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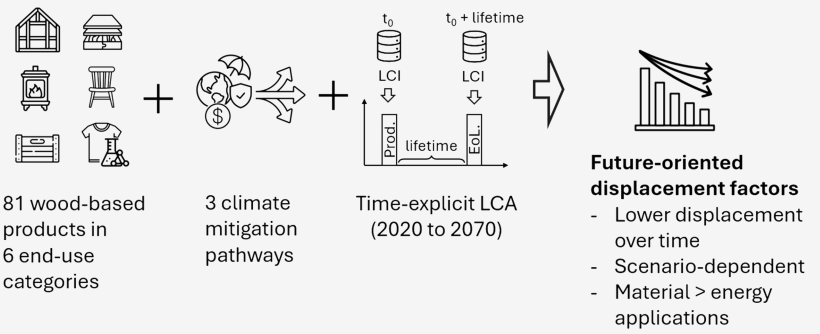
Revisiting the Climate Benefits Provided by Wood through Future-Oriented Material and Energy Displacement

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ABSTRACT: Displacement factors (DFs) quantify climate benefits of wood-based products relative to non-wood alternatives. Existing DFs are typically static whereas economy-wide decarbonization motivates a forward-looking assessment. Previous work focuses on semifinished materials and lacks harmonized, transparent modeling. 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 processes to the technology landscape as they occur, under three decarbonization scenarios for 2020−2070. Wood-based products showed positive DFs in 2020, with weighted averages from near-zero for furniture to 1.04 kg C/kg C for chemicals and textiles, though 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 decline was driven by faster decarbonization of non-wood products that 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, an effect not captured by conventional or prospective LCA. Energy-related DFs approached near-zero by 2070. 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, bioeconomy, time-explicit*

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.[1] Emission savings from wood-based products, sometimes referred to as harvested wood 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,[2] 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.[3] A growing body of studies has quantified DFs, finding that wood-based products tend to reduce fossil GHG emissions compared to non-wood alternatives.[1,3,4] Sathre and O'Connor[2] found in an early meta-analysis across 21 studies an average DF of 2.1 kg C/kg C, Knauf et al.[5] found 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.[1] found an average of 1.2 kg C/kg C across 51 studies, and Verkerk et al.[6] found a median of 0.9 kg C/kg C across 64 studies. For Canada, Smyth et al.[7] found material displacement at 0.45 and 0.54 kg C/kg C for panels and sawnwood, respectively, and 0.47−0.89 kg C/kg C for energy displacement. For China, Geng et al.[8] found weighted average DFs of 3.48 kg C/kg C for construction and 1.36 kg C/kg C for

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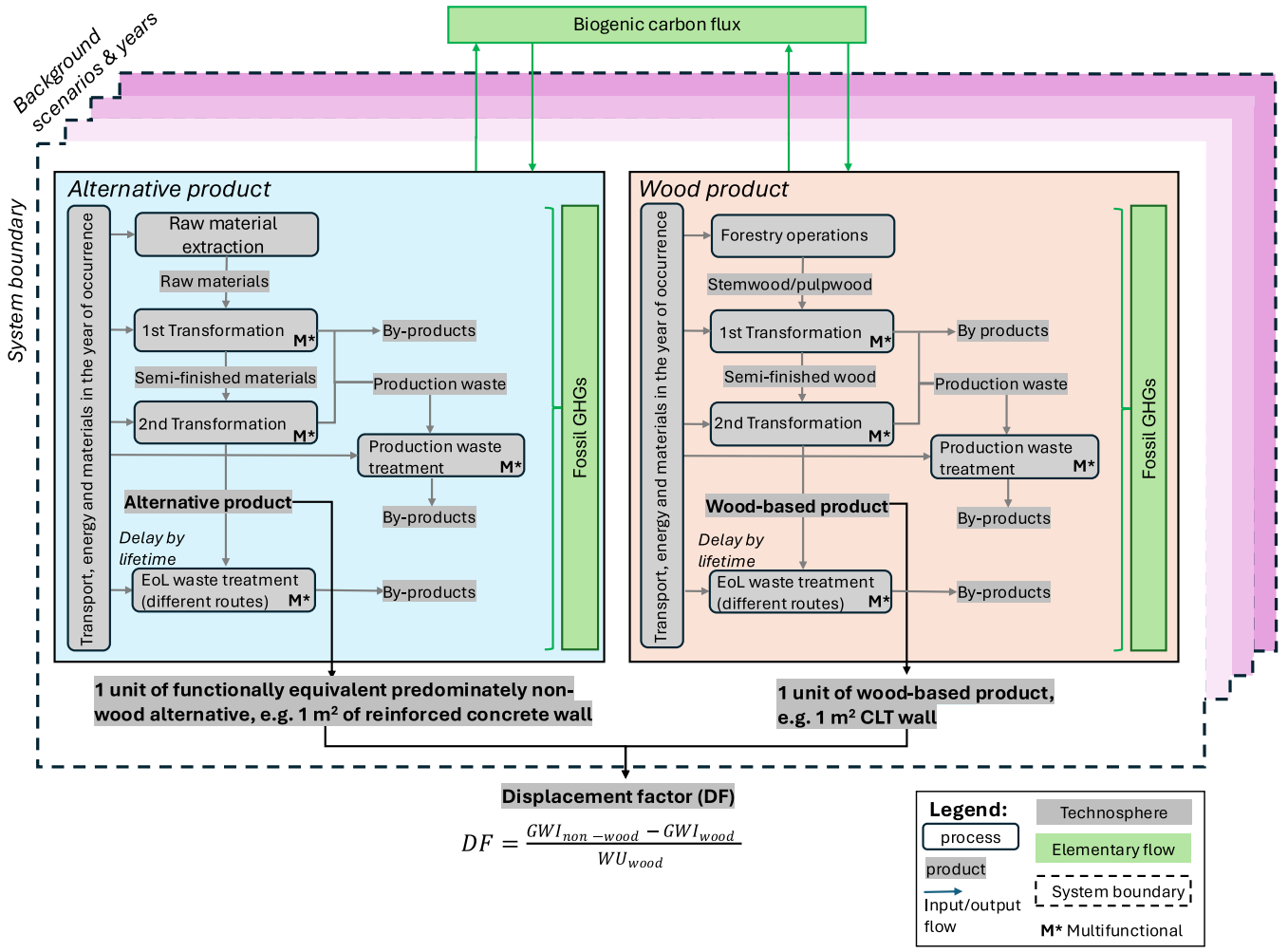


Figure 1. System boundaries of the study. DFs are calculated as the difference in Global Warming Impacts (GWIs) between functionally equivalent non-wood and wood-based products, scaled to the carbon content of the wood product. Time-explicit life cycle inventory modeling[15] is applied under three IMAGE scenarios (SSP1-L, SSP2-M, and SSP3-H).[23] Multifunctionality is solved via substitution.

furniture. Boiger et al.[9] reported average DFs of 0.41 kg C/kg C for material and 0.37 kg C/kg C for energy displacement 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.[6] 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 toward energy and construction applications, with limited data for emerging end-uses such as textiles and biochemicals.[3,6] Data robustness is a recurring concern. For example, 39% of studies reviewed by Hurmekoski et al.[10] 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 stage coverage that are not always transparently reported, the resulting estimates are often neither directly comparable nor jointly applicable.[1,3,6] The common use of aggregate LCA results, without sharing the underlying Life Cycle Inventory (LCI) data, makes it difficult to adapt values to new contexts.[3,4] DFs are furthermore often reported at the level of semi-finished wood materials rather than final products,[5] where the actual displacement occurs.[1,7]

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.[11] Although the importance of a forward-looking DF assessment has been emphasized,[3,9,12] 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 related 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.[6] At each of these times, the underlying technology landscape will have changed substantially.

Prospective LCA (pLCA) addresses the first of these two dimensions by modeling "the product system at a future point in time relative to the time at which the study is conducted",[13] capturing how evolving supply chains and technological learning affect future environmental impacts.[14] However, pLCA does not differentiate the timing of individual processes within the life

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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 and textiles	3	5	4	5[b] (textiles), 16[c] (chemicals)	10[b] (textiles), 51[c] (chemicals)
total	26	81	31		

[a]Ref 27. [b]Own assumptions. [c]Own assumption: usage of adhesive in furniture.

cycle: production, use, and EoL are modeled under the same future snapshot, regardless of when they actually occur. Time-explicit LCA extends this by explicitly assigning each process to the time at which it occurs, combining pLCA with an explicit representation of process timing.[15] This is particularly relevant for long-lived products, where life cycle 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[16] scales DFs as a whole downward linearly over time, Myllyviita et al.[17] apply linear emission reductions specifically to energy and concrete-related components, and Brunet-Navarro et al.[18] scale DFs proportionally to sector-wide GHG reduction trajectories. Hurmekoski et al.[19] 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.[20] 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.[21] However, they model only two discrete points in time without intermediate steps, and they apply the same LCI data to all life cycle processes, assuming no change in technologies between manufacture and EoL. To the authors' knowledge, no existing DF study addresses both temporal dimensions simultaneously by modeling the processes within the life cycle at the time that they occur and with the time-specific technology landscape.

The objective of this work is to assess the current and future potential of wood-based products in Europe to reduce fossil GHG emissions 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 modeling 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 carbon (C) contained in the wood-based product. The study was attributional, using prospective versions of ecoinvent v3.11 (cutoff system model),[22] modified with premise v2.3.8[21] under three climate scenarios from the integrated assessment model (IAM) IMAGE[23], see Table 3. The geographical scope was the European Union, defaulting to European process locations. A cradle-to-grave perspective was adopted (Figure 1), excluding the use phase that is often assumed to be small or uncertain and is inconsistently reported in the literature.[1,6] 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.[1] While conceptually more aligned with consequential LCA, we adopted this approach here to maintain comparability with the existing DF literature.

We modeled temporal dynamics using a time-explicit approach[15] at the LCI stage, with production processes modeled at 10-year intervals between 2020 and 2070 and EoL processes timed according to product lifetimes (Table 1, Section 2.3). At each process timing, the time-specific state of processes based on the IAM projections was used.

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)".[24] This followed the standard practice of reporting displacement effects and biogenic carbon balances separately to avoid double-counting when combining DFs with forest ecosystem carbon balances.[1,3] This method excludes biogenic CO_2 but includes CO_2 from direct land use change due to the long time scales of land use change. The DFs therefore do not represent the total climate benefit, which also requires biogenic carbon fluxes. As the scope is on the product level, market dynamics of displacement effects[10,25] are excluded.

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.[1] DFs 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 the 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

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

where DF—displacement factor in kg C avoided per kg C in the 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,[2] many studies account for a potential wood content in the alternative product, which generally

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Table 2. List of Wood-Based and Alternative Products Considered in This Study[h]

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, particleboard, 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%), aluminum cladding (12.5%)
	window[c]	window (variants: hardwood, softwood)	mix of PVC window (67%), aluminum 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
	nonresidential heat[e]	heat from CHP (variants: pellets, postconsumer wood, virgin wood chips, wood residues)	district and industrial heat mix
	nonresidential 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 and 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, biobased (variants: hardwood pulp, softwood pulp)	PET bottle

[a]Ref 34. [b]Ref 35. [c]Ref 27. [d]Ref 30. [e]Own modeling, based on refs21,22 [f]Ref 28. [g]Own modeling, based on refs 22,31−33 [h]Own modeling, based on refs22,29

increases DFs. We did not account for a potential wood content in the alternative product, in line with Knauf et al.,[5] 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 the 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. For example, a DF of 0.6 kg C per kg C means that, per 1 kg C of wood content, the wood product avoids 0.6 kg C emissions compared to its alternative, corresponding to 2.2 kg CO_2-eq per kg C (0.6 kg C/ (12/44)). Because both terms are expressed in carbon, DF is a dimensionless ratio, and it has the same value if both terms are expressed in CO_2.

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.,[26] 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 modeled as a separate mono-material variant containing a single semi-finished wood type, following Valada et al.,[27] resulting in 81 wood product semi-finished material variants (Table 1). Wood content was converted between semi-finished wood types based on total wood mass and densities given in Table S1. A total of 31 non-wood alternatives were modeled.

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 $\overline{DF}_p$ (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 $\overline{DF}_c$ (eq 3) then averages across m products within category c, giving equal weight to each product p.

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

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

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Table 3. Prospective Background Scenarios Used in This Time-Explicit Study

scenario	scenario name	economic paradigm (SSP)	representative concentration pathway (RCP)	global mean surface temperature (GMST) increase by 2100 (°C)[a]	time steps for databases (10-year intervals)
1	SSP1-L	sustainability	RCP2.6	1.7−2.0	2020−2100
2	SSP2-M	middle-of-the-road	RCP4.5	2.8−3.0	2020−2100
3	SSP3-H	regional rivalry	RCP7.0	3.2−3.5	2020−2100

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

Table 4. Sensitivity Analyses (SA) Carried Out in This Study[a]

scope	SA	name	description
background inventory and method	1	prospective modeling	use prospective modeling, i.e., all life cycle processes are modeled in the start year t_0, using premise-based LCI database at t_0
	2	conventional modeling	use ecoinvent v3.11 as background database, without prospective modifications by premise
foreground inventory	3	lifetime extension	use extended lifetimes (Table 1)
	4	reduced electricity consumption	reduce electricity consumption by 25% across foreground supply chains to reflect efficiency gains
	5	reduced heat consumption	reduce heat consumption by 25% across foreground supply chains to reflect efficiency gains
	6	heat pump only	replace substituted heat processes in heat recovery using the process "heat production, water−water heat pump, industrial, 100 kW" located in Western Europe (WEU)
	7	reduced production losses	reduce production losses of foreground supply chains by 25%
	8	local transport	reduce transportation distances by 80% in foreground supply chains

[a]Changes are applied to both wood-based and alternative products.

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

A detailed list of wood-based products, semi-finished wood variants, and alternatives is provided in Table 2, with underlying unit processes reported in Supporting Information 2. Unit-process data was sourced from peer-reviewed[28−32] and gray literature.[27,33−35] LCIs were modeled using different functional units (e.g., 1 kg of fibers for textiles, 1 m^2 for flooring, 1 MJ for heat) and 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. For textiles, only fiber-level data were available. The functional unit therefore does not account for differences in the garment type, weight, or durability between wood-based and alternative fibers. Differences in the use phase, for example washing and drying of textiles, are also not included.

Product lifetimes were modeled as identical for wood and non-wood alternatives within each product group, based on Valada et al.[27] and own assumptions for chemicals and textiles (Table 1). Wood products were therefore modeled as durable as their non-wood counterparts, while real-world service lives might differ. If non-wood products are more durable in practice, our approach overestimates the displacement benefit, and if wood products are more durable, it underestimates the displacement benefit.

2.4. Time-Explicit Modeling

This paper applied a time-explicit LCA method,[15,36] which combines prospective LCI background data with an explicit representation of the timing of life cycle processes. We generated prospective versions of ecoinvent v3.11 (cutoff)[22] at 10-year intervals from 2020 to 2100 using premise v2.3.8Ref 21, under three IMAGE climate scenarios[23] (Table 3). The scenarios span a broad range of possible future developments based on Shared Socioeconomic Pathways (SSPs)[37] 1, 2, and 3 and the Representative Concentration Pathways (RCPs)[38] 2.6, 4.5, and 7.0.

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 to the process timing using linear interpolation between adjacent time steps, with processes occurring beyond 2100 assigned to the 2100 database. Regional markets for commodities were taken from the IMAGE region Western Europe (WEU), so the DFs do not represent individual countries. To isolate the effect of temporal differentiation, results are compared in a sensitivity analysis with a purely prospective assessment, and an assessment using ecoinvent v3.11 without prospective modifications.

In the main analysis using time-explicit LCA, 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 10,287 (7 * 1458 + 1 * 81) data points. These data points are reported in Supporting 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). The cutoff was the 50 largest contributing processes or flows. A sensitivity analysis was performed to assess the influence of the key modeling assumptions on the results (Table 4), applied across all products, scenarios, and modeling years. SA3−SA8 are constant changes to the foreground inventories, applied in all modeling years and on top of the time-explicit modeling that connects the product system to evolving background inventories.

3. RESULTS

3.1. Time-Explicit Displacement Factors in 2020

For the time-explicit model and with production year t_0 in 2020, we found that wood-based products showed generally lower climate impacts than their alternatives 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 with production in 2020 under SSP1-L had a weighted average of 0.83 kg C/kg C and an IQR spanning 0.26−1.39 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

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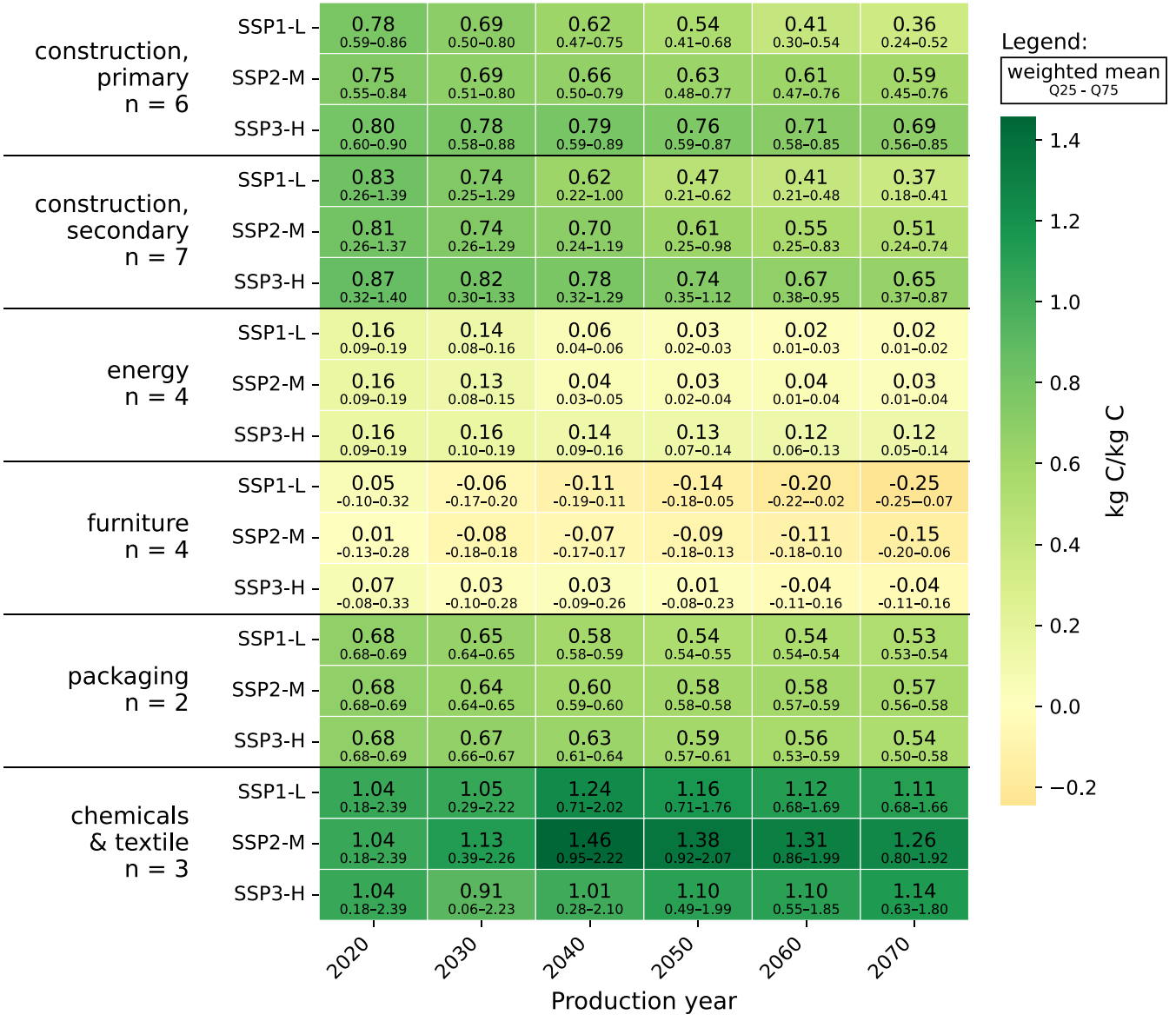


Figure 2. Time-explicit displacement factors by end-use category across different years and scenarios using weighted mean (see eqs 2 and 3) and interquartile ranges (q25−q75). *n* = number of products per end-use category. Products and semi-finished material variants are listed in Table 2. Plots in the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

two textile fibers). Small differences between scenarios were already visible for the production year 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 for the production year 2020.

3.2. Future Developments

Except for chemicals and textiles, DFs decreased in the time-explicit model 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 production years 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 in 2020, declined to −0.25 to −0.04 kg C/kg C by production year 2070, turning negative in all scenarios.

Chemicals and textiles showed a different trend, with DFs remaining mostly above 1.0 kg C/kg C and increasing over time (Figure 2, bottom). This development combines opposing trends between the adhesive and the two textile fibers (Figure S3). The DFs of viscose and lyocell decreased because the impacts of the alternative fiber mix declined more than those of the wood-based fibers. The adhesive DF was negative in 2020 because the wood-based adhesive had a higher impact than its alternative, driven by its electricity use for Kraft lignin production (Figure 6). As electricity supply decarbonized, this impact fell strongly while the non-wood alternative changed

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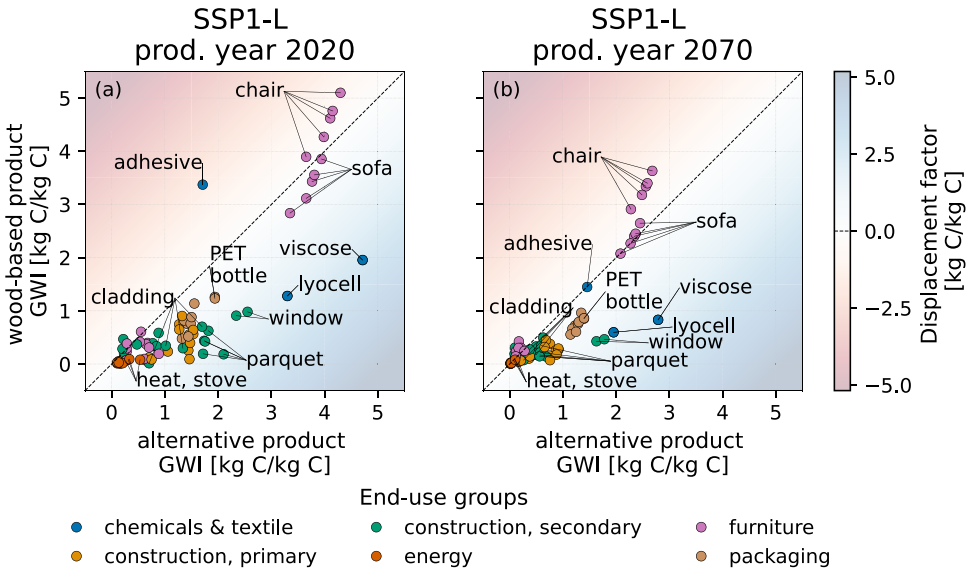


Figure 3. Displacement factors of all product-material variants for the production years 2020 and 2070 under SSP1-L, decomposed into the contributions by the wood-based product and its alternative. GWI = Global Warming Impact. The diagonal represents a displacement factor of zero.

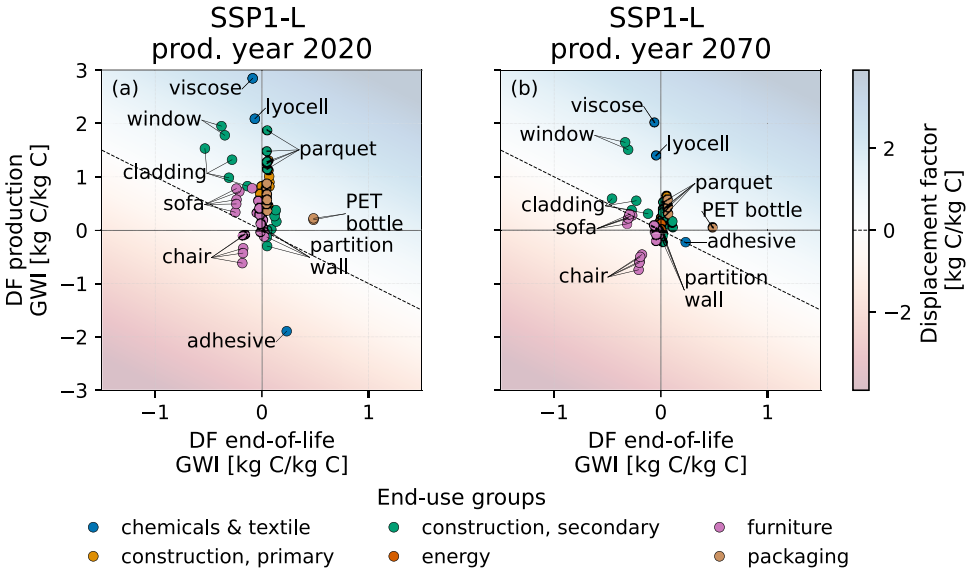


Figure 4. Displacement factors of all product-material variants for the production years 2020 and 2070 under SSP1-L, decomposed into production and end-of-life contributions. GWI = Global Warming Impact. The dashed line represents a displacement factor of zero.

little, so the DF increased, approaching zero by 2040−2050 in SSP1-L and SSP2-M but remaining slightly negative in SSP3-H (Figure S3). Because this end-use category contains only three products, the upward trend of the adhesive influences the category average substantially. The peak in SSP2-M in 2040 reflected a scenario-specific acceleration of clean electricity technologies at that time step (Figure S8).

3.3. Constituents of Displacement Factors

Figure 3 decomposes DFs into the contribution of the wood-based product and that of its alternative for all products in production years 2020 and 2070 for SSP1-L (other scenarios shown in Figures S4 and S5). Most products are below the diagonal, indicating positive DFs, with the majority clustering in the lower left where both alternatives have relatively low GWIs. The furniture products chairs and sofas stand out with high GWIs for both alternatives, but DFs near zero. The adhesive shows the lowest DF, driven by a high-impact wood-based product. Viscose, followed by lyocell, shows the highest DF across all products due to a high-impact alternative product. Between production years 2020 and 2070, the GWIs of most 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 4 decomposes DFs into production and EoL contributions for all products in production years 2020 and 2070 for SSP1-L (other scenarios shown in Figures S6 and S7). 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

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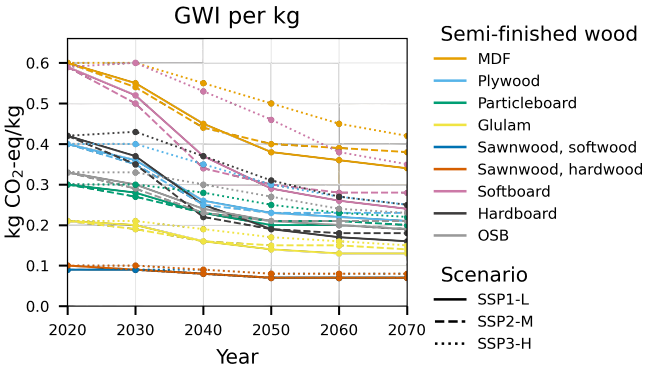


Figure 5. Global warming impact (GWI) of semi-finished wood materials used in this study across years and scenarios. Results are shown per kg of semi-finished wood material, using material densities given in Table S1.

EoL pathways are applied to all semi-finished materials, differing only in lower heating value and moisture content. Between production years 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.

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 (left and right subpanels per pane in Figure 6), the DF decline was driven by faster decarbonization of the components used in the alternative, non-wood products, particularly electricity, heat, cement, and metals, relative to wood-based products, where impacts declined mainly for semi-finished variants with high energy requirements such as MDF

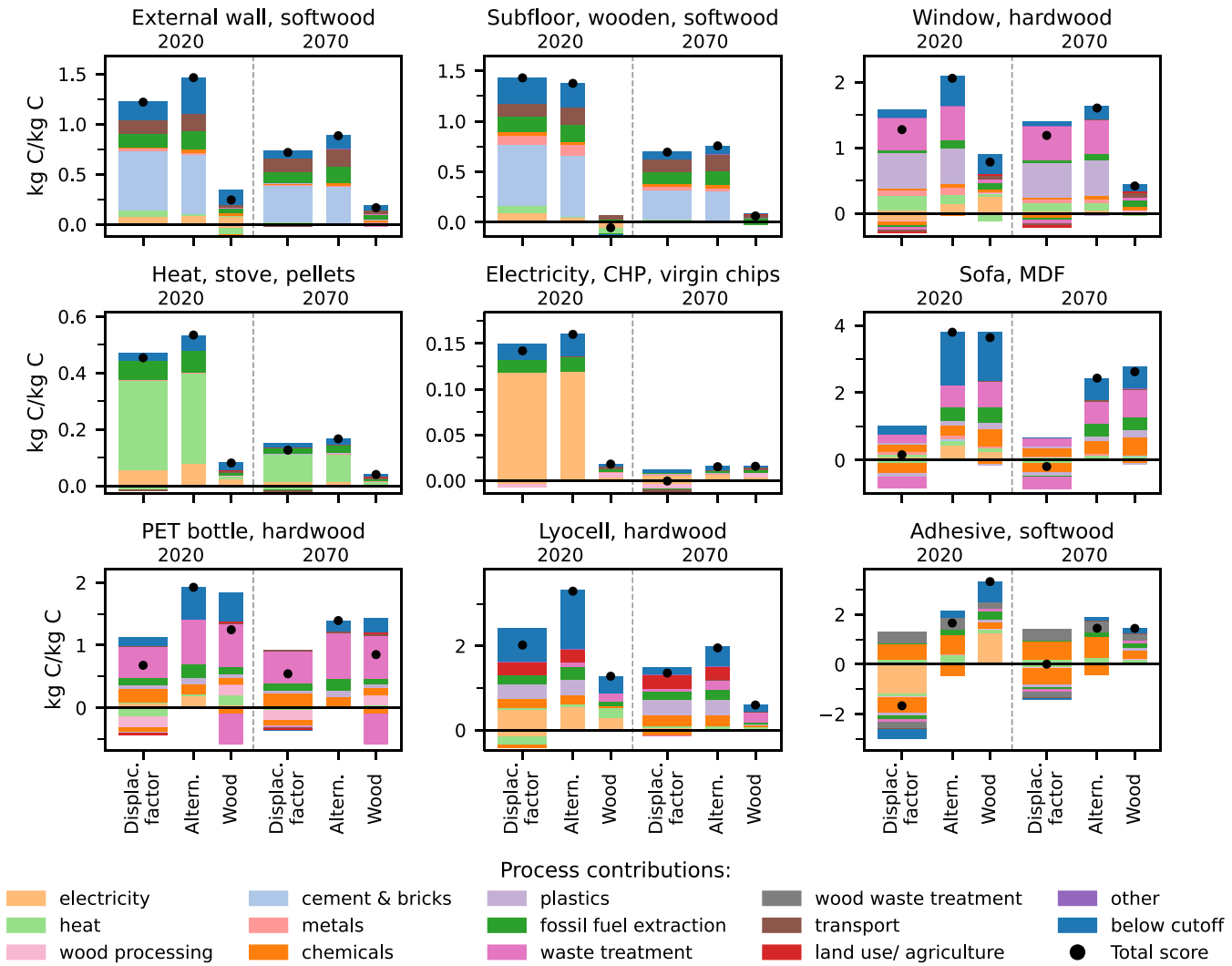


Figure 6. Process contributions for a selection of products for the years 2020 and 2070 in SSP1-L for displacement factors and their constituents of the wood-based and alternative product. Figures S13 and S14 show the other scenarios.

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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 Supporting Information 1 Section 2.5. Fossil CO_2 dominated elementary flow contributions across all products (Figure S12).

3.5. Sensitivity Analysis

Overall, results showed limited sensitivity to the tested parameters for changes to the foreground inventories (SA3−SA8) (Figures S26−S31), 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 partly canceled out.

The method-related sensitivity analysis (SA1 and SA2) showed larger effects, emphasizing that the choice of method and of background databases can influence results strongly. Replacing the time-explicit approach with a purely prospective model (SA1) yielded differences of up to 0.1 kg C/kg C higher DFs for long-lived products (Figure S21) because the prospective model applied a single scenario-year background database to all life cycle stages and so retains the higher energy-recovery benefit of earlier years for EoL processes. The differences between time-explicit and prospective approach converge by 2040−2050 as background databases beyond this point were largely similar. Using ecoinvent v3.11 (SA2), the conventional "static" LCA approach, changed DFs by between −0.74 and +0.76 kg C/kg C compared to the time-explicit results, with the difference widening in later years and under more ambitious scenarios (see Figure S22). This difference to ecoinvent combines two effects that should not be conflated with the temporal method itself: premise modifies the inventories relative to ecoinvent, causing a baseline divergence already for the 2020 database, while the temporal assignment of inventories to different prospective databases in the time-explicit approach adds to this difference.

4. DISCUSSION

4.1. Main Findings

This study confirms that wood-based products can lead to a reduction in fossil GHG emissions at the product level as they are on average associated with less fossil 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[3,39] 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 erode most quickly under the climate-stringent SSP1-L scenario. Our results show that diplacement using wood products becomes a less powerful mitigation lever over time. However, this declining trend is a positive sign from a system perspective because it reflects the decarbonization of supply chains assumed in our scenarios, which reduces total fossil GHG emissions across the economy.

Energy-related DFs in this study for 2020 are already lower than previously reported values,[3,5,7,9] 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 the competing 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 the ambitious decarbonization scenario. Material displacement thus provides more robust and sustained climate benefits than energy displacement a finding consistent with the broader literature.[1,40]

Similar to previous meta-reviews,[1,3,4,6] 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 the reviewed studies. In our study, all DFs were assessed within the same modeling 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 modeling choices also influence the results. The publicly available unit-process inventories make it possible to trace our modeling 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 modeling 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 modeling 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.

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4.2. Implications for Climate-Beneficial 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 sociotechnical developments.

In 2021, 47% of EU wood flows were directed to energy applications, 20% came from primary and 27% from secondary wood sources.[26] 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, 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 nonrenewable 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. In practice, wood is supplied in different dimensions and qualities, which limits its potential uses for some products. The allocation of wood to the most favorable end-uses is constrained by these material properties, as well as by market demands.

The significance of declining DFs becomes particularly clear 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.[41] and Buschbeck and Pauliuk[42] 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 deepen this gap.

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 modeling 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.

4.3.1. Integration of the Full Carbon Cycle. The DFs in this database cover fossil and land use change-related GHG emissions and exclude biogenic CO_2, consistent with the common practice of reporting displacement effects and biogenic carbon balances separately.[3] While our data gives insights into displacement-related, fossil climate impacts, the DFs are not intended for stand-alone 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 wood products, biogenic CO_2 emissions during production and EoL and carbon leakage.[1,5,39,43] Temporary carbon storage in wood-based products is not included in our DFs but can be calculated using established methods[44] and it can provide climate benefits independent of displacement and of economy-wide decarbonization. However, the net climate effect depends on the forest carbon stock changes caused by harvest, which may offset part of the product storage and displacement benefits.[45] Various approaches exist for assessing temporal dynamics of biogenic carbon within the LCA framework but they introduce significant methodological complexity and variability in results.[46]

4.3.2. Additionality, Market Effects, and Opportunity Costs. DFs quantify avoided emissions relative to a counterfactual reference system that never took place.[10] 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.[47,48] Given the comparative nature of DFs, the choice of the counterfactuals is as influential as the modeling of the wood-based products.[49] Our DFs assume a constant mix of products with equal weights for all products within end-use categories and constant lifetimes across the assessment period, whereas in reality the allocation of wood to end-uses, the product portfolio, and the service lives of wood-based and alternative products change over time, driven by market trends, user behavior, technological change, and policy. While this study assumed perfect product-level displacement, real-world displacement is often imperfect, which can substantially reduce the realized climate benefit.[10,25,50] 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,[51] which is uncertain under climate change and disturbances, and foregone displacement effects when wood use is shifted between applications.[9] Finally, the additionality of DFs causes methodological tension: GHG emissions avoided through displacement "inherently belong to the consequential modeling principle".[39] 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 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.

4.4.1. Coverage and Representativeness. The sample is not equally representative across all wood uses. Paper and paperboard, accounting for 24% of EU wood flows in 2021[26], were excluded entirely. For graphic paper, the wood-based product was considered dominant with no meaningful displacement effect consistent with previous work,[19,47] though comparisons to digital media have yielded both positive and

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negative DFs.[52] However, only 21% of paper and paperboard is graphic grade, while 62% is used for packaging and 12% for hygiene applications in 2024.[53] Our packaging products include wooden pallets and wood-based PET packaging but not paper-based packaging. Future research should prioritize hygiene and packaging applications of paper and paperboard to understand the achievable displacement effect of this large-volume end-use category. 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,[54] chemicals and textiles together constitute only 1% of EU wood use in 2021.[26] Our furniture LCIs, based on Geng et al.,[30] 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[26]) might be drawn with industry-average LCI data. The DFs of this study exclude the use phase, which may matter where the use phase impacts differ between wood-based and alternative products, for example textiles (washing, drying), windows (heating energy), cladding (maintenance), or packaging (weight during transport). The direction and size of this effect are unknown, and future work should collect robust use phase data for these products. 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.

4.4.2. Future Market Mixes. Our DFs compare today's wood and non-wood product pairs under supply chain decarbonization scenarios. However, the products in use, their market shares, and the counterfactuals are likely to differ in the future, for example, through novel wood-based and alternative products, changes in market structure, or wider use of wood. Future research should therefore investigate future products and market mixes to allow a more dynamic comparison of products.

4.4.3. 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. Moreover, using one aggregated region (WEU) for all background commodity markets does not allow country-level disaggregation of DFs. Furthermore, many ecoinvent datasets reflect past average conditions and limited regionalization: data limitations that are carried forward to the prospective versions for processes that the IAM does not update. The influence of the background database on the DFs is illustrated by sensitivity analysis SA2. Future research could expand the set of IAMs beyond IMAGE to test the sensitivity of results to IAM-specific projections for similar climate targets or at finer geographical resolution. For a detailed discussion of pLCI database limitations, the reader is referred to de Bortoli et al.[55] and Paris et al.[56]

4.4.4. 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[24] for all emissions regardless of when they occur, meaning that emissions from production in 2020 and EoL emissions 50 years later are treated as climatically equivalent although climate responses have been shown to be time-sensitive.[57] A fully time-consistent approach would align the temporal scope of the inventory with that of the LCIA step[58] 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.[59]

4.5. Outlook

Our harmonized, transparently documented study covering 81 wood product variants shows that although wood-based products deliver a real climate benefit today, with substantial variation across products and their alternatives, this benefit is expected to shrink if competing supply chains decarbonize. For long-lived products, time-explicit modeling is required to capture the actual state of processes occurring late in the life cycle, an effect that neither conventional nor purely prospective LCA captures.

Under the assumed decarbonization projections, these diminishing displacement effects call for a conservative evaluation of future benefits of the wood-based bioeconomy and for directing wood flows away from energy and toward long-lived material applications such as construction and textiles, where the benefit is largest and most durable. Climate-smart wood use should therefore aim not at expanding harvest volumes but at reallocating existing flows, since our results suggest that displacement benefits alone are unlikely to justify harvest intensification. Future climate strategies should shift the focus from maximizing displacement effects of wood products to system-wide emission reduction.

■ ASSOCIATED CONTENT

Data Availability Statement

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

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.6c10525.

Explanation of modeling choices, sensitivity analysis, and additional figures (PDF)

Foreground life cycle inventory (XLSX)

Product-level displacement factor results (XLSX)

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Notes

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