

BIOECONOMY MOVES FORWARD: PERSPECTIVES ON WOOD PRODUCT MARKETS

INNOVATIVE TECHNOLOGIES USED IN ENERGY-EFFICIENT WOODEN CONSTRUCTION

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Why energy-efficient wooden construction?

Construction is a major source of energy use, emissions, resource consumption and waste.

- Timber is renewable and has carbon-sequestration potential.
- Wood-based construction can have lower embodied energy than conventional materials.
- Advanced materials and digital technologies can improve performance across the building lifecycle.
- Energy-efficient timber construction connects material innovation with low-carbon building strategies.

Lifecycle perspective

Design → manufacturing → construction → operation → demolition / reuse

Technology convergence

Engineered wood + prefabrication + BIM/AI + renewable energy

Research focus

How technological adoption relates to energy and sustainability performance

What is an Industrial Property Patent?

Definition: A legal title issued by a government authority that protects technical innovations, manufacturing processes, and functional products.

Core Rights: Gives the owner the legal monopoly to stop others from making, using, or selling the invention without permission for a limited time.

Classification: Part of industrial property, which falls under the broader umbrella of intellectual property (alongside trademarks, designs, and trade secrets).

Key Characteristics of Patents

Duration: Generally lasts for 20 years from the original filing date, subject to the payment of maintenance fees.

Requirements: To qualify, an invention must be novel (new to the world), involve an inventive step (non-obvious), and be industrially exploitable (capable of being made or used in any kind of industry).

Patent Allocation by Technology (IPC Composition)

Innovation Sub-Sector	Core Focus Area & Market Share	Key Technology Patented
Cross-Laminated Timber (CLT)	Dominates product-level filings, holding a 62.68% market share.	Layering techniques, panel prefabrication, and composite panel core variations.
Connections & Joints	Fastest growing technology sub-category.	Seismic-resilient brackets, concealed metal-to-timber connectors, and self-tapping screw configurations.
Fire Resistance & Adhesives	Accounts for roughly 90.91% of adhesive-bonded system patents.	Intumescent fire-retardant chemical coatings, char-rate engineering, and eco-friendly/bio-based polyurethane adhesives.
Hybrid Structural Systems	Rapidly expanding segment.	Timber-concrete composite (TCC) slabs and timber-steel hybrid framework patents.

Source: Yan, L.; Klingner, R.; Al-Qudsi, A.; Chen, H.; Dand, J.A. *Current Market Landscape and Industry Voices in Key Timber Construction Markets*. Buildings 2025, 15, 3381. <https://doi.org/10.3390/buildings15183381>

Geographic Distribution of Industrial Property

Patent density is highly uneven globally and is closely linked to regional forestry resources and sustainable development policies:

- **Europe:** Continues to lead both industrial property generation and market volume, capturing **over 54% of the global share**. Nations like Austria, Germany, Sweden, and Switzerland hold the highest concentration of historical and modern structural wood patents.
- **North America:** The fastest accelerator in new patent filings. Substantial investment from companies in the United States and Canada has followed local adoptions of "Tall Mass Timber" code amendments.
- **Asia-Pacific:** Representing the fastest-growing region for manufacturing implementation (boasting a **17.38% CAGR**), patent submissions from China and Japan targeting automated modular prefabrication have spiked significantly.

Innovation landscape in modern timber construction

1 | Engineered wood

CLT, Glulam, composite panels and hybrid systems improve structural strength, dimensional stability and material efficiency.

2 | Prefabrication

Off-site manufacturing, CNC milling and laser-guided measurement increase accuracy and reduce waste and construction time.

3 | Digital technologies

BIM supports planning, clash detection, lifecycle management and energy-performance simulation; AI supports optimization and quality control.

4 | Renewable energy

Integration of renewable energy is positioned as a pathway for improved energy performance and sustainability.

5 | Circularity

Design for disassembly, robotic separation and recycling can extend timber material lifecycles.

6 | Emerging directions

Nanocellulose, smart panels/PCMs, embedded sensors, robotic assembly and 3D printing.

Engineered Wood Products: a technological cornerstone

EWP

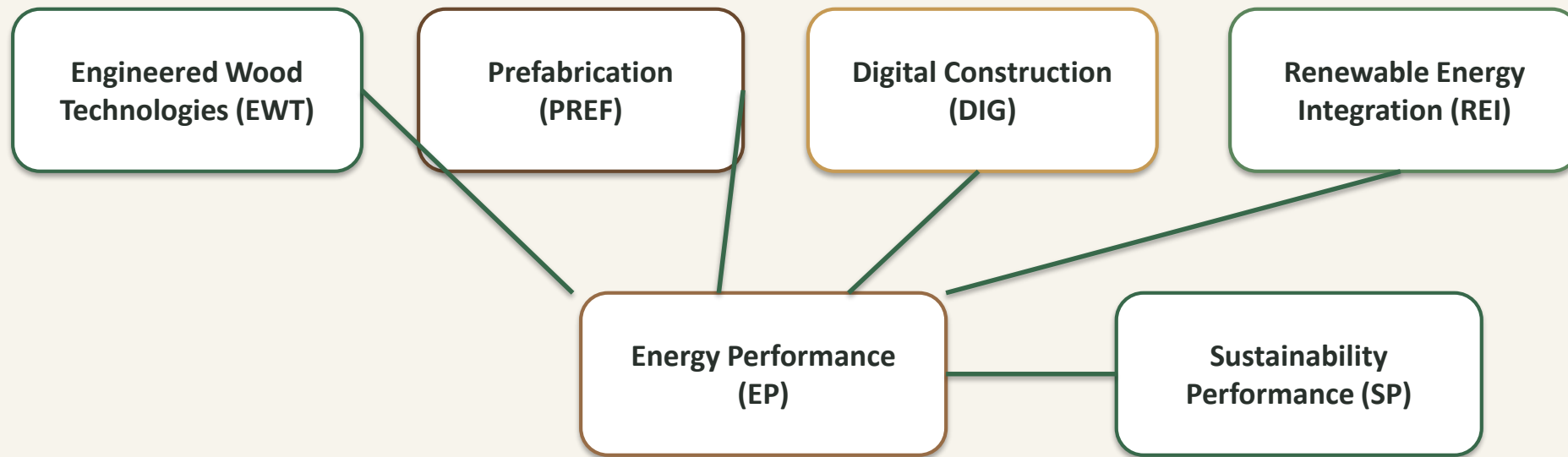
Innovation area	Primary objective	Technological impact
Cross-Laminated Timber (CLT)	Structural optimization	High
Composite wood panels	Material efficiency	High
Hybrid timber systems	Increased load capacity	High
Timber–concrete composites	Structural performance	Medium–High
Smart timber panels	Digital integration	Emerging
Structural connectors	Seismic resistance	High
Automated manufacturing	Productivity improvement	High
Lightweight timber panels	Material reduction	High

Patent activity is described as concentrated in North America, Europe, Japan and increasingly China.

Research aim and conceptual logic

Aim To examine the influence of innovative technologies on the energy performance of wooden buildings and their relationship with sustainability performance.

The manuscript proposes that technological innovation improves energy efficiency directly and through enhanced building performance.



Research methodology

METHOD

Design

Quantitative research design examining relationships among latent constructs.

Method

Structural Equation Modelling (SEM), implemented using SmartPLS 4 / PLS-SEM.

Measurement

30 questionnaire items on a 7-point Likert scale (1 = strongly disagree; 7 = strongly agree).

Target respondents

- Architects
- Structural engineers
- Construction managers
- Prefabrication manufacturers
- Energy consultants
- Researchers

Latent constructs

EWT

Engineered Wood Technologies

PREF

Prefabrication

DIG

Digital Construction Technologies

REI

Renewable Energy Integration

EP

Energy Performance

SP

Sustainability Performance

Sample statement in manuscript: 380 respondents were targeted; 250 observed applications were described as simulated for analysis.

Hypotheses H1–H8

HYPOTHESES

H1

EWT → Energy Performance
Positive influence

H2

Prefabrication → Energy Performance
Positive influence

H3

Digital Technologies → Energy Performance
Positive influence

H4

Renewable Energy Integration → Energy Performance
Positive influence

H5

Energy Performance → Sustainability Performance
Positive influence

H6

Digital Technologies → Prefabrication
Positive influence

H7

EWT → Renewable Energy Integration
Positive influence

H8

Technological innovation → Sustainability Performance
Indirect effect via Energy Performance

SEM structural model

MODEL

The structural equations specified in the manuscript:

Energy Performance

$$EP = \beta_1 EWT + \beta_2 PREF + \beta_3 DIG + \beta_4 REI + \varepsilon$$

Sustainability Performance

$$SP = \beta_5 EP + \varepsilon$$

Key variables

- EP = Energy Performance
- SP = Sustainability Performance
- EWT = Engineered Wood Technologies
- PREF = Prefabrication
- DIG = Digital Construction Technologies
- REI = Renewable Energy Integration
- β = standardized path coefficients; ε = error term

Interpretation

The model tests whether technology-related constructs explain energy performance and whether energy performance transmits technological effects to sustainability performance.

Measurement model assessment

Cronbach's Alpha

> 0.70
Internal consistency

Composite Reliability

> 0.70
Construct reliability

AVE

> 0.50
Convergent validity

Indicator Loadings

> 0.70
Indicator quality

VIF

< 3.3
Collinearity control

HTMT

< 0.85
Discriminant validity

The manuscript states that convergent validity is confirmed when loadings exceed 0.70 and AVE exceeds 0.50; discriminant validity is assessed using Fornell–Larcker and HTMT.

Structural model assessment and expected fit

ANALYSIS

β

Path coefficients

t

Test statistic

p

Significance; $p < 0.05$

R^2

Explained variance

Q^2

Predictive relevance

f^2

Effect size

Structural model assessment and expected fit

 β

Path coefficients

 t

Test statistic

 p Significance; $p < 0.05$ R^2

Explained variance

 Q^2

Predictive relevance

 f^2

Effect size

SRMR

Model fit

Recommended / expected thresholds reported in the manuscript

Cronbach's Alpha	> 0.70
Composite Reliability	> 0.70
AVE	> 0.50
HTMT	< 0.85
SRMR	< 0.08
R^2 – Energy Performance	> 0.50
R^2 – Sustainability Performance	> 0.60

Important: the manuscript presents these as expected/recommended criteria rather than reporting a full set of numerical empirical estimates.

Results and discussion: what the manuscript proposes

The manuscript's conclusion is framed around expected SEM findings rather than a detailed table of estimated coefficients.

Digitalisation

Expected to exert a significant positive effect on energy performance.

Engineered wood technologies

Expected to contribute positively to energy performance and enable sustainable structural solutions.

Prefabrication

Expected to support energy-efficient construction through precision, reduced waste and process efficiency.

Mediating role of EP

Improved energy performance is proposed as the mechanism linking technological innovation with sustainability performance.

No numerical β , t , p , R^2 or Q^2 values are reported in the manuscript; therefore the presentation does not invent or assign effect sizes.

Practical and strategic implications

IMPLICATIONS

For designers & engineers

Use BIM, engineered wood and energy-oriented design decisions early in the building lifecycle.

For manufacturers

Combine prefabrication, automated manufacturing and quality-control technologies to reduce waste and improve productivity.

For building projects

Consider renewable-energy integration alongside material and digital innovations rather than as isolated interventions.

For policymakers

The manuscript suggests that evidence on technology adoption can support the transition toward low-carbon buildings.

Overall strategic message

Technology convergence can be treated as a system: material innovation + manufacturing precision + digital intelligence + renewable energy.

Future directions for timber innovation

OUTLOOK

01

Intelligent structural health monitoring

02

AI-driven structural and energy optimization

03

Fully automated prefabrication and robotic construction

04

Carbon-negative building systems

05

Multifunctional and bio-inspired timber composites

06

Nanocellulose and smart timber materials

07

3D printing of wood composites

08

Integration with renewable energy technologies

The paper identifies convergence of digital manufacturing, material science and sustainable engineering as a major development direction.

Conclusions

- Energy-efficient wooden construction is increasingly shaped by advanced materials and digital technologies.
- Engineered wood products, prefabrication, BIM/AI and renewable-energy integration form the core technology set examined in the paper.
- The proposed SEM framework links technological adoption with Energy Performance and Sustainability Performance.
- Energy Performance is positioned as a potential mediator between technological innovation and sustainability outcomes.
- The approach provides a basis for evidence-informed technology adoption in low-carbon timber construction.

Core message

Sustainable timber construction is not only a material choice—it is a technology and management system spanning the whole building lifecycle.

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Full reference list: manuscript pp. 8–9.

„Polskie CLT” – Technologia płyt o podwyższonej odporności na ogień

Najbardziej rewolucyjnym projektem badawczo-wdrożeniowym w Polsce, realizowanym we współpracy z naukowcami z [SGGW \(Szkoły Głównej Gospodarstwa Wiejskiego w Warszawie\)](#), jest technologia produkcji **płyt konstrukcyjnych z klejonego krzyżowo drewna sosnowego o podwyższonej klasie reakcji na ogień.**

- **Czego dotyczy:** Pozwala na bezpieczne wznoszenie budynków drewnianych o wysokości **do 9 kondygnacji** (wcześniej w Polsce budowano obiekty maksymalnie 4-kondygnacyjne).
- **Innowacja:** Rozwiązanie to opiera się na rodzimym
- surowcu (sosna pospolita) i specjalnym procesie klejenia oraz impregnacji, co eliminuje problem rozprzestrzeniania
- ognia i spełnia rygorystyczne polskie przepisy przeciwpożarowe.



THANK YOU

Questions & Discussion

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