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# Revisiting the Climate Benefits provided by Wood through Future-Oriented Material and Energy Displacement

**Amelie Müller**

a.muller@cml.leidenuniv.nl

Institute of Environmental Sciences (CML), Leiden University, The Netherlands; Flemish Institute for Technology Research (VITO), EnergyVille, Belgium https://orcid.org/0000-0001-5609-5609

**Gustavo E. Martinez**

Flemish Institute for Technology Research (VITO), EnergyVille, Belgium https://orcid.org/0009-0004-9122-425X

**Pieter J. Verkerk**

European Forest Institute (EFI), Joensuu, Finland https://orcid.org/0000-0001-5322-8007

**Jeroen Guinée**

Institute of Environmental Sciences (CML), Leiden University, The Netherlands https://orcid.org/0000-0003-2558-6493

**Bernhard Steubing**

Institute of Environmental Sciences (CML), Leiden University, The Netherlands https://orcid.org/0000-0002-1307-6376

**Giuseppe Cardellini**

Flemish Institute for Technology Research (VITO), EnergyVille, Belgium https://orcid.org/0000-0003-0442-3580

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# Revisiting the Climate Benefits provided by Wood through Future-Oriented Material and Energy Displacement

*Amelie Müller*[*1,2], *Gustavo E. Martinez*[2], *Pieter J. Verkerk*[3], *Jeroen Guinée*[1], *Bernhard Steubing*[1], *Giuseppe Cardellini*[2]

1 Institute of Environmental Sciences (CML), Leiden University, The Netherlands

2 Flemish Institute for Technology Research (VITO), EnergyVille, Belgium

3 European Forest Institute (EFI), Joensuu, Finland

* corresponding author: a.muller@cml.leidenuniv.nl

## Abstract:

**Purpose:** Displacement factors (DFs) quantify climate benefits of wood-based products relative to non-wood alternatives. Existing DFs are typically static, focus on semi-finished materials, and lack harmonized, transparently documented modelling assumptions. Economy-wide decarbonization motivates a forward-looking assessment.

**Methods:** This study provides an open-access, unit-process-based database of future-oriented DFs for 81 wood-product-material-variants across six end-use categories. It uses time-explicit life cycle

assessment (LCA), which links each process to the technology landscape at the time it occurs, under three decarbonization scenarios for 2020–2070.

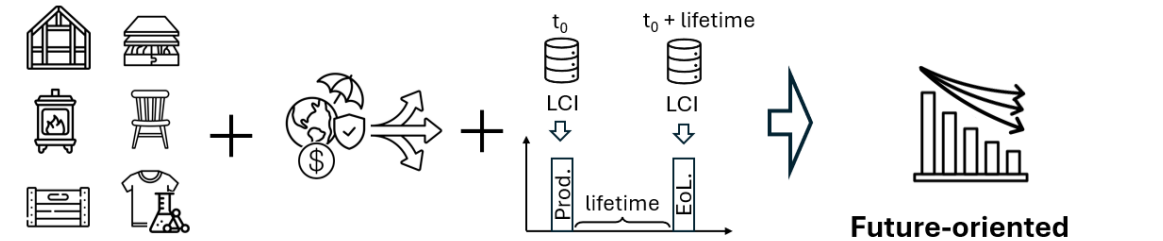
**Results:** Wood-based products showed positive DFs in 2020, with weighted averages ranging from near-zero for furniture to 1.04 kg C/kg C for chemicals and textiles, though generally lower than previous estimates. DFs declined over time for all products except chemicals, most steeply under climate-ambitious scenarios. Wood sustained the highest benefit in the least ambitious scenario. The DF decline was driven by faster decarbonization of non-wood products, which contain proportionally more fossil-intensive components. Time-explicit LCA yielded lower DFs for long-lived products as end-of-life processes were assigned to more decarbonized future years. Energy-related DFs approached near-zero by 2070.

**Conclusion:** The findings support redirecting wood flows from energy toward long-lived material applications and caution against harvest intensification justified on displacement arguments alone.

## Keywords:

Substitution, forest sector, harvested wood products, bio-economy, time-explicit

## Graphical Abstract




81 wood-based products in 6 end-use categories

3 climate mitigation pathways

Time-explicit LCA (2020 to 2070)

**Future-oriented displacement factors**
- Lower displacement over time
- Scenario-dependent
- Material > energy applications

# 1. Introduction

Forests play a dual role in climate change mitigation. They function as natural carbon sinks, while also providing low-carbon raw materials for the bioeconomy (Leskinen et al. 2018). Emission savings from wood-based products are commonly estimated using displacement factors (DFs), a metric that expresses the fossil greenhouse gas (GHG) emissions avoided when a wood-based product replaces a functionally equivalent non-wood alternative (Sathre and O'Connor 2010), often derived using comparative life cycle assessments (LCAs). Biogenic carbon is typically excluded from DFs, and reported separately, to avoid double-counting with forest carbon balances (Myllyviita et al. 2021). A growing body of studies has quantified DFs, finding that wood-based products tend to reduce fossil GHG emissions compared to non-wood alternatives (Leskinen et al. 2018; Myllyviita et al. 2021; Wedajo et al. 2025). Sathre and O'Connor (2010) found in an early meta-analysis across 21 studies an average DF of 2.1 kg C/kg C, Knauf et al. (2015) an average of 1.5 kg C/kg C for material displacement across 16 products and 0.67 kg C/kg C for energy displacement, Leskinen et al. (2018) an average of 1.2 kg C/kg C across 51 studies,

and Verkerk et al. (2022) a median of 0.9 kg C/kg C across 64 studies. For Canada, Smyth et al. (2017) found material displacement at 0.45 and 0.54 kg C/kg C for panels and sawnwood, respectively, and 0.47 to 0.89 kg C/kg C for energy displacement. For China, Geng et al. (2019a) found weighted average DFs of 3.48 kg C/kg C for construction and 1.36 kg C/kg C for furniture. Boiger et al. (2024) reported average DFs of 0.41 kg C/kg C for material and 0.37 kg C/kg C for energy substitution in Austria. These averages mask substantial variation across products and end uses. For example, the median of 0.9 kg C/kg C in Verkerk et al. (2022) comes with 95% of the values ranging between −1.1 and +5.2 kg C/kg C.

The existing DF literature is, however, subject to limitations. Coverage is skewed towards energy and construction applications, with limited data for emerging end-uses such as textiles and biochemicals (Myllyviita et al. 2021; Verkerk et al. 2022). Data robustness is a recurring concern. For example, 39% of studies reviewed by Hurmekoski et al. (2021) showed a major overlap in data sources, meaning that a large number of DF estimates rest on a much smaller number of truly independent data points. Because meta-reviews compile DFs from individual studies with varying system boundaries, allocation choices, and life cycle stages that are not always transparently reported, the resulting estimates are often neither directly comparable nor jointly applicable (Leskinen et al. 2018; Myllyviita et al. 2021; Verkerk et al. 2022). The common use of aggregate LCA results, without releasing the underlying Life Cycle Inventory (LCI) data, makes it difficult to adapt values to new contexts (Myllyviita et al. 2021; Wedajo et al. 2025). DFs are furthermore often reported at the level of semi-finished wood materials rather than final products (Knauf et al. 2015), where the actual displacement occurs (Smyth et al. 2017; Leskinen et al. 2018).

Given the long life cycles of wood-based products, an important shortcoming of existing DF studies is that they lack explicit consideration of temporal dynamics of impacts and benefits

(Beloin-Saint-Pierre et al. 2020). Although the importance of a forward-looking DF assessment has been emphasized (Myllyviita et al. 2021; Schulte et al. 2022; Boiger et al. 2024), most studies apply conventional, static LCA, capturing the current emission intensity of the systems, and apply these DFs unchanged across the entire study period. This static approach fails to reflect two distinct temporal dimensions. First, supply chains evolve over time, e.g. through economy-wide decarbonization, and these changes might affect supply chains of wood-based and alternative products differently. Second, the processes within a product's life cycle happen at different points in time: displacement effects due to production occur at the time of manufacture, while end-of-life (EoL) effects only arise once products reach the end of their service life, potentially decades later (Verkerk et al. 2022). At each of these times, the underlying technology landscape will have changed substantially.

Prospective LCA (pLCA) addresses the first of these two dimensions by modelling "the product system at a future point in time relative to the time at which the study is conducted" (Arvidsson et al. 2023), capturing how evolving supply chains and technological learning affect future environmental impacts (Thonemann et al. 2020). However, pLCA does not differentiate the timing of individual processes within the life cycle: production and EoL are modelled under the same future snapshot, regardless of when they actually occur. Time-explicit LCA (Müller et al. 2025) extends this by explicitly assigning each process to the time at which it occurs, combining pLCA with an explicit representation of process timing. This is particularly relevant for long-lived products, where production and EoL stages may unfold decades apart under substantially different technological conditions.

Only a few studies have applied future-oriented approaches to DFs, suggesting that the relative climate advantage of wood products erodes over time. The simplest approaches apply linear

scaling: Harmon (2019) scales whole DFs downward linearly over time, Myllyviita et al. (2022) apply linear emission reductions specifically to energy and concrete-related components, and Brunet-Navarro et al. (2021) scale DFs proportionally to sector-wide GHG reduction trajectories. Hurmekoski et al. (2020) model a decarbonization scenario in 2056, in which energy sector emissions are scaled down 80% compared to 2016 and only 20% of replaced energy would be fossil based. Yang et al. (2024a) provide the most methodologically advanced approach to date, applying prospective background LCI data under three climate scenarios for the years 2020 and 2050 using the premise package (Sacchi et al. 2022). However, they model only two discrete points in time without intermediate steps, and they apply the same LCI data to all processes, implicitly assuming no change in technologies between manufacture and disposal. To the authors' knowledge, no existing study addresses both temporal dimensions simultaneously at a fine temporal resolution.

The objective of this work is to assess the current and future climate change mitigation potential of wood-based products in Europe through a methodologically consistent open-access database of time-explicit DFs covering the period 2020–2070. The database spans a wide range of wood-based products and their functionally equivalent alternatives at the level of end uses, using detailed LCI data within a consistent LCA modelling framework. Applying time-explicit LCA provides a temporally granular picture of the displacement potential of wood-based products over time across future decarbonization scenarios.

# 2. Materials and methods

## 2.1. Goal and scope

This study quantified future-oriented DFs for global warming impacts (GWI) for wood-based products in the end-use categories primary and secondary construction, energy, furniture, packaging, textiles and chemicals. The functional unit was 1 kg C contained in the wood product. The study was attributional, using prospective versions of ecoinvent v3.11 (cut-off system model) (Wernet et al. 2016), modified with premise v2.3.8 (Sacchi et al. 2022) under three climate scenarios from the integrated assessment model (IAM) IMAGE (Stehfest 2014), described in Table 3. The geographical scope was European Union, defaulting to European process locations. A cradle-to-grave perspective was adopted (Figure 1), excluding the use phase given its small and uncertain contribution (Leskinen et al. 2018; Verkerk et al. 2022). We addressed multifunctionality from by-products, production waste treatment, and EoL processes using system expansion via substitution in both alternatives, consistent with existing DF studies (Leskinen et al. 2018). While conceptually more aligned with consequential LCA, we adopted this approach here to maintain comparability with the existing DF literature.

We modelled temporal dynamics using a time-explicit approach (Müller et al. 2025) at the LCI stage, with production modelled at 10-year intervals between 2020 and 2070 and EoL processes timed according to product lifetimes (Table 1, Section 2.3)

Our study excluded biogenic $CO_2$ fluxes using the life cycle impact assessment (LCIA) method "IPCC 2021, global warming potential (GWP100), climate change: total (excl. biogenic CO2)" (Smith et al. 2021), following the standard practice of reporting displacement effects and biogenic carbon balances separately (Myllyviita et al. 2021) to avoid double counting when combining DFs with forest ecosystem carbon balances (Leskinen et al. 2018). As the scope is on the product level,

market dynamics of displacement effects (Hurmekoski et al. 2021; Yang et al. 2024b) are excluded.

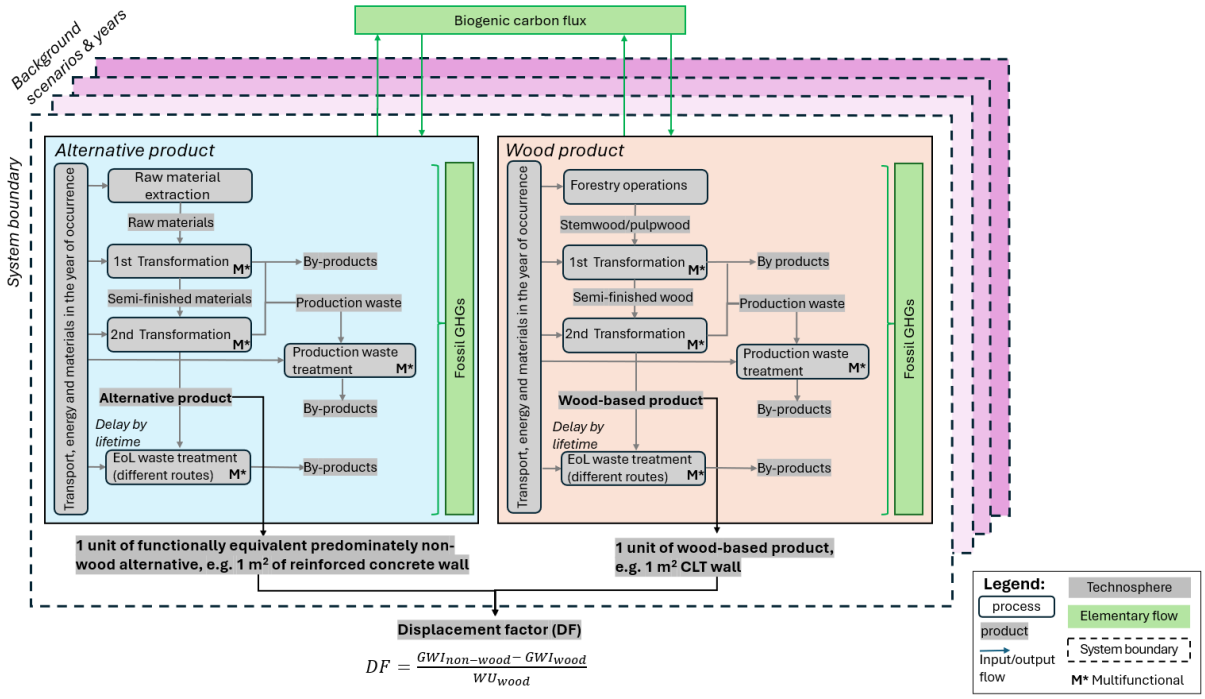



**Figure 1.** System boundaries of the study. DFs are calculated as the difference in Global Warming Impacts (GWIs) between functionally equivalent non-wood and wood-based products, scaled to the carbon content of the wood product. Time-explicit life cycle inventory modelling (Müller et al. 2025) is applied under three IMAGE scenarios (SSP1-L, SSP2-M and SSP3-H) (Stehfest 2014). Multifunctionality is solved via substitution.

## 2.2. Displacement factor

A DF describes the difference in fossil GHG emissions between a wood-based product and a predominantly non-wood alternative, relative to the difference in wood content between the wood-based and alternative product, with a positive value indicating lower impacts by the wood-based product (Leskinen et al. 2018). The values are relative, not absolute, as they reflect the difference between two product systems rather than stand-alone emission quantities. The term *substitution*

*factor* is sometimes used in literature, but it was avoided here to prevent confusion with the LCA concept of substitution (Section 2.1).

In this study, the DF was calculated as in Eq. 1:

$$DF_{Climate\ change} = \frac{GWI_{non-wood} - GWI_{wood}}{WU_{wood}} \quad (1)$$

Where:

DF - displacement factor in kg C avoided per kg C in wood product

$GWI_{wood}$ - global warming impacts of the wood-based product in kg C

$GWI_{non\text{-}wood}$ - global warming impacts of the non-wood product in kg C

$WU_{wood}$ - amount of wood contained in the wood-based product in kg C

Following Sathre and O'Connor (2010), many studies account for a potential wood content in the alternative product, which generally increases DFs. In line with Knauf et al. (2015), we did not, representing a conservative choice, relevant only for our furniture products where the alternative itself contains wood.

Two unit conversions were applied: (i) wood inputs reported at moisture content (10–20%) were converted to dry mass and multiplied by wood carbon content; for energy products, wood inputs were derived using lower heating values (LHV) of semi-finished products (Table S1); (ii) GWI results in kg $CO_2$-eq were converted to kg C using the stoichiometric factor 12/44.

## 2.3. Life cycle inventories

Our study comprised 26 wood products clustered into six end-use categories (Table 1), as identified by Orfanidou et al. (2026), but we grouped energy applications in one end-use category

instead of multiple. Where products can be manufactured from alternative semi-finished wood materials, either as mono-material variants using different wood types, or as composite products containing multiple wood materials, each was modelled as a separate mono-material variant containing a single semi-finished wood type, following Valada et al. (2016). Wood content was converted between semi-finished wood types based on total wood mass and densities given in Table S1, resulting in 81 wood product-semi-finished material variants (Table 1). A total of 31 non-wood alternatives was modelled.

To avoid products with many semi-finished material variants dominating aggregated results, end-use category DFs were calculated using a two-stage mean. The product-level mean $\bar{DF}_p$ (Eq. 2) averages across the $n$ material variants of product $p$, giving equal weight to each semi-finished material variant $v$. The end-use category mean $\bar{DF}_c$ (Eq. 3) then averages across the $m$ products within category $c$, giving equal weight to each product $p$.

$$\bar{DF}_p = \frac{1}{n} \sum_{v=1}^{n} DF_{v,p} \quad (2)$$

$$\bar{DF}_c = \frac{1}{m} \sum_{p=1}^{m} \bar{DF}_p \quad (3)$$

The spread of datapoints is reported using interquartile ranges (IQRs) and standard deviation across product means.

**Table 1**. Overview of studied products and their lifetimes.

| End-use category | Number of wood-based products in the category | Number of variants with different semi-finished wood materials | Number of alternative products | Lifetime of products in end-use category (years) | |
|---|---|---|---|---|---|
| | | | | Average | Max |
| Construction, primary | 6 | 13 | 7 | 50[a] | 86[a] |

| | | | | | |
|---|---|---|---|---|---|
| Construction, secondary | 7 | 20 | 11 | 33[a] | 78[a] |
| Energy | 4 | 13 | 3 | 1[a] | 2[a] |
| Furniture | 4 | 21 | 4 | 16[a] | 51[a] |
| Packaging | 2 | 9 | 2 | 3[a] | 4[a] |
| Chemicals & Textiles | 3 | 5 | 4 | 5[b] (textiles)<br>16[c] (chemicals) | 10[b] (textiles)<br>51[c] (chemicals) |
| **Total** | **26** | **81** | **31** | | |

[a] (Valada et al. 2016), [b] own assumptions, [c] own assumption: usage of adhesive in furniture

A detailed list of wood-based products, semi-finished wood variants, and alternatives is provided in Table 2, with underlying unit processes reported in Supplementary Information 2. Unit process data was sourced from peer-reviewed (Guo et al. 2021; Arias et al. 2020; Geng et al. 2019b; Hytönen et al. 2023; Chen et al. 2016) and grey literature (Ekosaari 2024; Vial and Radziminski 2019; Valada et al. 2016; Vial et al. 2018). LCIs were modelled using product-appropriate functional units (e.g. 1 kg for textiles, 1 m² for flooring, 1 MJ for heat), subsequently converted to kg C contained in the wood-based product using conversion data in Table S1. Thermal efficiencies used are reported in Table S2.

**Table 2**. List of wood-based and alternative products considered in this study

| End-use category | Product | Wood-based product | Alternative product |
|---|---|---|---|
| Construction, primary | Subfloor [a] | Subfloor (variants: OSB, softwood) | Concrete subfloor |

| | | | |
|---|---|---|---|
| | Subfloor, mixed [b] | Subfloor (variants: mixed concrete and plywood; mixed concrete and softwood) | Concrete subfloor |
| | External wall, high rise[b] | Wall, high rise (variants: CLT) | Reinforced concrete wall |
| | External wall, lower rise[c] | External wall (variants: MDF, OSB, particle board, plywood, softwood) | Mix of reinforced concrete wall (50%), brick wall (50%) |
| | Trusses[c] | Trusses (variants: hardwood, softwood) | Steel trusses |
| | Industrial roof frame[c] | Industrial hall (variants: Glulam) | Mix of reinforced concrete frame (50%), steel frame (50%) |
| Construction, secondary | High end flooring [c] | Parquet, solid wood (variants: hardwood, softwood) | Mix of ceramic floor (50%), stone floor (50%) |
| | Medium-high end flooring [c] | Parquet, multilayered (variants: Plywood, MDF, hardboard) | Mix of ceramic floor (50%), stone floor (50%) |
| | Medium-end flooring [c] | Laminate (variants: hardboard, MDF, OSB, particleboard) | Vinyl flooring |
| | Partition wall [c] | Partition wall (variants: MDF, OSB, particleboard, plywood) | Gypsum plasterboard |
| | Insulation board [c] | Insulation board (variants: softboard) | Mix of rock wool (41%), glass wool (27%), polystyrene foam (32%) |
| | Cladding [c] | Cladding (variants: hardwood, OSB, plywood, softwood) | Mix of steel cladding (87.5%), aluminium cladding (12.5%) |
| | Window [c] | Window (variants: hardwood, softwood) | Mix of PVC window 67%), aluminium window (33%) |
| Furniture | Kitchen cabinet [d] | Kitchen cabinet (variants: Glulam, particleboard, plywood, softwood) | Metal kitchen cabinet with less wood |
| | Sofa [d] | Sofa (variants: hardwood, MDF, particleboard, plywood, softwood) | Sofa with steel and less wood |
| | Dining chair [d] | Chair (variants: hardwood, MDF, particleboard, plywood, softwood) | Chair made from steel and plastic |

| | | | |
|---|---|---|---|
| | Storage cabinet [c] | Storage cabinet (variants: hardboard, hardwood, softwood, MDF, OSB, particleboard, plywood) | Metal cabinet |
| Energy | Heat at residential homes [e] | Wood stove (variants: Pellets, postconsumer wood, softwood, wood residues) | residential heat mix |
| | Non-residential heat [e] | Heat from CHP (variants: Pellets, postconsumer wood, virgin wood chips, wood residues) | District and industrial heat mix |
| | Non-residential electricity [e] | Electricity from CHP (variants: Pellets, postconsumer wood, virgin wood chips, wood residues) | Electricity mix, high voltage |
| | Industrial energy [e] | Energy (heat and electricity combined) from black liquor | District and industrial heat mix (83%), electricity mix, high voltage (17%) |
| Chemicals & Textiles | Glue [f] | Adhesive (variants: softwood lignin) | melamine urea formaldehyde-based adhesive |
| | Textiles [g] | Viscose (variants: hardwood pulp, softwood pulp) | Mix of polyester (70%), cotton (24%), nylon (6%) |
| | Textiles [g] | Lyocell (variants: hardwood pulp, softwood pulp) | Mix of polyester (70%), cotton (24%), nylon (6%) |
| Packaging | Pallet [c] | Wooden crate (variants: hardboard, hardwood, MDF, OSB, particleboard, plywood, softwood) | Plastic crate |
| | Bottle [f] | Bottle, bio-based (variants: hardwood pulp, softwood pulp) | PET bottle |

[a] (Vial et al. 2018), [b] (Vial and Radziminski 2019), [c] (Valada et al. 2016), [d] (Geng et al. 2019b), [e] Own modelling, based on Wernet et al. (2016) and (Sacchi et al. 2022), [f] (Arias et al. 2020)

[g] Own modelling, based on Wernet et al. (2016), Guo et al. (2021), Hytönen et al. (2023), Ekosaari (2024)

[f] Own modelling, based on Wernet et al. (2016), Chen et al. (2016)

## 2.4. Time-explicit modelling

This paper applied a time-explicit LCA approach (Müller et al. 2025), combining prospective LCI data with an explicit representation of the timing of life cycle processes. We generated

prospective versions of ecoinvent v3.11 (cut-off) (Wernet et al. 2016) at 10-year intervals from 2020 to 2100 using premise v2.3.8 (Sacchi et al. 2022), under three IMAGE climate scenarios (Stehfest 2014) (Table 3). The scenarios span a broad range of possible future developments based on Shared Socioeconomic Pathways (SSPs) 1, 2 and 3 (Riahi et al. 2017) and the Representative Concentration Pathways (RCPs) 2.6, 4.5 and 7.0 (van Vuuren et al. 2011).

**Table 3.** Prospective background scenarios used in this time-explicit study

| Scenario | Scenario name | Economic paradigm (SSP) | Global mean surface temperature (GMST) increase by 2100 (°C) | Representative concentration Pathway (RCP)[a] | Timesteps for databases (10-year intervals) |
|---|---|---|---|---|---|
| 1 | SSP1-L | Sustainability | 1.7-2.0 | RCP2.6 | 2020-2100 |
| 2 | SSP2-M | Middle-of-the-road | 2.8-3.0 | RCP4.5 | 2020-2100 |
| 3 | SSP3-H | Regional rivalry | 3.2-3.5 | RCP7.0 | 2020-2100 |

[a] approximate match by comparing GMST of IMAGE scenarios with GMST of RCPs.

Production processes were assigned to a start year $t_0$ (2020–2070 in 10-year intervals) and EoL processes were assigned to year $t_0$ + lifetime (Table 1). Background LCIs were linked using linear interpolation between adjacent time steps, with processes beyond 2100 assigned to the 2100 database. To isolate the effect of temporal differentiation, results are compared with a purely prospective LCA in a sensitivity analysis.

In total, 81 product-material variants and their alternatives are assessed across 6 starting years and 3 background scenarios, resulting in 1458 DFs, while the sensitivity analysis adds another 10206 (7 * 1458) data points. These datapoints are reported in Supplementary Information 3.

## 2.5. Contribution and sensitivity analysis

A contribution analysis of process and elementary flows was conducted for all products, scenarios and selected years (2020 and 2070, using the prospective model). A sensitivity analysis was performed to assess the influence of the key modelling assumptions on the results (Table 4), applied across all products, scenarios, and modelling years in the time-explicit model.

**Table 4.** Sensitivity analyses (SA) carried out in this study. Changes are applied to both wood-based and alternative products.

| SA | Name | Description |
|---|---|---|
| 1 | Prospective modelling | Use only prospective modelling, i.e. all life cycle processes are modelled in the start year $t_0$. |
| 2 | Lifetime extension | Use extended lifetimes (Table 1). |
| 3 | Reduced electricity consumption | Reduce electricity consumption by 25% across foreground supply chains. |
| 4 | Reduced heat consumption | Reduce heat consumption by 25% across foreground supply chains. |
| 5 | Heat pump only | Replace substituted heat processes in heat recovery using the process "heat production, water-water heat pump, industrial, 100kW" located in Western Europe (WEU). |
| 6 | Reduced production losses | Reduce production losses of foreground supply chains by 25%. |
| 7 | Local transport | Reduce transportation distances by 80% in foreground supply chains. |

# 3. Results

## 3.1. Displacement factors in 2020

We found that wood-based products showed generally lower climate impacts than their alternatives in 2020 across all end-use categories, though with substantial variation across categories and within them (Figure 2). The highest weighted average DFs were found in chemicals and textiles (1.04 kg C/kg C), followed by secondary construction (0.83–0.87 kg C/kg C), primary construction (0.78–0.80 kg C/kg C), and packaging (0.68 kg C/kg C) in 2020. Energy applications showed low positive values (0.16 kg C/kg C), while furniture was near zero to slightly positive (0.01–0.07 kg C/kg C). The IQRs revealed substantial variability within end-use categories. Secondary construction in 2020 under SSP1-L had a weighted average of 0.83 kg C/kg C and an IQR spanning 0.26 to 1.39 kg C/kg C. Chemicals and textiles showed the widest spread (IQR 0.18–2.39 kg C/kg C in 2020 under SSP1-L), reflecting strong variation between the individual products (one chemical and two textile fibres). Small differences between scenarios were already visible in 2020 for end-use categories with long product lifetimes, such as construction and furniture, because the EoL processes for these products occur in future years, in which scenario projections lead to deviating technology landscapes. End-use categories with short lifetimes, such as energy, packaging, or with minimal EoL contributions to DFs, such as chemicals and textiles, showed identical values across scenarios in 2020.

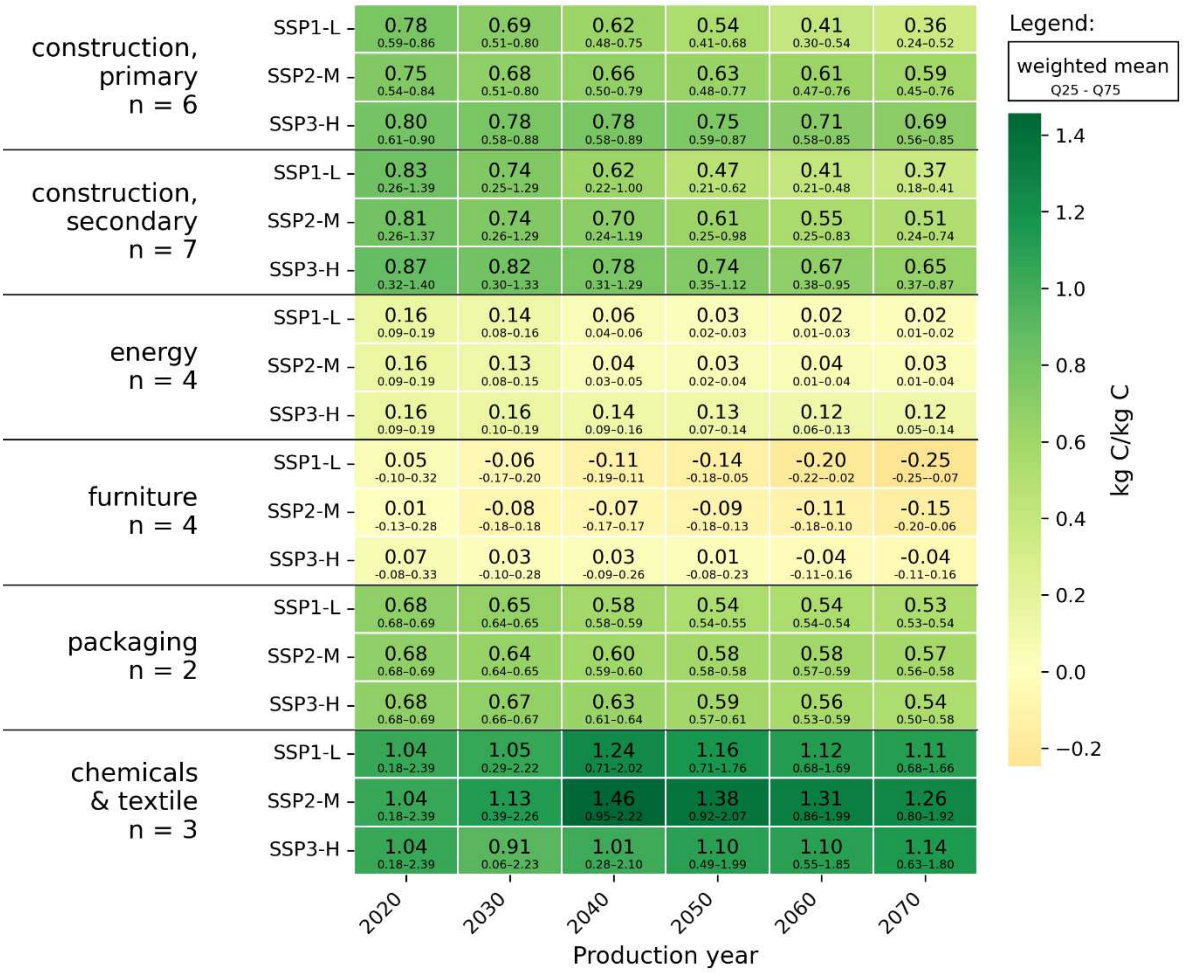



**Figure *2.*** Time-explicit displacement factors by end-use category across different years and scenarios using weighted mean (see Eq. 2 & 3) and interquartile ranges (q25 - q75). n = number of products per end-use category. Products and semi-finished material variants are listed in Table 2. Plots in supplementary information show mean (Figure S1) and standard deviation (Figure S2).

## 3.2. Future developments

Except for chemicals and textiles, DFs decreased over time for all end-use categories, with reductions generally strongest in SSP1-L, weakest in SSP3-H, and intermediate in SSP2-M (Figure 2). In absolute terms, we found the largest reductions between 2020 and 2070 in secondary

construction (−0.22 to −0.46 kg C/kg C), followed by primary construction (−0.11 to −0.42 kg C/kg C) and furniture (−0.11 to −0.30 kg C/kg C). Reductions were smaller for energy (−0.04 to −0.14 kg C/kg C) and packaging (−0.11 to −0.15 kg C/kg C). By 2070, secondary construction reached a weighted average of 0.37–0.65 kg C/kg C, primary construction 0.36–0.69 kg C/kg C, packaging 0.53–0.57 kg C/kg C, and energy 0.02–0.12 kg C/kg C. Furniture, which was near zero or slightly positive in 2020, declined to −0.25 to −0.04 kg C/kg C by 2070, turning negative in all scenarios.

Chemicals and textiles showed a different trend, with DFs remaining above 1.0 kg C/kg C and increasing over time. This was driven by diverging trends among the three products in this category: the DF of wood-based adhesive increased substantially over time, due to its electricity-intensive production process, while the DFs of viscose and lyocell slightly decreased (see Figure S3). The peak in SSP2-M in 2040 reflected a scenario-specific acceleration of clean electricity technologies at that timestep.

## 3.3. Constituents of the displacement factors

Figure 3 decomposes DFs into the contribution of the wood-based product and that of its alternative for all products in 2020 and 2070 for SSP1-L (other scenarios shown in Figure S4-5). Most products are below the diagonal, indicating positive DFs, with the majority clustering in the lower-left where both alternatives have relatively low GWIs. Chairs and sofas stand out with high GWIs for both alternatives, but DFs near zero. Adhesive and viscose show the most extreme DFs, driven respectively by a high-impact wood-based product and a high-impact alternative product. Between 2020 and 2070, the GWIs of the alternative products declined faster than those of the wood-based products, visible as a stronger leftward than downward shift, which reduces DFs over time.

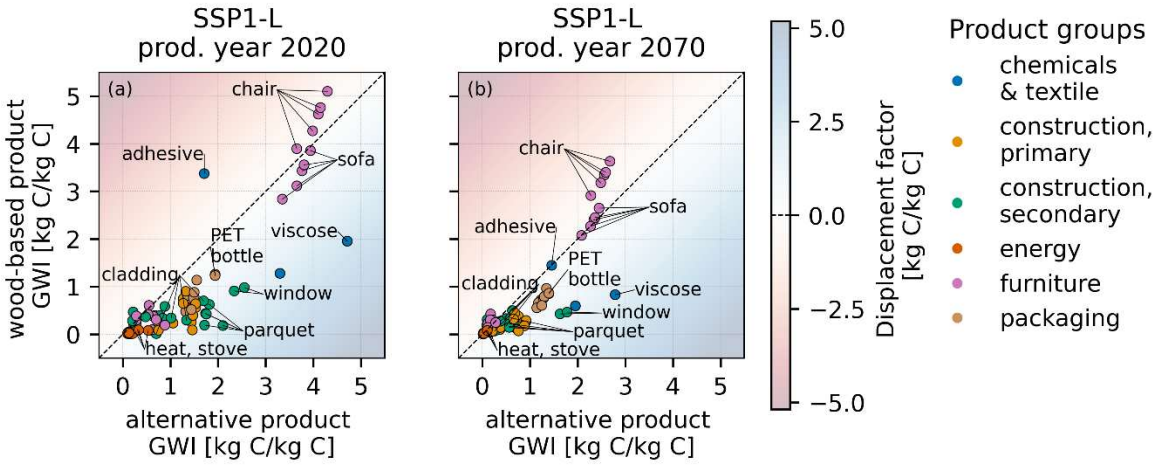



**Figure 3.** Displacement factors of all product-material variants for the production years 2020 and 2070 under SSP1-L, decomposed into the contributions by the wood-based products and its alternatives. GWI = Global Warming Impact. The diagonal represents a displacement factor of zero.

Figure 4 decomposes DF into production and EoL contributions for all products in 2020 and 2070 for SSP1-L (other scenarios shown in Figure S6-7). Most products cluster in the upper left quadrant, indicating that wood-based products emit less than their counterparts during production while EoL contributions are near-neutral or slightly negative. Products made from different semi-finished materials appear vertically stacked in Figure 4 (e.g., parquet or sofa), reflecting differences in production-related impacts across semi-finished material variants, which narrow over time as shown in Figure 5. EoL impacts remain similar across variants, as the same EoL pathways are applied to all, differing only in lower heating value and moisture content. Between 2020 and 2070, DFs decrease mainly due to production-related changes, visible as a downward shift, while EoL contributions remain relatively stable with little horizontal shift.

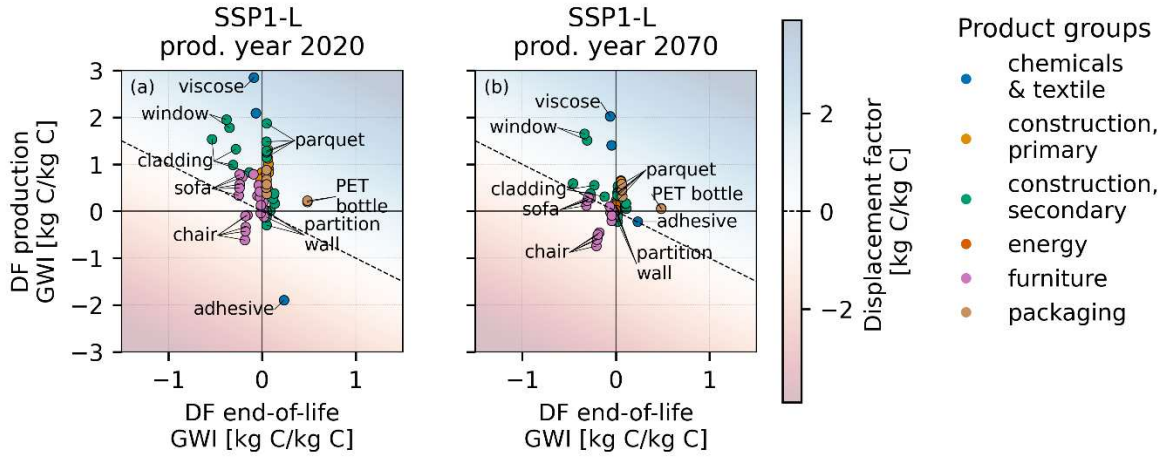



**Figure 4.** Displacement factors of all product-material variants for the production years 2020 and 2070 under SSP1-L, decomposed into production and end-of-life contributions. GWI = Global Warming Impact. The dashed line represents a displacement factor of zero.

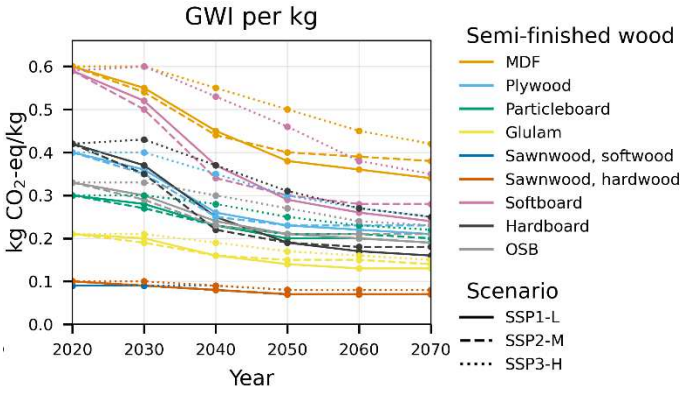



**Figure 5.** GWI of semi-finished wood materials used in this study across years and scenarios. Results are shown per kg of semi-finished wood material, using material densities given in Table S1.

## 3.4. Contribution analysis

Electricity and heat were major process contributors across most products (Figure 6), appearing both as supply chain inputs and as avoided processes where multifunctional waste treatment with energy recovery was solved by substitution. These credits reduced net energy demand rather than appearing as explicit offsets in Figure 6, and their contribution declined over time as electricity and heat supply decarbonized. Emission-intensive bulk materials, such as cement, bricks and metals, dominated contributions where they appeared in the product systems, e.g. in construction products, while products with more heterogeneous compositions in both products, such as furniture or textiles, showed a broader mix of contributors. Transport contributions were small, rarely exceeding the cutoff.

Between 2020 and 2070, the DF decline was driven by faster decarbonization of the components used in the alternative, non-wood products, particularly electricity, heat, cement and metals (see Figure S8 to S11), relative to wood-based products, where impacts declined mainly for semi-finished variants with high energy requirements such as MDF and softboard (Figure 5). Contributions from plastics, chemicals, and waste treatment remained relatively stable, becoming comparatively more prominent in future years as energy-related contributions declined. A detailed process contribution analysis per end-use category and product is provided in Supplementary Information 1 section 2.5. Fossil $CO_2$ dominated elementary flow contributions across all products (Figure S12).

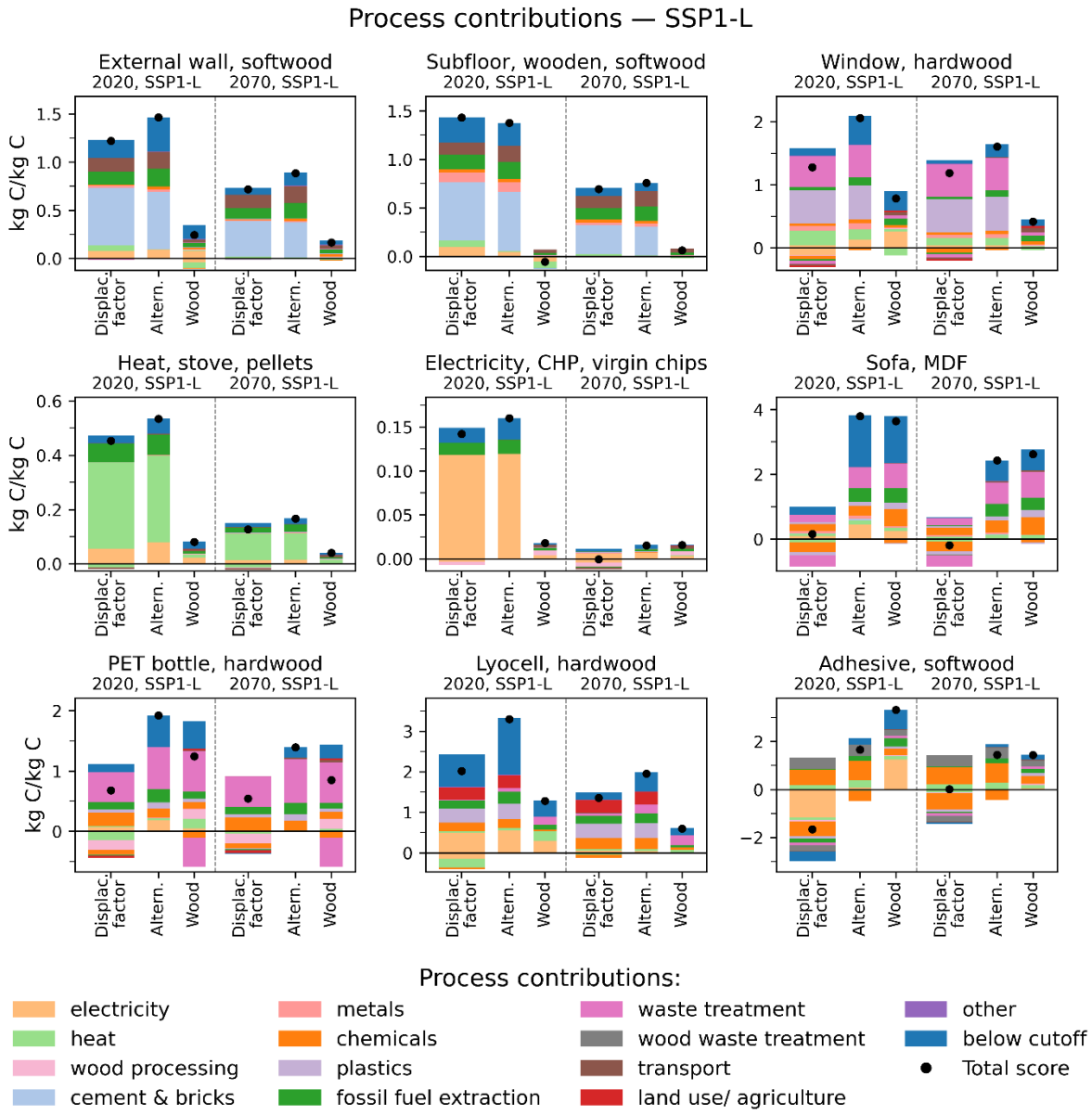



**Figure 6**. Process contributions for a selection of products for the year 2020 and 2070 in SSP1-L for displacement factors, and their constituents of the wood-based and alternative product. Figure S13 & S14 show the other scenarios.

### 3.5. Sensitivity analysis

Overall, results showed limited sensitivity to the tested parameters (Figures S21–S27), with the largest sensitivity observed for heat-related assumptions, and effects more pronounced in the start of the assessment period when process emission intensities are still considerable. Since perturbations were applied to both the wood-based and alternative products, their effects on the DFs were partly offset. Replacing the time-explicit approach with a purely prospective model (SA1) yielded differences for long-lived products, where the time-explicit model assigned LCI data from decarbonized future years to EoL processes, with differences converging by 2040–2050 as background databases beyond this point were largely similar.

## 4. Discussion

### 4.1. Main findings

This study confirms that wood-based products provide benefits for climate change mitigation at the product level as they are on average associated with less GHG emissions over their life cycle, compared to products made from predominantly non-renewable materials. However, our future-oriented assessment shows that these benefits are not fixed but decrease over time depending on the degree of economy-wide decarbonization, a trend that has previously been anticipated (Myllyviita et al. 2021; Soimakallio et al. 2022) but not yet quantified across a comprehensive set of products and time steps. This finding implies that the use of wood products yields greater climate benefits in the current fossil-based economy and that the benefit declines when the economy becomes increasingly decarbonized in the future.

The decline in DFs is driven by asymmetric decarbonization of the supply chains of wood-based products and their alternatives. As a relative metric, DFs change only when the impact of the two alternatives changes at different rates. The alternative, non-wood products contain more emission-

intensive components (steel, cement, glass, plastics) that are projected to decarbonize in the future, while the material composition of wood-based products is already comparatively low-carbon and therefore has less room to benefit from future decarbonization. The time-explicit approach reinforces this pattern, as end-of-life energy recovery, proportionally more important for wood-based products in our model, yields less emission savings in the future as energy systems decarbonize. The largest decarbonization potential thus lies not in wood-based products themselves, but in the materials they potentially replace. Consequently, the relative advantage of wood is highest under the least climate-ambitious scenario (SSP3-H), where competing materials remain emission-intensive for longest, and erodes most quickly under the climate-stringent SSP1-L scenario.

Energy-related DFs in this study for 2020 are already lower than previously reported values (Knauf et al. 2015; Smyth et al. 2017; Myllyviita et al. 2021; Boiger et al. 2024), since we model the alternative products as market mixes of fossil and renewable technologies, rather than purely fossil-based competitors. As energy systems move away from fossil-based technologies, the assumption of pure fossil-based alternatives is increasingly difficult to justify. Under the climate-ambitious scenario in our study, energy-related DFs reach near zero in 2070, as these market mixes almost fully decarbonize. Material-related DFs also decline over time but alternative materials such as cement and steel retain residual emissions even under ambitious decarbonization scenario. Material substitution thus provides more robust and sustained climate benefits than energy substitution, a finding consistent with the broader literature (Geng et al. 2017; Leskinen et al. 2018).

Similar to previous meta-reviews (Leskinen et al. 2018; Myllyviita et al. 2021; Verkerk et al. 2022; Wedajo et al. 2025), our study finds substantial variation in DFs both between and within

end-use categories. In previous meta-reviews, however, this spread is partly shaped by methodological confounding, e.g. varying system boundaries, background databases, allocation choices, and life cycle stages considered in various studies. In our study, all DFs were assessed within the same modelling framework, meaning the observed variability between DFs is more robust against methodological confounding and reflects genuine differences in product compositions and material inputs, although our own modelling choices also influence the results. The publicly available unit-process inventories make it possible to trace our modelling choices and their influence on results and to adapt the DFs to alternative contexts or scenarios, going beyond previous efforts that report only aggregate impact scores.

DFs in our study are generally lower than previously reported values, also for the baseline year 2020. This follows the trend of lower DFs found in subsequently published meta-reviews. Direct comparison is limited by differences in system boundaries, reference products, and modelling choices, but three factors likely contribute to our lower results: the use of a more recent version of background database (ecoinvent v3.11) reflecting current emission intensities for 2020, the conservative modelling of non-wood alternatives as market mixes rather than purely fossil-based products, and the time-explicit assignment of EoL processes to future years with more decarbonized supply chains.

## 4.2. Implications for climate-benefitial wood use

Wood is a finite resource that cannot simultaneously serve as a forest carbon sink, supply materials, and provide energy. The results of this study can help prioritize end-use applications with the strongest climate benefit through displacement under different future socio-technical developments.

In 2021, 47% of EU wood flows were directed to energy applications, 20% came from primary wood sources, and 27% from secondary (Orfanidou et al. 2026). Our finding that energy applications deliver diminishing climate benefits in a decarbonizing world calls for a structural shift away from using primary and secondary wood for energy in the future. Such a shift would not only strengthen displacement effects but also increase biogenic carbon storage, especially if wood is redirected toward material applications with long product lifetimes.

Within material applications, the climate benefit of wood use is highly product-specific and depends on the composition and emission intensity of the wood-based product and displaced alternative. The strongest displacement benefits arise where wood-based products contain few additional non-renewable components and replace alternatives that remain hard to decarbonize. Where wood-based products contain substantial shares of emission-intensive components, such as foam, plastics, and metals, the displacement benefit is significantly reduced and can turn negative, as our results for furniture illustrate.

Where functional requirements allow, semi-finished materials with low-impact processing steps such as sawnwood or glulam should be preferred over those with emission-intensive processing steps, such as MDF and plywood. However, engineered wood products also serve an important role by their special technical properties required in certain applications and by enabling the use of wood residues and waste streams, broadening the volume of secondary wood flows that can be used for materials. Additionally, future decarbonization narrows the difference in production-related impacts between semi-finished wood materials.

The significance of declining DFs becomes particularly striking when viewed against the concept of required displacement factors (RDFs), which describe the minimum DF needed for increased wood harvesting to deliver net climate benefits. Seppälä et al. (2019) and Buschbeck

and Pauliuk (2022) found that current average DFs already fall short of the RDFs in Finland and Germany respectively, meaning that displacement effects are currently insufficient to justify harvesting intensification from a climate perspective. Our findings that future DFs are likely to decline further only deepens this gap. Thus, we emphasize that climate-smart wood use should not aim at expanding volumes but at directing existing and additional wood flows toward material applications where the benefit is largest and most durable, such as construction or textiles.

## 4.3. Responsible use of the DF database

We provide a transparently documented database of product-level, future-oriented DFs across a wide range of end uses, estimated with consistent modelling assumptions and publicly available unit-process inventories. Future users are encouraged to use our results and database in their own contexts and scenarios and should consider the following recommendations for responsible use.

**Integration of the full carbon cycle.** The DFs in this database cover fossil GHG emissions and exclude biogenic $CO_2$, consistent with the common practice of reporting displacement effects and biogenic carbon balances separately (Myllyviita et al. 2021). While our data gives insights into displacement-related, fossil climate impacts, the DFs are not intended for standalone use. A complete climate assessment requires combining them with temporally resolved biogenic carbon flows across the full system, which includes changes in forest and soil carbon stocks, temporary carbon storage in HWPs, biogenic $CO_2$ emissions during production and EoL and carbon leakage (Knauf et al. 2015; Soimakallio et al. 2022; Leskinen et al. 2018; Schulte et al. 2025). Here, reduction in forest carbon sinks and displacement effects of wood utilization may pose a tradeoff (Soimakallio et al. 2016). Various approaches exist for assessing temporal dynamics of biogenic carbon within the LCA framework but they introduce significant methodological complexity and variability in results (Jong et al. 2026).

**Additionality, market effects and opportunity costs.** DFs quantify avoided emissions relative to a counterfactual reference system that never took place (Hurmekoski et al. 2021). They should therefore only be applied to *changes* in wood use relative to a baseline, not to total wood production volumes, as the latter overestimates the displacement contribution of the sector (Leturcq 2020; Schulte et al. 2023). Given the comparative nature of DFs, the choice of the counterfactuals is as influential as the modelling of the wood-based products (Koponen et al. 2018). While this study assumed perfect product-level displacement, real-world substitution is often imperfect, which can substantially reduce the realised climate benefit (Yang et al. 2024b; Hurmekoski et al. 2023; Hurmekoski et al. 2021). The counterfactual scope should also account for opportunity costs beyond the product-level displacement: foregone forest carbon sequestration from harvest-induced reductions of forest carbon stocks (Maierhofer et al. 2024) and foregone substitution effects when wood use is shifted between applications (Boiger et al. 2024). Finally, the additionality of DFs causes methodological tension: GHG emissions avoided through substitution "inherently belong to the consequential modelling principle" (Soimakallio et al. 2022). Yet most studies, including ours, rely on attributional background databases based on average market data, creating an internal inconsistency between the consequential research question and foreground model on the one hand and the attributional LCI data on the other.

## 4.4. Areas for future research

This study provides the most comprehensive future-oriented DF compilation to date using unit-process inventories that are publicly available. Beyond the recommendations for responsible use outlined in section 4.3, the following improvements to the DF database and methodology would strengthen future assessments.

**Coverage and representativeness.** The sample is not equally representative across all wood uses. Paper and board, accounting for 24% of EU wood flows in 2021 (Orfanidou et al. 2026), was excluded entirely, as the wood-based product was considered dominant with no meaningful displacement effect consistent with previous work (Hurmekoski et al. 2020; Leturcq 2020), though comparisons to digital media have yielded both positive and negative DFs (Achachlouei and Moberg 2015). Future research should investigate the achievable substitution effect of paper and board products. Chemicals are poorly represented (n=1) due to limited LCI data and the difficulty of identifying a meaningful end-use reference as chemicals feed into diverse downstream applications. Despite their projected growth and potential (Arts et al. 2024), chemicals and textiles together constitute only 1% of EU wood use in 2021 (Orfanidou et al. 2026). Our furniture LCIs, based on Geng et al. (2019b), show similar material compositions between wood-based and alternative furniture items. Different conclusions for the displacement effects of the furniture sector (8% of wood flows in 2021 (Orfanidou et al. 2026)) might be drawn with industry-average LCI data. Moreover, our DFs cover one life cycle of products, including EoL treatment, while multi-life cycle DFs would help to better understand cascading wood uses.

**Prospective LCI database limitations.** The future-oriented assessment should be interpreted with respect to the limitations of IAMs and their integration into LCA databases, including differences in technological representation and system boundary definitions. Not all industrial sectors are covered with equal detail in IAMs: while electricity, heat, cement, steel, and transport are well represented, plastics, chemicals, and recycling are only partly included, meaning that the stability of some DFs over time may reflect this coverage gap as much as genuine decarbonization trends. Future research could expand the set of IAMs beyond IMAGE to test the sensitivity of

results to IAM-specific projections for similar climate targets. For a detailed discussion of pLCI database limitations, the reader is referred to Bortoli et al. (2025) and Paris et al. (2026).

**Temporal harmonization in impact assessment.** This study assigns each life cycle process to the year it occurs and uses scenario-specific background inventories at each time step. However, climate impacts are characterized using a static GWP100 metric (Smith et al. 2021) for all emissions regardless of when they occur, meaning that emissions from production in 2020 and EoL emissions fifty years later are treated as climatically equivalent although climate responses have been shown to be time-sensitive (Barbosa Watanabe and Cherubini 2026). A fully time-consistent approach would align the temporal scope of the inventory with that of the LCIA step (Ventura 2022) and apply time-differentiated characterization factors that reflect the timing of emissions and the atmospheric conditions at that time. This remains an active area of research as methodological consensus develops (Heijungs 2026).

## 4.5. Concluding remarks

This study provides a comprehensive, future-oriented database of DFs for 81 wood product-semi-finished-material combinations across six end-use categories, assessed consistently under three decarbonization scenarios between 2020 and 2070 using transparently reported unit-process inventories.

We find that wood-based products provide declining climate benefits over time, with the largest decline in energy applications. The decline is driven by faster decarbonization of non-wood supply chains, which contain proportionally more fossil-intensive, while the supply chains of wood-based products are already comparatively low-carbon. As a result, the relative climate advantage of wood is highest under the least climate-ambitious scenario and lowest under the most climate-ambitious scenario. Time-explicit LCA captures an additional effect: EoL processes occur in more

decarbonized future years, resulting in slightly lower DFs for long-lived products compared to static or purely prospective approaches.

The harmonized modelling assumptions reduce the methodological confounding that has affected previous cross-study DF compilations, and the openly shared unit-process data allow practitioners to scrutinize our modelling assumptions and adapt the data to their needs, while adopting the recommendations for responsible use. The database would benefit from broader product coverage and improved decarbonization projections for sectors currently underrepresented in IAMs. Application of these product-level DFs at the market level should integrate market substitution effects and must be combined with biogenic carbon balances for a complete climate assessment.

Our findings on the diminishing displacement effects of wood use call for a conservative evaluation of future displacement benefits of the wood-based bio-economy, a shift of wood flows from energy toward long-lived material applications such as construction and textiles, and caution against harvest intensification justified on displacement arguments alone. Future climate strategies should shift the focus from maximizing displacement effects of wood products to system-wide emission reduction.

# Supporting Information

Supplementary information 1: Explanation of modelling choices, sensitivity analysis and additional figures.

Supplementary information 2: Foreground life cycle inventory (Placed on ZENODO upon acceptance).

Supplementary information 3: product-level displacement factor results (Placed on ZENODO upon acceptance)

Data availability

All underlying data available in the article itself and its Supporting Information. Ecoinvent datapoints have been removed from Supplementary Information 2, but complete SI2 is available upon request by ecoinvent license holders.

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## Abbreviations

CHP, Combined heat and power; CLT, Cross-laminated timber; DF, Displacement factor; GHG, Greenhouse gas; GWI, Global warming impact; GWP, Global warming potential; IAM, Integrated assessment model; IPCC, Intergovernmental Panel on Climate Change; IQR, Interquartile range; LCA, Life cycle assessment; LCI, Life cycle inventory; LCIA, Life cycle impact assessment; LHV, Lower heating value; MDF, Medium density fiberboard; OSB, Oriented strand board; pLCA, Prospective life cycle assessment; SSP, Shared Socioeconomic Pathway; WEU, Western Europe.

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