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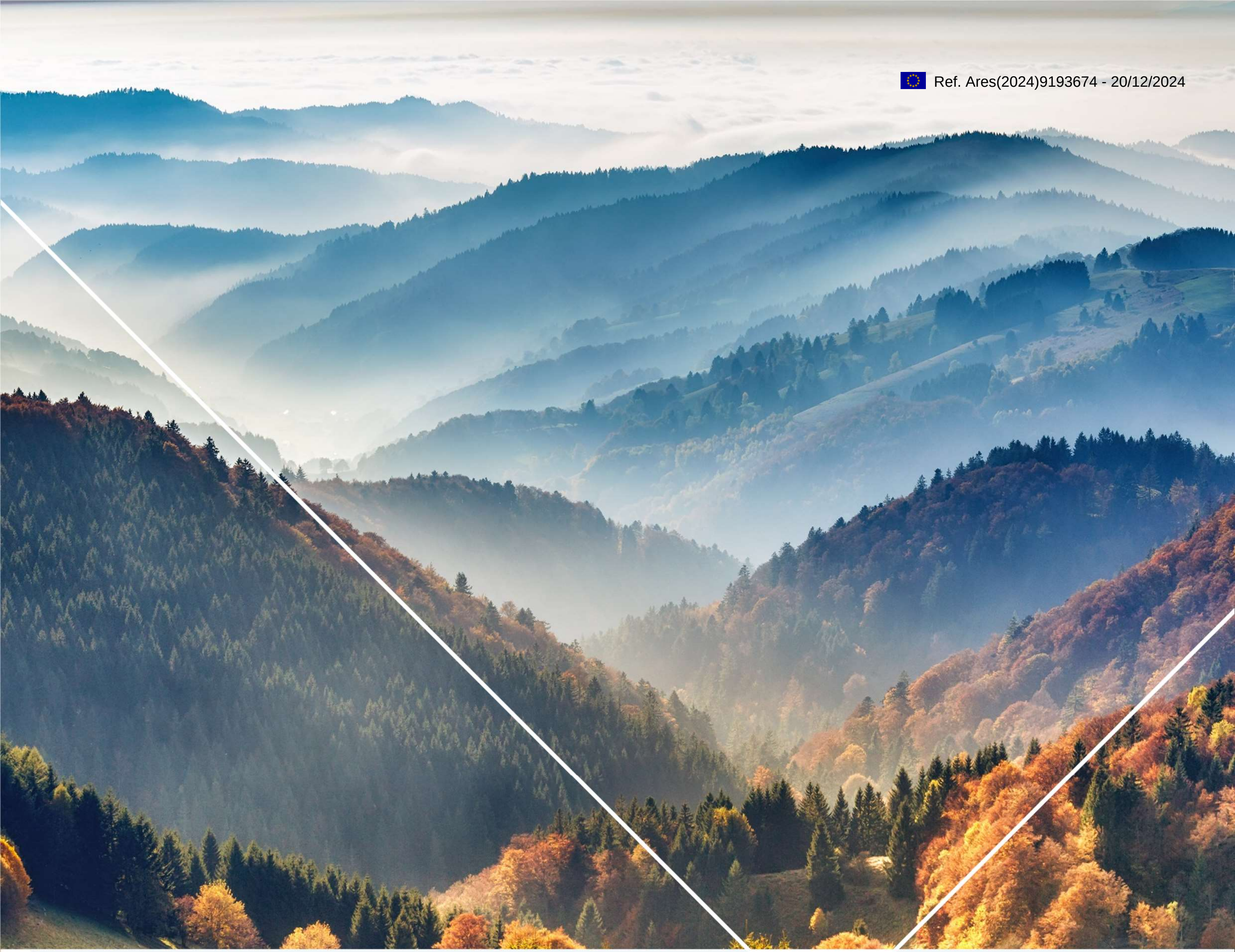

Report on environmental impact assessment of selected wood products relative to the products they substitute

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Executive summary

This deliverable addresses the critical question of how the different use cases of wood, starting from the current supply, can be shifted to optimize environmental performance. The transition to an optimized use of wood requires a thorough understanding of the current supply chain and the ecological implications of various applications. To provide a comprehensive analysis, this study will focus on the wood supply at NUTS1 level in the region of Flanders. Using a consequential life cycle assessment (LCA), the analysis followed four key steps: 1) outlining the wood processing chain and associated sectors (i.e., constructions, furniture, packaging, bioenergy, and paper and cardboard) as well as the replacement products for wood within these sectors, 2) identifying relevant alternative wood use scenarios for consideration in the LCA, 3) modeling the existing wood processing and usage market as a business-as-usual (BAU) scenario, and 4) modeling the wood processing and usage markets for the alternative use scenarios to calculate the environmental impact of wood utilization in reference to the BAU.

We find that scenarios typified by a diversion of wood towards use in long-lived products (scenarios 1 and 3) result in the largest environmental improvements across the impact categories. Scenario 1 is defined by a 20% reduction in wood allocated to bioenergy, diverting this wood instead to construction and furniture. Likewise, scenario 3 is defined by a reallocation of wood to panel materials and furniture as a result of a decrease in demand for paper products. Simultaneously, we find limited improvements relative to the BAU for scenario 2, which is defined by a reallocation of wood within the bioenergy sector. Our results demonstrate that increasing the share of wood destined for long-lived wood products may hold significant potential for improving environmental performance and sustainable resource management in Flanders; more so than diverting wood use within short-lived use cases such as bioenergy.

Introduction

This deliverable addresses the critical question of how the different use cases of wood, starting from the current supply, can be shifted to optimize environmental performance. Wood, as a renewable resource, holds significant potential for mitigating environmental impacts, particularly when managed and harvested sustainably. However, the environmental implications of its extraction and use must be carefully considered. Harvesting wood from forests reduces the carbon uptake ability of the land for a significant period—often decades—until newly planted trees can compensate for the lost capacity. This dynamic approach highlights the immediate short-term increase in atmospheric carbon that can result from forest management practices.

The transition to an optimized use of wood requires a thorough understanding of the current supply chain and the ecological implications of various applications. To provide a comprehensive analysis, this study will focus on the wood supply at NUTS1 level in the region of Flanders. The first step in this analysis involves modeling the existing wood processing and usage market as a baseline scenario, allowing for the calculation of the environmental impact of wood utilization in its current state. A consequential Life Cycle Assessment (LCA) approach will be employed as this allows us to model the environmental outcomes of decisions that affect product flows. This approach is crucial as it considers the potential for wood-based products to replace non-renewable materials in various applications; for example, wooden beams in construction can substitute a specific quantity of concrete and steel. The identification of alternative products for each wood use category will be informed by expert opinions, ensuring the validity and relevance of the findings.

The ultimate goal of this research is to model several alternative wood use scenarios. For instance, one scenario may explore the allocation of all wood with suitable characteristics to construction applications. It is essential to note that the total volume of wood available is constrained, as are the wood fractions with varying dimensions; thus, an increase in wood use for construction will result in reduced availability for other applications. For each of these scenarios, the overall environmental impacts will be calculated, enabling a comparison of the sustainability of different wood utilization pathways. This research aims to identify the most effective strategies for optimizing wood use, contributing to improved environmental performance and sustainable resource management in Flanders.

Material and methods

Wood harvest and processing

In this section, we detail the modeling of wood harvesting and processing in this study, providing a thorough explanation of the assumptions, data sources, and calculations that were used to estimate the wood flows in Flanders. These assumptions and methods form the basis for our LCA, allowing us to assess the environmental impacts of wood-based products across various sectors.

Wood Harvest Modeling

The modeling of wood harvest focuses on the sustainable extraction of wood from Flemish forests. While specific forest management strategies and harvesting practices are not the focus of this study, we rely on existing Ecoinvent (v3.9.1) processes for the growth of softwood and hardwood species. These processes represent typical forest growth conditions and forest management practices in Europe, thereby providing a reliable background for our modeling.

For the purpose of this study, we assume a given quantity of wood that is harvested annually from Flanders' forests. The annual harvest volumes are calculated based on:

- Forested area: The total area of forested land in Flanders is derived from reports such as (BIOWOOD report, Lopez et al., (2022))
- Species distribution: Data from forest inventories by ANB (Agentschap voor Natuur en Bos, https://www.natuurenbos.be/dossiers/bosinventaris) and INBO (Instituut voor Natuur- en Bosonderzoek) is used to determine the distribution of tree species within these forested areas.
- Forest yield tables: Yield tables, typically based on long-term studies of forest growth rates, provide the annual growth rate of different tree species, expressed in cubic meters (m^3) per hectare per year. These tables form the foundation for calculating the potential wood yield from Flemish forests.

The total growth of wood for each tree species is estimated by multiplying the species-specific annual growth rate by the forest area covered by that species in Flanders. Tree species are categorized into softwood (such as pine and spruce) and hardwood (such as oak, beech, and poplar), and the total yearly growth for each category is calculated accordingly. The results of these calculations are shown in Table 1.

Table 1: Estimated yearly growth and potential sustainable harvest of hardwood and softwood in Flanders

	Estimated yearly growth (m^3)	**Potential sustainable yearly harvest (m^3)**
Hardwood	699 517	489 662
Softwood	722 708	505 895

Sustainable Harvest Assumptions

To ensure that wood harvesting is sustainable, we assume that only a portion of the annual wood regrowth is harvested, in line with sustainable forest management practices. Based on current guidelines and recommendations for sustainable forestry, we assume that 70% of the yearly forest regrowth can be harvested without degrading forest ecosystems (EEA, 2017). This figure reflects the balance between wood extraction and the maintenance of healthy forest growth, biodiversity, and carbon sequestration capacity.

Using this 70% factor, we calculate the potential sustainable yearly harvest for both softwood and hardwood categories (Table 1). These values represent the upper limit of wood that can be sustainably harvested from

Flanders' forests each year. Interestingly, our estimated sustainable harvest is approximately twice the actual wood harvest reported in the Eco2Eco project (eco2eco, 2021), highlighting the relatively low rate of wood extraction in Flanders. This discrepancy may be attributed to under-utilization of forest resources, due to either economic constraints or policy choices aimed at preserving forest ecosystems.

Wood Processing Chain

Following the identification of sustainable harvesting assumptions we examine the journey of harvested logs through the wood processing chain. Our approach follows the frameworks established by Jonsson et al. (2018) and Ramage et al. (2017), which provide a comprehensive representation of the wood supply chain from forest to final product.

1. **Transportation of logs:** After trees are felled, the logs are transported to various processing facilities, most commonly sawmills. At the sawmills, the logs are sorted into different streams based on their size, quality, and intended application. The three primary categories are:
    - Sawlogs: high-quality logs suitable for timber production;
    - Pulpwood logs: logs destined for paper, particleboard, and fiberboard production;
    - Energy logs: lower-quality logs or residues that are used for bioenergy purposes, either at a household scale (e.g., log stoves) or in larger-scale power plants.
2. **Processing of sawlogs:** Sawlogs are processed into sawn timber, which can be treated or left untreated, depending on the intended application. Timber can be further processed into engineered wood products such as glued laminated timber (glulam) or cross-laminated timber (CLT), both of which are commonly used in modern construction. Logs may also undergo peeling to produce plywood sheets, or stranding, a process used to create oriented strand board (OSB) and fiberboard. These sheet materials are widely used in the construction industry for paneling, structural sheathing, and insulation.
3. **Processing of pulpwood logs:** Pulpwood logs are primarily used in the production of paper, particleboard, and fiberboard. Some of this pulpwood is also processed into wood pellets, a product used for bioenergy applications, including pellet stoves and industrial combined heat and power (CHP) plants.
4. **Waste streams and by-products:** During the processing of sawlogs and pulpwood logs, a variety of waste streams are generated, such as wood chips, sawdust, and bark. These by-products are often utilized in secondary applications, either as inputs for pulp and paper production, as feedstock for bioenergy, or for on-site energy generation in sawmills and other wood-processing facilities.

The wood processing system modeled here is illustrated in Figure 1, detailing the flow of wood through each stage from the initial harvest to final product production. Notably, the model also includes the energy requirements for each processing step, such as milling, drying, peeling, and stranding. In many wood-processing facilities, the heat and electricity needed for these operations are supplied by burning wood residues, making the process energy self-sufficient to a large extent. Waste wood that cannot be used for product manufacturing is typically directed to bioenergy applications. Logs classified as unsuitable for pulpwood or timber are either burned in small-scale domestic stoves or sent to large-scale bioenergy plants, where they are used for electricity and heat production.

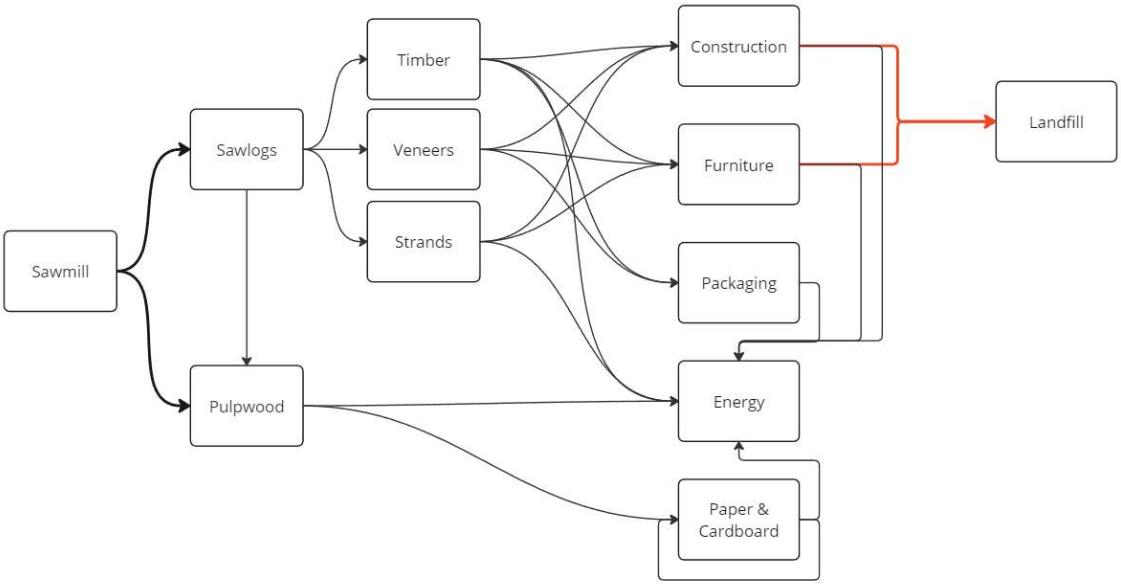

Figure 1: Wood processing system

For paper production, the input flows of softwood and hardwood are mixed, and for this study, we assume that the distribution of wood types is not critical to the environmental impacts. Paper products are typically manufactured using a combination of both softwood and hardwood pulp, with no significant differentiation in their environmental performance in the scenarios we modeled.

Each of these categories is further divided into specific products, such as particleboard, fiberboard, and plywood for construction, or sawn timber for furniture manufacturing. By modeling these flows, we aim to capture the entire lifecycle of wood products from harvest to end-of-life, providing a comprehensive picture of the environmental impact associated with wood use in Flanders.

Replacement products

In order to accurately assess how shifts in wood use influence the total environmental impact, it is critical to account for the broader market effects of increasing or decreasing the availability of certain wood products. In a consequential LCA, we aim to model the environmental outcomes of decisions that affect product flows. Therefore, when the supply of a particular wooden product changes, we need to understand what materials would likely replace the wooden product in the market or, conversely, what wood products could replace non-wood materials.

This process of substitution is essential for evaluating the indirect effects of changes in wood supply. Each wooden product is paired with one or more non-wood alternatives that could realistically substitute for the wood product in specific applications. The substitution products were selected based on their prevalence in the market and functional equivalence to the wooden products. For example, in construction, wood can often be replaced by reinforced concrete, depending on the specific function of the product.

Table 2 presents the product categories examined in this study, their associated wood products, the type of wood used, and the identified replacement materials. Each substitution relationship is modeled with a fixed conversion factor that represents the equivalency of the wooden product and its non-wood counterpart. This ensures that when the flow of a wood product decreases, the corresponding increase in the replacement material reflects realistic market behavior.

Table 2: Overview of replacement products per product category

Product category	Wood product	Wood type	Replacement product
Construction	Beam	Sawnwood	Reinforced concrete
	Column	Glulam	Reinforced concrete
	Panels	OSB	gypsum plasterboard
	Flooring	Laminate	PVC flooring
		Parquet	Ceramic tiles
	Window frame	Sawnwood	Aluminium window frame
			PVC window frame
	Insulation material	Wood fibers	Rockwool
			PUR
Furniture	Table legs	Sawnwood	Coated steel
	Chair	Sawnwood	Plastic
Packaging	Pallet	Sawnwood	Plastic pallet
Bio energy	Log stove	Cleft timber/sawnwood	Natural gas
	Pellet stove	Wood pellets	Natural gas
	Industrial CHP	Wood	Natural gas
Paper and cardboard	Container board	Pulpwood	No replacement products
	Carton board		
	Wrapping paper		
	Sanitary and household paper		
	Coated paper		
	Uncoated paper		
	Newsprint		

Construction Products

In the construction sector, wood is a versatile material commonly used in beams, columns, panels, flooring, and insulation. To model the potential shifts in environmental impact, we identified the following substitutions:

- Beams and columns made from sawnwood and glulam can replace reinforced concrete, a typical non-wood structural material. Reinforced concrete has a much higher environmental footprint in terms of CO_2 emissions and resource use, making its substitution significant for overall environmental impact.
- OSB panels used for sheathing in construction can be substituted by gypsum plasterboard, which has different material properties but can fulfill similar functions in terms of structural sheathing and internal wall applications.
- For flooring, wood-based products such as laminate and parquet can replace PVC flooring and ceramic tiles, respectively. These alternatives are common in modern building applications but come with

different environmental trade-offs, particularly in terms of fossil fuel use and chemical inputs in production.

- Window frames made from sawnwood are modeled with two possible substitution materials: aluminum and PVC window frames, both of which are commonly used alternatives. The environmental impact of these materials varies, with aluminum having a higher energy demand during production compared to PVC, while PVC has issues related to plastic waste and toxic by-products.
- Insulation materials made from wood fibers can substitute Rockwool and PUR (polyurethane), which are widely used insulation materials with different thermal properties and environmental impacts. Rockwool is a mineral-based insulation material, while PUR is a petroleum-based product, contributing to the use of non-renewable resources.

Furniture Products

In the furniture sector, wood remains a popular material, but there are a variety of substitute materials. Table legs and chairs made from sawnwood can replace coated steel and plastic, respectively. Coated steel, though durable, has a higher environmental burden due to energy-intensive manufacturing processes. Plastic, while lighter, brings concerns related to end-of-life waste management and the potential for pollution.

Packaging Products

In the packaging industry, pallets made from sawnwood can substitute plastic pallets, which are increasingly being used due to their durability and reusability. However, plastic pallets have a higher environmental cost in terms of fossil fuel dependency and waste disposal challenges, particularly in regions with poor recycling infrastructure. The substitution between wood and plastic in this context has significant implications for the circular economy and material efficiency strategies.

Bioenergy Products

For bioenergy, wood products such as cleft timber, sawnwood, and wood pellets are used for heat generation in stoves and combined heat and power (CHP) plants. The identified substitute for these bioenergy applications is natural gas, a widely used fossil fuel.

In the case of log stoves using cleft timber or sawnwood, the substitution is natural gas, which provides a stable and consistent energy source but contributes to greenhouse gas emissions through fossil fuel combustion.

For pellet stoves and industrial CHP plants, where wood pellets and other wood products are used for energy, the substitution is also natural gas. The shift from wood to natural gas in energy applications raises important questions about carbon neutrality, as wood, when sustainably sourced, is considered renewable, whereas natural gas is a finite resource contributing to climate change.

Paper and cardboard products

In the case of paper and cardboard products, none of these items have clear replacement products. For sanitary and household paper, we assume there are no non-wood alternatives in the market. Consumers continue to require these essential daily-use products without viable substitutes.

For other types of paper and cardboard, such as container board, carton board, wrapping paper, coated paper, uncoated paper, and newsprint, a reduction in wood-based production does not lead to a direct replacement with non-wood alternatives. For instance, when fewer people purchase physical newspapers, it does not imply that they will buy a digital device like a tablet or laptop specifically to read online newspapers. This shift towards digitalization does not equate to direct material substitution.

This lack of substitution indicates that changes in wood supply within the paper and cardboard category do not result in increased demand for alternative materials. Instead, shifts in consumer behavior or reduced demand for physical paper products typically lead to an overall decrease in material use, rather than substitution by other non-wood materials.

Fixed Conversion Factors

Each of these product substitutions is modeled with a fixed conversion factor to reflect the functional equivalency between the wood product and its substitute. For example, a given volume of sawnwood for construction might replace a corresponding volume of reinforced concrete, while a certain mass of wood fibers for insulation is replaced by Rockwool or PUR at a rate that reflects their respective thermal efficiency and density.

The use of these conversion factors is critical in the modeling process because it ensures that the LCA results accurately capture the environmental trade-offs of substituting wood with non-wood materials (or vice versa). It allows the consequential LCA to estimate how a change in the supply of wood would affect the demand and production of other materials, and consequently, their associated environmental impacts.

Scenarios

The evaluation of environmental impacts can vary significantly based on assumptions made about wood use. The purpose of the scenario modeling is to understand how different decisions about wood use in Flanders could alter environmental outcomes. By shifting wood flows away from certain products and towards others, we can better estimate the consequences of strategic decisions related to sustainable forest management, wood processing and product usage.

Business-As-Usual

The “Business-As-Usual” (BAU) scenario provides the baseline against which other scenarios are compared. It reflects the current state of wood harvesting and processing in Flanders and is constructed based on the data from the Eco2Eco project WP3 report (Oldenburger et al., 2017). In their report, they give a distribution of the flows of different types of wood (softwood, hardwood and poplar) over six different product types for wood harvested and processed in Flanders. From these values, we calculated the percentage of wood that goes to each of the six product types for total hardwood (hardwood and poplar combined) and softwood. These percentages were then multiplied by the total harvested volumes from Flanders (see earlier) to get the amount of each wood type, in m³, that is sent to each of the 6 product categories, as displayed in table 3.

Table 3: Estimated amount of softwood and hardwood sent to different product categories in Flanders

	Softwood (m³)	**Hardwood (m³)**
Veneer	0	14419
Sawnwood	13710	9012
Packaging	93227	61283
Paper and cardboard	35646	11415
Panel material	274198	42057
Fire wood	89114	351475

Scenario adjustments and assumptions

Building upon the BAU scenario, several alternative scenarios were developed to explore how changes in the distribution of wood flows could affect environmental outcomes. In this study, we also considered the theoretical sustainable harvest potential from Flemish forests. According to prior research and data, this sustainable harvest level is significantly higher than the current harvest (Oldenburger et al., 2017). As a result, our scenarios implicitly assume that wood harvest in Flanders could increase substantially, reflecting potential future shifts toward more intensive yet sustainable forest management. Below, three scenarios are described that are compared to the BAU-scenario.

These scenario adjustments reflect a broader strategy of promoting sustainable wood use in Flanders. By shifting wood away from short-lived and high-impact uses like bioenergy and paper production, and towards long-lived products like construction materials, furniture, and panel materials, we can maximize carbon storage and reduce the environmental impacts of wood processing. Each scenario highlights different pathways for optimizing wood flow distribution in line with sustainability goals, offering valuable insights for policymakers and industry stakeholders.

Scenario 1: decrease in bioenergy

In Scenario 1, the distribution of wood for bioenergy is reduced by 20%, with the diverted wood allocated primarily to construction and furniture. The rationale for this adjustment is that using wood for bioenergy results in significant greenhouse gas emissions due to combustion, while reallocating this wood to construction and furniture promotes carbon sequestration and reduces the need for more carbon-intensive materials like steel and concrete.

The shift away from bioenergy has several implications:

- Construction: Wood used in construction serves as a carbon sink, locking in carbon for decades or even centuries, while also substituting for non-renewable materials.
- Furniture: Similar to construction, the use of wood in furniture prolongs the lifecycle of wood products, keeping carbon sequestered for a longer period compared to immediate combustion for energy.

This scenario assumes that the technology and infrastructure for shifting wood from bioenergy to long-lived products are available, and that there is a growing market demand for wood-based construction materials and furniture. The expected outcome is a reduction in overall climate change impacts, as more carbon is stored in wood products rather than released during energy production.

Scenario 2: shift in bioenergy towards pellets

Scenario 2 examines a shift within the bioenergy sector itself, by altering the composition of wood used for conventional pellets and high-efficiency pellets. Currently, the distribution is 90% conventional pellets and 10% high-efficiency pellets. In this scenario, the ratio is adjusted to 50% conventional pellets and 50% high-efficiency pellets.

This adjustment is based on the premise that high-efficiency pellets result in lower emissions during combustion and higher energy output per unit of wood. By increasing the share of high-efficiency pellets, this scenario aims to reduce the overall environmental burden of bioenergy use, particularly in terms of:

- Energy efficiency: More energy is extracted from the same amount of wood.
- Greenhouse gas emissions: High-efficiency pellets lead to fewer emissions per unit of energy generated compared to conventional pellets.

This scenario assumes technological advances and policy incentives that encourage the production and use of more efficient pellet types, ultimately reducing the negative impacts associated with wood combustion for energy.

Scenario 3: decrease demand for paper

In Scenario 3, the demand for paper products is significantly reduced, leading to a reallocation of wood that would typically be used for pulp and paper production. In this scenario, all the pulpwood that would have gone into paper manufacturing is instead diverted to panel materials and furniture.

The decreased demand for paper is based on assumptions about the digitalization of communication and documentation, reducing the need for physical paper. For sanitary and household paper, the demand remains fixed, since consumers continue to require these essential daily-use products without viable substitutes. Additionally, societal and industrial shifts towards more sustainable packaging alternatives could further reduce the reliance on wood for paper production. By reallocating this wood to panel materials and furniture, this scenario seeks to:

- Reduce energy and chemical use: Paper manufacturing is resource-intensive, requiring significant energy and chemicals for pulp processing.
- Extend product lifecycles: Panel materials and furniture are long-lived products that contribute to carbon storage, as opposed to the short lifespan of most paper products.

This scenario assumes a market shift driven by technological and environmental trends, where digitalization and the circular economy reduce paper demand, freeing up more wood for durable goods.

These scenario adjustments reflect a broader strategy of promoting sustainable wood use in Flanders. By shifting wood away from short-lived and high-impact uses like bioenergy and paper production, and toward long-lived products like construction materials, furniture, and panel materials, we can maximize carbon storage and reduce the environmental impacts of wood processing. Each scenario highlights different pathways for optimizing wood flow distribution in line with sustainability goals, offering valuable insights for policymakers and industry stakeholders.

LCA modelling

Goal and scope definition

This LCA study adheres to the ISO 14040/44 guidelines, ensuring a standardized and transparent approach to environmental impact analysis. A consequential LCA approach is adopted, focusing on the environmental consequences of changes in the wood product system. This approach allows us to explore how shifts in wood flows and product substitution affect the overall lifecycle impacts.

System boundaries

The system boundaries for this study are defined as *cradle to grave*, meaning the analysis covers the entire lifecycle – from the initial wood supply (forest growth and harvesting in Flanders) to the disposal of waste wood at the end of its useful life. Although the raw material production stage (forest growth) is modeled in the background using pre-existing Ecoinvent v3.9.1 processes, the evaluation of different forest management practices is outside the scope of this study. This ensures that we focus on the downstream impacts of wood processing, use and disposal without delving into forest management dynamics.

Each wooden product evaluated in this study has one or more non-wood alternatives, such as steel or concrete for beams in construction. These non-wood alternatives are include to reflect the consequential nature of the study, where the substitution of materials plays a key role in determining the environmental impacts. This allows for a more comprehensive understanding of how increase wood use can replace less sustainable materials in various applications.

Functional unit

The functional unit in this study is defined as the *total wood production and use in Flanders*. This functional unit represents the amount of wood harvested, processed, and distributed across different sectors, reflecting the entirety of the wood flow system in Flanders. It serves as the reference point for all environmental impact assessments, ensuring that the comparisons between scenarios are based on a consistent and comprehensive measure.

By adopting the total wood production and use as the functional unit, the study captures both the supply-side dynamics (harvesting and processing) and the demand-side uses (from bioenergy to long-lived products like construction and furniture). This approach ensures that the environmental impacts are assessed across the full spectrum of wood utilization, providing a holistic view of how shifts in wood flow distribution affect the overall system.

In addition, the functional unit aligns with the study's cradle-to-grave scope by incorporating the entire lifecycle of wood products, including waste production and disposal. Therefore, not only does it account for the wood that is used in construction, furniture, and other long-lived applications, but it also covers the waste generated at the end of the wood's useful life. This waste wood, whether used for bioenergy or discarded, is a critical part of the system boundaries and directly influences the study's environmental impact analysis.

Life Cycle Inventory (LCI)

As detailed earlier, the modeling of the wood market is based on data from relevant academic papers and industry reports (European Commission, 2023; Jonsson et al., 2018; Oldenburger et al., 2017), which help quantify the wood flows within the Flanders market. This data forms the foundation for the allocation of wood to various product categories and scenarios.

For secondary data, the Ecoinvent v3.9.1 database is used to model the background processes. This includes data for the processing, manufacturing, and waste management steps for both wood and substitution products (e.g., steel, concrete). Where possible, market processes from Ecoinvent are used, incorporating the transportation of raw materials and products into the overall process.

In alignment with the EN 15804 standard, the LCA considers the entire lifecycle of wooden products, divided into multiple stages: (A) production, (B) use, (C) end-of-life and (D) reuse, recovery and recycling beyond the lifecycle.

The production phase consists of the following stages:

- A1 Raw Material Supply: The raw material supply includes the growth and harvesting of trees, based on forestry production data from Flanders. Since forest management practices are excluded from this study's scope, this stage uses pre-existing datasets from the Ecoinvent database.
- A2 Transportation of Raw Materials: This stage models the transport of harvested wood from the forest to the processing or manufacturing site. Data includes transportation distances, types of vehicles used, and fuel consumption.
- A3 Manufacturing/Processing: All wood processing steps are included in this stage, from logs to the finished product. These steps can involve sawing, drying, milling, gluing, and other relevant treatments, depending on the specific product being modeled. For substitution materials, the equivalent manufacturing processes are included, allowing for a comparative analysis of impacts.
- A4 Transport to Installation Site: The transportation of finished wood products from the manufacturing site to their installation location (such as a construction site) is modeled, with transportation logistics varying based on the scenario and product type.

- A5 Installation/Construction: This phase considers the installation of wood-based products in their respective applications (e.g., beams in construction). The specific processes required for installation are included, which can vary depending on the product and its end use.

The use phase covers multiple aspects, including:

- B1 Use: Direct use of the product in its functional role (e.g., wooden beams in construction).
- B2 Maintenance: Any maintenance required to extend the functional lifespan of the wood product (e.g., surface treatments or repairs).
- B3 Repair: Processes required to repair damaged wood products.
- B4 Replacement: Replacement of parts or the entire product when necessary.
- B5 Refurbishment: Refurbishment processes to restore wood products for extended use.
- B6 Operational Energy Use: Energy consumed during the use phase, such as in temperature control for wooden buildings.
- B7 Operational Water Use: Water consumption associated with wood use, though typically minor in most wood applications.

The end-of-life phase considers what happens when the wood product reaches the end of its useful lifespan:

- C1 Demolition: Processes involved in dismantling or demolishing wooden structures or products.
- C2 Transportation to Waste Processing: Transportation of waste wood to recycling or disposal facilities.
- C3 Waste Processing: The processing of wood for recycling or repurposing, or its preparation for disposal.
- C4 Disposal: The final disposal of wood waste, including landfilling or incineration.

Finally, the last stage “beyond the lifecycle” examines the potential for wood materials to be reused, recycled, or recovered after their initial lifecycle ends. For example, wood can be repurposed for lower-value applications or recovered for energy production.

Life Cycle Impact Assessment (LCIA)

The environmental impacts of each scenario are assessed using the ReCiPe 2016 v1.03 (Huijbregts et al., 2016) method at the midpoint level. The following ReCiPe impact categories are included in the analysis:

- Acidification terrestrial (kg SO_2-eq) refers to the contribution of various pollutants, such as sulfur dioxide (SO_2), to the acidification of soils and waters. Acidification can lead to harmful effects on plant life, soil microorganisms, and aquatic ecosystems, ultimately disrupting biodiversity and altering nutrient cycling. A reduction in this impact category is indicative of a healthier terrestrial ecosystem.
- Climate change (kg CO_2-eq) measures the total greenhouse gas emissions resulting from wood production and use, expressed as carbon dioxide equivalents. This category is critical as it directly relates to global warming potential. Scenarios with lower climate change impacts indicate a transition towards more sustainable wood utilization practices that can help mitigate climate change.
- Freshwater ecotoxicity (kg 1.4-DCB-eq) assesses the potential toxic effects of pollutants released into freshwater ecosystems. This category is crucial for understanding the impacts of wood production on aquatic life, including fish and other species. Lower values in this category suggest reduced toxicity and improved water quality in freshwater systems.

- Marine ecotoxicity (kg 1.4-DCB-eq) similarly evaluates the potential harmful effects of pollutants on marine ecosystems. Given the interconnectedness of marine and freshwater systems, minimizing marine ecotoxicity is vital for preserving biodiversity and maintaining healthy aquatic environments.
- Terrestrial ecotoxicity (kg 1.4-DCB-eq) addresses the toxicity impacts on terrestrial ecosystems due to chemical releases, such as heavy metals or pesticides. High values in this category indicate significant harm to soil and plant health, affecting agricultural productivity and natural habitats.
- Energy resources: non-renewable, fossil (kg oil-eq) quantifies the consumption of non-renewable energy resources, specifically fossil fuels. This category highlights the reliance on fossil fuels in the wood production lifecycle, and reductions in this impact reflect a shift towards more sustainable energy sources.
- Freshwater eutrophication (kg P-eq) measures the nutrient loading, particularly phosphorus, in freshwater systems, leading to excessive growth of algae and subsequent oxygen depletion. Reducing this impact is critical for maintaining the health of freshwater bodies and preventing harmful algal blooms.
- Marine eutrophication (kg N-eq) focuses on nitrogen loading in marine environments, which can also lead to eutrophication. High nitrogen levels can significantly impact marine life, highlighting the importance of minimizing nutrient runoff in wood production and use.
- Human toxicity, carcinogenic (kg 1.4-DCB-eq) assesses the potential health risks to humans from exposure to carcinogenic substances released during the wood production process. Lower values indicate a reduced risk of cancer among populations living near wood production facilities.
- Human toxicity, non-carcinogenic (kg 1.4-DCB-eq) measures the potential health impacts from exposure to non-carcinogenic toxins. This category is essential for evaluating the overall health implications for workers and communities affected by wood production activities.
- Ionizing radiation (kg Co-60-eq) quantifies the potential impact of ionizing radiation emitted from various processes associated with wood production. This impact category is crucial for understanding the health risks associated with radiation exposure.
- Land use (m^2*a crop-eq) assesses the amount of land area required for wood production, expressed in terms of crop equivalency. This metric reflects the land efficiency of wood production systems and their sustainability in terms of habitat preservation and land resource allocation.
- Material resources: metals/minerals (kg Cu-eq) quantifies the consumption of non-renewable metal and mineral resources in wood production. Reducing this impact is vital for minimizing resource depletion and promoting circular economy practices.
- Ozone depletion (kg CFC-11-eq) measures the potential impacts on the stratospheric ozone layer, which protects the Earth from harmful ultraviolet radiation. Reductions in this category are essential for preventing environmental and health-related issues associated with increased UV exposure.
- Particulate matter formation (kg $PM_{2.5}$-eq) assesses the emissions of fine particulate matter from wood production and use, which can significantly affect air quality and human health. Lower values indicate improved air quality and reduced respiratory health risks.
- Photochemical oxidant formation: human health (kg NOx-eq) quantifies the emissions of precursors to photochemical oxidants, such as ozone, which can adversely affect human health. Reducing this impact is crucial for enhancing public health, particularly in urban areas.
- Photochemical oxidant formation: terrestrial ecosystems (kg NOx-eq) similarly evaluates the effects of photochemical oxidants on terrestrial ecosystems, impacting plant health and biodiversity. Minimizing these emissions is essential for sustaining healthy ecosystems.

- Water use (cubic meter) assesses the total volume of water consumed throughout the wood production lifecycle. Reducing water use is critical for sustainable resource management, especially in regions facing water scarcity.

The Activity Browser software is used for this assessment, ensuring that the LCIA results are comprehensive and cover all relevant environmental factors.

Results

Baseline: BAU

The BAU-scenario represents the baseline for evaluating the environmental impacts of wood use in Flanders, based on current practices of wood harvesting, processing, and distribution, as reflected in the Eco2Eco project. Wood in Flanders is primarily processed into five product categories: construction materials, furniture, pallets, paper and bioenergy. The environmental impacts are distributed across impact categories as shown in Table 4 (Appendix A). For each impact category the total impact is estimated, as well as the share of this total impact attributed to the five wood-use sectors (i.e., construction, furniture, pallets (packaging), paper and bioenergy). The total impacts for acidification are primarily driven by the construction sector, which contributes 52%, highlighting the sector's extensive use of materials and energy-intensive processes. The pallet (packaging), bioenergy and furniture contribute a further 20% and 11.5% and 10%, respectively. The implications of acidification in this scenario suggest a serious risk to soil and water quality due to the release of nitrogen and sulfur oxides.

In terms of climate change, the bioenergy sector contributes 96% to the overall impact, showcasing its dual role as both a renewable energy source and a contributor to climate change impacts, as its production processes are not without environmental costs.

The construction sector is the largest contributor to marine ecotoxicity, fossil fuel use, freshwater eutrophication, human toxicity (both carcinogenic and non-carcinogenic), ionizing radiation and water use. This can be largely attributed to the large volumes of wood that are sent to the construction sector in the BAU scenario.

The furniture sector is the largest contributor to freshwater ecotoxicity (42.5%), followed by the construction sector (33%). Furthermore it contributes 75% to the overall impact on marine eutrophication. Bioenergy is the largest contributor to photochemical oxidant formation for both human health and terrestrial ecosystems, 47% and 52% respectively. Finally for land use, particulate matter formation and metals and mineral use both the construction and bioenergy sector contribute just over a third each to the total impact.

These baseline results establish a reference point for assessing the potential environmental benefits of alternative scenarios that emphasize shifting wood use toward long-lived construction applications and engineered wood products. Figure 2 summarizes the LCA results for each of the three considered scenario per impact category, in reference to the BAU. For each impact category on the x-axis, the y-axis shows the percentage (%) change for each scenario compared to the BAU scenario. In Figure 2 the BAU scenario is therefore considered as the baseline (zero) value, though the results highlighted above and in Table 4 (Appendix A) illustrate that this impact of the BAU in absolute terms is not zero. Positive values indicate an improvement for a particular impact category in reference to the BAU, while negative values indicate a deterioration in impact. The magnitude of the values represent a percentage change in impact from the BAU. Many of these percentage values have very large magnitudes as a result of restrictions related to the underlying assumptions and data used in the LCA. The absolute impact of each scenario across the impact categories is included in Appendix A and references in the following sections.

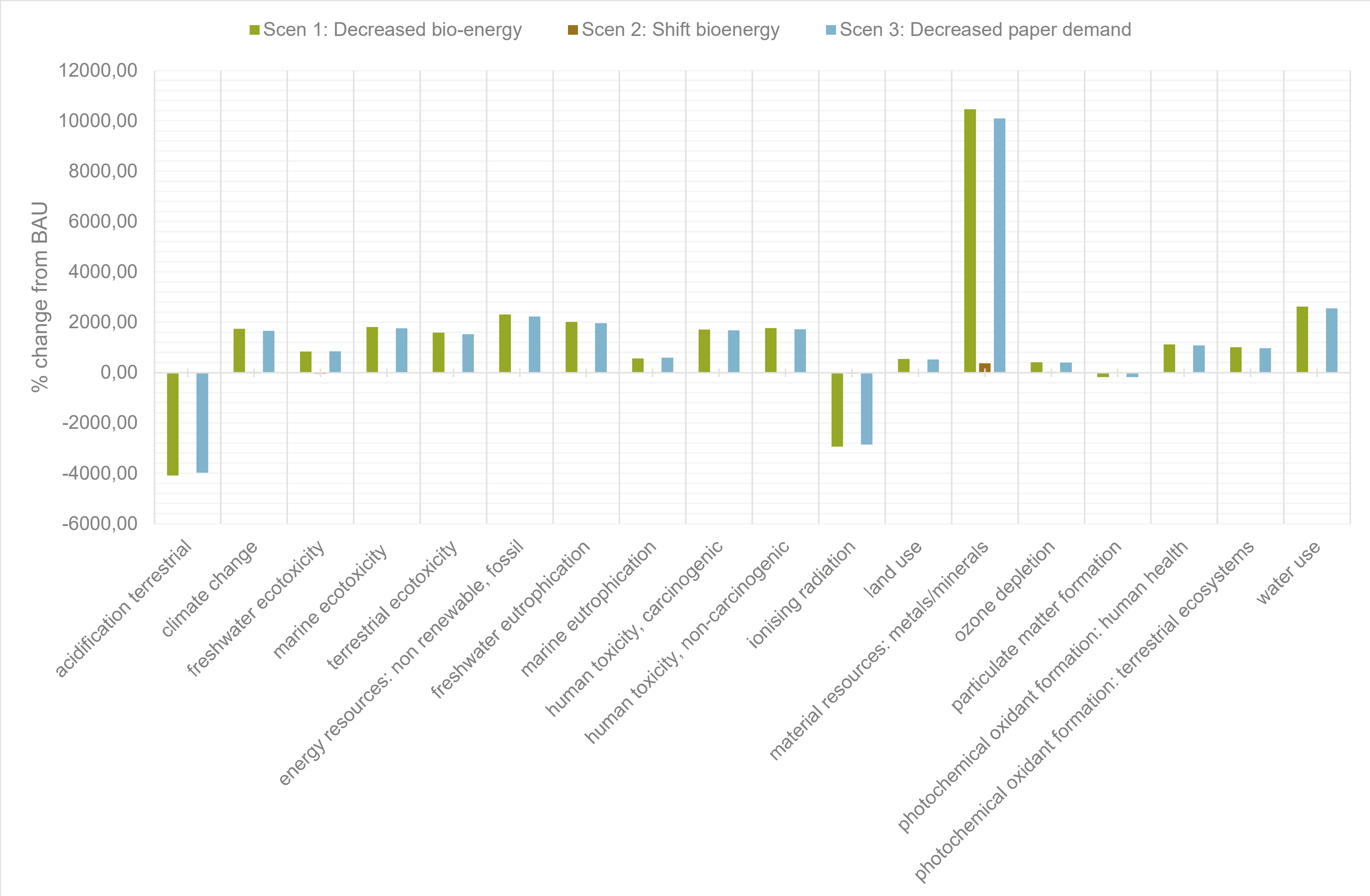

Figure 2: LCA results across different impact categories and scenarios in reference to the BAU

Scenario 1: decrease in bioenergy

In scenario 1, the proportion of wood allocated to bioenergy is reduced, shifting more wood toward long-lived products like construction materials and furniture. This change aims to reduce wood combustion, which is linked to high emissions, and to promote carbon-sequestering uses.

Improvement

As shown in Figure 2 as well as in Table 2 and Table 5 (Appendix A), scenario 1 results in notable improvements in most impact categories compared to the BAU. One of the most notable changes occurs in the **use of material resources, specifically metals and minerals**, where scenario 1 sees a 10462.23% improvement relative to the BAU as a result of total impacts falling to -56.5 million kg Cu-equivalent, compared to 550,000 kg in the baseline. The construction sector's contribution drops significantly to -56.4 million kg, while the bioenergy sector contributes 82,000 kg, down from 184,000 kg.

Following this, the second largest improvement is seen for **water use**, which decreases to -74.9 million cubic meters, compared to 14.4 million cubic meters in the baseline. Resulting in a 2622.82% improvement in impact. This reduction is driven by the construction sector, which contributes -76.3 million cubic meters, a significant improvement from the baseline 12.7 million cubic meters. The bioenergy sector sees a slight increase, contributing 153,000 cubic meters, up from 121,000 cubic meters.

The consumption of **non-renewable fossil energy** resources shows a significant decrease in scenario 1 represented by a 2307.63% improvement in impact compared to the BAU. This is driven by the total impacts dropping to -1.82 billion kg oil-equivalent, compared to 83.1 million kg in the baseline. The construction sector is responsible for this sharp decline, showing a net negative consumption of -1.83 billion kg oil-equivalent, compared to the baseline 48.1 million kg. The bioenergy sector sees a reduction in fossil fuel use, contributing -11.7 million kg, down from 5.98 million kg in the BAU. Furniture sees a slight increase in energy consumption to 2.96 million kg, while the other sectors remain stable. This shift indicates a significant reduction in dependency on fossil fuels, particularly through the reduced reliance on bioenergy.

Freshwater eutrophication improves by 2015.10%, with total impacts dropping to -8.43 million kg P-equivalent, from 445,000 kg in the BAU. The construction sector drives this change with a net negative contribution of -8.62 million kg, compared to the baseline 249,000 kg. The bioenergy sector contributes 6,560 kg, down from 10,300 kg. Similarly, marine eutrophication sees a reduction, with total impacts dropping to -556,000 kg N-equivalent, compared to 122,000 kg in the baseline. The bioenergy sector reduces its contribution to 1,080 kg, from 1,530 kg in the baseline, while the construction sector contributes -719,000 kg, a dramatic improvement from the baseline.

Marine ecotoxicity improves by 1805.53%, with total impacts falling to -2.35 trillion kg 1.4-DCB-equivalent from the BAU 139 million kg. This massive improvement is driven by the construction sector, now contributing -2.4 trillion kg, compared to 72.2 million kg in the baseline. This negative value suggests a drastic reduction in pollutants affecting marine ecosystems, possibly due to lower energy consumption and emissions in the construction processes. The bioenergy sector sees a reduction to 12.1 million kg from 17.1 million kg, while the other sectors remain relatively stable.

Human toxicity, both carcinogenic and non-carcinogenic, sees significant improvements. Carcinogenic impacts improve with 1706.25% due to a fall to -29.7 billion kg 1.4-DCB-equivalent, compared to 1.8 billion kg in the BAU. This reduction is largely due to the construction sector, which now shows a net negative contribution of -29.7 billion kg. Non-carcinogenic impacts show a similar trend, with an improvement of 1770.41% as a result of total impacts falling to -2.01 trillion kg, compared to the BAU 122 billion kg. The construction sector's emissions decrease sharply, contributing -2.07 trillion kg, compared to 63.5 billion kg in the baseline. Bioenergy shows improvements as well, contributing 1.05 billion kg (down from 14.7 billion kg).

We also observe a significant improvement in the **climate change** impact category, where scenario 1 sees a 1734.119% impact improvement as a result of a net negative impact of -10.7 billion kg CO_2-equivalent, in stark contrast to the 660 million kg in the BAU. This reduction is driven by the construction sector, which now contributes a negative 11.2 billion kg CO_2-equivalent, compared to the baseline -3.94 million kg. This is mainly attributed to the replacement of polluting materials like concrete and steel and possibly reflects an increase in carbon sequestration in wood products. The bioenergy sector shows a significant drop in emissions to 464 million kg, from the baseline 635 million kg, due to the 20% reduction in wood sent to bioenergy and the replacement by more efficient natural gas for heating. Other sectors show modest changes, with the furniture sector contributing 4.26 million kg (down from 103 million kg), and the paper and pallets sectors maintaining similar emissions.

Terrestrial ecotoxicity shows an improvement of 1583.48%, with total impacts reducing to -18.6 billion kg 1.4-DCB-equivalent, compared to 1.27 billion kg in the BAU. The construction sector drives this reduction, with emissions dropping to -19.3 billion kg, compared to 408 million kg in the baseline. The bioenergy sector also sees a reduction, contributing 453 million kg, down from 612 million kg. Other sectors, such as furniture and pallets, show modest changes, with slight increases from the baseline. Overall, the reduction in bioenergy usage and the increased allocation of wood to construction have led to a substantial decrease in the environmental burdens on terrestrial ecosystems.

Photochemical oxidant formation for human health decreases to -19.4 million kg NOx-equivalent, compared to 1.94 million kg in the BAU. Resulting in a 1002.92% improvement in impact. The construction sector contributes -20.5 million kg, a dramatic decrease from the baseline. For terrestrial ecosystems, impacts decrease to -19.8 million kg, compared to 2.21 million kg in the baseline, again driven by the construction sector's reduced emissions.

Freshwater ecotoxicity sees an improvement in scenario 1, with a 839.15%% impact improvement driven by total impacts decreasing to -180 million kg 1.4-DCB-equivalent, compared to 24.7 million kg in the BAU. This decrease is largely attributed to the construction sector, which now shows a net negative contribution of -202 million kg, a significant improvement from the 7.46 million kg in the baseline. The furniture sector's contribution increases slightly to 16.6 million kg, compared to 11 million kg in the baseline. The bioenergy sector also sees a reduction, contributing 1.14 million kg, down from 1.98 million kg. This shift suggests that reallocating wood from bioenergy to construction significantly reduces chemical emissions affecting freshwater ecosystems.

Land use under scenario 1 is reduced, with total impacts dropping to -2.41 billion m^2*a crop-equivalent, compared to 555 million m^2*a in the BAU, resulting in a 538.56% improvement. The construction sector now contributes -2.73 billion m^2*a, a drastic decrease from the baseline 195 million m^2*a. This reduction suggests that reallocating wood to construction reduces the demand for land use, potentially due to more efficient use of wood in long-lived products. Bioenergy shows a smaller contribution, with 155 million m^2*a, down from 194 million m^2*a in the baseline.

Finally, **ozone depletion** improves by 410.62%, with total impacts dropping to -2.84 kg CFC-11-equivalent, compared to 927 kg in the BAU. The bioenergy sector reduces its contribution to 536 kg, from 682 kg in the BAU. The construction sector shows a significant decrease, with impacts falling to -3.63 kg from 78 kg.

Deterioration

Nevertheless, not all impact show an improvement. For instance, the **acidification potential** increases with a -4085.52% deterioration in impact. The increase is predominantly attributed to the increase in the construction sector. This large increase more than compensates the decrease by about 30% in the bioenergy sector. While for all other sectors the impact barely changes compared to the BAU.

Additionally, **ionizing radiation** increases in scenario 1 compared to the BAU, with total impacts rising to 628 million kg Co-60-equivalent, compared to 20.8 million kg in the BAU. This results in a -2946.20% deterioration in impact. The construction sector's contribution increases to 619 million kg, from 11.4 million kg in the BAU. This increase may be linked to shifts in energy sources or materials used in construction. Other sectors, including bioenergy and furniture, see slight increases.

Finally, **particulate matter formation** worsens by -177.08%, with total impacts increasing to 4.24 million kg PM2.5-equivalent, compared to 1.54 million kg in the BAU. The construction sector contributes 3.38 million kg, up from 542,000 kg in the baseline, while bioenergy's contribution decreases to 455,000 kg, from 583,000 kg.

Overall, scenario 1, with a 20% reduction in bioenergy and increased wood allocation to construction and furniture, leads to significant improvements in most environmental impact categories. The construction sector plays a central role in driving these improvements, especially in terms of climate change, ecotoxicity, human toxicity, and resource use. However, the increase in particulate matter formation and ionizing radiation highlights potential trade-offs that may require further consideration.

Scenario 2: shift in bioenergy towards pellets

In scenario 2, which adjusts the composition of wood used for bioenergy by increasing the proportion of high-efficiency pellets, the results show both improvements and negative impacts across various environmental categories.

Improvement

Similarly to scenario 1, one of the most notable positive changes is seen in the **use of material resources, particularly metals and minerals**. Here, a 363.58% improvement is noted relative to the BAU. Following this, **climate change** impacts improve notably (26.82%), with the overall emissions decreasing compared to the BAU. The total climate change impact is 485 million kg CO_2-eq in scenario 2, down from 660 million kg CO_2-eq in the BAU. This reduction is primarily driven by the bioenergy sector, which sees its emissions reduced from 635 million kg in the baseline to 600 million kg in Scenario 2, and by the construction sector, which goes from – 4 million kg to – 130 million kg. The shift to high-efficiency pellets contributes to this improvement, as these pellets are more carbon-efficient. Other sectors, such as furniture, pallets, and paper, remain stable, contributing little to the overall change.

Photochemical oxidant formation, both human health and terrestrial ecosystems decrease respectively from 19,4 million kg NOx-eq to 1,6 million kg Nox-eq (a 17.39% improvement) and from 2,21 million to 1,73 million kg Nox-eq (a 22.15% improvement). The decreases are mostly related in lower bioenergy impacts, but there is also a decrease in construction, despite the increase in the furniture sector.

Another improvement is seen in energy resource consumption, specifically the impact on **non-renewable fossil resources** improves by 8.57%. The total impact in scenario 2 is 76.1 million kg oil-eq, which marks a reduction from the BAU of 83.1 million kg oil-eq. This reduction is mostly related to a reduced impact in the furniture industry, where fossil fuel resource savings of 941 000 kg oil-eq occur, indicating a negative impact, compared to a positive impact of 5 770 000 kg oil-eq in the BAU.

Additionally, **terrestrial ecotoxicity** impacts decrease from 1,27 billion kg 1.4-DCB-eq to 1,20 billion kg 1.4-DCB-eq, or by about 5.75% relative to the BAU. While the bioenergy sector experiences an impact increase, the furniture and construction sectors show decreases in their contributions. There are also savings in mineral and metal resources, resulting in a net negative impact of 1,43 million kg Cu-eq, compared to a net positive impact of 550,000 kg Cu-eq in the baseline. This improvement is primarily linked to savings in construction and furniture. Ozone depletion impacts decrease from 92,700 kg CFC 11-eq to 68,600 kg CFC 11-eq, which is related to a decrease in the bioenergy sector and a smaller reduction in the construction sector. Particulate matter impacts also decline from 1,54 million kg PM2.5-eq to 1,44 million kg PM2.5-eq, primarily related to reductions in the bioenergy sector.

Deteriorations

While the number of deteriorating impacts is much larger in scenario 2 compared to scenario 1 and 3, the magnitude of these impacts are smaller. **Freshwater ecotoxicity** sees total impacts increasing to 36.2 million kg 1.4-DCB-eq from 24.7 million kg in the BAU (a -47.01% deterioration of impact). The bioenergy sector contributes significantly to this rise, with an increase from 1.98 million kg in the baseline to 2.76 million kg in scenario 2. This suggests that while high-efficiency pellets may reduce carbon emissions, they introduce more toxic chemicals into freshwater systems, likely due to the production processes or additives used in manufacturing high-efficiency pellets. Construction also sees notable increases in their contributions to freshwater ecotoxicity, amplifying the overall environmental burden.

Ionizing radiation impacts also increase in scenario 2, with total impacts rising to 27.7 million kg Co-60-eq from 20.8 million kg in the BAU. This represents a -33.68% deterioration in impact. The bioenergy sector sees an increase in its contribution from 1.01 million kg to 3.43 million kg. While this is not a massive increase compared to other categories, it still reflects a negative consequence of the shift toward high-efficiency pellets, as their production and use seem to require more energy inputs associated with radiation impacts.

In terms of **human toxicity**, both carcinogenic and non-carcinogenic categories see significant increases in scenario 2. Carcinogenic human toxicity rises from 1.8 billion kg 1.4-DCB-eq in the BAU to 2.21 billion kg in scenario 2 (a -23.27% deterioration in impact), with the bioenergy sector contributing a notable portion of this increase. Similarly, non-carcinogenic human toxicity jumps from 122 billion kg to 128 billion kg (a -5.00% deterioration in impact), again driven by the bioenergy sector. These results suggest that while high-efficiency pellets may offer energy efficiency and carbon reductions, they introduce more harmful emissions and substances that pose risks to human health.

The increase in **freshwater eutrophication** is also a concerning outcome, with total impacts increasing from 445,000 kg P-eq in the BAU to 524,000 kg P-eq in Scenario 2, a -17.96% deterioration. The bioenergy sector sees a rise in its contribution to 13,000 kg P-eq, compared to 10,300 kg in the baseline. This increase is likely tied to the pollutants released during the production or combustion of high-efficiency pellets, which contribute to nutrient over-enrichment in freshwater systems, leading to problems like algal blooms and water quality degradation.

Land use impacts increase from 555 million m^2 crop-eq to 614 million m^2 crop-eq, primarily related to an increase in construction impacts. Finally, water use impacts increase from 3 million m^3 to 3,29 million m^3, largely attributed to higher water use in the bioenergy sector.

A similar trend is observed in **marine ecotoxicity**, which shows a -5.85% deterioration as a result of an increase from 139 million kg 1.4-DCB-eq in the BAU to 147 billion kg in scenario 2. This is an extraordinarily large shift, driven predominantly by the construction sector's contributions, which increases to 84.5 billion kg. The bioenergy sector also worsens, contributing 17.8 billion kg in scenario 2 compared to the baseline's 17.1 billion kg. This suggests that the environmental trade-offs associated with high-efficiency pellets extend beyond freshwater systems and into marine ecosystems, where the introduction of more toxic substances during production has significant ecological consequences.

For **terrestrial acidification** we see a -4.47% deterioration relative to the BAU. While the overall impact in scenario 2 shows only a marginal increase, the sector-specific comparison reveals that most sectors see little change, and in fact, the bioenergy sector shows a minimal increase from 252,000 kg SO_2-eq to 254,000 kg SO_2-eq. Similar slight increases occur in construction, while a slight decrease occurs in furniture.

Finally, a similar but less dramatic increase is seen in **marine eutrophication**, where total impacts rise from 122,000 kg N-eq in the baseline to 128,000 kg in Scenario 2, a -4.28% deterioration. The bioenergy sector contributes 2,590 kg in Scenario 2, compared to 1,530 kg in the baseline, indicating that more nitrogen compounds are being released into marine environments, contributing to nutrient pollution.

In summary, Scenario 2 presents a complex scenario with various improvements and deteriorations relative to the BAU, though none as large as those noted in scenario 1. While there are notable improvements in climate change impacts and reductions in fossil energy consumption, the transition to high-efficiency pellets also leads to significant drawbacks. Specifically, increases are observed in freshwater and marine ecotoxicity, human toxicity, freshwater and marine eutrophication, and ionizing radiation. These changes raise important concerns regarding the overall environmental and health impacts associated with this shift in bioenergy production.

Scenario 3: decreased demand for paper

In scenario 3, the demand for paper products significantly decreases due to the rise of digitalization and the adoption of more sustainable packaging alternatives. This results in the reallocation of wood that would typically go into paper production, diverting it instead toward the construction and furniture sectors, primarily for the creation of panel materials. This shift leads to important changes in environmental impacts across various sectors and impact categories. The changes seen here are very similar to those seen in scenario 1, although the magnitude of the changes is slightly lower for this scenario, as can be seen in Figure 2 where the green bars of scenario 1 are generally a couple of percentage points larger than the blue bars of scenario 3. The only exception to this is in the marine eutrophication impact, where the savings generated by scenario 3 are slightly larger than those seen in scenario 1.

Improvements

Once again, the most notable improvement in this scenario is in the **material resource extraction**, with savings of 54.4 million kg Cu-eq resulting in a 10087.50% improvement relative to the BAU. This improvement likely arises from the lower demand for metals and minerals in construction and furniture compared to the machinery and infrastructure needed for intensive paper production.

The second largest improvement is noted in the **water use** impact category, with a 2553.11% improvement relative to the BAU. The total water use showings savings of 72.8 million cubic meters. Paper production is water-intensive, so its reduction leads to this significant decline. The construction and furniture sectors, which typically use less water, also contribute to this lower water consumption.

Freshwater eutrophication improves with savings of 8.2 million kg P-eq, representing a 1963.31% improvement relative to the BAU. While there is a large improvement from the paper sector, due to less runoff of phosphates and other nutrients from the paper industry, which often leads to eutrophication in freshwater bodies the main contributing factor here is again the construction sector. Marine eutrophication also shows improvement, with savings of 597,000 kg N-eq. The shift away from paper production, which contributes nitrogen-rich waste, leads to this decrease. The construction and furniture sectors now show negative marine eutrophication impacts.

Marine ecotoxicity and terrestrial ecotoxicity also see large reductions in overall impact with 1754.13% and 1527.77% improvements, respectively. For marine ecotoxicity, the savings amount to a significant 2.27 trillion kg 1.4-DCB-eq, which can largely be explained by the reduced need for energy and chemical inputs in the construction paper industry. Similarly, the terrestrial ecotoxicity impact decrease, showing savings of over 1.79 billion kg 1.4-DCB-eq. Another significant area of improvement is seen in freshwater ecotoxicity. With a 839.81% improvement, the total impact in this category decreases, also showing savings of over 181 million kg 1.4-DCB-eq, largely due to the substantial reduction in construction. There is also a slight decrease in the use of chemicals and energy that would otherwise be required for paper manufacturing. In this case, the construction sector again leads in terms of positive outcomes, as the diverted pulpwood is used in panel production, which is less chemically intensive than paper production. These reductions highlight the benefits of reallocating wood resources away from the resource-intensive paper sector and toward construction and furniture, where fewer harmful substances are required.

Human toxicity (carcinogenic and non-carcinogenic) impacts both improve notably. In carcinogenic impacts, a saving of 28.1 billion kg 1.4-DCB-eq (a 1679.09% improvement relative to the BAU) is observed, while non-carcinogenic toxicity is shows savings of approximately 1.95 trillion kg 1.4-DCB-eq (1720.24% improvement relative to the BAU). Again, these improvements stem from a reduced need for harmful chemicals in paper production. Similar trends are seen in ozone depletion, and in photochemical oxidant formation (both for human health and terrestrial ecosystems), where reduced emissions are seen across most sectors, particularly in construction and furniture. There are fossil-fuel savings of 1.75 billion kg oil-eq (net negative impact) compared to a positive impact of 83,1 million kg oil-eq in the BAU – a 2223.88% improvement. This is mostly related to savings in construction.

Notable improvements are also seen in the **climate change** impact category, with a 1659.90% improvement relative to the BAU. The total emissions associated with climate change decrease, involving savings of over 10 billion kg of CO_2-eq, which represents a major improvement from the BAU. This large reduction can be attributed mainly to the construction sector, where wood replaces high impact materials and there benefits from the increased use of wood in long-lived products. These products have the advantage of storing carbon over long periods, thereby reducing the net carbon emissions. While the bioenergy sector shows an increase in emissions, this is relatively minor in comparison to the significant climate benefits achieved in the construction sector.

There are additional improvements across several other impact categories. For example, **land use** sees a substantial reduction, with land occupation also showing savings of about 2.30 billion m^2*a crop-eq (an improvement of 520.17%). Shifting wood resources to long-lived products like panel materials, which require less intensive land use than paper production, explains this improvement.

Deteriorations

As is the case in scenario 1, some impacts categories show a deterioration in scenario 3 relative to the BAU. For instance, the impact on **terrestrial acidification** deteriorates with -3971.89% compared to the baseline, with the total impact rising to 82.1 million kg SO_2-eq. This increase is mainly driven by the construction sector, which takes on a larger share of wood resources because of the reduced demand for paper.

Ionizing radiation shows a slight increase, with total impacts rising to 610 million kg Co-60-eq – a 2861.82% deterioration relative to the BAU. The increase could be related to energy use in sectors like construction and furniture, where energy sources that contribute to ionizing radiation are still used, though not as intensively as in paper production.

Finally, the **particulate matter formation** category also shows a modest increase, with emissions rising to 4.26 million kg PM2.5-eq – a178.35% deterioration relative to the BAU. Again, this is likely tied to the increased industrial activity in the construction and furniture sectors as a result of the reallocation of wood from paper production.

Overall, scenario 3 demonstrates significant environmental benefits in key impact categories like climate change, ecotoxicity, and human toxicity. These improvements are largely driven by the increased use of wood in construction and therefore the decreased use of high impact products that are replaced. Furthermore the reduction of impact from the paper sector adds to the savings in these impact categories. However, there are some trade-offs, particularly in terms of acidification and fossil fuel use, where increases occur due to the greater focus on construction and furniture production. Despite these minor drawbacks, the scenario suggests that reallocating wood to longer-lived products offers substantial environmental advantages, particularly when compared to the highly resource-intensive paper industry.

Discussion

The production and use of wood in Flanders has significant implications for environmental sustainability and resource management. The BAU impacts highlight the complex relationship between wood utilization and various environmental indicators, particularly concerning climate change, ecotoxicity, and resource depletion. This baseline scenario reveals considerable emissions from the bioenergy sector, which, while intended to promote renewable energy, contributes significantly to acidification, climate change, and various toxicity categories. The heavy reliance on bioenergy raises questions about its sustainability, especially considering that it often leads to high emissions associated with combustion processes.

In scenario 1, a 20% reduction in wood allocated to bioenergy results in a substantial reallocation towards long-lived products, such as construction materials and furniture. The environmental implications of this shift are profound. The reduction in bioenergy usage leads to notable decreases in acidification and climate change impacts, illustrating the potential benefits of prioritizing wood for products that promote carbon sequestration over combustion. The construction sector emerges as a primary beneficiary of this shift. However, while the scenario demonstrates significant reductions in emissions across various categories, it also highlights potential trade-offs, particularly in terms of increased particulate matter formation and ionizing radiation. This underscores the need for careful consideration of all environmental impacts when developing policies aimed at promoting wood use.

The findings from scenario 2, which emphasizes a shift towards high-efficiency pellets in the bioenergy sector, illustrate the nuanced outcomes associated with technological advancements. While there are reductions in climate change impacts due to improved carbon efficiency, the increase in freshwater and marine ecotoxicity signals that there are some tradeoffs present. The trade-off between carbon efficiency and increased toxicity necessitates a holistic approach to environmental management that considers the broader ecological impacts of energy production technologies.

Scenario 3, characterized by a significant reduction in paper demand due to digitalization, provides a compelling case for the benefits of reallocating wood resources towards sectors where they can replace non-renewable alternatives with high embedded impacts, like concrete and steel. The drastic reductions in climate change impacts, ecotoxicity, and overall resource consumption reinforce the idea that shifting focus to long-lived products can yield substantial environmental benefits. This shift also highlights the importance of adapting to changing consumer behaviors and technological advancements that diminish the reliance on paper products. However, the slight increases in acidification and fossil fuel use in this scenario remind us that the transition to sustainable practices must be accompanied by careful monitoring of all environmental indicators to avoid unintended negative outcomes.

The construction and furniture sectors stand to gain substantially from increased allocations of wood, which can lead to enhanced sustainability and reduced environmental burdens, even though they were modelled by a limited number of products in this study. This shift can catalyze the development of innovative products and processes that prioritize longevity and carbon storage, thereby aligning industry practices with broader climate goals. However, the bioenergy sector must navigate the challenges posed by its environmental impacts. Emphasizing a transition to sustainable practices, such as reducing reliance on bioenergy and investing in cleaner technologies, is essential for mitigating the sector's contribution to climate change and ecotoxicity.

Suggestions for future research

Future research should focus on increasing the number of products that are included in each of the sectors and at finding more primary data. These steps are necessary to increase the robustness of the study, as the results are now dominated by a relative small number of products where the found replacement products show significantly higher impacts, which can potentially skew the results in an unrealistic way. Due to a lack of responses from people in the wood sector this study was constructed mainly from secondary data for both the production of wood products and the non-renewable alternatives.

Another avenue for future research would be to further elucidate the lifecycle impacts of wood production and use, particularly focusing on the environmental implications of transitioning to high-efficiency bioenergy pellets. Investigating the specific production processes and their contributions to ecotoxicity could provide invaluable insights for refining production methods and minimizing ecological harm. Additionally, examining consumer behavior trends, especially regarding digitalization and sustainable packaging, can inform policies that anticipate and shape market demands. Research efforts should also emphasize the need for integrated assessment models that account for various environmental indicators, helping to build a comprehensive understanding of the trade-offs associated with wood utilization across sectors. By addressing these areas, future research can guide effective policy-making and industry practices that support sustainable wood production and use in Flanders.

Conclusion

This deliverable addresses the critical question of how the different use cases of wood can be shifted to optimize environmental performance. We find that scenarios typified by a diversion of wood towards use in long-lived products (scenarios 1 and 3) result in the largest environmental improvements across the impact categories. Scenario 1 is defined by a 20% reduction in wood allocated to bioenergy, diverting this wood instead to construction and furniture. Likewise, scenario 3 is defined by a reallocation of wood to panel materials and furniture as a result of a decrease in demand for paper products. Simultaneously, we find limited improvements relative to the BAU for scenario 2, which is defined by a reallocation of wood within the bioenergy sector. Our results demonstrate that increasing the share of wood destined for long-lived wood products may hold significant potential for improving environmental performance and sustainable resource management in Flanders; more so than diverting wood use within short-lived use cases such as bioenergy.

Under the European Green Deal, the European Commission has launched the new circular economy action plan (CEAP) in an effort to promote sustainable growth by reducing pressure on natural resources. Here, the emphasis is placed on high-potential sectors such as packaging, construction and building. Our findings demonstrate the relevance of targeting the construction sector specifically, with many environmental improvements in our analysis driven by optimized use in this sector. Simultaneously we demonstrate that some environmental improvements in the packaging (paper) sector are possible, though these remain small and are mainly driven by decrease in overall demand.

In line with the CEAP, which aims to “make circularity work for people, regions and cities” (“Circular economy action plan - European Commission,” n.d.), we also highlight the need to consider the local context when identifying high-potential alternative wood-use cases. While we find large environmental improvements are possible when diverting wood to long-lived uses, the environmental deteriorations, though few, are large in magnitude. It is important to take note of these environmental deteriorations and to consider their trade-offs with the environmental improvements. Accurately capturing the trade-off between impact categories will require context-specific considerations, for example through the engagement of local stakeholders. Depending on the weight placed on each of the environmental impact categories, reallocating wood to long-lived use cases may therefore be more or less favorable for a given context.

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Appendix A: LCA results

Table 4: LCA impacts in BAU scenario

	Unit	Construc-tion	Furniture	Pallets	Paper	Bioenergy	Total
Acidification terrestrial	kg SO2-eq	9.98E+05	2.26E+05	4.57E+05	1.02E+05	2.52E+05	2.04E+06
Climate change	kg CO2-eq	-3.94E+06	1.03E+07	-2.80E+07	4.69E+07	6.35E+08	6.60E+08
Freshwater ecotoxicity	kg 1.4-DCB-eq	7.46E+06	1.10E+07	3.43E+06	8.45E+05	1.98E+06	2.47E+07
Marine ecotoxicity	kg 1.4-DCB-eq	7.22E+10	8.94E+09	3.42E+10	6.55E+09	1.71E+10	1.39E+11
Terrestrial ecotoxicity	kg 1.4-DCB-eq	4.08E+08	6.65E+07	9.69E+07	8.65E+07	6.12E+08	1.27E+09
Energy resources: non-renewable, fossil	kg oil-eq	4.81E+07	5.77E+06	1.79E+07	5.29E+06	5.98E+06	8.31E+07
Freshwater eutrophication	kg P-eq	2.49E+05	2.94E+04	1.23E+05	3.28E+04	1.03E+04	4.45E+05
Marine eutrophication	kg N-eq	1.91E+04	9.39E+04	6.92E+03	9.37E+02	1.53E+03	1.22E+05
Human toxicity, carcinogenic	kg 1.4-DCB-eq	9.57E+08	1.21E+08	4.65E+08	9.95E+07	1.54E+08	1.80E+09
Human toxicity, non-carcinogenic	kg 1.4-DCB-eq	6.35E+10	7.83E+09	3.01E+10	5.64E+09	1.47E+10	1.22E+11
Ionizing radiation	kg Co-60-eq	1.14E+07	2.15E+06	5.85E+06	3.75E+05	1.01E+06	2.08E+07
Land use	m²*a crop-eq	1.95E+08	2.30E+07	1.14E+08	2.87E+07	1.94E+08	5.55E+08
Material resources: metals/minerals	kg Cu-eq	1.78E+05	3.86E+04	9.74E+04	5.23E+04	1.84E+05	5.50E+05
Ozone depletion	kg CFC-11-eq	7.81E+01	1.39E+02	1.96E+01	8.67E+00	6.82E+02	9.27E+02
Particulate matter formation	kg PM2.5-eq	5.42E+05	6.87E+04	2.65E+05	8.08E+04	5.83E+05	1.54E+06
Photochemical oxidant formation: human health	kg Nox-eq	6.02E+05	9.11E+04	2.33E+05	5.74E+04	9.53E+05	1.94E+06
Photochemical oxidant formation: terrestrial ecosystems	kg Nox-eq	6.17E+05	9.28E+04	2.37E+05	5.94E+04	1.21E+06	2.21E+06
Water use	cubic meter	1.47E+06	3.97E+05	6.27E+05	2.76E+05	2.29E+05	3.00E+06

Table 5: LCA impacts in scenario 1: decrease in bioenergy

	Unit	Construc-tion	Furniture	Pallets	Paper	Bioenergy	Total
Acidification terrestrial	kg SO2-eq	8.33E+07	2.82E+05	4.57E+05	1.02E+05	1.77E+05	8.44E+07
Climate change	kg CO2-eq	-1.12E+10	4.26E+06	-2.80E+07	4.69E+07	4.64E+08	-1.07E+10
Freshwater ecotoxicity	kg 1.4-DCB-eq	-2.02E+08	1.66E+07	3.43E+06	8.45E+05	1.14E+06	-1.80E+08
Marine ecotoxicity	kg 1.4-DCB-eq	-2.40E+12	5.81E+09	3.42E+10	6.55E+09	1.21E+10	-2.35E+12
Terrestrial ecotoxicity	kg 1.4-DCB-eq	-1.93E+10	4.65E+07	9.69E+07	8.65E+07	4.53E+08	-1.86E+10
Energy resources: non-renewable, fossil	kg oil-eq	-1.83E+09	2.96E+06	1.79E+07	5.29E+06	-1.17E+07	-1.82E+09
Freshwater eutrophication	kg P-eq	-8.62E+06	2.64E+04	1.23E+05	3.28E+04	6.56E+03	-8.43E+06
Marine eutrophication	kg N-eq	-7.19E+05	1.54E+05	6.92E+03	9.37E+02	1.08E+03	-5.56E+05
Human toxicity, carcinogenic	kg 1.4-DCB-eq	-2.97E+10	4.57E+08	4.65E+08	9.95E+07	1.12E+08	-2.86E+10
Human toxicity, non-carcinogenic	kg 1.4-DCB-eq	-2.07E+12	5.03E+09	3.01E+10	5.64E+09	1.05E+10	-2.01E+12
Ionizing radiation	kg Co-60-eq	6.19E+08	2.52E+06	5.85E+06	3.75E+05	3.62E+05	6.28E+08
Land use	m²*a crop-eq	-2.73E+09	2.48E+07	1.14E+08	2.87E+07	1.55E+08	-2.41E+09
Material resources: metals/minerals	kg Cu-eq	-5.64E+07	-2.47E+05	9.74E+04	5.23E+04	8.20E+04	-5.65E+07
Ozone depletion	kg CFC-11-eq	-3.63E+03	2.21E+02	1.96E+01	8.67E+00	5.36E+02	-2.84E+03
Particulate matter formation	kg PM2.5-eq	3.38E+06	5.94E+04	2.65E+05	8.08E+04	4.55E+05	4.24E+06
Photochemical oxidant formation: human health	kg Nox-eq	-2.05E+07	8.01E+04	2.33E+05	5.74E+04	7.20E+05	-1.94E+07
Photochemical oxidant formation: terrestrial ecosystems	kg Nox-eq	-2.11E+07	8.04E+04	2.37E+05	5.94E+04	9.17E+05	-1.98E+07
Water use	cubic meter	-7.63E+07	3.70E+05	6.27E+05	2.76E+05	1.53E+05	-7.49E+07

Table 6: LCA impacts in scenario 2: shift in bioenergy towards pellets

	Unit	Construc-tion	Furniture	Pallets	Paper	Bioenergy	Total
Acidification terrestrial	kg SO2-eq	1.11E+06	2.00E+05	4.57E+05	1.02E+05	2.54E+05	2.13E+06
Climate change	kg CO2-eq	-1.30E+08	-4.00E+06	-2.80E+07	4.69E+07	6.00E+08	4.85E+08
Freshwater ecotoxicity	kg 1.4-DCB-eq	1.97E+07	9.41E+06	3.43E+06	8.45E+05	2.76E+06	3.62E+07
Marine ecotoxicity	kg 1.4-DCB-eq	8.45E+10	3.91E+09	3.42E+10	6.55E+09	1.78E+10	1.47E+11
Terrestrial ecotoxicity	kg 1.4-DCB-eq	1.97E+08	2.88E+07	9.69E+07	8.65E+07	7.89E+08	1.20E+09
Energy resources: non-renewable, fossil	kg oil-eq	4.35E+07	-9.41E+05	1.79E+07	5.29E+06	1.03E+07	7.61E+07
Freshwater eutrophication	kg P-eq	3.31E+05	2.33E+04	1.23E+05	3.28E+04	1.30E+04	5.24E+05
Marine eutrophication	kg N-eq	2.36E+04	9.35E+04	6.92E+03	9.37E+02	2.59E+03	1.28E+05
Human toxicity, carcinogenic	kg 1.4-DCB-eq	7.82E+08	6.99E+08	4.65E+08	9.95E+07	1.65E+08	2.21E+09
Human toxicity, non-carcinogenic	kg 1.4-DCB-eq	7.44E+10	2.81E+09	3.01E+10	5.64E+09	1.49E+10	1.28E+11
Ionizing radiation	kg Co-60-eq	1.57E+07	2.35E+06	5.85E+06	3.75E+05	3.43E+06	2.77E+07
Land use	m²*a crop-eq	2.60E+08	2.78E+07	1.14E+08	2.87E+07	1.83E+08	6.14E+08
Material resources: metals/minerals	kg Cu-eq	-1.38E+06	-4.23E+05	9.74E+04	5.23E+04	2.17E+05	-1.43E+06
Ozone depletion	kg CFC-11-eq	6.18E+01	1.34E+02	1.96E+01	8.67E+00	4.62E+02	6.86E+02
Particulate matter formation	kg PM2.5-eq	6.37E+05	4.90E+04	2.65E+05	8.08E+04	4.03E+05	1.44E+06
Photochemical oxidant formation: human health	kg Nox-eq	5.91E+05	6.34E+04	2.33E+05	5.74E+04	6.58E+05	1.60E+06
Photochemical oxidant formation: terrestrial ecosystems	kg Nox-eq	5.97E+05	6.23E+04	2.37E+05	5.94E+04	7.72E+05	1.73E+06
Water use	cubic meter	1.58E+06	3.09E+05	6.27E+05	2.76E+05	4.93E+05	3.29E+06

Table 7. LCA impacts in scenario 3: decrease demand for paper

	Unit	Construc-tion	Furniture	Pallets	Paper	Bioenergy	Total
Acidification terrestrial	kg SO2-eq	8.10E+07	2.27E+05	4.57E+05	9.51E+04	2.52E+05	8.21E+07
Climate change	kg CO2-eq	-1.08E+10	1.04E+07	-2.80E+07	4.44E+07	6.35E+08	-1.02E+10
Freshwater ecotoxicity	kg 1.4-DCB-eq	-1.98E+08	1.10E+07	3.43E+06	7.55E+05	1.98E+06	-1.81E+08
Marine ecotoxicity	kg 1.4-DCB-eq	-2.34E+12	8.99E+09	3.42E+10	5.95E+09	1.71E+10	-2.27E+12
Terrestrial ecotoxicity	kg 1.4-DCB-eq	-1.88E+10	6.69E+07	9.69E+07	7.92E+07	6.12E+08	-1.79E+10
Energy resources: non-renewable, fossil	kg oil-eq	-1.78E+09	5.81E+06	1.79E+07	4.83E+06	5.98E+06	-1.75E+09
Freshwater eutrophication	kg P-eq	-8.39E+06	2.96E+04	1.23E+05	3.11E+04	1.03E+04	-8.20E+06
Marine eutrophication	kg N-eq	-7.01E+05	9.39E+04	6.92E+03	7.64E+02	1.53E+03	-5.97E+05
Human toxicity, carcinogenic	kg 1.4-DCB-eq	-2.89E+10	1.21E+08	4.65E+08	9.24E+07	1.54E+08	-2.81E+10
Human toxicity, non-carcinogenic	kg 1.4-DCB-eq	-2.01E+12	7.88E+09	3.01E+10	5.13E+09	1.47E+10	-1.95E+12
Ionizing radiation	kg Co-60-eq	6.01E+08	2.16E+06	5.85E+06	2.05E+05	1.01E+06	6.10E+08
Land use	m²*a crop-eq	-2.66E+09	2.31E+07	1.14E+08	2.73E+07	1.94E+08	-2.30E+09
Material resources: metals/minerals	kg Cu-eq	-5.48E+07	3.88E+04	9.74E+04	4.75E+04	1.84E+05	-5.44E+07
Ozone depletion	kg CFC-11-eq	-3.53E+03	1.39E+02	1.96E+01	7.60E+00	6.82E+02	-2.68E+03
Particulate matter formation	kg PM2.5-eq	3.26E+06	6.91E+04	2.65E+05	7.58E+04	5.83E+05	4.26E+06
Photochemical oxidant formation: human health	kg Nox-eq	-2.00E+07	9.17E+04	2.33E+05	5.34E+04	9.53E+05	-1.87E+07
Photochemical oxidant formation: terrestrial ecosystems	kg Nox-eq	-2.05E+07	9.34E+04	2.37E+05	5.52E+04	1.21E+06	-1.89E+07
Water use	cubic meter	-7.43E+07	3.99E+05	6.27E+05	2.39E+05	2.29E+05	-7.28E+07

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