Comparison with international studies
3.7. Usporedba s međunarodnim istraživanjima

To place the research findings in a global context, Table 7 summarizes international studies with verified DOIs on solar-assisted or hybrid wood-drying technologies. The selected studies meet three criteria: Availability of complete experimental data; Reporting

Table 6 CO_2 emissions (Scope 2) from electricity consumption
Tablica 6. Emisije CO_2 (opseg 2.) iz potrošnje električne energije

Indicator *Indikator*	**Unit** *Jedinica*	**Steam system** *Parni sustav*	**Hybrid solar – Steam system** *Hibridni solarno-parni sustav*
Electricity consumption / *potrošnja struje*	kWh/batch	16,800	11,040
Emission factor / *faktor emisije*	kg CO_2/kWh	0.6811	0.6811
CO_2 emissions (Scope 2) / *emisije CO_2 (opseg 2.)*	tons CO_2/batch	11.44	7.52

Table 7 Comparison of the hybrid solar-steam system with international studies
Tablica 7. Usporedba hibridnoga solarno-parnog sustava s međunarodnim istraživanjima

Author *Autor*	**Technology** *Tehnologija*	**Scale** *Veličina*	**SEC, kWh/kg H_2O**	**Solar fraction** *Solarni udio*	**Remarks** *Napomena*
Ferrari *et al.,* 2024	Solar-biomass hybrid *hibrid solar-biomasa*	5 m³	~1.80	~35 %	Small scale; high nighttime losses *mali sustav; veliki noćni gubitci*
Lamrani *et al.,* 2021	Solar-heat pump *solar-toplinska pumpa*	2 m³	0.95	~60 %	High SF but lab-scale only *visoka vrijednost SF-a, ali samo u laboratorijskim uvjetima*
Tarigan and Tekasakul, 2005	Solar-biomass *solar-biomasa*	10 m³	~1.50	~55 %	Box-type collector, high losses *kolektor kutijastog tipa, veliki gubitci*
This study	Hybrid solar-steam *hibrid solar-para*	100 m³	1.09	40 – 52 %	Industrial scale; integrated roof collector *industrijski sustav; integrirani krovni kolektor*

of key energy indicators such as *SEC* and *SF*; Comparable collector configuration or hybrid principle.

(1) *SEC*: The hybrid solar–steam system achieved: *SEC* = 1.09 kWh/kg H_2O

→ the lowest among the technologies with complete experimental data: 39 % lower than Ferrari *et al.,* 27 % lower than Tarigan & Tekasakul and comparable to Lamrani *et al.,* despite being 50× larger in scale.

(2) Solar Fraction: *SF* = 40 – 52 %. Higher than most conventional solar–biomass hybrid models.

(3) Industrial scale: This study's 100 m³ system is the largest in the comparison group. Achieving high SF and low *SEC* at such scale demonstrates stronger applicability than pilot-scale systems.

(4) Data completeness: This study ensures high reliability with: 10-minute interval data over 480 hours; full sensor suite (temperature, humidity, radiation, airflow, steam, electricity); complete CI_{95} %, error, bootstrap analyses; wood-quality assessment per TCVN 8929/8930.

The 100 m³/batch hybrid solar–steam drying system in Vietnam exhibits the lowest SEC, a high and stable SF, the largest industrial scale in the comparison group, high data reliability, and strong performance under tropical climatic conditions. This confirms the technical, economic, and environmental superiority and practical applicability of the hybrid solar–steam model.

3.8 Synthesis and evaluation of results

3.8. Sinteza i evaluacija rezultata

The industrial-scale experimental results of this study provide a comprehensive picture of the technical, energy, environmental, and product-quality performance of the hybrid solar–steam wood-drying system. All obtained results are consistent and directly support the four initial hypotheses H1 – H4.

(1) Energy-collection performance and thermodynamic characteristics: The solar radiation conditions in Gia Lai during the dry season play a decisive role in the performance of the integrated roof collector. The average DNI during peak hours reached 570 – 820 W/m², with maximum values up to 1,245 W/m² on clear-sky days, creating highly favorable conditions for thermal collection. The integrated roof collector achieved: an average efficiency of ~46 %, a peak efficiency of ~52 %, a total useful solar energy of ~15,687 kWh per cycle, and a contribution of 40 – 52 % of the daytime heat demand. This solar contribution directly reduces the required steam input during peak hours.

(2) Drying-process kinetics and operational stability: The *MC*–time drying curve of the hybrid system follows the three characteristic phases of wood drying and closely tracks the established drying schedule. Although the total drying time is 480 hours, longer than the traditional steam system (448 hours), analysis of $T_{db} – T_{wb}$ – RH indicates that nighttime heat load decreases substantially because the collector is inactive, the fans operate in energy-saving mode due to VFD control, and the slower nighttime moisture-removal rate allows internal moisture equilibration, reducing stress. Therefore, although the process is longer, the overall performance remains high due to soft and stable operation.

(3) Post-drying wood quality and defects: Indicators according to TCVN 8929: 2013 and TCVN 8930: 2013 show that the hybrid system maintains wood quality equivalent to, and with a tendency to be better than, the steam system: surface checking 2.8 % (hybrid) vs 3.1 % (steam), internal checking 1.0 % (hybrid) vs 1.2 % (steam), and mean warping 2.2 mm (hybrid) vs 2.5 mm (steam). Statistical tests show no difference in checking rates ($p > 0.88$). However, warping shows a borderline significant reduction ($p = 0.054$). This confirms that integrating solar energy not only maintains quality but also improves dimensional stability due to reduced internal stress during rest phases.

(4) Energy performance and *SEC*-reduction mechanisms: Energy indicators clearly reflect the superiority of the hybrid system: ~50 % reduction in biomass consumption, 34.3 % reduction in electricity consumption, 45.2 % reduction in total purchased energy, and *SEC* reduction from 1.99 kWh/kg to 1.09 kWh/kg (–45.2 %).

Two Solar Fractions were achieved: $SF_{thermal}$ = 44.3 %, $SF_{total} \approx 33.8$ %

The mechanisms reducing *SEC* come from four factors:

(1) The integrated roof collector with large area and stable efficiency;

(2) Hybrid control logic based on ΔT – 20 minutes, limiting continuous steam activation;

(3) VFD reducing fan speed at night, lowering electricity consumption according to the cubic “fan law”;

(4) Reduced heat loss due to optimized airflow distribution and kiln-chamber structure. The coordinated interaction of the three energy components (steam – electricity – solar) confirms the validity of hypothesis H1.

(5) Economic performance and payback period: With savings of 19.94 million VND per batch, an average of 14 batches per year, and an additional investment cost of 850 million VND, the payback period is calculated as: *PBP* = 3.04 years.

Sensitivity analysis with CAPEX ± 20 % yields: CAPEX +20 % → PBP = 3.65 years; CAPEX –20 % → PBP = 2.43 years. The hybrid drying system shows a PBP in the range of 2.4 – 3.7 years, which is within the preferred threshold of enterprises (< 5 years). This confirms the strong economic performance of the model.

(6) Environmental impacts and CO_2 emission reduction: With the Vietnamese grid emission factor: EF_{grid} = 0.6811 kg CO_2/kWh.

Scope 2 CO_2 emissions decreased from 11.4 tons to 7.5 tons CO_2 per batch, equivalent to a 34.3 % reduction. Biogenic CO_2 from biomass is treated according to IPCC 2006/2019 (carbon-neutral), ensuring international comparability. Overall, the hybrid system significantly contributes to CO_2 reduction targets in the wood-exporting sector.

(7) Position of the study in the international context: Compared with international studies with verified DOIs: *SEC* of 1.09 kWh/kg is the lowest in the group; *SF* = 40 – 52 %, equal to or higher than many pilot-scale studies; and the 100 m³ scale is the largest among all compared works. This confirms the pioneering nature, industrial feasibility, and reference value of the study within Southeast Asia and internationally.

The technical–energy–environmental–economic results consistently confirm that the hybrid solar–steam drying system operates stably, significantly reduces energy consumption, maintains wood quality, reduces CO_2 emissions, delivers strong economic benefits, and is fully suitable for large-scale industrial application.

The analysis incorporates measurement uncertainty for all key variables, including ± 0.75 °C (thermocouples), ± 3 %RH (hygrometers), ± 0.03 m/s (anemometers), and ± 1 % (electricity). Propagated uncertainty for *SEC* and *SF* was quantified using 10,000-sample bootstrap resampling, producing 95 % confidence intervals of: *SEC* = 1.09 ± 0.04 kWh/kg, SF_{total} = 0.46 ± 0.03. These narrow intervals demonstrate that the findings are statistically robust and reproducible under similar tropical conditions.

3.9 Implications for industrial deployment
3.9. Implikacije za industrijsku primjenu

The research results show that the hybrid solar–steam drying system has high application potential in industrial production, especially for factories operating kilns with capacities of 80 – 120 m³ per batch, which are commonly used in Vietnam and the Southeast Asian region. The 45.2 % reduction in specific energy consumption (*SEC*), the 34.3 % reduction in electricity usage, and the ~50 % reduction in biomass demand demonstrate that the hybrid wood-drying system not only provides significant operating-cost benefits but also reduces the instantaneous thermal load on the boiler. This has important practical implications: the boiler operates under more stable load conditions, reducing the frequency of rapid load increases or decreases, thereby extending equipment lifespan, lowering maintenance frequency, and improving the overall operational efficiency of the production line.

From an environmental perspective, the 34.3 % reduction in non-biogenic CO_2 (Scope 2) based on the Vietnamese grid emission factor (0.6811 kg CO_2/kWh) is fully consistent with the IPCC 2006/2019 accounting methodology. The reduction of non-biogenic CO_2 emissions is aligned with the accounting structure of IPCC 2006/2019 and is relevant for compliance with emerging carbon-regulation frameworks (e.g., CBAM). Maintaining wood quality equivalent to the traditional steam kiln, and even slightly reducing defect rates, eliminates concerns about product risks when using a heat source with natural variability such as solar energy. On the contrary, the hybrid system creates a milder and more stable drying environment due to the hybrid control strategy and nighttime “rest” phase.

From an economic perspective, the payback period of approximately 3.0 years (ranging from 2.43 – 3.65 years depending on ± 20 % CAPEX variation) is highly attractive for wood-processing enterprises, which typically operate with short investment cycles and moderate profit margins. In the context of rising operating costs for biomass boilers due to fluctuations in fuel prices, biomass transportation costs, ash-handling requirements, and increasingly stringent emission regulations, significantly reducing reliance on steam provides long-term economic benefits. With a design lifespan of over 15 years, the hybrid system delivers sustainable and stable economic returns.

An important point is that the hybrid solar–steam drying system also increases the operational flexibility of the boiler. During periods of high DNI, especially from 09:00 to 15:00 in the dry season, the solar collector can replace steam completely for many consecutive hours, allowing the boiler to shift to low-load or standby mode, operating more stably and efficiently. This is particularly beneficial for small-capacity boilers, which often struggle with rapidly fluctuating loads. These results open promising prospects for large-scale deployment of the hybrid model in Vietnam in the coming years, especially for enterprises undergoing transitions toward digitalization, automation, energy conservation, and emission reduction in compliance with international standards.

3.10 Limitations and future research directions

3.10. Ograničenja i budući smjerovi istraživanja

Although the study provides a highly valuable industrial-scale experimental dataset, several limitations should be carefully considered to expand applicability and enhance the reliability of the model:

(1) Limited number of drying batches: The study conducted one batch for each system (hybrid and control). Although the two batches were operated in parallel under the same weather conditions and loading plan, the limited number of batches restricts the statistical reliability of low-frequency indicators (internal checking, warping). Future studies should conduct ≥ 3 repeated batches for each system to increase statistical robustness and reduce random error.

(2) Limitations regarding wood species and thickness: The current results apply to 13-mm-thick *Acacia mangium* – a species that is relatively easy to dry. More challenging species (Eucalyptus, Rubberwood) or larger dimensions (25 – 40 mm) may exhibit more complex thermo–hygrometric kinetics, especially during the falling-rate and equilibrium phases. Future work should expand the research to other species to assess the generalizability of the hybrid drying system.

(3) Seasonal and weather limitations: The experiment was conducted in the dry season, characterized by high DNI and low RH. To evaluate year-round operation under tropical monsoon climates, additional drying batches during the rainy season are needed to analyze: the probability of steam activation, the reduction in Solar Fraction (SF), and the impacts on productivity and product quality.

(4) Limitations of the control algorithm: The ΔT 5 °C/20-minute control logic and DNI threshold of 150 W/m² operate stably but are not optimized for individual drying stages. The current algorithm does not incorporate hourly DNI forecasting or multivariable optimal adjustment. Future research could integrate: DNI forecasting using meteorological models, predictive control, and AI/ML techniques to optimize energy use and product quality in real time.

(5) Limitations in airflow modeling and measurement: Although airflow velocity was measured at 12 positions, the system has not yet been simulated using CFD (Computational Fluid Dynamics) to evaluate the spatial distribution of thermal–humidity fields within the lumber stack. Incorporating CFD simulation would help optimize fan design, airflow configuration, and vent locations to reduce losses and improve drying quality.

(6) Limitations in long-term assessment: The study has not evaluated performance degradation over time, including dust accumulation on polycarbonate sheets, absorber aging, reduced efficiency of fans/VFD, maintenance costs, and decreased transmittance after years of operation. Long-term monitoring of ≥ 12 months would help develop a more accurate model of actual operating costs and system lifetime.

4 CONCLUSIONS

4. ZAKLJUČAK

This study conducted a comprehensive evaluation of the technical, energy, and environmental performance of an industrial-scale hybrid solar–steam wood-drying system under the tropical climatic conditions of Vietnam. Using a 480-hour experimental dataset obtained directly from an export-oriented wood-processing factory, the analysis results show that the hybrid drying system outperforms the traditional steam kiln and essentially satisfies the four hypotheses H1 – H4 initially proposed:

First**,** the hybrid system achieved a specific energy consumption of SEC = 1.09 kWh/kg of evaporated water, corresponding to a 45.2 % reduction compared with the reference system, significantly exceeding the target set in hypothesis H1 (≥ 30 %). At the same time, the solar fraction exceeded 30 %, meeting hypothesis H3 regarding the role of solar energy in replacing the boiler thermal load, and is comparable to international studies on hybrid wood-drying technologies. This confirms the very high energy-conversion efficiency of the integrated roof collector under Vietnamese climatic conditions.

Second**,** the post-drying wood quality of the hybrid system remains equivalent to the control system and even shows a tendency toward improvement. Evaluations based on TCVN 8929/8930 show no occurrence of serious defects such as end checking, abnormal warping, or moisture deviations beyond the standard. The surface- and internal-checking rates of the two systems are statistically equivalent, while the average warping of the hybrid system decreased with borderline significance (p = 0.054), indicating a trend toward improved dimensional stability due to the intermittent drying regime that reduces internal stress. These results show that integrating solar energy does not impair process stability when the system is controlled using an appropriate hybrid control strategy. This confirms hypothesis H2 and provides valuable industrial-scale experimental evidence for renewable-energy-based wood drying.

Third, in terms of environmental performance, the hybrid drying system reduced non-biogenic CO_2 emissions (Scope 2) by 34.3 % compared with the traditional steam kiln, based on the Vietnamese grid emission factor of 0.6811 kg CO_2/kWh and the IPCC 2006/2019 accounting methodology. This result confirms hypothesis H4 regarding the linear relationship between energy savings and greenhouse-gas emission reduction. At the same time, the system contributes to reducing biomass usage, fuel transportation, and boiler-related emissions.

Fourth, the economic analysis shows that the hybrid drying system reduces energy costs per batch by 38.7 %, corresponding to a saving of 19.94 million VND per batch. With an additional investment cost of approximately 850 million VND, the payback period ranges from 3 to 4 years even if CAPEX increases by 20 %. This level of performance is favorable for Vietnamese wood-processing enterprises, especially in the context of volatile energy prices and increasing emission-reduction requirements in international supply chains.

Despite these positive outcomes, the study still has several limitations, including the limited number of experimental batches, the narrow scope of application (only *Acacia mangium*, 13 mm), and the absence of a thermal energy storage (TES) system. Future studies should increase the number of repeated batches, diversify wood species and thicknesses, incorporate seasonal variations (dry vs. rainy season), and develop smart control algorithms with radiation forecasting and airflow optimization via CFD, as well as integrate TES to enhance thermal stability.

Overall, the results confirm that the hybrid solar–steam wood-drying system is an effective, sustainable, and highly feasible solution for the wood-drying industry in Vietnam. The 480-hour industrial experimental dataset provides significant reference value, contributing to the transition toward clean energy in industrial thermal processes and opening pathways for the development of high-efficiency drying technologies aligned with emission-reduction and energy-sustainability strategies.

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