Forest Sector *Net-Zero Roadmap*

Phase II: Catalogue of key decarbonization actions

World Business Council for Sustainable Development

Forest Solutions Group

Contents

Key Takeaways

→ Phase I of the **Forest Sector Net-Zero Roadmap** released in 2021 described three key levers of impact that constitute the forest sector's unique contribution to the transition to a net-zero economy: A. Reduce GHG emissions in operations and across the value chain; B. Increase carbon removals through sequestration in working forests and storage in forest products; C. Grow the circular bioeconomy through the substitution of non-renewable and fossil-based materials with forest products.

→ This Catalogue of Key Decarbonization Actions builds on the content of Phase I and is designed to support forest companies in the choice and implementation of actions to decarbonize their operations and value chains (lever A) and leverage the greatest opportunities for carbon removals (levers B and C). In alignment with the carbon mitigation hierarchy, in this catalogue higher emphasis is put on reducing emissions in operations and across the value chain (lever A) **(see section 1. Introduction)**.

→ To support forest companies in the choice and implementation of actions to address emissions hotspots the catalogue first identifies the most carbon intensive stages along the full value chain of three forest product categories: Engineered wood products, paper-based consumer packaging, and cellulose-based textiles. **(see section 2. Emissions hotpots along the value chain)**.

→ It then introduces the ten most impactful decarbonization actions (in the form of reduced emissions or increased removals) forest companies can take to tackle these emissions hotspots, based on an assessment of their level of maturity, emission abatement potential, and short-term economic feasibility **(see section 3. Introducing the 10 decarbonization actions)**.

→ Deep dives into each of the ten decarbonization actions offer an overview of the solution, usage data, insights into the potential climate and business impacts, as well as potential co-benefits and side effects to factor into the decision-making. These come alongside practical implementation advice based on experience from members of the Forest Solutions Group (FSG) **(see section 6. Deep dives into the 10 decarbonization actions)**.

→ The catalogue concludes with an overall assessment of the combined abatement potential of the 10 actions, along with suggestions to further magnify the impact (See section 4. Progressing towards net-zero). It leaves the reader with a simplified step by step approach to start or accelerate an individual company's decarbonization journey building on the content of the catalogue and taking into consideration enabling policies that might impact the feasibility **(see section 5. Next steps on decarbonization journey)**.

→ This catalogue is part of Phase II of the Forest Sector Net-Zero Roadmap that offers a series of tools and guidance to support forest companies in the implementation of credible and science-based net-zero strategies. It builds on the foundations established as part of Phase I released in 2021. The catalogue was developed by the members of the Forest Solutions Group, with McKinsey Sustainability as a knowledge partner, and in collaboration with WBCSD's Climate team. The ten most impactful decarbonization actions are also featured on the Action Library of **WBCSD's Climate Drive**.

Foreword

As the effects of climate change become increasingly visible across the globe, climate-related risks commonly factored into long term economic decision-making are now materializing across operations and value chains. Business leaders are confronted with the need to rapidly future-proof their business while transitioning away from fossil fuels, while scaling up the adoption of low-carbon technologies.

Designing and implementing an actionable and cost effective corporate decarbonization plan presents numerous challenges, notably tied to uncertainties, the scarcity of proven technologies and access to finance. Indeed, a recent study estimated that financing the net-zero transition between 2021 and 2050 would require an increase in global annual spending on physical assets for energy and land use systems of around USD $3.5 trillion per year, an amount equivalent to half of global corporate profits in 2020[1]

Despite the challenges, the transition to a net-zero economy is well on its way across the forest sector. Companies are setting targets for net-zero by 2050 or sooner, striving to reduce emissions and increase efficiencies across the value chain. While all sectors share a responsibility to reduce greenhouse gas (GHG) emissions, specific technologies and approaches differ in the forest sector. The sector is also in a unique position to support the global net-zero transition through the provision of carbon removals from sustainable working forests and storage in forest products. This catalogue of key decarbonization actions will equip business leaders in the forest sector with valuable and actionable industry-specific guidance to address emissions hotspots and amplify carbon removals.

As business leaders in the forest sector, we are committed to urgently decarbonizing our operations and value chains, and deploying the climate change mitigation potential of our sustainable working forests and products. We hope peers in the sector will find inspiration and guidance in this catalogue, and join us on this journey.

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1. Introduction

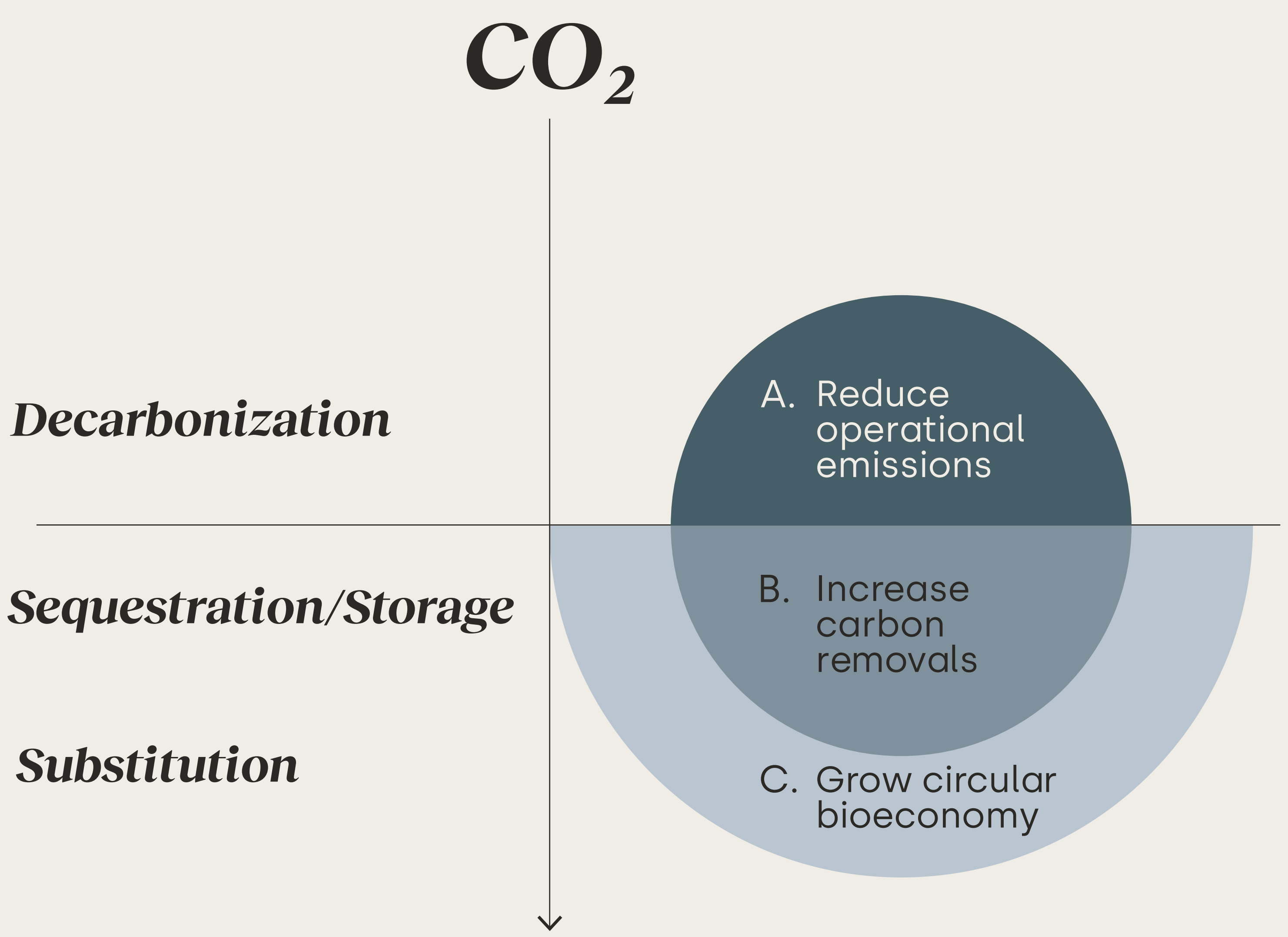
Note: Throughout this report, kindly click on the hyperlinks, **underlined in orange,** and the pop-up boxes highlighted in **orange** text to read more.

Introduction

In order keep rising temperatures within a 1.5°C safe operating space and avoid the most severe impacts of climate change, the world must reach the target of net-zero emissions by 2050. This will require a deep transformation of every aspect of the economy, including the acceleration of business transformation. With this Forest Sector Net-Zero Roadmap, leading members of **WBCSD's Forest Solutions Group (FSG)** are rising to the challenge and joining forces to lead the way to a transition within the sector and across the global economy. Phase I of the Roadmap titled **'Enabling the transition to a net-zero economy'**, released in 2021, delivered a holistic overview of the forest sector's contributions to climate change mitigation. It describes three key levers of impact that constitute the forest sector's unique contribution to the transition to a net-zero economy *(Refer to Figure 1)*.

This Catalogue of Key Decarbonization Actions builds on the content of Phase I to offer a comprehensive set of actions forest companies can implement in their operations and value chains to drive progress on all three levers of impact. In alignment with the carbon mitigation hierarchy this catalogue puts higher emphasis on lever A - reducing operational and value chain emissions.

Figure 1: The forest sector's three levers of impact



A. Reduce greenhouse gas emissions in operations and across the value chain

B. Increase carbon removals through sequestration in sustainable working forests and storage in forest products

C. Grow the circular bioeconomy through the substitution of non-renewable and fossil-based materials with forest products

Objective

This Catalogue of Key Decarbonization Actions forms part of Phase II of the Net-Zero Roadmap, focused on the provision of tools and guidance to support forest companies in the implementation of credible and science-based net-zero strategies. Its objective is to support forest companies in the choice and implementation of actions to address emission hotspots and leverage the greatest opportunities for carbon removals.

Approach

The catalogue was developed in two consecutive steps:
Step 1: Identification of the emissions hotspots, and largest opportunities for carbon removals along the life cycle of three forest product categories: Engineered wood products, paper-based consumer packaging, and cellulose-based textiles.
Step 2: Identification of the most impactful decarbonization actions (in the form of reduced emissions or increased removals) linked to the hotspots, combined with an assessment of their maturity level, abatement potential and economic feasibility.

The analysis was based on the following sources:
→ Three in-depth consultations with FSG members and external stakeholders
→ Analysis of climate disclosures from forest companies, including members of the FSG
→ Most recent scientific literature, industry disclosures, Life Cycle Assessments (LCA) and reports
→ Consultations with McKinsey Sustainability experts.

This catalogue complements the decarbonization actions available in the **Action Library of WBCSD's Climate Drive** a digital platform centralizing sector-specific and high-quality resources needed for businesses to take climate action. While many actions described in the Climate Drive Action Library can be applied to forest sector, this catalogue describes actions that are most impactful and relevant to the forest sector.

Scope

1. This catalogue focuses almost exclusively on climate change, however it is crucial that net-zero strategies address the interconnectedness between climate, nature and social inequality. Individual companies should keep the impacts on nature and people at the forefront of their net-zero strategies and implementation plans. For more guidance on Nature Positive strategies, refer to **WBCSD's Forest Sector Nature Positive Roadmap**.

2. This catalogue aims to offer a global perspective that transcends local and regional specificities. This is done in full recognition that the local context will play a significant role in the interpretation and implementation of its content.

Audience

This Roadmap primarily aims to inspire action, and guide companies operating in the forest sector on the adoption and execution of ambitious climate strategies. To achieve that aim, this catalogue introduces a selection of impactful decarbonization actions at different stages of the forest sector value chain, along with implementation advice.

It also offers insights on the forest sector for value chain partners, investors and policymakers who are critical to creating the enabling environment to accelerate the implementation of these actions.

2. Emissions hotspots *along the value chain*

Overview

This section provides an overview of the **'emissions hotspots'** along the lifecycle of three forest product categories: engineered wood products, paper-based consumer packaging, and cellulose-based textiles. To identify emission hotspots for each category, the stages of the value chain were assessed based on their emissions intensity relative to other stages within the same chain. The second part of the catalogue offers a comprehensive list of actions to tackle these emissions hotspots, as well as opportunities to increase carbon removals for each of the three product categories.

Introducing the three product categories

Three product categories were selected to be representative of FSG members' current markets, while offering significant future growth potential. The categories are linked to three distinct downstream industries: construction, consumer packaging, and the textile industry.

Engineered wood products

These are largely used in the construction sector in the form of beams and structural lumber (e.g. cross-laminated timber, laminated strand and veneer lumber) and boards (e.g. plywood and fiberboards). They are made by binding together wood strands, fibers, veneers, or other forms of solid wood using adhesives or mechanical fasteners. These products currently represent a growing part of the total solid wood usage globally, and have boomed globally in recent years, with the market expanding by 4 – 15% since 2019, depending on the product.[2] Demand for engineered wood products is expected to increase by 6 – 7% per year from 2023 to 2038,[3] driven by the attractive characteristics of the product such as fire resistance, high strength-to-weight ratio, ease of installation, versatility and low carbon intensity.[4]

Paper-based consumer packaging

These include a wide range of items such as cardboard boxes, food packaging, shipping sacks and paper bags. As of 2019, paper-based packaging accounted for up to 50% of the worldwide paper and paperboard **market,** making it the most popular product category in the paper industry. The market for paper-based packaging has doubled since the early 1990s, and is expected to grow by 15 – 20% towards 2030,[2] driven by demographic shifts, an increase in e-commerce and growing concerns over plastic waste.[2]

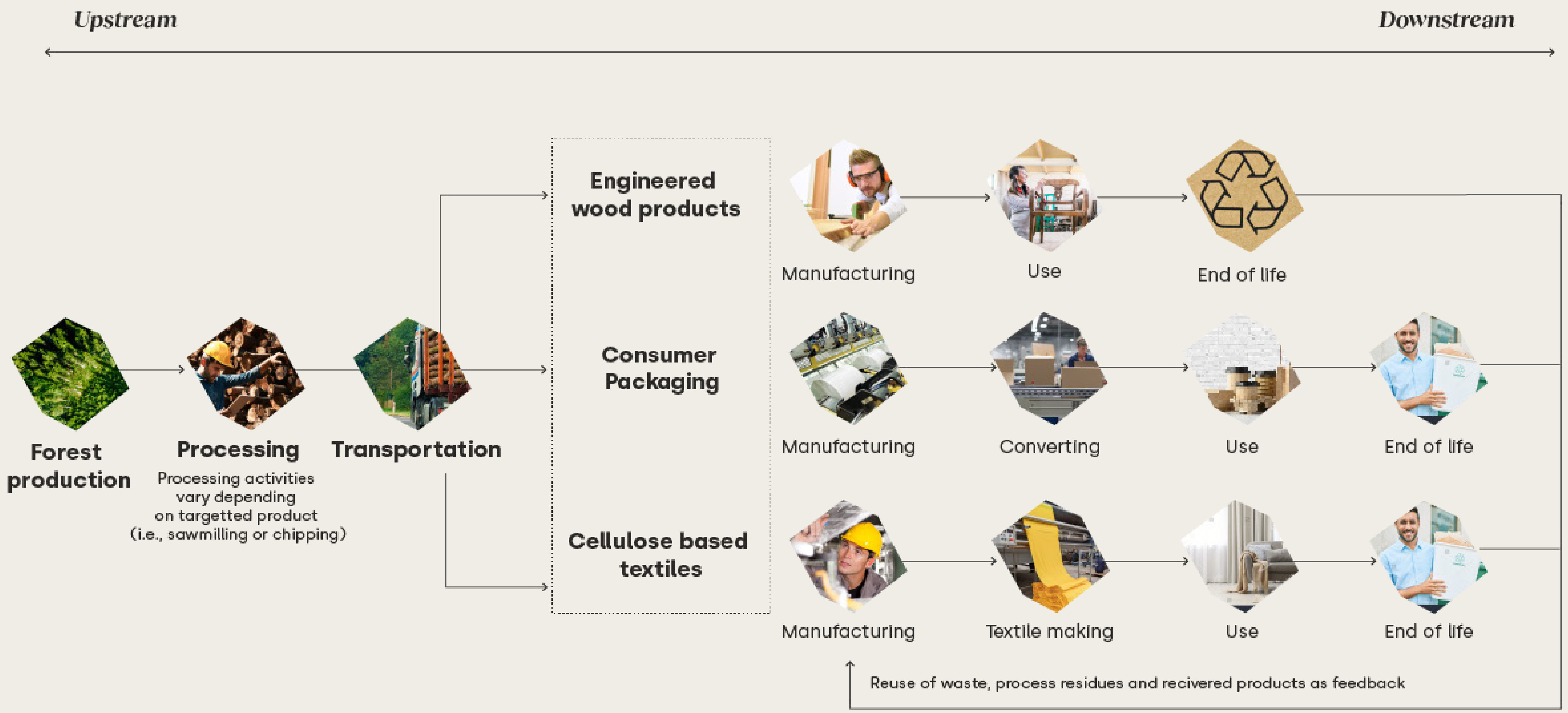
Cellulose-based textiles

Manmade cellulose fibers, also called 'regenerated cellulose fibers', are produced by dissolving cellulose from wood pulp (and in some cases, from other cellulose-rich plants, such as bamboo) and regenerating it through extrusion and precipitation. The most common fibers are viscose or rayon, acetate and lyocell. They are used in a diverse set of products, from sportswear to healthcare textiles, alone or combined with other natural or synthetic fibers. The cellulose-based textile market has grown rapidly, with global production doubling since 1990.[5] Demand is expected to rise, as regenerated fibers have popular physical properties (e.g. softness), and when sourced from sustainably working forests and produced with low emissions, can offer better environmental outcomes than alternatives such as cotton or oil-derived synthetic fibers.[6]

Emissions hotspots along the value chains

Here, we explore the value chains of the three selected product categories, and provide an assessment of potential emission hotspots along the full product lifecycle.
All forest products' value chains begin in the forest, where timber is grown and harvested in a perpetual cycle. Wood logs are transported into a lumber manufacturing facility, and chips into a mill to be transformed into different finished products or distributed for further processing (e.g. paper is converted into paper packaging), before reaching consumers. Once used (and reused), the timing of which can vary from the short life of paper packaging to decades for wooden buildings, the forest product reaches its end of life. Products are often recycled and re-enter the value chain as feedstock, or otherwise incinerated or disposed in landfill *(Refer to Figure 2)*.

Figure 2: Overview of the value chains of the three selected products



As illustrated in *Figure 3*, each phase along the value chain is characterized by different operations associated with energy consumption and varying levels of GHG emissions depending on the energy source. The relative emissions of each phase of the value chain were compared to the total emissions of the value chain, and ranked 'low' (<10%), 'medium' (10-30%) or 'high' (>30%) based on its share of total emissions.
See Methodology in Box 1 for more details.

The transportation hotspot

Transportation is common to the value chains of all three selected product categories, and occurs at multiple stages of these value chains, as visualized in *Figure 4*.

Upstream transportation from the forest to the sawmill typically covers short distances, ranging between 50 and 200 km on average. However, midstream and downstream transportation cover much longer distances, and wood or wood-based products often travel intercontinentally. In 2020, around 550 million tons of wood or wood-based products were exported worldwide, a great proportion of which occurred intercontinentally, with major trade flows between North America, Europe, China and Latin America.[7]

Trucks are the most frequently used mode of transport in the forest sector, however trains are often used for longer distances, and ships for international trade on overseas transportation. For this reason, transportation should be treated as an emission hotspot, although the intensity will vary depending on the operations and logistics of each specific value chain. On average, across different products, upstream and downstream transport and distribution accounts for around 5-10% of the sector's (Scope 3) emissions.[8] Relevant decarbonization Actions to address this hotspot can be found under the 'Mobility' section of **WBCSD's Climate Drive**.

Figure 3: Overview of the value chains of the three selected products

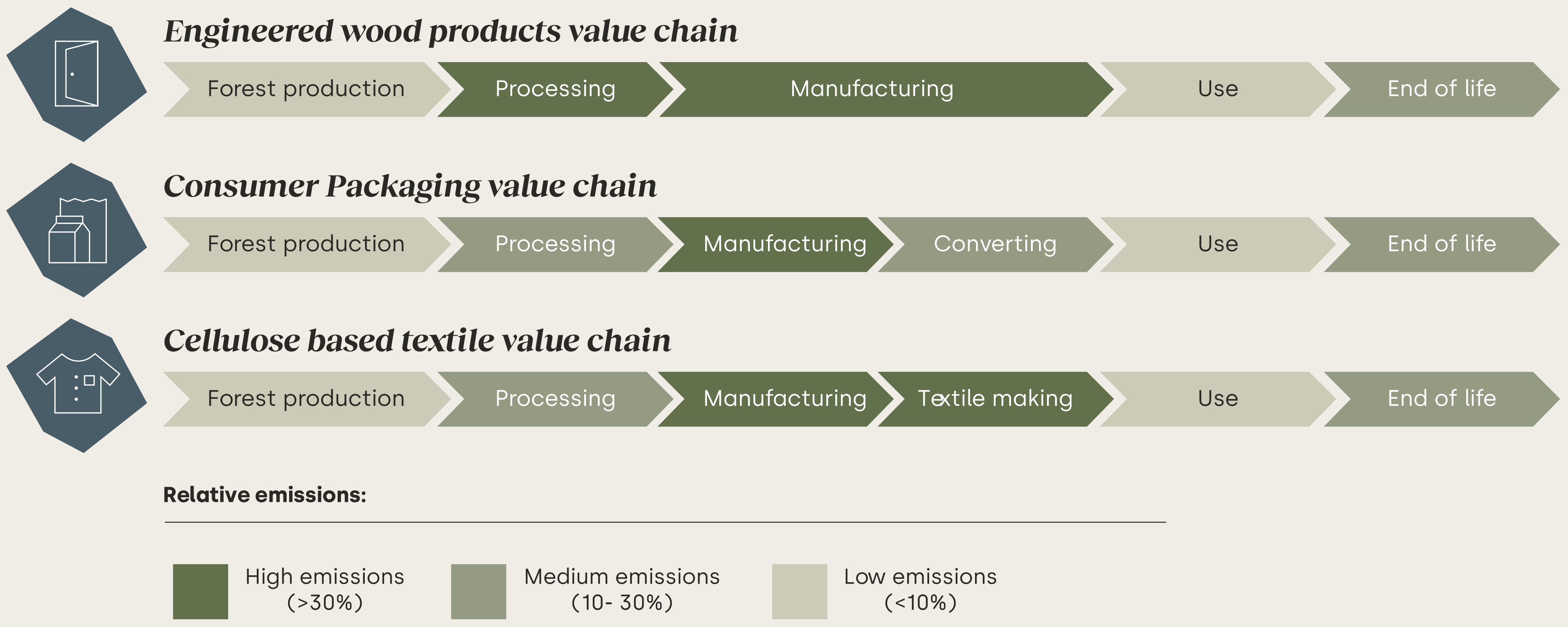
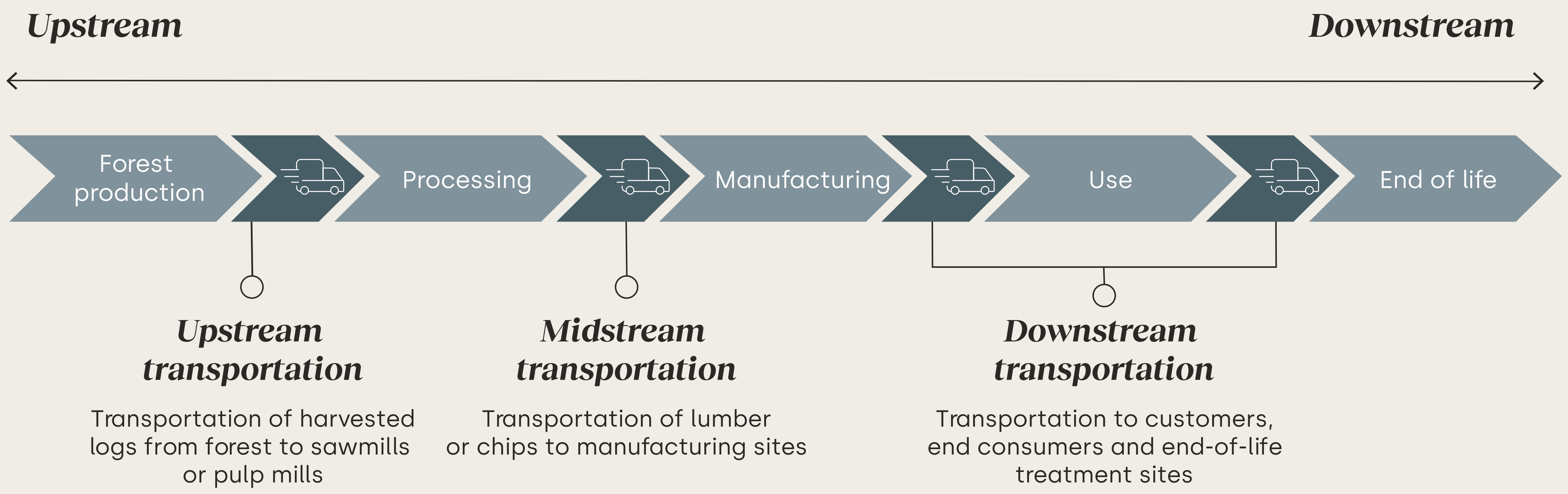


Figure 4: Overview of transportation along the value chain of forest products



Box 1. Emissions hotspot methodology

For each product category, data on GHG emissions related to the different stages of the value chain was compared to the emissions associated with the value chain as a whole. Emissions data comes from lifecycle assessments published in scientific literature as well as corporate CDP disclosures.[9] A score was attributed to each phase based on the relative share of emissions: 'low emissions' when it contributes to less than 10% of GHG emissions compared to those of the whole value chain; 'medium emissions' when it contributes 10 – 30% of value chain emissions; emission hotspots or 'high emissions' when the stage contributes more than 30% of emissions connected to the entire value chain.

The approach focuses on the assessment of GHG emissions from energy use. Biogenic carbon emissions were excluded from the hotspot assessment as the GHG Protocol and the IPCC requires them to be reported separately to non-biogenic emissions. The hotspot assessment focuses exclusively on GHG emissions, and does not capture the opportunities for climate change mitigation through carbon removals or avoided emissions.

Limitations

The emission assessment is based on global averages and captures estimates pertaining to different processes, facilities and systems. It is therefore indicative, and does not represent particular products and processes. In this regard, it is acknowledged that:

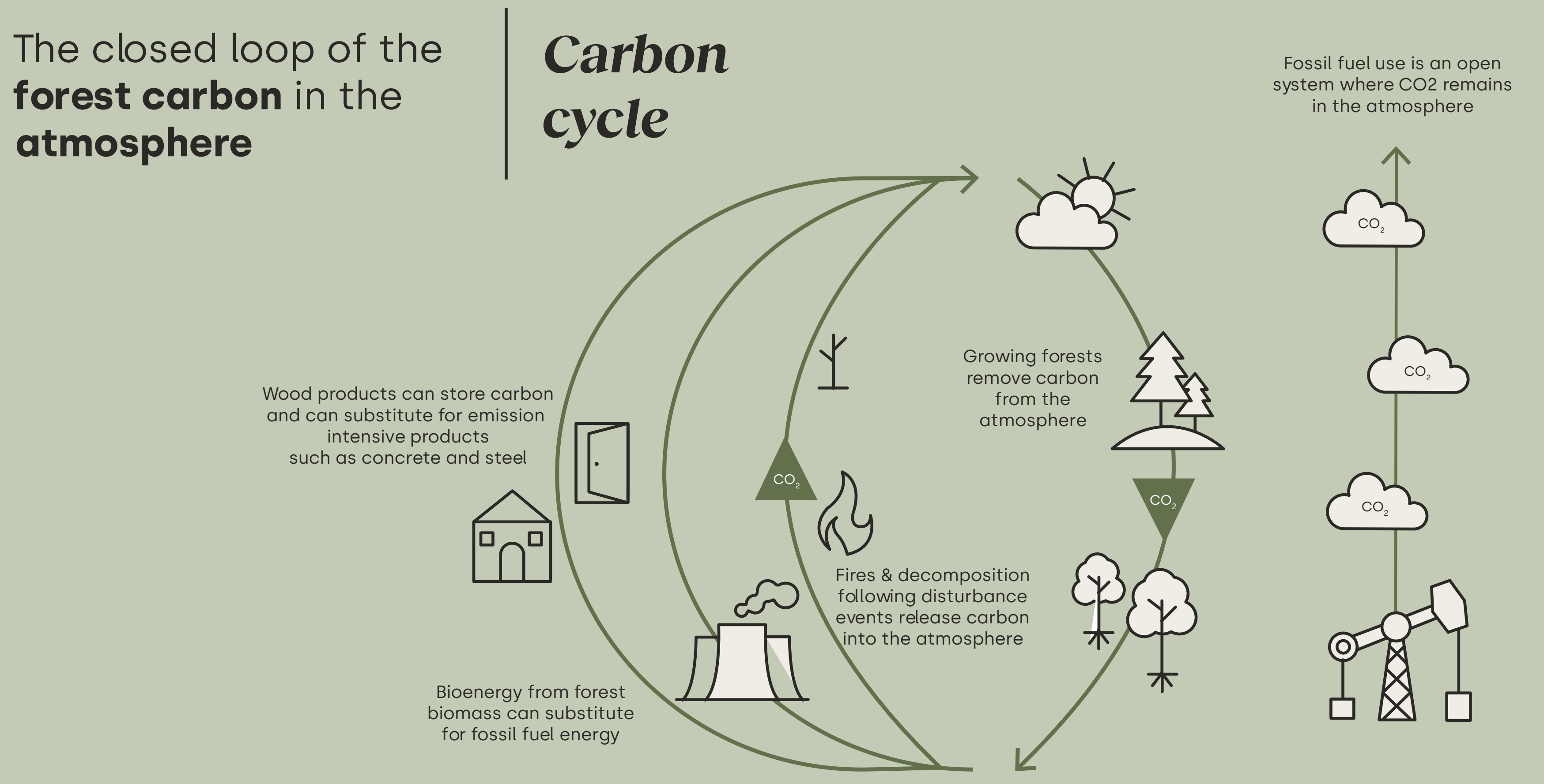
→ Geography can play a substantial role in determining the emissions intensity of processes along the value chain due to the local energy mix;
→ Processes within each phase can substantially differ, resulting in different emissions levels. For instance, pulping can be conducted through different processes (e.g. kraft, chemical, semi-chemical, etc.), and processes can be integrated (e.g. pulp and paper making vs non-integrated mills where pulping and paper making occur in separate sites), which can impact on energy efficiency and demand;
→ Additionally, emissions associated with the use of sold products (Scope 3 emissions, category 11) were excluded from the assessment in order to focus on the phases and processes over which forest companies have direct control.

Box 2. Fossil vs biogenic carbon emissions

Fossil emissions refer to the release of CO_2 that has been sequestered underground in the form of fossil fuels, such as coal, oil and natural gas into the atmosphere. These fuels were formed over millions of years from the remains of ancient plants and animals that lived and died in prehistoric times. In contrast, biogenic carbon emissions refer to the release of CO_2 from natural sources, such as comparably recently decomposed plants and animals, into the atmosphere. Whereas fossil fuel use contributes to an increase in the total amount of carbon present, biogenic CO_2 emissions form part of the natural carbon cycle and represent a balance between carbon uptake by photosynthesis and carbon release through respiration and decay *(Refer to Figure 5).*[10]

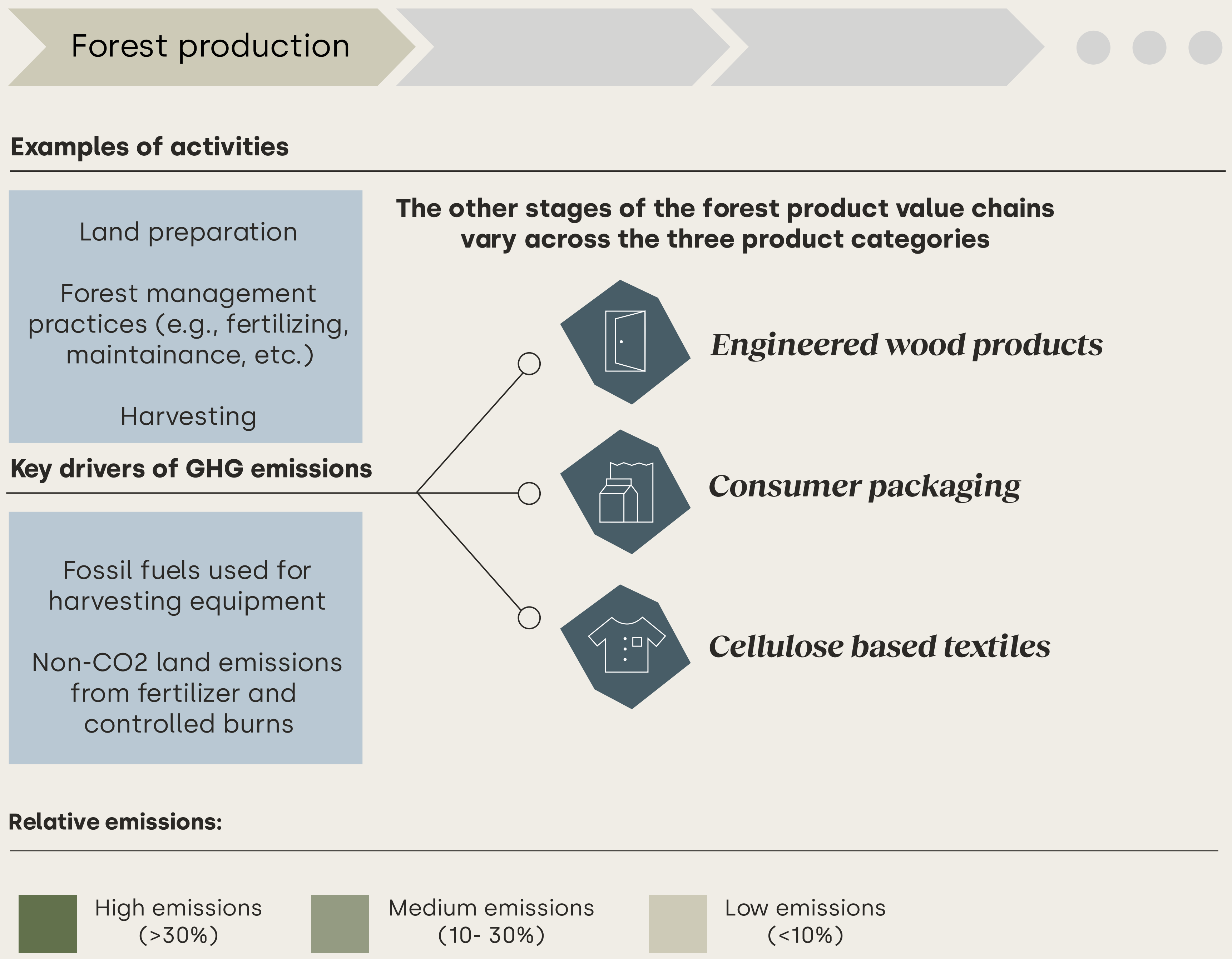
The International Energy Agency[11] summarizes the difference between fossil and biogenic CO_2 emissions as follows: "Fossil fuel use increases the total amount of carbon in the biosphere-atmosphere system, while bioenergy systems operate within it; biomass combustion simply returns to the atmosphere the carbon absorbed by plants."

Figure 5: Forest carbon cycle (USDA 2019)



Forest production stage of the value chain

Figure 6: Forest production stage of the value chain



Source: McKinsey analysis based on literature review, climate disclosure of companies in the forest sector, and consultation with FSG members. **See Box 1 for more details on the methodology.**

As the value chain of all forest products originates in working forests (natural, semi-natural and plantations), this stage of the value chain is similar across all three product categories, acknowledging that different forest types and management practices are linked to varying levels of emissions.

Once afforestation or reforestation is complete (land preparation, growing and planting of seedlings), these forests are managed though a number of practices such as thinning, vegetation control or fertilization to ensure optimal forest growth, while protecting and enhancing climate and biodiversity benefits. Harvesting takes place when trees reach their maximum product value, the age of which differs depending on the region, growing conditions, and species of trees. After harvest, sustainably managed forests either regenerate naturally or are replanted.

Fewer GHG emissions derive from forest production and harvesting activities compared to operations further downstream in the forest product value chain, accounting for less than 10% of total GHG emissions across value chains *(Refer to Figure 6)*. While machineries for both forest production and harvesting (e.g. log cutters, loaders, etc.) still mostly rely on fossil fuels, studies estimate that only around 40-60 kg GHG emissions are released into the atmosphere per ton of wood produced.[12, 13] Additionally, through sustainable forest management, forest companies maintain and increase carbon stocks and sequestration in forests, as well as storage in forest products.[14]

After harvesting, the wood is transported to the sawmill or pulp mill, where it is treated and processed. Sawmill operations slightly differ from one product category to another, marking the divergence into different value chains. Roundwood, for example, is debarked and sawn, while pulpwood is chipped.

Engineered wood products: emissions hotspots along the value chain

Figure 7: Mapping of GHG emission hotspots in the value chain of engineered wood products

Engineered wood products value chain

	Processing	Manufacturing	Use	End of life
Examples of activities	Debarking, sawing Drying, seasoning Planning	Process depending on end-product. Includes gluing, forming, joining, hot pressing.	Use by end-consumers	Recycling Burning without energy recovery Landfilling
Key drivers of GHG emissions	CO_2 from fuel combustion for energy, especially for heavy machineries and wood drying	CO_2 from fuel combustion for energy for machineries Non-energy inputs such as resins and coating	Fuel use for heat and electricity generation in buildings not included in methodology	Treatment of sold products at their end-of-life Release of GHG emissions from incineration or decomposition

Relative emissions:

- High emissions (>30%) – Processing, Manufacturing
- Medium emissions (10- 30%) – End of life
- Low emissions (<10%) – Use

Source: McKinsey analysis based on literature review, climate disclosure of companies in the forest sector, and consultation with FSG members. **See Box 1 for more details on the methodology.**

Engineered wood products: emissions hotspots along the value chain Continued

Processing

Wood processing is a relatively high energy intensive phase, generating more than 30% of the emissions of the entire value chain *(Refer to Figure 7)*. Processing requires heavy machinery, fuelled by either fossil fuels or biofuels, largely derived from bio-based process residues and by-products. Additionally, the drying of wood – a key phase to controlling the quality of final wood products – is an energy intensive process, requiring large quantities of heat.[15] Wood drying can be responsible for 60 to 80% of emissions in the sawmill, although energy consumption as well as GHG emissions largely depend on a wide range of factors, such as the type and dimension of wood, the type of drying systems, the climate and temperatures, as well as the energy sources used in kilns.[12]

Manufacturing

The manufacturing of engineered wood products is another emission hotspot, responsible for more than 30% of the value chain's emissions. Manufacturing involves several key phases, such as lumber preparation (sawing, chipping, stripping), gluing and jointing, pressing, and panel finishing. These processes require energy inputs, such as fuel and electricity, and other non-energy inputs, such as resins and coatings, which also increase the GHG emissions associated with **manufacturing.** Studies suggest that the on-site manufacturing of engineered wood products can be 1 to 2 times more emission intensive compared to the lumber production phase.[4]

Use

The use phase of buildings is a major source of GHG emissions. In 2021, around 27% of global energy and process-related emissions resulted from building use, excluding emissions from the manufacture of construction materials that could be substituted by **timber.**[16] The methodology used in this report excludes emissions from the use of sold products, which dominate any other emissions from the value chain. This allows a focus instead on the phases and processes over which forest companies have more direct control.

End of life

The end of life treatment of timber products, such as recycling and reuse, is a moderate source of emissions, accounting for 10 – 30% of emissions compared to those of the entire value chain. The decomposition of biogenic products releases not only CO_2, but also CH4 and N2O into the atmosphere. These gases have a significantly higher Global Warming Potential (GWP) than CO_2.[17] Although biogenic carbon emissions are excluded from the emissions hotspot analysis **(see Box 1)**, it is worth highlighting that this stage can present a good opportunity for energy recovery and increased circularity[18]

Relative emissions:

- High emissions (>30%)
- Medium emissions (10- 30%)
- Low emissions (<10%)

Consumer packaging: emissions hotspots along the value chain

Figure 8: Mapping of the GHG emission hotspots in the value chain of paper consumer packaging

Consumer packaging value chain

	Processing	Manufacturing	Converting	Use	End of life
Examples of activities	Wood processing Wood chipping and drying	Pulping and refining Paper making Waste management	Paper conversion Customization (printing, finishing, etc.)	Retail and use by end-customers	Recycling Burning without energy recovery Landfill
Key drivers of GHG emissions	Combustion of fuels for wood chipping and drying	Combustion of fuels for boilers Non-CO_2 emissions from anaerobic wastewater treatment	Combustion of fuels for conversion of paper, printing and finishing	No emission from packaging use Emission from transport to and from retrailer excluded	Treatment of sold products Release of GHG emissions from incineration or decomposition

Relative emissions:

- High emissions (>30%)
- Medium emissions (10- 30%)
- Low emissions (<10%)

Source: McKinsey analysis based on literature review, climate disclosure of companies in the forest sector, and consultation with FSG members.
See Box 1 for more details on the methodology.

Consumer packaging: emissions hotspots along the value chain Continued

Processing

Pulpwood, from forest thinning and residuals, and wood chips, usually from saw mills, are purchased by pulp and paper mills to be further processed. As shown in Figure 8 from the previous page, the processing of pulpwood is a 'medium' emissions hotspot in this value chain. Compared to the total emissions of paper-based consumer packaging, this phase generates less than 30% of **emissions**.

Manufacturing

The pulp and paper making process is the largest emission hotspot in the paper packaging value chain, accounting for more than 30% of emissions compared to those associated with the entire value chain *(Refer Figure 8 from the previous page)*. Although the pulp and paper industry uses significant amounts of biofuels – representing more than 60% of all used fuels, at a global level - the industry still relies on fossil fuels, such as gas, coal and other oils.[19] Manufacturing processes in this industry require large amounts of energy to produce the power and steam required to run a mill. In kraft pulp mills, CO_2 emissions arise primarily from four major sources: the lime kiln, multi-fuel boiler, the recovery boiler, and the power generator boiler.[20] In addition to direct emissions from fossil fuel combustion, there also are non-energy related sources such as carbon dioxide emissions as a by-product of the chemical reaction in the lime kiln.[21]

Converting

Converting paper into a final product produces fewer emissions than the manufacturing phase, although it is still responsible for up to 20% of emissions in the overall value chain. In this phase, paper is transformed by converting, printing and finishing the final product. This relies on the use of electricity and fossil fuels to power machines, as well as on non-energy inputs such as inks, varnish, labels and others.

Use

The only emissions associate with the use phase of consumer packaging result from the transport and distribution of packaging products. Decarbonization actions related to transportation are not addressed in the context of this catalogue, but are available under the 'Mobility' section of **WBCSD's The Climate Drive**.

End of life

After the product is sold and used, re-used and recycled, it ultimately reaches end of life. Companies in the forest sector report that end of life treatment of sold products, such as recycling, incineration or landfilling, are, on average, responsible for 15% of a company's total GHG emissions.[22]

Relative emissions:

High emissions (>30%) | Medium emissions (10- 30%) | Low emissions (<10%)

Cellulose-based textiles: emissions hotspots along the value chain

Figure 9: Mapping of the GHG emission hotspots in the value chain of cellulose-based textiles

Cellulose-based textiles value chain

	Processing	Manufacturing	Textile making	Use	End of life
Examples of activities	Wood processing Wood chipping and drying	Pulping Dissolving wood pulp (DWP) manufacturing Waste management	Textile manufacturing (e.g, yarn preparation, spinning, dying) Waste management	Retail and use	Recycling Burning without energy recovery Landfill
Key drivers of GHG emissions	Combustion of fuels for wood chipping and drying	Combustion of fuels for boilers Non-CO2 emissions from anaerobic wastewater treatment	Combustion of fuels for machineries and steam generation Non energy inputs such as chemicals used in the dying phases	Low emissions from use phase (e.g. washing) Other environmental impacts (water use, plastics) dominate	Treatment of sold products Incineration and decomposition

Relative emissions:

- High emissions (>30%)
- Medium emissions (10- 30%)
- Low emissions (<10%)

Source: McKinsey analysis based on literature review, climate disclosure of companies in the forest sector, and consultation with FSG members.
See Box 1 for more details on the methodology.

Cellulose-based textiles: emissions hotspots along the value chain Continued

Processing

Pulpwood, from forest thinning and residuals, and wood chips, usually from saw mills, are purchased by pulp and paper mills to be further processed. As shown in Figure 9 from the previous page, the processing of pulpwood is a 'medium' emissions hotspot in this value chain. Compared to the total emissions of cellulose based textiles, this phase generates less than 30% of emissions.

Manufacturing

As cellulose fibers are produced from wood pulping, similar to paper packaging products, manufacturing is an energy and emission intensive phase of the value chain. The difference is that dissolving wood pulp is a higher purity pulp produced through more intensive cooking and bleaching processes, which remove lignin and hemicelluose - a weaker polysaccharide in the pulp.

Textile making

Textile making comprises several steps and processes, all requiring large amounts of energy and driving more than 30% of emissions of the cellulose-based textile value chain. The fibers go through spinning, fabric production, dyeing and finishing, all processes fuelled by the combustion of biogenic and fossil fuels to produce heat and steam, and electricity to run machinery.[23 24 25] The textile making process consumes high volumes of chemicals which also contribute to GHG emissions through Scope 3 emissions.

Use

The use phase of textiles includes retail and clothes washing. The latter is a major source of water use and of micro-plastics pollution, but GHG emissions from this phase, excluding transport, are low. This methodology ignores these emissions and focuses on the phases and processes over which forest companies have direct control.

End of life

Similar to paper consumer packaging, the end of life treatment of sold products is associated with up to 20% of GHG emissions. The recycling of textiles has had slow uptake, resulting in many textiles still being sent to landfill. In fact, there are several barriers to textile recycling and fiber recovery, from the sorting of materials (e.g. separating by material type can be difficult and labor intensive), to recycling correctly, given the challenge of increasing fiber in products. However, new technologies are being developed, such as sensors and cameras to help detect, sort and recover cellulose fibers, which can be reused and have their life extended.

The analysis of the value chains and related emissions is vital to identifying the emission hotspots and high potential areas for emission reduction. Leading forest companies are taking action to tackle GHG emissions along the value chain, adopting a variety of technologies and practices. The following section presents some of the key actions that forest companies can adopt to decarbonize their operations and products.

Relative emissions:

- High emissions (>30%)
- Medium emissions (10- 30%)
- Low emissions (<10%)

3. Introducing the 10 *decarbonization actions*

Overview

This section presents ten actions that forest companies can implement to decarbonize their operations and value chains. In line with the **forest sector's three levers of impact** *(introduced in Figure 1)*, the majority of actions are focused on reducing the company's own footprint (A), while others contribute through carbon removals in forest and forest products (B), and by growing the circular bioeconomy through the substitution of fossil-based materials with renewable and recyclable wood-based materials (C).

To promote comparability between the different actions, the ten actions were assessed and scored based on their emission abatement potential, maturity level and economic feasibility. They were also tied to the forest sector's three levers of impact *(see Table 1)*.

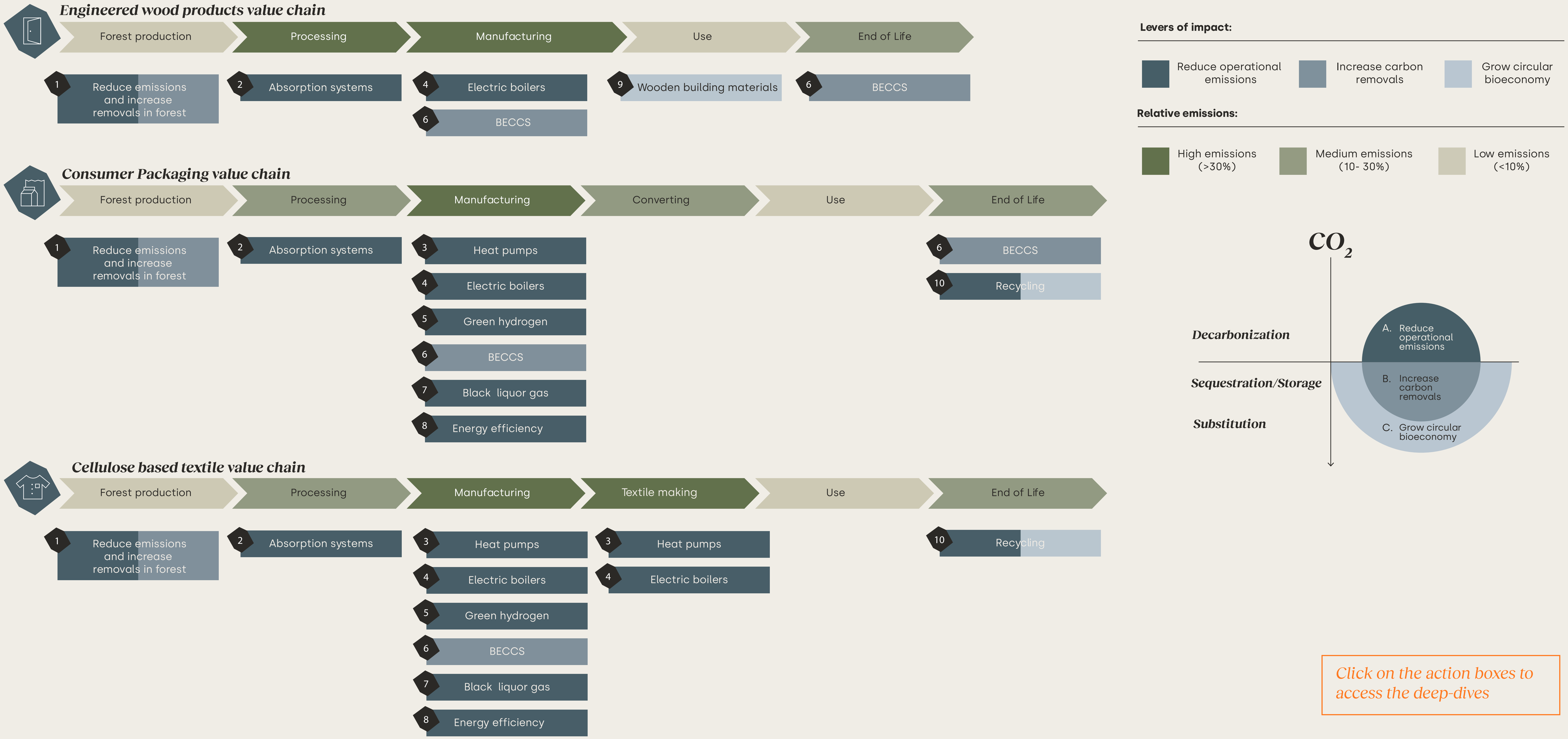
The ten actions presented in this catalogue were selected for performing well on the criteria, for their specific relevance to the forest sector, coverage of the full value chain, as well as their ability to address the emissions hotspots and/or leverage the opportunities for carbon removals or avoided emissions. The selected decarbonization actions are complementary and should be implemented simultaneously to maximize impact.

Table 1: Selection of decarbonization actions assessed based on criteria (Box 3)

Nr	Decarbonization action	Abatement potential*	Maturity level*	Economic feasibility*	Forest sector 3 levers of impact
1	Implement measures to increase carbon removals and reduce emissions in sustainable working forests	High	High	High	A. Reduce operational emissions & B. Increase carbon removals
2	Adopt heat recovery technologies in the sawmill: deep dive on absorption systems	High	High	High	A. Reduce operational emissions
3	Adopt heat recovery technologies in the pulp and paper mill: deep dive on heat pumps	High	High	High	A. Reduce operational emissions
4	Switch to industrial electric boilers in manufacturing	High	High	High	A. Reduce operational emissions
5	Switch to low-carbon fuels: deep dive on low-carbon hydrogen	High	Medium	Low	A. Reduce operational emissions
6	Adopt BECCS technologies	High	High	High	B. Increase carbon removals
7	Maximize waste recovery technologies in the pulp and paper mill: deep dive on liquor gasification	Medium	High	Low	A. Reduce operational emissions
8	Invest in innovative pulping and paper making technologies to increase energy efficiency	High	Medium	High	A. Reduce operational emissions
9	Increase the adoption of wood products for construction	Medium	High	High	C. Grow circular bioeconomy
10	Promote and lead on recycling and sorting technologies for paper products and textiles: deep dive on sensor-based technologies and textile recycling	High	High	High	A. Reduce operational emissions & C. Grow circular bioeconomy

For most actions, there is a significant variation in abatement potential, maturity level and economic feasibility depending on regional and technological specificities as well as business considerations. As a way to simplify, the highest possible potential was applied.

Figure 10: Mapping of decarbonization actions along the three value chains



Click on the action boxes to access the deep-dives

Box 3: Methodology for assessment against criteria

Level of maturity
The level of maturity score for each action is based on the 'Technology Readiness Level' (TRL). This indicator estimates the maturity of technologies, measured through an assessment of their progress and capabilities. The scale originally ranges from 1 to 9, where TRL 1 is the lowest and TRL 9 is the highest. When a technology is at TRL 1, scientific research is underway and results are being translated into future research and development, while at TRL 9 the technology has already been proven to work. The International Energy Agency (IEA) has extended the TRL scale used in this report to incorporate two additional levels of readiness: one where the technology is commercial and competitive but needs further innovation efforts for the technology to be integrated into energy systems and value chains when deployed at scale (TRL 10). Finally, there is a level where the technology has achieved predictable growth **(TRL 11)**.

Emission abatement potential
The emission abatement potential of each action, whether a technology or practice, describes the potential to reduce GHG emissions with respect to the counterfactual technology or practice, meaning the technology or practice that is part of the 'business as usual' scenario, or that is substituted or improved by adopting a decarbonization action. Emission abatement potential is usually expressed as a percentage, and the higher it is, the higher GHG emission reductions can be achieved:

Low	*15% of GHG emissions*
Medium	*15-50% of GHG emissions*
High	*>50% of GHG emissions*

Category	TRL score (1-11)	Description	Maturity level score
Concept	1	**Initial idea.** Basic principles have been applied	*Low*
	2	**Application formulated**. Concept and application of solution have been formulated	
	3	**Concept needs validation.** Solution needs to be prototyped and applied	
Small prototype	4	**Early prototype.** Prototype proven in test conditions	
Large prototype	5	**Large prototype**. Components proven in conditions to be deployed	*Medium*
	6	**Full prototype at scale.** Prototype proven at scale in conditions to be deployed	
	7	**Pre-commercial demonstration.** Solution working in expected conditions	
Demonstration	8	**First of a kind commercial.** Commercial demonstration, full scale deployment in final form	
Early adoption	9	**Commercial operation in relevant environment.** Solution is commercially available, needs evolutionary improvement to stay competitive	*High*
	10	**Integration needed at scale.** Solution is commercial and competitive but further integration effort are required	
Mature	11	**Proof of stability reached.** Predictable growth	

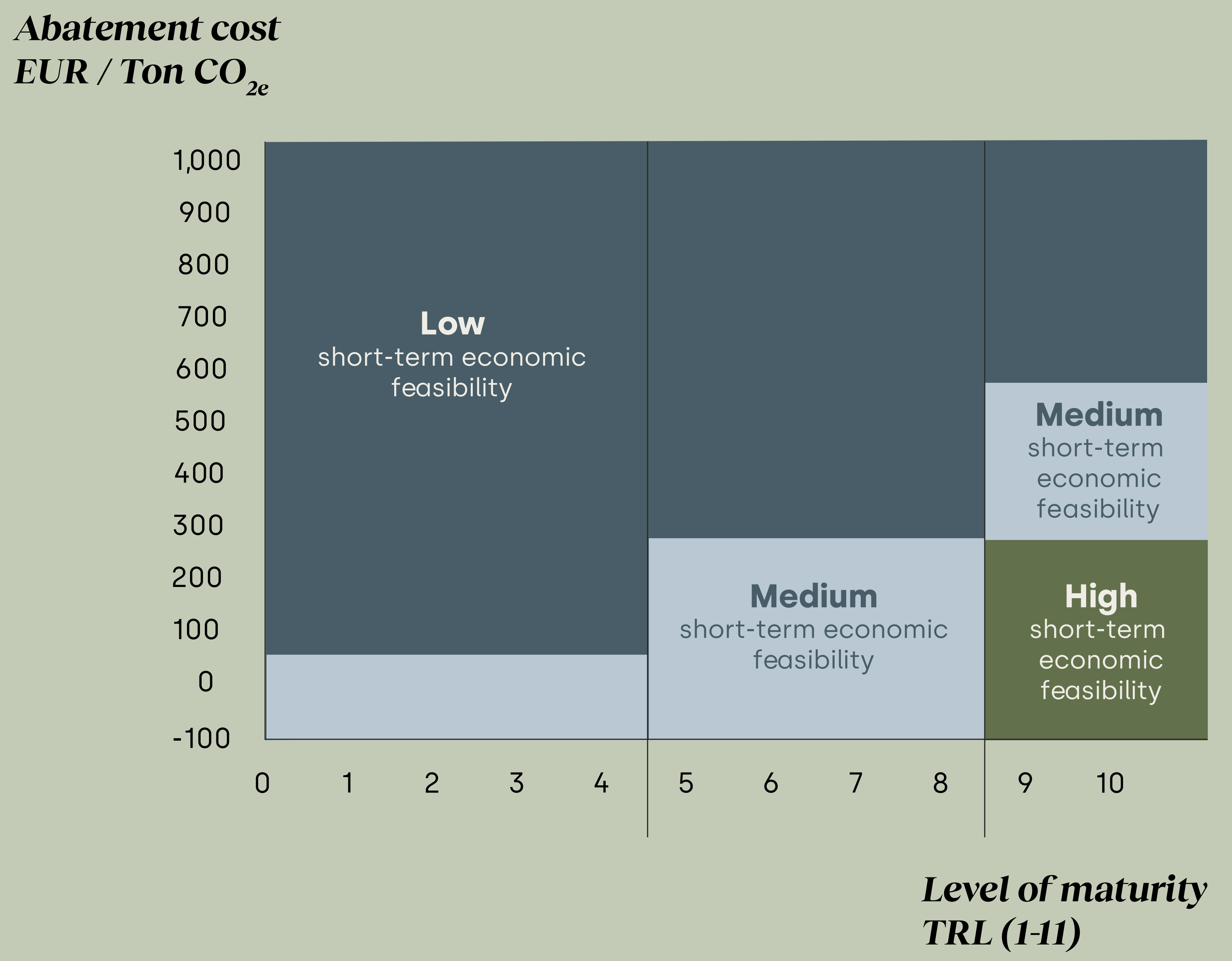
Box 3: Methodology for assessment against criteria
Continued

Emission Abatement

The emission abatement cost is an indicator that measures the costs associated with abating one ton of GHG emissions (EUR/ton CO_2e abated). The lower the abatement cost, the cheaper it is to reduce emissions, and therefore the more attractive the action.

Short-term economic feasibility

Economic feasibility is assessed based on the maturity level and the abatement cost of each action, as per the visualization below. Actions with a low maturity level (≤ 4) are considered to have low economic feasibility in the short term, given the need to validate and deploy the technology in relevant environments. However, if the abatement cost has already proven to be low, the action is assessed as medium. Actions with medium maturity (TRL 5-8) may have low or medium economic feasibility in the short term, depending on the abatement cost (≤ 250 EUR/tCO_2e). Similarly, the short-term economic feasibility of actions with higher maturity (TRL 9-11) varies depending on the abatement cost (low when < 550 EUR/tCO_2e, medium if the cost ranges between 250-450 EUR/tCO_2e, or high if the cost is lower than 250 EUR/tCO_2e). The thresholds that determine short-term economic feasibility are defined by taking into consideration that additional benefit, including revenue generating opportunities. They are not monetized or included in the abatement cost estimates.



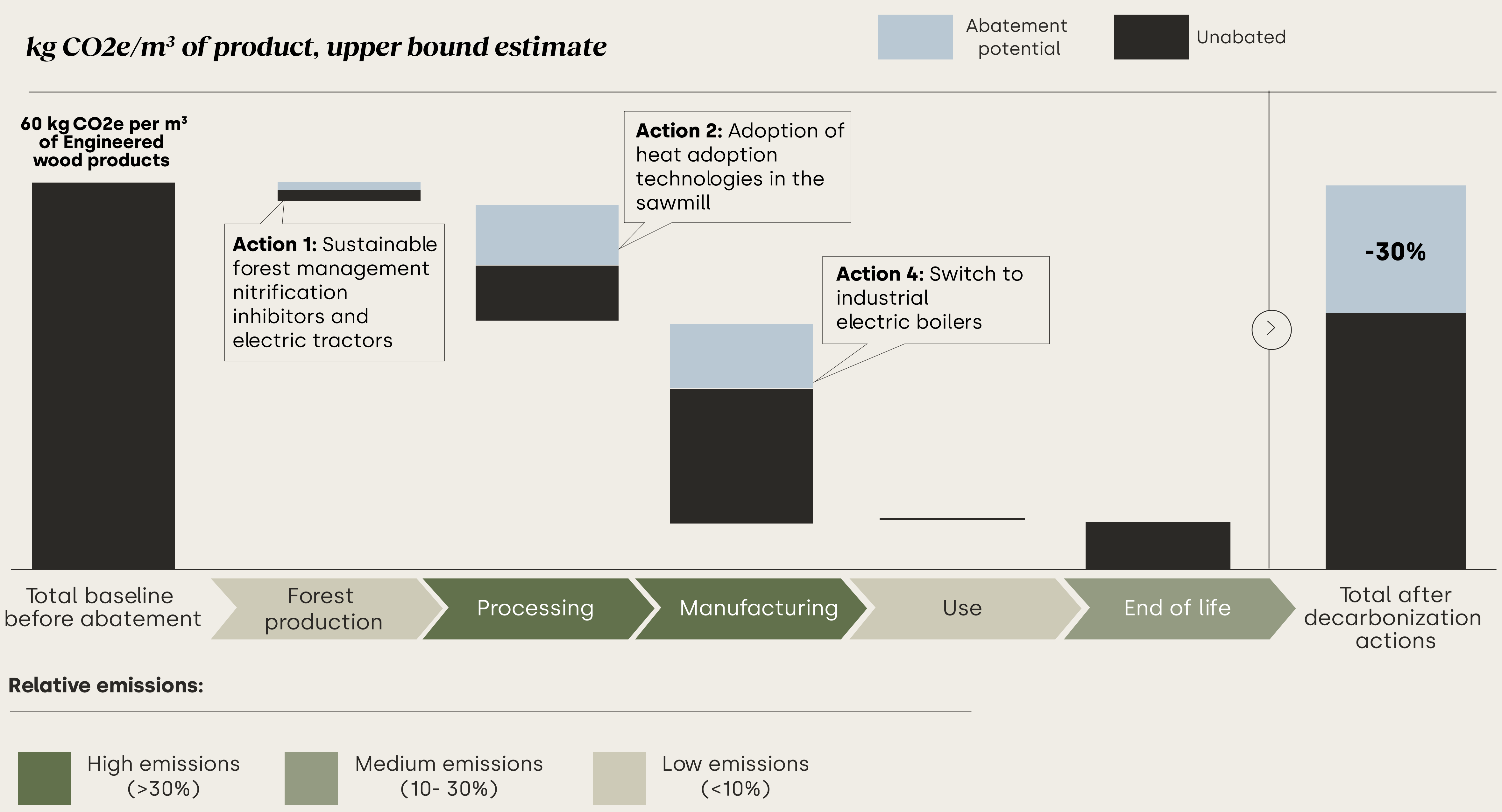
4. Progressing towards *Net-Zero*

Overview

A study of the cumulative impact of the key decarbonization actions described in this catalogue indicates that at least 30-40% decarbonization is possible using abatement actions of high technical maturity and feasibility. This estimate only includes actions focused on reducing GHG emissions, and excludes those linked to nature-based or technological carbon removals (Actions 1 Sustainable Forest Management and 6 BECCS). It also excludes the forest sector's contribution to decarbonizing other sectors through avoided emissions (Action 9 Forest products for construction). It is important to note that this catalogue profiles only a small selection of decarbonization actions and there is still a lot to gain from the broader use of mature and more widespread actions such as rolling out energy efficiency measures, as well as increasing the use of sustainable biomass for energy production.

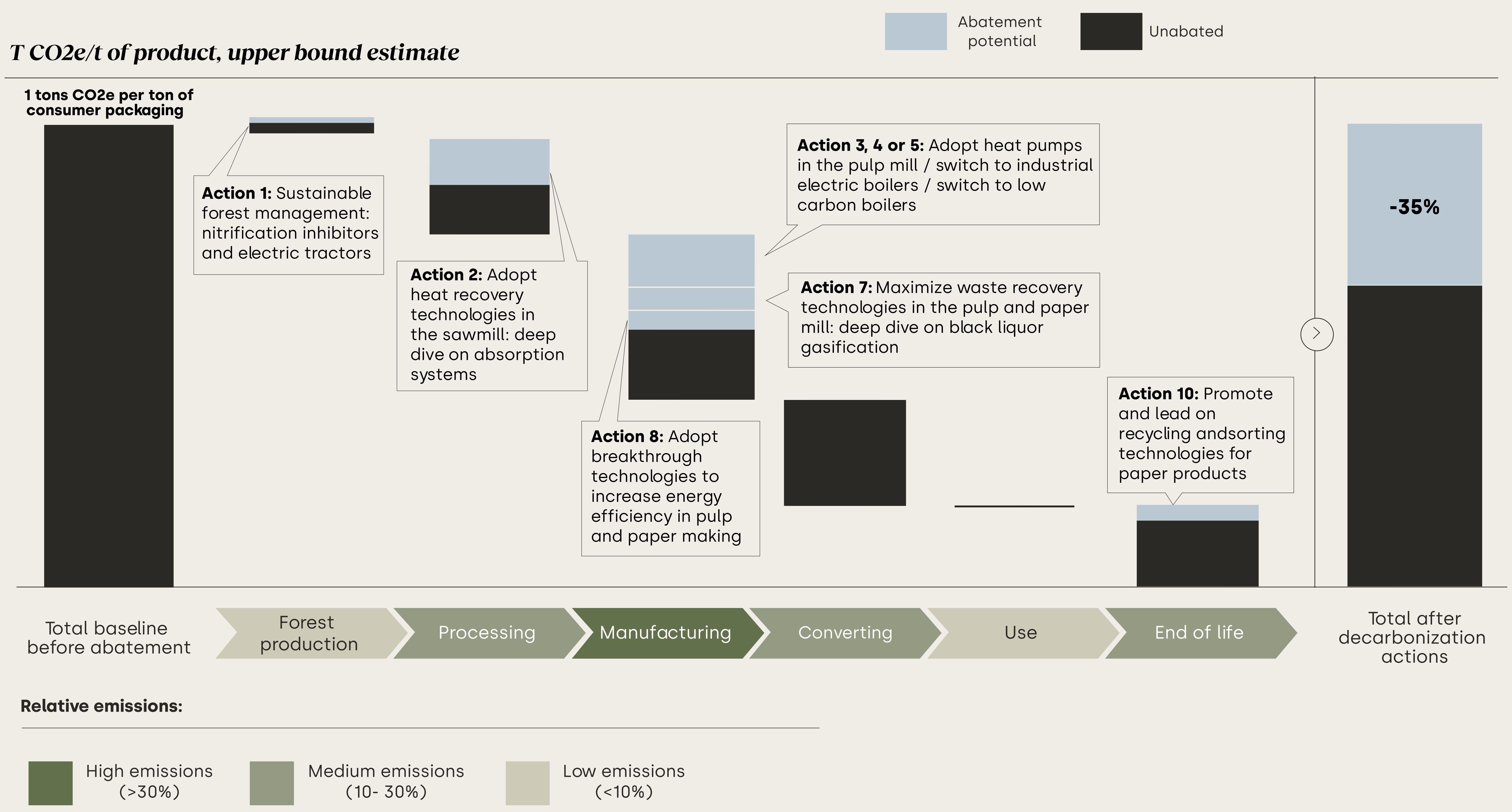
Figures 11 to 13 show the breakdown of the total emissions abatement potential achieved through the deployment of a selection of actions in each of the three value chains (engineered wood products, consumer packaging products, cellulose-based textile products). Among the three product categories, engineered wood products are the least carbon intensive, with cross-laminated timber's emissions ranging from 30 to 300 kg CO_2e per cubic meter *(see Figure 11)*. It was estimated that around 30% of these emissions could be abated through the deployment of the selected decarbonization actions. Paper packaging is associated with higher emissions, ranging between 1 and 4.5 tons of CO_2e per ton of product *(see Figure 12)*, and tied to an estimated total abatement potential of 35%. Finally cellulose-based textiles can drive as much as 1.5 to 13 tons of CO_2e per ton of product, with an estimated total decarbonization potential of 40% *(see Figure 13)*.

Figure 11: Engineered wood products - breakdown of the abatement potential by stage of the value chain



Source: McKinsey analysis. *See Appendix B for underlying assumptions*

Figure 12: Consumer packaging products - breakdown of the total abatement potential by stage of the value chain



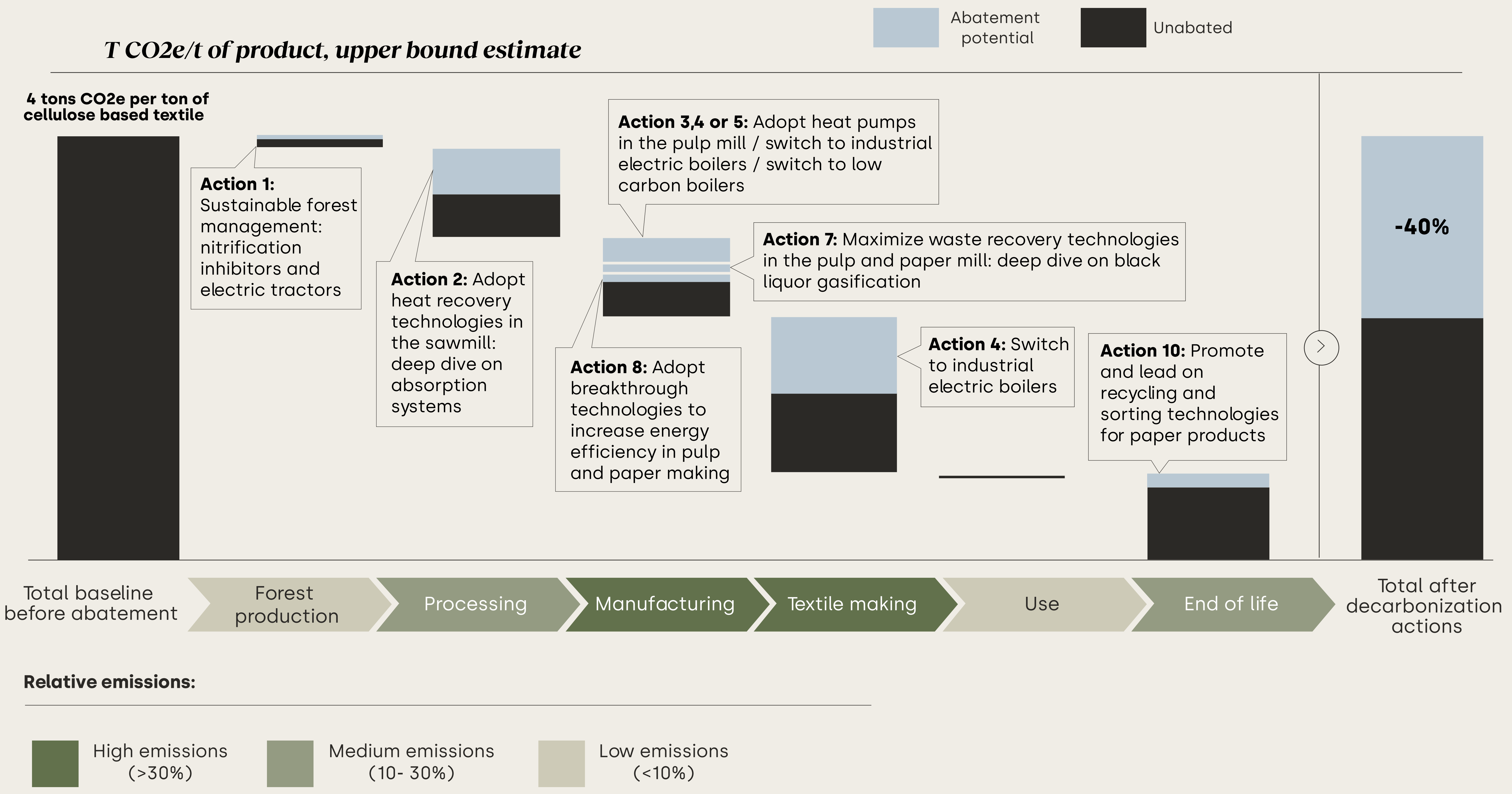
Source: McKinsey analysis. *See Appendix B for underlying assumptions*

In order to go beyond the estimated 30-40% total abatement potential, the implementation of most decarbonization actions can lead to higher abatement when combined with renewable electricity. This applies to heat recovery technologies (Action 2 and 3), electric boilers (Action 4), BECCS technology (Action 6) and, in certain cases, black liquor gasification (Action 7) and recycling technologies (Action 10). The difficulties associated with the procurement of renewable energy in countries with low penetration can present a significant barrier to decarbonization. Faced with this challenge, companies can enter procurement agreements and/or develop on-site renewable energy generation:

Offsite renewable energy power purchase agreements (PPAs)

Companies can enter into long-term agreements that involve the purchase of power and associated renewable energy certificates (RECs) from a renewable energy generator at a fixed price. Under these PPAs, the electricity is either delivered to the site via the power grid (Physical PPA), or the purchaser buys electricity from its utility provider (Virtual PPAs). See **WBCSD Climate Drive** for more information and examples of PPAs.

Figure 13: Cellulose-based textile products - breakdown of abatement potential by stage of the value chain



Source: McKinsey analysis. *See Appendix B for underlying assumptions*

On-site or behind-the-meter (BTM) renewable energy generation

Companies can invest in developing their own renewable energy projects on-site to generate a proportion of their energy needs. In addition to the use of sustainable biomass, in the pulp and paper industry, geothermal, wind and solar energy could be used on site.[26] Mills, particularly in Southern Europe, have demonstrated the potential of solar to meet a proportion of their electricity needs.[27] Additionally, solar panels have proved to be a viable energy source for consumer packaging companies.[28] Installing solar panels on existing buildings may be most suitable for downstream and midstream companies, particularly for organizations with space constraints. Small wind turbines may also be a cost effective option for companies with sufficient land available. Companies lacking the expertise or finance to install renewable energy on site can overcome these barriers by leasing land to a developer, entering a purchase agreement for the electricity produced, a practice used in the forestry sector.[29]

5. Next Steps on *decarbonization journey*

Overview

Achieving a net zero economy requires a deep transformation of every aspect of the economy. Business is expected to play a leading role by investing in the decarbonization of its operations and value chains, as well as engaging with stakeholders to create the right enabling conditions. Accelerating action in the forest sector to decarbonize in line with 1.5°C pathways will send a strong signal to customers, investors and regulators, as well as spur innovation and collaboration across the full forest sector value chain.

Introducing the next steps

If your company operates in the forest product value chain, the sequential steps below will help you leverage the content of this catalogue of key decarbonization actions to start or accelerate your individual company's decarbonization journey.

→ **Assess your GHG emissions hotspots along the full lifecycle of your products,** using **Figure 3** as a sector-level average to inform the assessment for your individual company emissions hotspots along the full value chain. Prioritize the emission hotpots that offer the highest abatement potential, and on which you have the most operational control.

→ **Build and communicate a clear strategy** to maximize emissions reductions and increase carbon removals, identifying both short and long-term targets, as well as a list of possible actions. **Figure 10** and **Table 1** will help you maximize emissions reductions and increase carbon removals taking into consideration their relative level of maturity, emissions abatement potential, and economic feasibility.

→ **Conduct a feasibility assessment** to determine the technical, economic and environmental viability of the selected action(s), including an evaluation of the existing infrastructure, energy requirements etc. As part of your assessment consider public investments, subsidies, and other regulation in your region of operation, as these will likely impact the economic feasibility assessment (**see Appendix A** examples of enabling policies linked to key jurisdictions and tied to specific actions).

→ **Conduct initial pilot in your operations** by engaging with manufacturers to develop the technologies, and testing them through the collection of data to evaluate performance, efficiency and emissions.

→ **Undertake training and education** of all staff and suppliers to build support for climate strategy. Employees responsible for operating and maintaining the technology should be trained on the system's functionalities, operating procedures, safety precautions and regular maintenance requirements. Ensure they understand the benefits of the system, and how to monitor and troubleshoot potential issues.

→ **Implement a monitoring and management system** to track performance and savings from the decarbonization action, by collecting and analyzing data regularly, informing decision-making, and identifying opportunities for further optimization.

Focus on building the right enabling environment through active engagement with key stakeholders such as value chain partners, investors and policy makers with the following calls to action:

→ **Value chain partners** join forces with the forest sector to address shared emissions hotspots such as those linked to transportation, or to increase recycling rates of forest products through infrastructure investments. You can also accelerate your own decarbonization journey by choosing sustainable forest products to complement or substitute for less sustainable alternatives.

→ **Investors** accelerate your portfolio's transition to net-zero with forest sector investments that reward companies driving ambitious decarbonization strategies, while contributing carbon removals, and the substitution of fossil-based materials with less carbon intensive alternatives.

→ **Policy makers** promote policies that incentivize low carbon technologies, and facilitate financing and R&D to support decarbonization efforts across the sector. To deploy the forest sector's full climate change mitigation potential, promote policies that account for the full climate benefits of working forests and wood-based products.

6. *Deep dives into the 10 decarbonization actions*

Action 1: Implement measures to increase carbon removals and reduce emissions in sustainable working forests

Summary

Level of maturity
The level of maturity score for each action is based on the 'Technology Readiness Level' (TRL). This indicator estimates the maturity of technologies, measured through an assessment of their progress and capabilities. The scale originally ranges from 1 to 9 where TRL 1 is the lowest and TRL 9 is the highest. When a technology is at TRL 1, scientific research is underway and results are being translated into future research and development, while at TRL 9 the technology has already been proven to work. The International Energy Agency (IEA) has extended the TRL scale used in this report to incorporate two additional levels of readiness: one where the technology is commercial and competitive but needs further innovation efforts for the technology to be integrated into energy systems and value chains when deployed at scale (TRL 10). Finally, there is a level where the technology has achieved predictable growth (TRL 11).

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Low	15% of GHG emissions
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High	50% of GHG emissions

Emission Abatement
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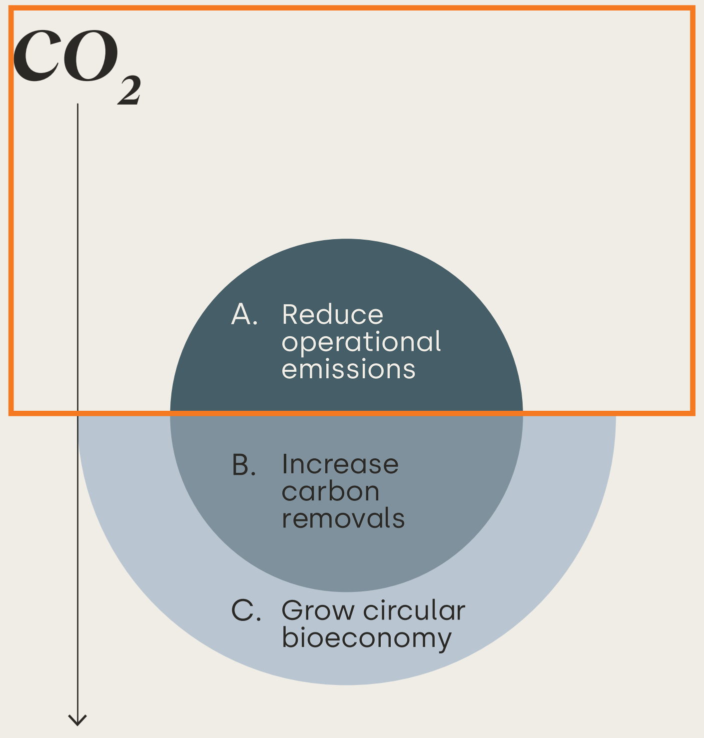
Forest sector 3 levers of impact



LOW TO HIGH

Carbon removals: Technologies availabe and widely adopted (TRL 9-11)

Reduce emissions: Technologies partially available, not widely used (TRL 4-6)

MEDIUM TO HIGH

Emission abatement potential varies depending on the technologies and practices adopted

Short-term economic feasibility

LOW TO HIGH

Low/medium economic feasibility for low maturity practices to reduce operational emissions, high economic feasibility for carbon removal practices

Overview of the solution

Forests are the largest terrestrial carbon sink, absorbing CO_2 from the atmosphere and storing it for long periods of time in the trees and soil. Working forests transfer some of this carbon to forest products, where it is also stored for long periods of time.

Sustainable forest management is key to securing these carbon stocks and ensuring these forests continue to sequester carbon. Forest managers and owners have a critical role to play in maintaining and increasing carbon removals in sustainable working forests, and reducing operational emissions associated with forest production. *As shown in Table 1 on the following page*, several practices can be implemented with the aim of:

Maintaining carbon stocks and removals

The most available practice is to maintain or enhance forest carbon stocks by ensuring growth is equal to or greater than the combination of harvesting and mortality. Practices in this space are aimed at preventing the loss of carbon by mitigating natural disturbances, such as pests and disease, and avoiding major carbon losses from forest fires. This includes monitoring for fire and pest outbreaks to provide early warnings and coordinate the response to minimize damage. In addition to conventional methods like ground-based monitoring, innovative technologies such as unmanned aerial vehicles (i.e., drones), remote sensing and weather monitoring can support forest managers in monitoring forests. In addition, climate resilience – that is, the capacity of forests to cope with hazardous events or disturbances due to climate change – could be enhanced through prescribed fires in ecologies where this measure is appropriate and supportive of biodiversity outcomes. This can reduce the amount of leaf litter, pine needles, shrubs and other fuels in the forest, thus reducing the risk of wildfires. Other measures for building climate resilience in managed forests include enhancing road infrastructure to ensure forest access (thus aiding fire response), changing the timing of harvesting to accommodate altered timing of spring thaws, and monitoring and management for disease and pests.[30, 31] In addition to the critical role of forest conservation and restoration, the IPCC emphasizes the critical role that sustainable forest management plays in maintaining and enhancing carbon stocks in working forests as forest degradation and conversion of forests to other land uses are major drivers of carbon release in the atmosphere.[32]

Enhancing carbon removals

The amount of carbon dioxide sequestered from the atmosphere can be increased by optimizing management and harvesting practices. Such practices should be tailored for the regional and subregional diversity of forestry ecologies (both domestically and globally). Examples of practices that could increase carbon sequestration rates include pruning and thinning, introducing species or genotypes that are better adapted to future conditions, changing the forest structure and targeted fertilization.[32]

Reducing operational emissions

Forest managers can also take action to reduce GHG emissions from forestry operations such as reducing fuel use in harvesting equipment, replacing fuel with lower-emitting fuels, and/or moving to electric equipment, as appropriate. Additionally, reducing the amount of fertilizer used, or ensuring it is only used where necessary and will be absorbed by the growing trees. It is important, however, not to reduce the net impact of the forests' removal capability with decreased fertilizer application.

Table 1: Non-exhaustive list of technologies and practices to reduce operational emissions and maintain and increase carbon removals

Practice/technology	Description	Impact
Adoption of low-emission machinery	The forest sector can improve fuel efficiency and reduce emissions by adopting hybrid or electric machinery and vehicles (e.g. electric or hybrid forwarders, harvesters and skidders), as well as machinery powered by hydrogen and biomass-based fuels, which are currently under development. In addition, companies can save fuel by optimizing transportation routes and considering multimodal transportation opportunities combining freight via road and rail.[33]	● Reducing operational emissions
Reduce wildfire risk and damage	In some ecologies, prescribed burning is used as a preventive measure to reduce wildfire risks and preserve forests (helping to reduce emissions [34]). Forest managers can complement this approach with additional practices to lower both the frequency and intensity of wildfires, such as by clearing small trees from dense areas, reducing forestry slashing, thinning trees or increasing spacing between trees. In addition, recently developed forest fire detection systems based on artificial intelligence are instrumental for detecting and localizing forest fires at an early stage to minimize damage.[35] Once a wildfire has been detected, such systems can also be leveraged to predict the spread of a fire, which will benefit incident commanders to make critical judgment calls, such as where to send their limited firefighting personnel. Aerial firefighting through drones constitute another effective but costly measure for minimizing the damage of wildfires, as in contrast to conventional human-piloted firefighting aircraft, they can fly after dark and in smoky conditions.	● Reducing operational emissions ● Maintaining carbon stocks and removals
Optimize fertilizer application, and adopt inhibitors	The adoption of best management practices for fertilization is vital to both reducing emissions and increasing carbon removals. Supplemental nutrient applications can increase forest carbon sequestration capacity by both fostering plant growth and increasing litterfall and deposition of organic material on the soil. However, application of fertilizer to increase carbon removals must be targeted to the specific site, and optimized in terms of frequency, amount and rate of fertilization in order to increase nitrogen use **efficiency**. In fact, maximizing the share of nutrients taken up by the trees reduces nutrient losses to the environment, preventing potential detrimental impacts on air quality and on water resources.[36] Targeted fertilization can be supported by digital technologies to inform site-specific management. Additionally, increasing the adoption of inhibitors and controlled-release fertilizers can further reduce GHG **emissions**.	● Reducing operational emissions ● Enhancing carbon removals
Pruning, thinning and partial cutting	In some ecologies, pruning improves stem quality, while thinning reduces competition for light, water, and nutrients, thereby improving tree growth, biomass and soil carbon content. Similarly, the partial cutting – that is, harvesting only a subset of trees from a forest to select high quality trees – was found to have a positive impact on carbon content in soil.[37]	● Reducing operational emissions ● Maintaining carbon stocks and removals ● Enhancing carbon removals
Optimizing harvest rotation lengths	Rotation length can impact the rate at which carbon is sequestered by growing trees and forests. Optimizing this process depends on the tree species, climatic zone and harvesting goals.	● Maintaining carbon stocks and removals ● Enhancing carbon removals
Incorporating mixed species into plantations	Incorporating different species into forest plantations can help to improve resilience to droughts, pests, diseases and wildfires as well as increase the carbon sequestration potential of a stand.[38] Although a few studies highlight potential productivity gains from mixed species production models,[39, 40] their viability largely depends on the existence of profitable markets for the grown timber.	● Maintaining carbon stocks and removals ● Enhancing carbon removals
Tree genetics	Breeding of fast growing tree species well adapted to the location and resilient to the effects of climate change contributes to maintaining and enhancing carbon sequestration, while increasing productivity.[41, 30]	● Maintaining carbon stocks and removals ● Enhancing carbon removals
Use of technology	The use of digital data capture and planning contributes to the implementation of more targeted forest management practices and tight operational control. Some example practices involve: site-specific fertilization treatment based on granular assessment of soil nutrient deficiencies, digital forest inventory using drones and lidar, fully mechanized harvesting integrated with supply chain planning, satellites and drones to provide early fire detection.	● Reducing operational emissions ● Maintaining carbon stocks and removals ● Enhancing carbon removals

Maintaining carbon stocks and removals

Enhancing carbon removals

Reducing operational emissions

Usage

The adoption of practices and technologies to reduce operational emissions, as well as to maintain and increase carbon removals, largely varies depending on the type of action: technologies to reduce operational emissions, including precision forestry, are largely at a prototype stage and therefore adoption is limited (TRL 3-5). However, sustainable forestry practices to maintain and enhance carbon removals – such as thinning and pruning, are often used, particularly for larger scale forest managers (TRL 9-11).

Table 2: Adoption of technologies/practices to reduce operational emissions, and maintain or increase carbon removals

Impact	Technology / practices	Level of maturity (TRL 1 - 11)	Current adoption	Barriers to adoption
Reduce operational emissions	Adoption of low-emission machinery	Low maturity (TRL 4/5)	Electric machinery for forest operations is currently being developed, especially forwarders, harvesters and skidders, although most projects are still in a pilot phase.[42] Hydrogen fuel cells are under development for the agricultural sector (in tractors) and may become available for the forest sector, although the technology still requires refinement and further development before adaptation at full scale.	Electrification of machinery and vehicles within forestry faces unique challenges compared to automotive applications. For instance, forestry machinery operates in rural or off-grid areas where there is limited access to charging infrastructure, meaning batteries must last long enough to cover for limited charging infrastructure.[43]
	Optimize fertilizer application, and adopt inhibitors	Medium maturity (TRL 6)	Fertilizer inhibitors also require further research and product development to make these technologies more affordable, better understand the synergies between them, and improve understanding of wider environmental impacts.[44]	Low maturity, high costs, variability in effects, which is highly dependent on soil chemistry, climate and nutrient availability, regulatory constraints.
Maintain or increase carbon removals	Innovative technologies for precision forestry	High maturity (TRL 9-11)	Technologies to support precision forestry, such as drones and software already exist and are commercially available. However, precision forestry techniques are still limited to a few players.[45]	High initial investment costs, uncertain returns and results, low institutional support and technological complexity.[46]
	Other sustainable forestry practices to maintain and increase carbon removals	High maturity (TRL 11)	Conventional sustainable forestry practices, such as pruning, thinning, practices for sustainable intensification (e.g. tree genetics and seedling selection) are all widely adopted in the forest sector.	Costs and uncertainty as to the financial benefits, inadequate regulatory and market incentives, lack of information and guidance.

Climate and business impacts

The adoption of practices and technologies to reduce operational emissions, as well as to maintain and increase carbon removals, largely varies depending on the type of action: technologies to reduce operational emissions, including precision forestry, are largely at a prototype stage and therefore adoption is limited (TRL 3-5). However, sustainable forestry practices to maintain and enhance carbon removals – such as thinning and pruning, are often used, particularly for larger scale forest managers (TRL 9-11).

Climate impacts	
Targeted emissions sources	The adoption of technologies and best practices to reduce operational emissions targets GHG emissions from, for example, vehicle fuels, fertilizer volatilization, and others, whereas practices and technologies to maintain and increase carbon removals are negative-emission solutions aimed at storing carbon in biomass, soils, and forest products.
Emission abatement potential	The emission abatement potential of sustainable forest management to reduce operational emissions will largely vary based on the type of practices adopted: improved energy efficiency due to hybrid propulsion systems in forest vehicles would result in a significant reduction in GHG emissions, depending on the type of vehicle (hybrid or fully electric) and the energy mix from the grid. Inhibitor technologies can achieve up to 50% emission reduction compared to no use.[47] The impact of sustainable management practices to maintain and increase carbon removals will also largely vary based on the type of practice and the specific context. In an Australian case study, pruning was found to improve carbon sequestration potential by 33% and 62% six weeks after upper and middle crown treatments, with a significant effect lasting for 40 weeks.[53] Choosing tree species with strong carbon sequestration properties may also be effective. For example, Scot pines and the soil beneath them were found to sequester around 33% less carbon than oak trees in another case study.[36]

Business impacts	
Benefits	
Reduced operating costs	Some technologies relevant to reducing emissions and maintaining carbon removals also reduce costs. These include forest-mapping drones (cost effective compared to ground methods) and targeted fertilizer application. Other examples are electric tractors that cost less to recharge than fuel-powered alternatives or management software. For instance, wood logistic optimization software can lower delivery costs of wood to mills by 2.5%.[48]
Increased revenue by boosting productivity and securing forest assets	Increased productivity not only increases carbon removals but also potentially generates additional revenue by providing more timber.[48] By improving forest resilience to climate change, forest managers are securing forest assets for the future, thereby reassuring investors and regulators, which can facilitate access and reduce capital costs. In some scenarios, carbon credit payments for increasing carbon removals may cause a forest manager to optimize the land for carbon, in addition to or instead of timber. Forest carbon credits would need to meet integrity requirements such as additionality, permanence and leakage.
Costs	
Investment required	As for electric machineries, estimates project electric (yard) tractors will cost around 160,000-275,000 EUR (compared to about 115,000 EUR for a typical diesel tractor)[49]
Operating costs	Some recurring spending will also be required. For instance, nitrification inhibitors could cost **24 EUR/ha**, GPS surveying is estimated to cost 90 EUR/ha,[50] while some software for regenerative forestry cost about 770 EUR/year.[51]
Indicative abatement cost	Because of the wide range of technologies that can be used in sustainable forest management, abatement costs may vary substantially. It is estimated that many forestry mitigation options (including sustainable forest management) could help lower emissions for about 20 EUR/tCO_2.[52] Some technologies may even have negative abatement cost due to co-benefits. For instance, the abatement cost of nitrification inhibitors is estimated to range from - **14-34 EUR/tCO_2e** due to higher expected yield and a reduced impact on nature, while electrification of machinery could lead to net savings of -66EUR/tCO_2e due to lower fuel **costs**.

Potential co-benefits and side effects

The adoption of practices and technologies to reduce operational emissions, as well as to maintain and increase carbon removals, largely varies depending on the type of action: technologies to reduce operational emissions, including precision forestry, are largely at a prototype stage and therefore adoption is limited (TRL 3-5). However, sustainable forestry practices to maintain and enhance carbon removals – such as thinning and pruning, are often used, particularly for larger scale forest managers (TRL 9-11).

Co-benefits	
Biodiversity protection	Some practices, such as increased species diversity, can have a beneficial impact on biodiversity. Benefits can be high in areas with many endemic species or in regions that used to be prone to deforestation.[53] Investment in research and involvement of experts will help prevent potential detrimental impacts in specific ecologies.
Air quality	Reducing the frequency and intensity of wildfires will benefits local air quality and health outcomes as wildfires are known to release a range of harmful air pollutants, including cancer-causing substances to tiny particles that can increase the risk of a heart attack or stroke.
Soil health	Practices that maintain and increase carbon removals by increasing soil organic carbon also directly impact soil health. In turn, this may have positive impacts on climate adaptation, by preventing soil erosion and flood damage. This is expected to become increasingly important in the future, as forests could help adapt against the projected increase in extreme precipitation events.[53]
Water quality	Sustainable forest management can improve water quality due to better retention of nitrogen and phosphorus by the vegetation due to better forest health, as well as fewer instances of over applying fertilizers.[53]
Side-effects	
Site-specific assessments	Sustainable forest management practices need site-specific assessments, which may require significant human resources and time.
Increased reliance on the grid	Machines need to have a long autonomy as there are likely no charging capacities in the forest. This is particularly important for vehicles such as tractors, in order to avoid operators having to recharge vehicles too often or risk being stuck in an area difficult to access.

Implementation

These are the most common steps to implement measures to enhance carbon removals and reduce emissions in sustainable working forests

→ **Manage the forests that are owned, leased or managed to the highest standards of sustainable forest management**
Organizations should follow guidelines prescribed by globally recognized forest certification systems such as Forest Stewardship Council (FSC), Programme for Endorsement of Forest Certification (PEFC) and Sustainable Forestry Initiative (SFI). operational control.

→ **Identify appropriate actions to implement**
The organization should assess the different technologies/practices that can be applied within the operations. This includes an assessment of their relevance based on the operation and characteristics of the forests (e.g. tree species, location), and of their economic feasibility. It is important to note that the size and level of maturity of the company can potentially be a limiting factor in the implementation of some of these actions.

→ **Engage with forest managers**
Companies that do not own forests should engage with suppliers and forest managers to uphold high standards of forest management and to encourage the use of technologies to remove carbon and reduce emissions.

→ **Certify efforts to increase removals**
Reputable and high-integrity carbon credit certification programs for carbon removals and capture schemes (e.g. Verra, Gold Standard) demonstrate the company's adherence to rigorous standards and best practice in environmental sustainability. In addition to being a pre-requisite to sell credits in voluntary and compliance carbon markets, they also serve as powerful tools to demonstrate transparency and accountability in decarbonization efforts.

Key challenges/hurdles	Potential solutions
Accurate measurement of carbon sequestration In many regions there is a lack of affordable carbon measurement services and expertise for use by forest companies. In addition, in some cases, unclear rules and guidelines around carbon sequestration and mapping of land systems can create uncertainty around mitigation measures and deter investment in abatement mechanisms. When organizations do not own the forests that they manage, this can further increase the challenge in implementing these measures in the absence of the right incentives for forest owners to implement them. **High costs and low margins from forest management** The investment required for emissions reduction technologies come in addition to already high costs of forest management, exacerbated by rising land prices. Moreover, due to concerns around the legitimacy of claims, extracting high premiums from improved forest management practices is difficult, and margins are low as a result. The additional costs from emissions reduction technologies, however, may be partly offset by increased productivity and the benefits from the improved forest resilience to the effects of climate change.	**Building a highly skilled workforce in forest management** Organisations should focus on building the right skills in their workforce to lead actions on climate change mitigation. **Engagement with policymakers on carbon sequestration data** Organizations may work with policymakers to improve access to better quality forest carbon data and decision-making tools, as well as on improving governance mechanisms to determine land ownership and ensure the protection of human rights. **Engagement with policymakers on carbon sequestration data** Organizations may work with policymakers to improve access to better quality forest carbon data and decision-making tools, as well as on improving governance mechanisms to determine land ownership and ensure the protection of human rights.

Action 2: Adopt heat recovery technologies in the sawmill: deep dive on absorption systems

Summary

Product category & value chain

Engineered wood products value chain

Forest production → **Processing** → Manufacturing → Use → End of life

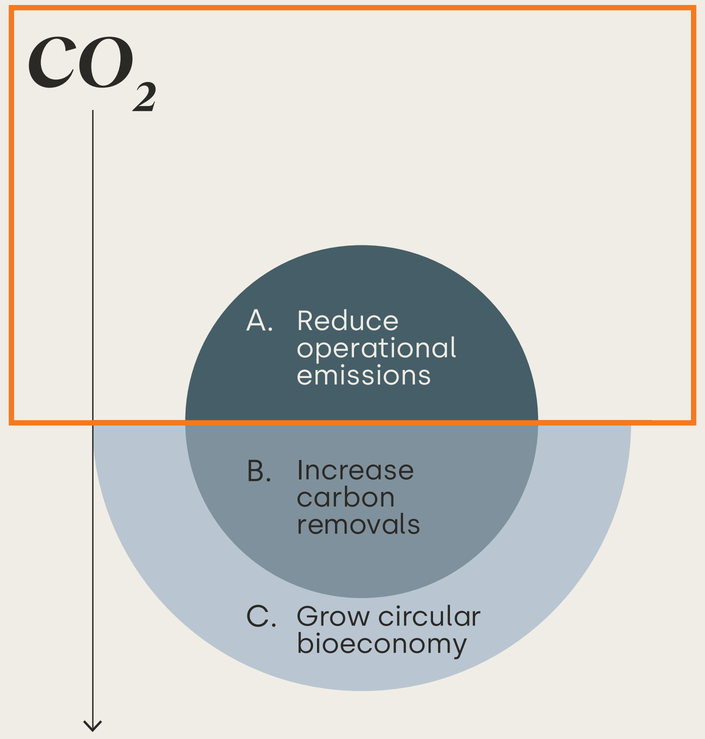
Consumer Packaging value chain

Forest production → **Processing** → Manufacturing → Converting → Use → End of life

Cellulose based textile value chain

Forest production → **Processing** → Manufacturing → Textile making → Use → End of life

Forest sector 3 levers of impact



Level of maturity

MEDIUM TO HIGH

First of a kind commercial demonstration to operation in relevant environment (TRL 8-9)

Emission abatement potential

LOW TO HIGH

0% - 70% compared to the counterfactual and on the energy source

Short-term economic feasibility

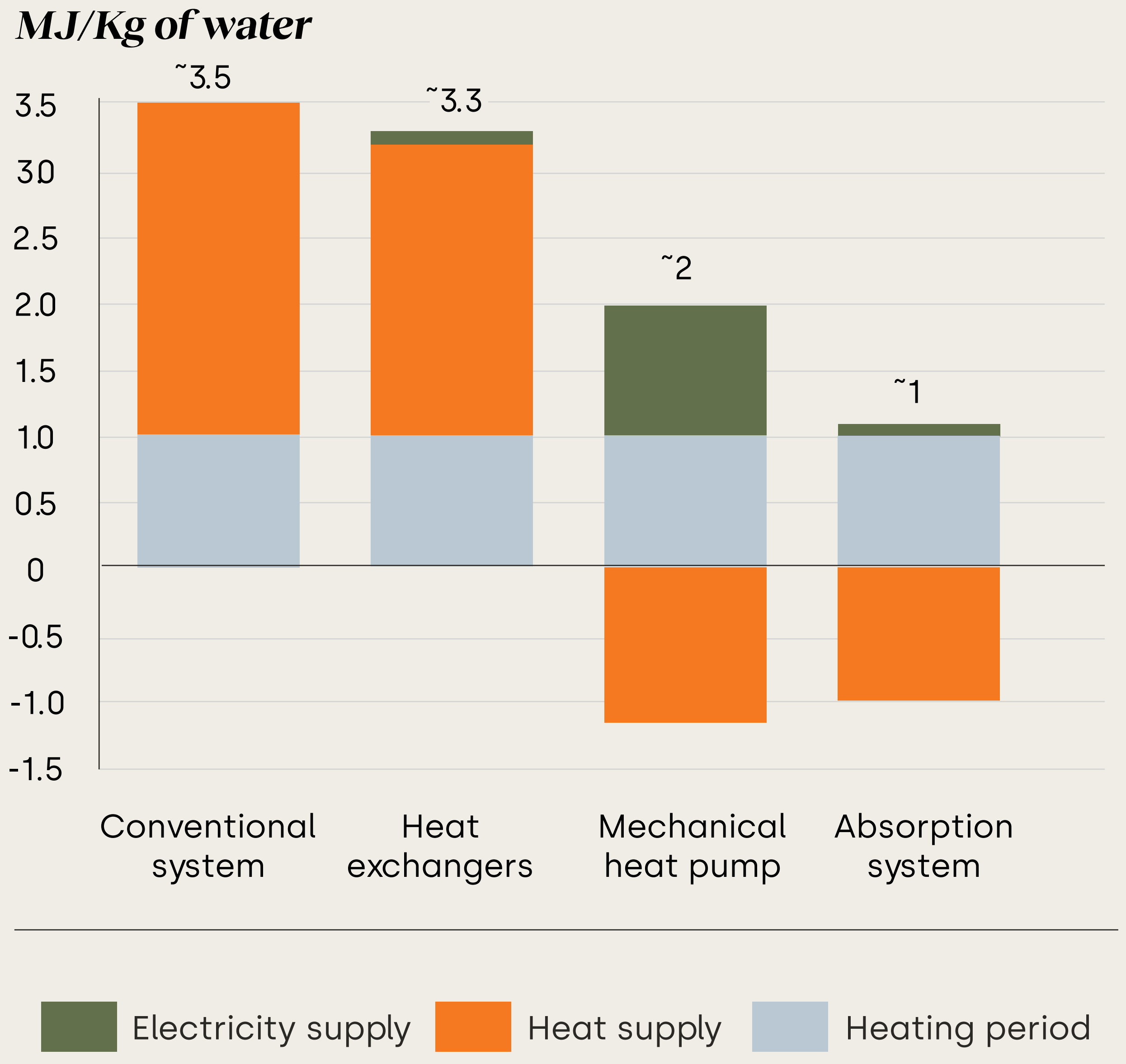
LOW TO HIGH

CAPEX : 400-2000 EUR/kW
Abatement cost : 200-800 EUR/tCO2
depending on size, capacity and technology

Overview of the solution

In the sawmill, fuel is used to operate machinery such as debarkers and saws, and power drying kilns that dry wood (logs or chips). Wood drying is often the most energy-intensive phase, requiring high heat demand and conventional drying systems unequipped with heat recovery technologies that may 'waste' up to 80% heat through losses.[54] To address this inefficiency, heat recovery technologies, such as heat exchangers or heat pumps, can be employed to increase efficiency and reduce heat loss in the sawmill, particularly in the drying kilns. By adopting these technologies, the sawmill can save a significant amount of energy, leading to reduced fuel combustion and GHG emissions associated with the sawmill operations.

Figure 1: Heat demand (MJ) per kg of evaporated water for different heat recovery technologies



Source: Anderson and Westerlund[54]

Among other heat recovery technologies *(see Box 1)*, absorption heat pumps are best placed to increase energy efficiency in sawmills but are still in the early stage of development and are the most CAPEX intensive of the heat pump options.[55] Absorption systems (or alternatively absorption heat pumps) are devices that can efficiently increase the temperature of waste heat given from a heating source, therefore reducing the heat required *(see Box 1)*. Differently from heat pumps, the absorption systems use an additional 'absorber', which dries the saturated air from the kiln and recirculates either air or water into the drying kiln or the generator. Moreover, whereas a mechanical heat pump is driven by electric energy, an absorption heat pump is driven by thermal energy. For this reason, they are more suitable to sawmills where energy can be produced through biomass combustion, and overall require the least heat supply *(see Figure 1 for a comparison of several heat recovery technologies in the sawmill)*. Key features of absorption systems are that they can deliver a far higher temperature lift (the temperature difference between waste heat temperature and upgraded process heat temperature) than the other systems. Their energy performance does not decline steeply at higher temperature lift, and they can be customized for combined heating and cooling applications. In theoretical studies, absorption heat pumps were found to reduce heat demand by up to 70%.[15]

The graph compares the performance of four different systems: one conventional system with no heat recovery technologies, and three more with distinct heat recovery technologies, including absorption systems. The graph shows the amount of energy required to evaporate one kg of water from the dried wood. Absorption systems have the best performance. Mechanical heat pumps have higher energy efficiency (reducing heat demand by 100%) but require higher electricity inputs (in green). Absorption heat pumps reduce energy demand by ~70% but require no additional electricity.[54]

Note: the heating period is identical across technologies, and it is the amount of energy needed to start the drying process.

Usage

Although heat recovery technologies, including absorption systems, have been around and commercially available for many years (TRL 8-9), their adoption in sawmills is not yet widespread according to the **available literature**. There is evidence of heat pumps being adopted into newly built drying kilns, especially in northern European countries, but their overall application may still be limited in most parts of the world. Adoption could be limited by the relatively high capital costs, especially for smaller sawmills.[58] Moreover, lack of awareness about heat recovery technologies among sawmill operators, technical challenges (e.g. in installation, process re-design, etc.) or even geographical factors (e.g. efficiency in cold climates) can all represent potential barriers to more widespread adoption among smaller sawmills.

Figure 2: Illustrative example of a heat pump used in the chemical industry

Source: Borealis[56]

Box 1: Other heat recovery technologies in the sawmill

Other heat recovery technologies applicable in sawmills are:[54]

Heat exchangers
These devices use the thermal energy in the air leaving the kiln to heat the cold air entering the kiln, thereby increasing energy efficiency. Heat exchangers are the most used recovery technology for the industrial kiln dryer, continuous drying kilns as well as in belt driers for wood chips or bark. Heat exchangers are well known, have low operation costs after installation, and can achieve substantial energy efficiency gains: belt driers equipped with heat exchangers can deliver up to 35%-55% energy efficiency gains.[57]

Dehumidification kilns with mechanical heat pumps
The air exiting the drying kiln, with a high moisture content, is circulated to an evaporator, where water condenses. This cools the air, and the condensed water flows down a drain. Parallelly, an electricity or steam-powered compressor increases the pressure of the heat pump's working fluid. The high-pressure refrigerant gas goes from the compressor to the condenser, where the gas condenses, in turn releasing heat. The cool dry air absorbs the heat from the fluid, and then warm dry air is recirculated in the system. While dehumidification kilns with mechanical heat pumps are an effective technology for heat recovery in the sawmill, they use a substantial amount of electricity to power the compressor.

Climate and business impacts

Climate impacts	
Targeted emissions sources	Absorption systems help reduce GHG emissions from fuel combustion in sawmills by increasing energy efficiency.
Emission abatement potential	The potential for reducing emissions through heat recovery technologies is closely tied to their ability to improve energy efficiency, as well as the energy sources utilized in the sawmill. For instance, open absorption systems can reduce heat demand by nearly 70%. However, in cases where sawmills rely heavily on biomass, the emissions abatement potential may be negligible, while it can reach up to 70% when fossil fuels are utilized.

Business impacts	
Benefits	
Reduced costs for biomass and opportunities for revenues	Increased energy efficiency can help reduce consumption of biomass for energy, allowing the production of biofuels for external use. Adopting heat recovery can therefore deliver benefits that go beyond emissions reduction by minimizing energy costs and potentially providing additional revenues through the sale of saved biomass. Cost reductions may also be achieved through relevant industry emissions trading schemes.
Reduced costs by reducing the need for emission allowances	Applicable to countries with relevant industry emissions trading schemes.
Optimize operations	Absorption heat pumps, as well as other heat recovery technologies, can also help sawmills optimize operations, as heat recovery systems can be controlled to adapt to external conditions. For instance, heat recovery systems can be operated when outside temperatures are high and heating energy demand is low and vice versa, by saving heating power in winter when temperatures are low. This results in a substantial reduction in the heating power needed for the dryer and in improved management of the process over winter, when cold temperatures and freezing periods can create delays due to insufficient heat production.
Costs	
Investment required	Depending on the technology installed, upfront investment varies: absorption heat pumps may cost from 400-2000 EUR/KW.
Operating costs	The operating costs for absorption heat pumps depend on the source of energy used. Assuming sawmills would use mostly woody biomass from bark, chips and lower-quality logs, the operating price may range between approximately 10 and 90 EUR/MWh (considering the price of woody biomass from 10-80 EUR/MWh, and the maintenance costs 2-10 EUR/MWh). [59 60] The availability of biomass on-site as well as the (current and future) prices for biomass have a large role in determining.[59]
Indicative abatement cost	Abatement costs depend intrinsically on the prices operating costs, therefore on the current and future prices of biomass in each country, as well as on the set-up, the industry size and the processes. Estimates range between 20-160 EUR **per tonne of CO_2e**. [61 62]

Potential co-benefits and side effects

Co-benefits	**Air quality in the factory**	Unlike fuel-powered heating, absorption systems and electric heat pumps produce heat without producing onsite emissions, improving air quality in the factory and surrounding areas. This can in turn deliver health benefits to workers and the local population.[63]
Side effects	**Impact on process**	*As illustrated in Figure 2* industrial absorption heat pumps take up a lot of space and the installation may require substantial changes to the sawmills' set-up and processes.

Implementation

These are the most common steps to adopt heat recovery technologies in the sawmill:

→ **Assess energy savings potential and requirements**
Conducting an energy audit will enable the company to determine its heat requirements and identify prospects for heat recovery. The audit will identify areas where energy is being wasted due to inefficient equipment, outdated technology or operational practices that can be improved, quantify the potential savings and recommend energy conservation measures. Furthermore, the audit may yield additional insights related to the lifetime of the energy systems and equipment, the relative GHG emission intensity of local electricity sources, and the availability of local, state, or federal incentives to facilitate financing. Moreover, audits may underscore potential gaps in local employee knowledge in the domains of energy efficiency and emissions reduction.

→ **Select the appropriate equipment**
Select an appropriate heat pump system that suits the specific requirements of the sawmill. Consider factors such as the desired output, temperature requirements, efficiency, and reliability. Companies may benefit from consulting with heat pump suppliers and experts to determine the most suitable system.

→ **Adapt existing infrastructure**
Modify the sawmill's infrastructure to accommodate the heat absorption system, undertaking necessary changes to piping, ductwork and electrical connections.

→ **Install and commission the heat recovery technology**
Conduct the installation of the best-suited heat recovery technology. Ensure proper integration with existing heating systems and follow best practices for installation, including proper insulation, sealing, and safety measures. Once the installation is complete, conduct thorough commissioning and testing of the heat pump system. Make any necessary adjustments, based on initial tests, to ensure optimal performance.

Key challenges/hurdles	Potential solutions
Physical constraints Industrial absorption heat pumps may not be suitable for some sawmills, especially for small producers, due to their size or require substantial redesign of the production process. **Shortage of qualified installers**[64] key heating markets are experiencing undersupply of qualified installers, which may deter companies from installing heat pumps due to concerns about quality and delays to installation.	**Engage with suppliers and invest in R&D** Manufacturers of pulp and paper could partner with manufacturers to advance research and development on heat pumps, so to increase compatibility with existing infrastructure and processes (e.g. by reducing size). **Collaborate with government, training providers and heat pump manufacturers** Organizations can work with relevant stakeholders to increase the supply of heat pump installers. Measures can include advocating for the creation of financial incentives for workers to train in the industry, providing work placement opportunities, and ensuring the integration of expertise in industrial applications as part of training programs.

Action 3: Adopt heat recovery technologies in the pulp mill: deep dive on heat pumps

Summary

Product category & value chain

Engineered wood products value chain

Forest production → Processing → Manufacturing → Use → End of life

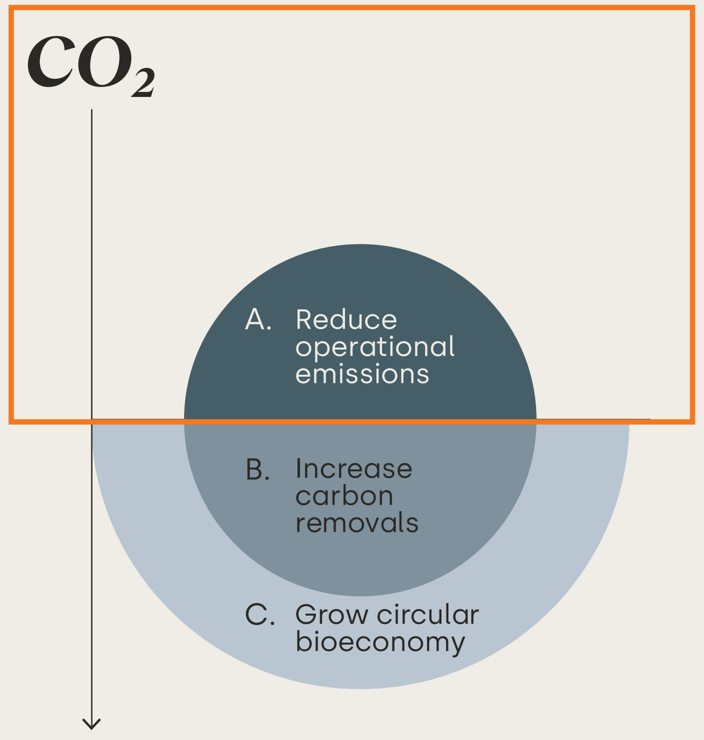
Consumer Packaging value chain

Forest production → Processing → Manufacturing → Converting → Use → End of life

Cellulose based textile value chain

Forest production → Processing → Manufacturing → Textile making → Use → End of life

Forest sector 3 levers of impact



Level of maturity

LOW TO HIGH

Level of maturity varies per technology and temperature range of the heat pump (TRL 4-11)

Emission abatement potential

MEDIUM TO HIGH

20% - 80% compared to natural gas boiler and depending on local electricity mix

Short-term economic feasibility

MEDIUM TO HIGH

CAPEX : 200-2100 EUR/kW
Abatement cost : 0-100 EUR/tCO2

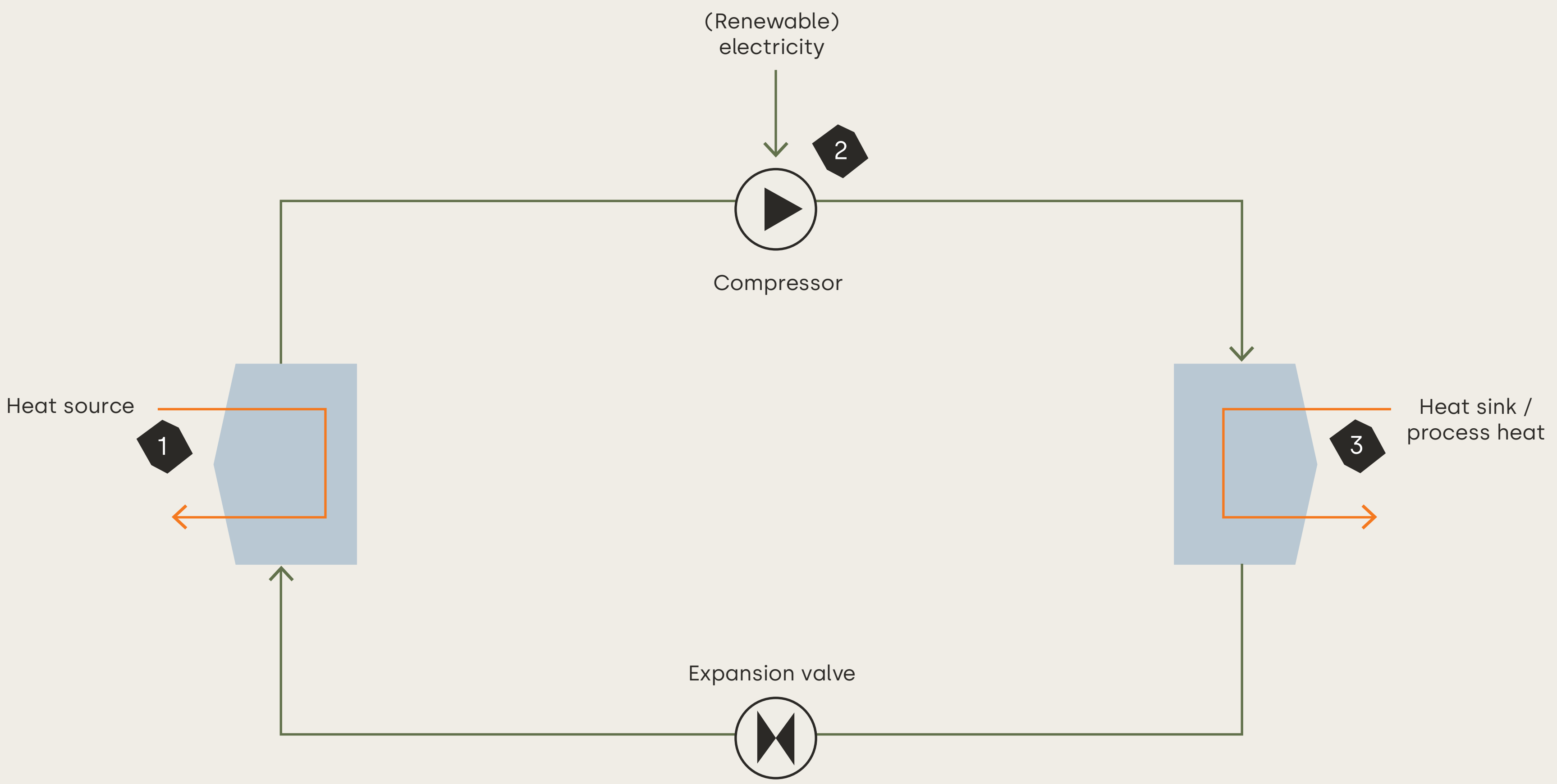
Overview of the solution

Heat recovery technologies are vital to increasing the energy efficiency of mill operations, as they can recover waste heat generated as a by-product of the pulping and papermaking process. Most of this heat cannot be reused otherwise, as it has a high level of humidity and/or contains unwanted gaseous or particulate contamination.

Among all heat recovery technologies applicable in the pulp and paper mill *(see Box 1)*, mechanical heat pumps offer the greatest potential for heat recovery and energy efficiency for existing facilities. These devices transfer and upgrade thermal energy from waste heat sources to 'heat sinks' using a small amount of additional energy – usually from electricity. More detail on heat pumps functioning can be found *in Figure 1*. In contrast to an absorption heat pump, mechanical heat pumps are driven by electrical (rather than thermal) energy.

Industrial heat pumps are substantially more efficient at heating than conventional boilers: **the coefficient of performance** (COP) can be as high as 300-400% in heat pumps achieving **low-temperature lifts**, while conventional heating systems usually offer an energy efficiency level.[65] When performing heat lifts, the difference between the input and output temperatures can be between 30-50°C for **heat pumps currently on the market.**[64] Analysis from CEPI found that the application of heat pumps to paper drying can achieve potential energy savings of more than 50%. Nevertheless, while mechanical heat pumps constitute an important decarbonization action for existing old facilities, more efficient heat recovery technologies are available and should be prioritized over mechanical heat pumps in the case of new facilities.

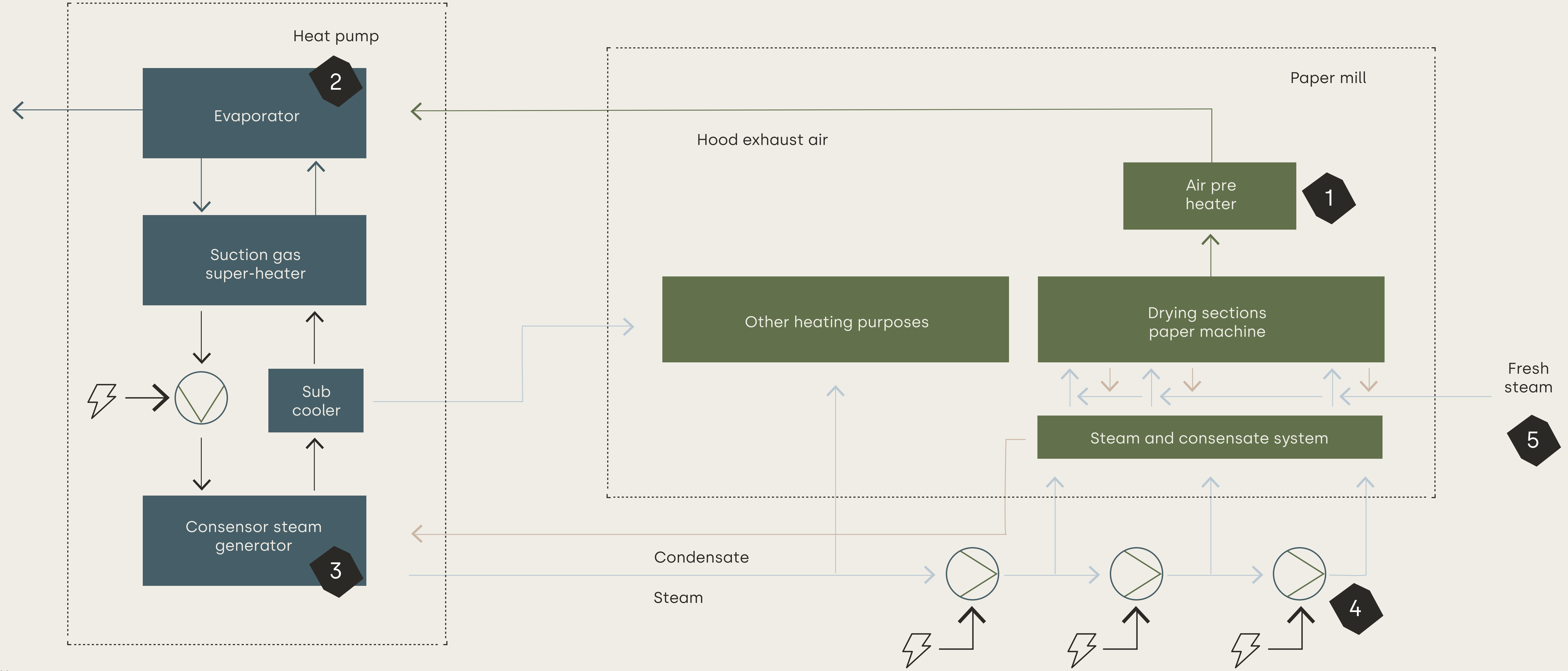
Figure 1: Simple diagram of a mechanical heat pump



Source: Agora Industry, FutureCamp [59]

Figure 1 visualizes the processes of a mechanical heat pump, where an operating fluid circulates inside a closed circuit. A heat source (1), which can be industrial waste heat or environmental heat, transfers heat at low pressure and low temperature. The heated operating fluid is compressed by an electrically driven compressor (2), which also raises the temperature. The heat can be transferred and used at higher temperatures. Following heat extraction (3), the operating fluid is depressurized in the expansion valve, which causes a further decrease in temperature. Heat pumps, as well as other heat recovery technologies, can be applied to multiple phases of the pulping and paper making process. Paper drying in particular offers a high potential for heat recovery. Paper drying is energy intensive, as it requires heat and steam at high temperatures. Heat pumps can be integrated in the process to further optimize heat recovery, as shown in *Figure 2*.

Figure 2: Integrating heat pumps in paper making



Source: EHPA & CEPI [66]

Following heat transfers to pre-heat the incoming air feeding the drying sections of a paper machine (1), the latent heat of the water vapour recuperates via the drying hood, and could be used to evaporate the refrigerant in the heat pump (2). The refrigerant is compressed and returns to liquid form, while the resulting heat is used to evaporate the condensate coming from the drying cylinders (3). To lift the steam to higher pressures, steam compressors are installed (4). Fresh steam from boilers can be added to ensure pressure control in the cylinders (5).[66]

Box 1: Further heat recovery technologies for pulping and paper making

Heat recovery technologies can be applied to multiple phases of the pulping and paper making process, and through different technologies, including and not limited to:

Heat exchangers
These devices are used to heat or cool a process fluid to a desired temperature, and can also improve a system's energy efficiency by transferring heat between two or more process streams. Studies found a 15% reduction in energy adopting heat recovery technologies in multi-cylinder dryers using heat exchangers.[67]

Absorption chillers
These devices use waste from other processes or equipment to produce and distribute chilled water for cooling needs. They are different from other chillers in that they do not have a compressor. Instead, they dissolve the vapor in an absorbent. The resulting product is transferred to a higher-pressure environment using a pump with low electricity demands. It can be used for gas turbine inlet air-cooling applications, outdoor applications in hazardous areas and bleaching.

Organic Rankine Cycle
These systems can convert low-grade waste heat into electricity with efficiency levels ranging from 5% to 15%. These systems consist of components like generators, condensers, and evaporators, and they come in diverse sizes. Additionally, ORC systems are adaptable for recovering medium-grade heat from sources like recovery boilers, requiring heat in the range of 90-150 degrees Celsius.

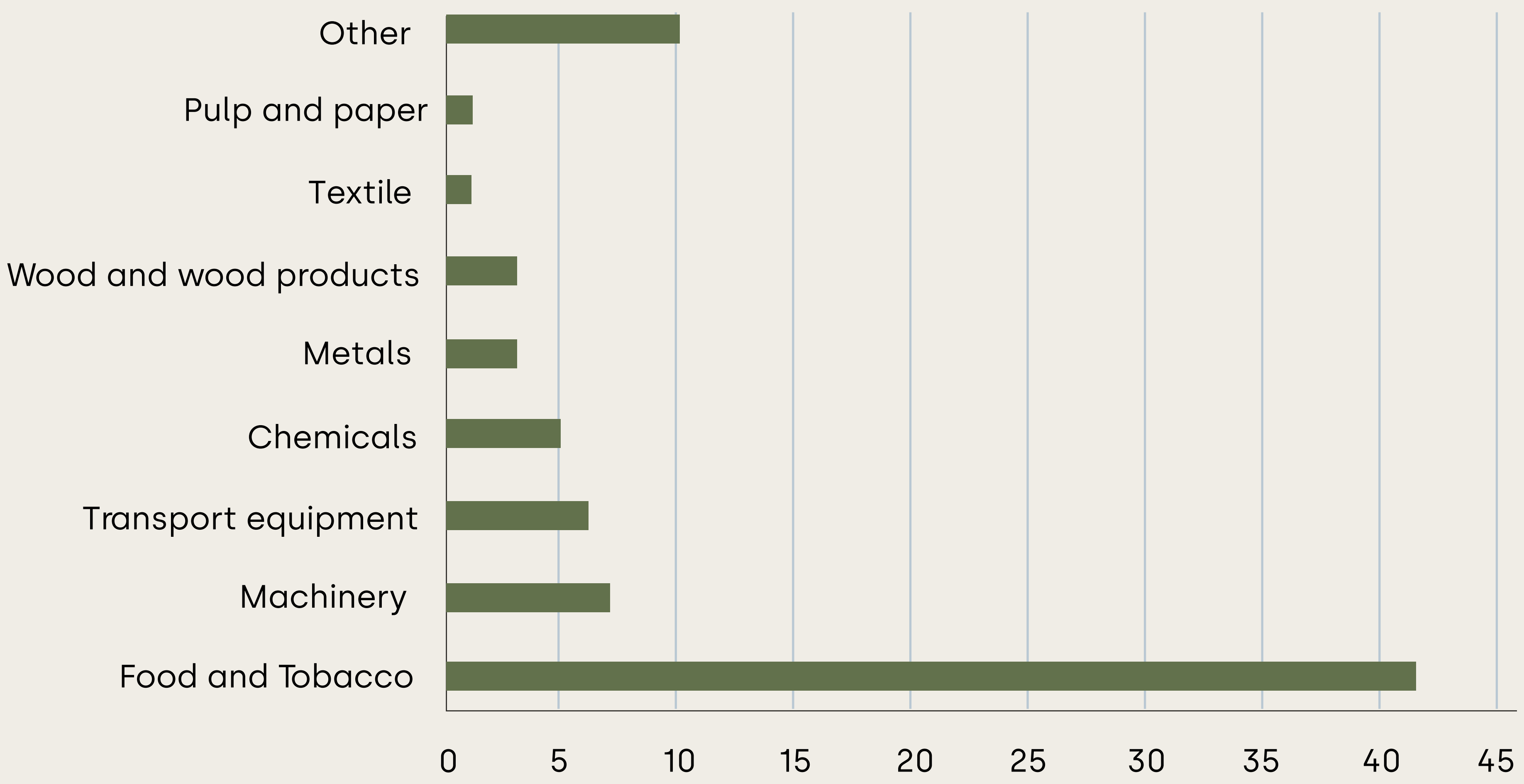
Stationary siphons and mechanical vapor decompensations
These devices can replace the dryers in the paper machine, and help achieve 5-10% efficiency gains.

Closed hood for paper machines
Closed hoods for paper machines, instead of an open or semi-open system, are specially designed drying and ventilation systems used to save steam and heat, reducing energy consumption and associated GHG emissions.

Usage

As it stands, heat pump adoption in the forest sector, including in pulp and paper and the textile industry, is limited in comparison to other sectors such as the food and tobacco industry, machinery, transport equipment and chemicals *(Figure 3)*. However, there has been some increase in uptake due to the benefits of improved energy efficiency.[68]

Figure 3: Adoption of heat pumps in different industries



Source: WBCSD[65]

Adoption is largely inhibited by the high cost of electricity compared to marginal fuel cost and the limited commercial availability of high-temperature heat pumps, achieving temperatures above 90°C *(see Table 1)*. In fact, there are only a few pioneering manufacturers demonstrating temperatures in the range of 120–165°C, and a number of research projects are developing heat pumps that aim to demonstrate sink temperatures in the range of 160– 200°C.[69]

Table 1: Industrial heat pump technology readiness by temperature range

Temperature range	Technology readiness level (TRL, 1-11)	Example of process in the pulp and paper industry
<80 °C	TRL 11: Proof of market stability	De-inking
80-100 °C	TRL 10: Commercial and competitive, but large-scale deployment not yet achieved	Bleaching
100-140 °C	TRL 8-9 First-of-a-kind commercial application in relevant environments	Paper drying
140-160 °C	TRL 6-7 Pre commercial demonstration	Pulp boiling
160-200 °C	TRL 4-5: Early to large prototype	Steam production
> 200 °C	TRL 4: Early prototype	High temperature steam production

Source: Adapted from IEA[64]

Climate and business impacts

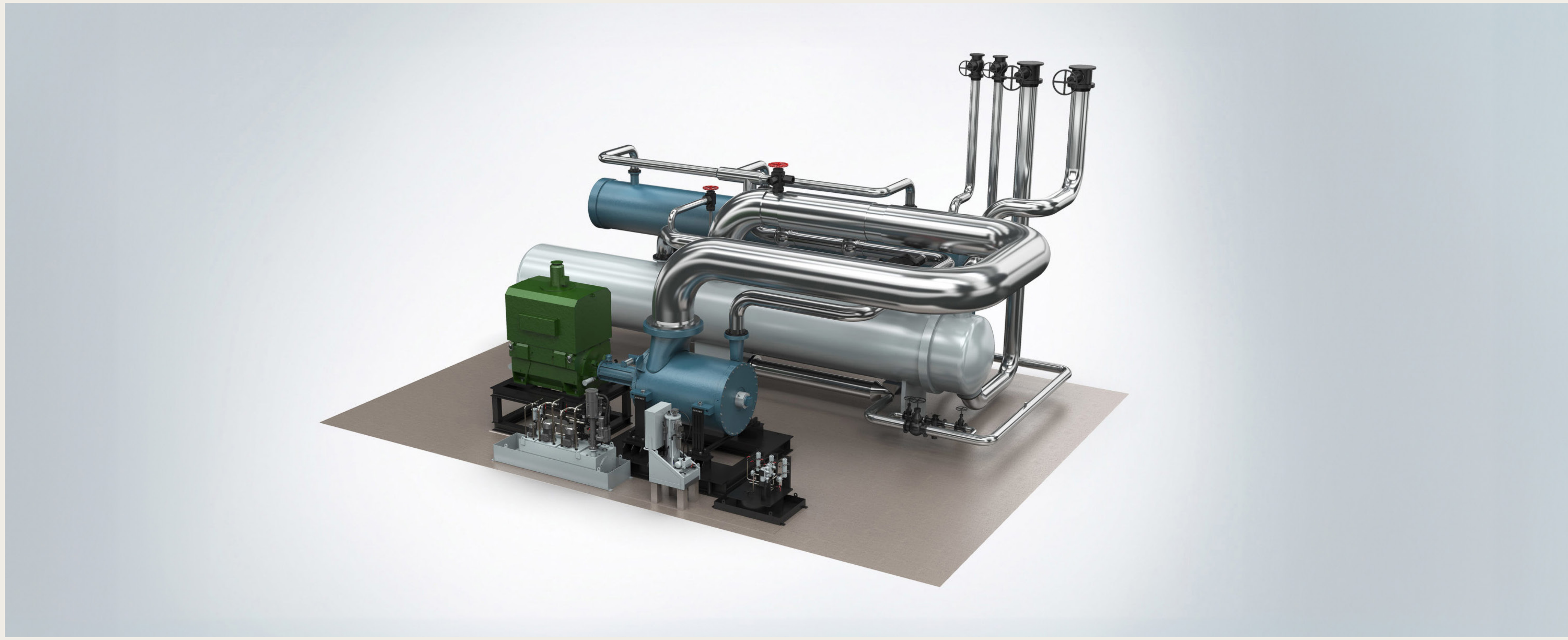
Climate impacts	
Targeted emissions sources	Heat pumps can substantially reduce emissions by improving energy efficiency, displacing fuels, reducing heat waste, and by using electricity sourced from an increasingly low carbon grid.
Emission abatement potential	Emission reductions will depend on the energy efficiency gains and on the emission intensity of the local electricity grid. According to IEA, emission reduction compared to a gas boiler can range between 20% to 80% in countries with cleaner electricity. In the EU, heat pumps can currently achieve approximately 50% emission reductions compared to a **natural gas boiler**. However, current estimates do not account for future decarbonization of the grid, which would result in even higher emission reductions. Moreover, off-grid solutions (e.g. when electricity is generated on-site through renewable sources) could reduce emissions even further.

Business impacts	
Benefits	
Potential operational cost reduction	Depending on the prices for natural gas and electricity, heat pumps may lead to reduced **costs per unit of heat**.
Reduced costs by reducing the need for emission allowances	Applicable to countries where emissions trading schemes exist and apply to the industry.[70]
Increased supply security	When using local renewable sources, improved supply security can be achieved by reducing the reliance on (often) imported fuels.[65]
Costs	
Investment required	Capital cost of industrial heat pumps currently ranges between 200-1,200 EUR/kW, depending on temperature range, capacity and other factors.
Operating costs	Due to the limited utilization of high temperature industrial heat pumps, comprehensive data on their operational costs remains scarce. Existing studies suggest a range of approximately 20-50 EUR/MWh.[59 64] Yet any estimate is expected to evolve as technology advances, adoption increases and the market for renewable energy develops. In fact, operating costs depend on both electricity prices (and consequently on future supply, demand, the geographical location and local subsidies) and the coefficient of performance. Heat pumps can help achieve substantial cost savings, ranging between 30-80% compared to other systems (e.g. an electric boiler only). Heat pumps with higher COP and lower temperature lifts can achieve the higher savings, while those achieving higher temperature lifts (and therefore with lower COP) are closer to the lower bound.
Indicative abatement cost	Abatement costs depend on the price of electricity and gas in each country, as well as on the set-up, industry size and processes. Estimates range between slightly negative abatement costs[71] to **just above 100 EUR/tO2e**.[61]

Potential co-benefits and side effects

Co-benefits	**Air quality in the factory**	Unlike fuel-powered heating, absorption systems and electric heat pumps produce heat without producing onsite emissions, improving air quality in the factory and surrounding areas. This can in turn deliver health benefits to workers and the local population.[63]
Side effects	**Impact on process**	*As illustrated in Figure 4*, industrial heat pumps are large devices, which weigh up to two tonnes and may require large installation rooms (up to 70 m2, although smaller models exist). Therefore, the installation of heat pumps requires substantial changes to the process. Companies can consider adding them during the refurbishment of existing facilities, allowing for the additional time required.

Figure 4: Model of a high temperature heat pump



Source: Siemens

Figure 4 shows an illustrative heat pump, with a capacity of 9-70 MW and heat sink up to 160 C°. Heat pumps can weigh several tons, and take up several m^2: the smallest heat pumps (e.g. 0.1 MW) may take up less than 2 m^2, while those with larger capacities may require up to 70 m^2 for installation.

Implementation

These are the most common steps to adopt heat recovery technologies in the pulp mill:

→ **Energy savings potential requirements**
As explained in the implementation section of Action 2, an energy audit will help to understand the mill's energy consumption patterns, identify areas for heat absorption, and quantify the potential savings. Analysis of the current heating systems, including boilers, kilns and dryers can determine heat requirements and opportunities for heat recovery.

→ **Select the appropriate equipment**
Select an appropriate heat pump system that suits the specific requirements of the pulp mill. Consider factors such as the desired output, temperature requirements, efficiency, and reliability. Companies may benefit from consulting with heat pump suppliers and experts to determine the most suitable system.

→ **Adapt existing infrastructure**
Modify the pulp mill's infrastructure to accommodate the heat absorption system, undertaking necessary changes to piping, ductwork and electrical connections.

→ **Install and commission the heat-pump**
Install the heat absorption system. Ensure correct integration with existing heating systems and follow best practices for installation, including insulation, sealing, and safety measures. Once the installation is complete, conduct thorough commissioning and testing of the heat pump system. Make any necessary adjustments, based on initial tests, in order to ensure optimal performance.

Key challenges/hurdles	Potential solutions
Availability of suitable heat pumps commercially available heat pumps typically are not designed to handle the temperatures required in some phases of the pulp and paper manufacturing process, including paper drying and pulp boiling.[72]	**Combine steam heat pump with a steam compressor** This can help to mitigate the problem of commercial heat pumps not yet able to achieve very high temperatures, as the compressor compresses the steam directly, recovering the heat and using low-grade waste heat to generate high-temperature steam.
Physical constraints industrial absorption heat pumps may not be suitable for some pulp mills, especially for small producers, due to their size or require substantial redesign of the production process.	**Engage with suppliers and invest in R&D** Manufacturers of pulp and paper could partner with heat pump manufacturers to develop specialised heat pumps capable of handling the temperatures used in production and to increase compatibility with existing infrastructure and processes (e.g. reducing size).
Shortage of qualified installer[64] Key heating markets are experiencing undersupply of qualified installers, which may deter companies from installing heat pumps due to concerns about quality and delays to installation.	**Collaborate with government, training providers and heat pump manufacturers** Organizations can work with relevant stakeholders to increase the supply of heat pump installers. Measures can include advocating for the creation of financial incentives for workers to train in the industry, providing work placement opportunities and ensuring the integration of expertise in industrial applications as part of training programs.

Action 4: Switch to industrial electric boilers in manufacturing

Summary

Product category & value chain

Engineered wood products value chain

Forest production → Processing → **Manufacturing** → Use → End of life

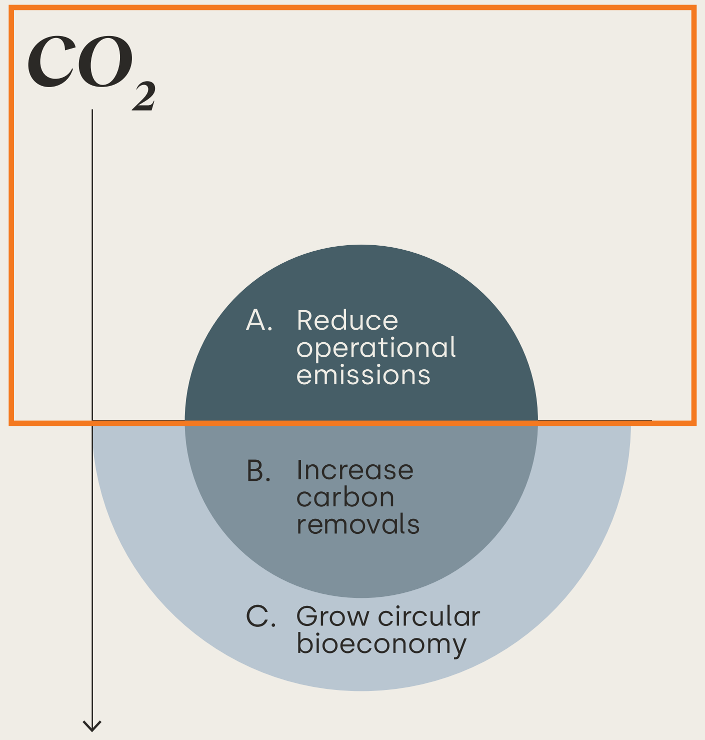
Consumer Packaging value chain

Forest production → Processing → **Manufacturing** → Converting → Use → End of life

Cellulose based textile value chain

Forest production → Processing → **Manufacturing** → **Textile making** → Use → End of life

Forest sector 3 levers of impact



Level of maturity

HIGH

Commercially available
(TRL 9-10)

Emission abatement potential

LOW TO HIGH

100% abatement potential compared to fuel-powered boilerswhen using electricity from renewable sources

< 100% depending on grid carbon intensity

Short-term economic feasibility

MEDIUM TO HIGH

CAPEX : 150-200 EUR/kW
Abatement cost : 130-450 EUR/tCO2

Overview of the solution

Heat is used in the forest sector across industries (e.g. pulp and paper, textiles), and phases of the value chain (e.g. paper conversion and customization). Currently, most heat (in the form of steam) is produced in boilers, fuelled by either biomass or other fuels. When using fuels, particularly fossil fuels, heat production is associated with GHG emissions. To reach the highest abatement potential, electrification of heat must be combined with renewable electricity (procured or produced on site). If renewable electricity is not available, energy efficiency improvements associated with e-boilers can also indirectly reduce emissions.

Electric boilers convert electricity into heat to produce steam, with almost 100% efficiency, and only negligible energy losses. Commercially available electric boilers can provide low to high temperatures of up to 400°C, and steam with temperatures of up to 350°C and 70 bar. Therefore, electric boilers can meet the demands of both the pulp and paper industry, which usually requires heat at 200°C, and the textile industry, requiring up to 140°C.[20] As Electric boilers can achieve high temperatures, their adoption can complement the adoption of, for instance, heat pumps (which are more energy efficient) to help achieve higher emission reductions for heat and steam production.

Electric boilers offer an added advantage as they complement existing installations and provide flexible generation. They can be easily switched on and off, and used during periods of excess energy when renewable sources produce more electricity due to favourable weather conditions (e.g. sunny and windy hours or days). As a result, operating electric boilers during low-cost electricity periods can lead to significant cost savings. Another benefit of electric boilers is their easy adoption, as they do not require retrofitting or conversion of infrastructure. They may however require large modifications to the steam and power, as well as to the boiler feedwater systems.

Box 1: Complementing electric boilers with long-duration thermal energy storage

Electric boilers can be complemented with long-term thermal **energy storage technologies**, which offer unprecedented benefits to store heat and sustain heat provision. Thermal storage technologies can store thermal energy for prolonged periods, providing system flexibility: by storing energy at times of surplus or when electricity prices are low, and releasing it when needed, long-term energy storage can help manage fluctuations in demand and supply and offers a way of integrating and providing flexibility to the entire energy system. This would in turn enable reduced costs for electricity. Thermal storage technologies are already available and can be scaled at low marginal costs.[73]

Source: Parat[74]

Electrode boilers are a type of electric boiler that use electricity flowing through streams of water to create saturated steam. They automatically adjust the water level in the boiler to heat only what is required. When there is no demand, they deactivate. The boiler in the figure has up to 75 MW capacity in one unit.

Usage

Electric boilers are commercially available, and the technology can be easily adopted (TRL 9-10), as installation is straightforward and does not require a complete redesign of primary processes.[75] As electric boilers provide a low emission and high efficiency way of producing heat and steam, they can be adopted by all relevant industries. This includes the forest sector, as processes such as pulping, paper making and textile manufacturing require steam. Although the adoption of electric boilers is not yet widespread, there are several examples of companies switching to electric boilers to reduce their carbon footprint.

The most common barrier to the increased adoption of this technology is the high costs compared to fuel-fired boilers. Although electric boilers require a similar capital investment as the conventional alternatives (for medium- and high-temperature heat applications), the financial benefit of electrification depends on the difference between the ongoing costs of energy to run electric equipment and conventional fuel equipment. Currently, average electricity prices are usually higher compared to conventional fuels in most locations, which makes electric boilers more costly compared to e.g. natural gas boilers. However, some actions, such as price arbitrage (i.e. the process of buying and selling electricity in different markets at different prices in order to exploit the differences in electricity prices between different locations, time of day, or seasons) or storing electricity (e.g. through Thermal Energy Storage) can help make it a positive business case already today.

An additional obstacle to higher adoption is the availability of the electricity grid infrastructure. Electric boilers increase the electricity demand considerably, and the adoption of electric boilers must be supported by the grid.

Climate and business impacts

Climate impacts	
Targeted emissions sources	The adoption of electric boilers replaces emissions from fuel combustion in traditional boilers, although emission abatement potential is entirely dependent on the energy sources.
Emission abatement potential	When electricity is purchased from the grid, emission reduction will depend on the local energy mix. When renewable electricity is purchased (e.g. with Power Purchase Agreements) or generated on-site, electric boilers can achieve 100% operational emissions reduction compared to fuel-powered boilers. The generation of a CO_2-free electricity grid would lead to complete decarbonization of the processes requiring heat and steam.

Business impacts	
Benefits	
Reduced carbon costs	Reduced carbon costs in countries where a carbon price is applied to industrial emissions, in the form of a carbon tax or an emissions trading scheme. Small facilities may already be exempt.
Increased supply security	Supply security can be increased by reducing the reliance on (often) imported fuels, although this also requires additional investments in grid reliability.
Simple operations	Electric boilers can also offer several benefits in terms of operations: electric boilers do not require any fuel handling system, and are safer as there is no risk of gas leaks, other hazardous emissions or combustion-related hazards. Maintenance is often reduced, thanks to the compact design and less maintenance requirements. They offer precise temperature control to match heat needs.
Costs	
Investment required	Initial investment for industrial electric boilers ranges between 150–200 EUR/kW, including Installation costs. However, contextual variables can introduce supplementary charges. For instance, additional costs may arise if upgrades to the distribution systems, grid connections, boiler feedwater system or steam condenser are required. In this instance, initial investment can be as high as 400-500 EUR/kW.[76]
Operating costs	Operating costs typically depend on local electricity prices. Current electricity prices are variable and may range between 25 and 60 EUR per MWh, although it's important to keep in mind that strategies to reduce reliance on the grid and achieve lower costs exist, such as price arbitrage and thermal energy storage. Additionally, there are other operating costs, such as grid charges, costs for the internal power distribution system and for the water feed system, as well as fixed costs (e.g. insurance premiums, annual inspections, permits, safety equipment, training, maintenance, and administrative costs).
Indicative abatement cost	The abatement cost depends on the cost of electricity and on the emission-intensity of electricity in the location: it can range from 130 EUR/tCO_2e up to 450 EUR/tCO_2e.[62]

Potential co-benefits and side effects

Co-benefits	**Improved safety and reduced regulatory requirements**	Electric boilers are a safer boiler design, as they do not pose risk of gas leaks or risk of burnings or explosions when there are fuel lines, flumes, flames or storage tanks.
Side effects	**Risk of increased emissions in the short term**	If a company exclusively uses electricity from renewable sources (generated on-site or purchased via agreements), it can completely eliminate operational GHG emissions from heat and steam generation. However, if the company relies on electricity from the grid, the GHG emissions associated with using an electric boiler will vary depending on the local energy source mix. In countries with limited energy generation from renewable sources, the electrification of steam boilers can potentially increase annual GHG emissions, due to higher GHG emission factors of the electricity grid compared to other fuels, which cannot be offset by the higher efficiencies of electric boilers. For example, in many countries around the world, using natural gas to power a boiler results in a lower carbon footprint than **using electricity**.

Implementation

These are the most common steps to switch to electric boilers in manufacturing

→ **Assess requirements**
Determine the specific heating needs of the organization, such as the required heating capacity, operating pressure, and temperature.

→ **Select the appropriate equipment**
Select an electric boiler that suits the heating requirements of the paper mill. Consider factors such as boiler capacity, efficiency, reliability, and compatibility with the existing system.

→ **Adapt existing infrastructure**
Ensure that the electrical infrastructure is installed to support electric boilers and that the boiler water feed systems meets quality requirements. This may involve upgrading the electrical system, installing additional wiring, connecting to the grid and providing the necessary electrical connections to power the boilers if generation is on-site.

→ **Install and commission the boilers**
Install the electric boiler. Once the electric boilers are installed, they need to be commissioned. This involves performing initial start-up procedures, testing the boilers for proper operation and verifying their performance according to the design specifications. Optimize use, balancing heat requirements and operating patterns based on renewable electricity price and availability.

Key challenges/hurdles	Potential solutions
Higher operating costs Besides the fact that electricity prices are typically higher than the prices of conventional fuels such as natural gas, electrification may also involve additional costs such fees for grid connection.	**Identify cost savings** Operating electric boilers during low-cost electricity periods can reduce the cost of operation. Additionally, a cost benefit analysis may determine that higher operating costs can be offset by energy use reductions and avoided carbon costs associated with the use of electric boilers.

Action 5: Switch to low-carbon fuels: deep dive on low-carbon hydrogen

Summary

Product category & value chain

Engineered wood products value chain

Forest production → Processing → Manufacturing → Use → End of life

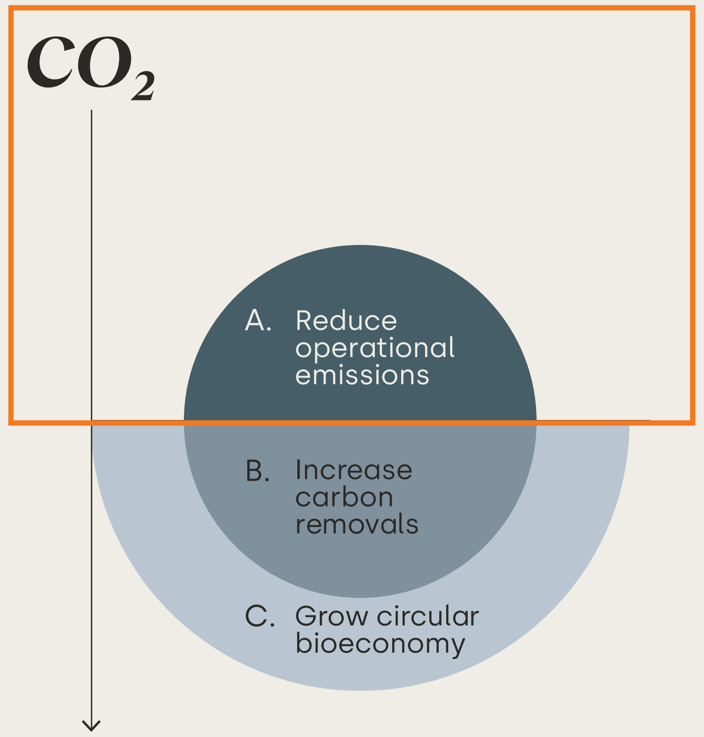
Consumer Packaging value chain

Forest production → Processing → Manufacturing → Converting → Use → End of life

Cellulose based textile value chain

Forest production → Processing → Manufacturing → Textile making → Use → End of life

Forest sector 3 levers of impact



Level of maturity

MEDIUM

Large prototype to first of a kind commercial (TRL 5-8)

Emission abatement potential

HIGH

100% operation emissions reduction compared to fossil fuel powered boilers

Short-term economic feasibility

LOW

CAPEX : 100-250 EUR/kW
Abatement cost : 400-1300 EUR/tCO2

Overview of the solution

As a fuel, hydrogen has several advantages. It is an abundant chemical element in nature (although typically only available in molecular forms such as water and organic compounds, and therefore not immediately available), and does not emit CO_2 into the atmosphere when burned. It can also be stored in large volumes in comparison to electricity. Hydrogen is appealing for the pulp and paper industry, as it can be derived from the generation of bleaching chemicals or as a by-product from the pulping process as the mill sludge can be used to produce hydrogen through anaerobic digestion. Importantly, this produces a gas mixture consisting mainly of methane, which needs to be upgraded to biomethane, before the hydrogen **can be separated out**.

Hydrogen-fuelled boilers use hydrogen instead of other higher-emission fuels to generate temperatures between 300-500°C for producing steam in pulp and paper mills.[111] They can be used in other phases of the forest products value chains, such as in textile manufacturing. However, adoption in the pulp and paper manufacturing segment offers the most synergies and benefits.

The switch to hydrogen as fuel for combustion boilers can occur in two ways:

→ By converting/retrofitting traditional fuel-powered (e.g. natural gas) boilers to accommodate hydrogen gas properties, making the boilers 'hydrogen-ready' or 'hydrogen-only' *(see Box 1)*, or

→ By replacing conventional (coal, gas) fuel-powered boilers with new 'hydrogen-ready' or 'hydrogen-only' boilers.

In the case of conversion of industrial boiler into hydrogen ready boilers, several parts of the boiler must be converted to accommodate the properties of hydrogen, such as **the flame detector, the pipework**, and the burner.

Box 1: Hydrogen for low, medium or high heat?

In global net zero scenarios, hydrogen is expected to play a vital role in achieving carbon neutrality, and industry is expected to be one of its largest consumers. However, the specific industrial uses for hydrogen vary, and its use is more or less recommended depending on the industry.

The application and demand of hydrogen across industries varies due to several considerations, including the existence of alternatives such as direct electrification. In fact, electric heating, and particularly heat pumps, offer superior energy performance compared to any gas technology, as well as compared to hydrogen. Despite the common perception that electric technologies may face limitations in reaching the high temperatures needed for medium- and high-heat industries, some electricity-based technologies can in fact achieve high-temperatures (for instance, an Electric Arc Furnace for steel production can achieve temperatures above 1500 °C). And in fact, in the case of pulp and paper mills, which utilize medium-temperature heat (temperatures up to 400 °C), electric boilers and heat pumps are likely to offer greater efficiency and to be more economically viable. Hydrogen may in fact have a more significant role to play in industries where hydrogen is needed as feedstock or a reagent (e.g, production of steel and chemicals, including plastics and fertilizer), where hydrogen is either a reagent or a feedstock.

However, hydrogen remains an interesting lever for industrial heat decarbonization, especially given that hydrogen may be more scalable than any other technology given its many applications across sectors (e.g., power, industry, transportation, buildings). This, together with the possibility for pulp mills to produce hydrogen on-site as a by-product, could make hydrogen an applicable lever.

Box 2: Other fuel-switching actions

Low-carbon hydrogen is part of a suite of fuel-switching technologies being considered to lower emission from fossil fuel combustion in boilers in pulp and paper mills by switching to lower emission fuels, such as:

Biomass
Although the pulp and paper industry already largely uses forest biomass, pulp mills can increase and optimize the use of biomass from woody residues, such as sawdust, barks, pins and fines from chip screening, and other wood residues, in order to increase the share of renewable energy sources.

Other biofuels
In addition to woody biomass, other biofuels can be used, such as clean methane (also known as biomethane), biogas or black liquor. The advantage for pulp and paper mills is that biogas and biomethane can be produced within the pulp and paper mill directly from by-products.

Natural gas
While burning natural gas does emit greenhouse gases, it contains far less CO_2 and air pollutants than many of the fuels it is increasingly replacing, especially coal. Switching from oil or coal to natural gas would therefore lead to lower emissions, although the reduction in emissions is unlikely to be large enough for companies to reach relevant decarbonization targets. Hence, switching to renewable energy sources should be preferred over natural gas, even in the short term, if companies are to meet their decarbonization targets.

Box 3: Definitions

To ensure all hydrogen produced and used has the lowest possible carbon intensity and is consistent with the 1.5°C scenario and net-zero scenario in 2050, WBCSD recommends the following taxonomy (on a full life-cycle basis), adding where relevant the source of primary energy (for example renewable):

1. ***Reduced-carbon hydrogen*** ≤ 6 Kg CO_2eq/Kg H2 only relevant as a stepping stone to achieving lower carbon hydrogen for existing higher intensity production installations
2. ***Low-carbon hydrogen*** ≤ 3 Kg CO_2eq/Kg H2
3. ***Ultra low-carbon hydrogen*** ≤ 1 Kg CO_2eq/Kg H2

Green hydrogen
Green hydrogen is obtained from water electrolysis using electricity produced with renewable sources. Hydrogen can be procured from external sources or produced onsite. In case of hydrogen electrolysis, any production surplus can also be sold to other industries/grid. If only green hydrogen is used, the emissions from the boilers would approach zero, but not reach it due to the remaining embodied emissions released during the lifecycle of the boilers. Green hydrogen can qualify as 'low, or ultra low-carbon hydrogen' when the carbon intensity meets the above threshold.

Hydrogen-ready
Hydrogen-ready boilers can be defined as equipment that is optimally designed to run on 100% hydrogen but initially configured to run on natural gas. This equipment may require a minimum number of components to be changed at the point of switchover but will have been specifically developed to facilitate this process.[78]

Hydrogen-only boilers
Hydrogen-only boilers are entirely fuelled by hydrogen.

Usage

The adoption of hydrogen-ready and hydrogen-only boilers in the pulp and paper industry is currently low, as the maturity of hydrogen-ready boilers is also medium (TRL 5-8).

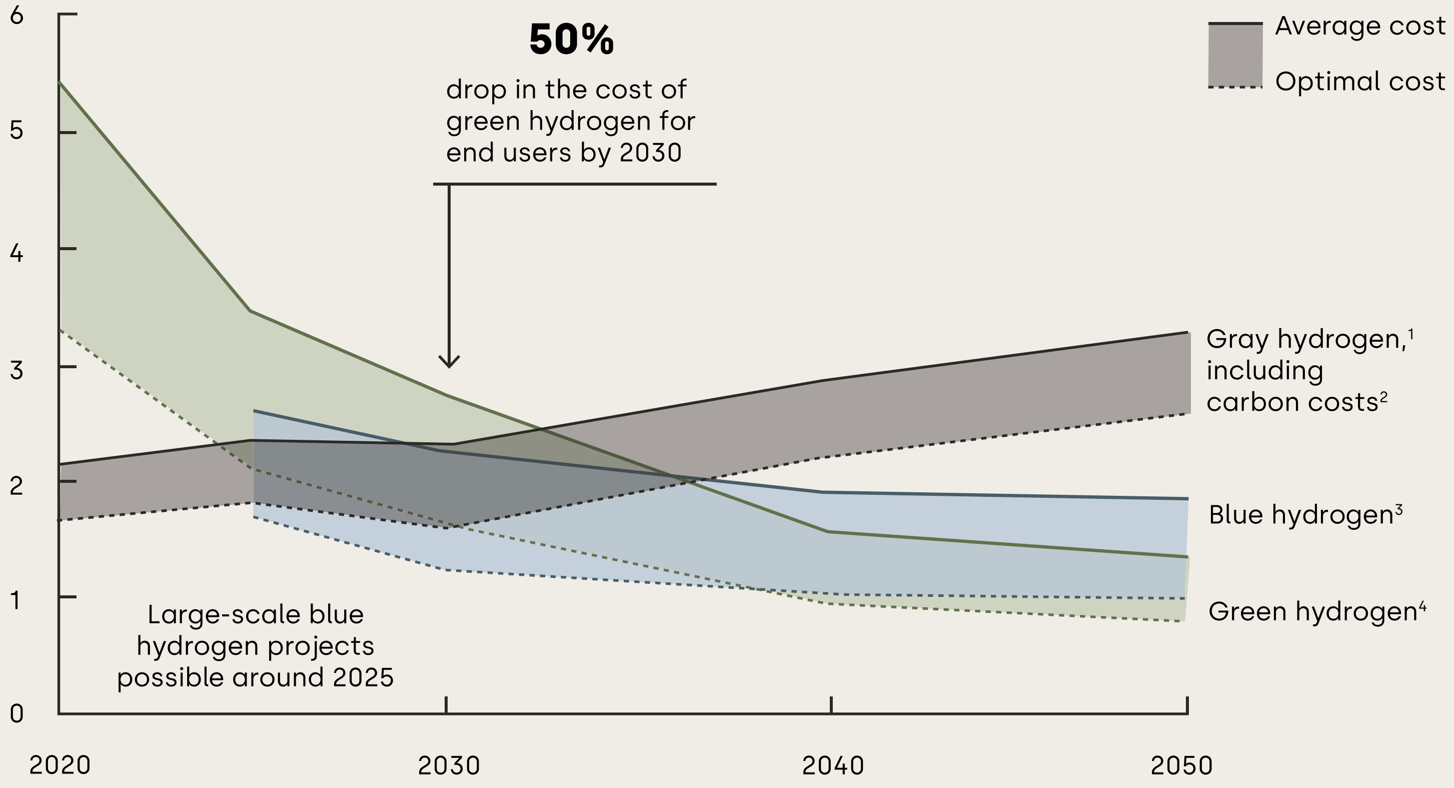
Hydrogen-ready boilers are under development, mostly designed to accommodate an initial 20% blend of hydrogen (complementary to natural gas). Industrial hydrogen-fuelled boilers are expected to be ready for a wider market by 2025, and ready for the mass market by 2035. Hydrogen-only boilers are not yet commercially available, although pilot projects exist.[77]

The technology costs, the lack of uptake, high electricity prices (sometimes reaching 70% of total costs) and lack of renewable hydrogen certification are all major limiting factors. This may change as there are currently over a hundred hydrogen project initiatives in industry, transportation, built environment and energy sector, which are expected to accelerate technology development. The realization of all the projects in the pipeline could lead to more than 24 million tonnes of **low emission** hydrogen produced annually by 2030, 40% higher than the expectation from 2022.[75,79]

Climate and business impacts

Climate impacts	
Targeted emissions sources	Switching to hydrogen-fuelled boilers abates emissions from combustion of fuels for heating.
Emission abatement potential	Switching to hydrogen-fuelled boilers would abate 100% of the operational emissions compared to fossil fuel-powered boilers. However, some emissions are associated with boiler production, the production and transport of hydrogen. Nonetheless, this remains a low carbon emissions option.

Figure 1: Projected global production costs of hydrogen, USD / kg



Source: McKinsey[80]

Business impacts	
Benefits	
Reduced carbon costs	Reduced carbon costs in countries where a carbon price is applied to industrial emissions, in the form of a carbon tax or an emissions trading scheme. Small facilities may already be exempt.
Revenue-generating opportunity of producing and selling hydrogen	Hydrogen produced in pulp mills can be used on-site or sold to other end users if hydrogen pipes are available or road transport is a viable option.
Increased supply security	Supply security is increased by reducing the reliance on (often) imported fuels.
Costs	
Investment required	The upfront investment for a new hydrogen-ready boiler ranges between 100-250 EUR/kW for capacities between 50-300 MW. The cost of converting existing boilers to hydrogen ready ranges between 6-20 EUR per kW, with prices expected to decrease marginally in the next decades. The conversion may cost approximately 20,000 EUR for a 1MW capacity boiler to almost 50,000 EUR for 10MW boiler and 160,000 EUR for a 25MW boiler. At higher capacities, boiler equipment tends to become bespoke due to additionalities requested by end-users, therefore higher costs are expected for upfront equipment leading to a higher premium at these capacities. Depending on the capacity of the boiler it may be more cost-effective to install a hydrogen-ready industrial boiler than to install a natural gas industrial boiler and subsequently convert it to hydrogen-ready.[78]
Operating costs	Costs for hydrogen fired boilers include maintenance, spare parts, labour, and overheads. Fixed operating costs were estimated to be 15-20% higher for hydrogen fired boilers compared to natural gas. This is due to the increased cost in technical and safety requirements involved in the use of hydrogen.[78] Variable costs depend on energy prices. Costs for renewable hydrogen are expected to decrease as production scales up, while costs for end users could drop by 50% from 2020 to 2030 *(see Figure 1)*, which will also likely lower prices.[80]
Indicative abatement cost	The abatement cost of hydrogen-fuelled boilers is largely dependent on the prices of hydrogen. High-level estimates are at 400-1,300 EUR/t CO_2e.[62]

Potential co-benefits and side effects

Co-benefits	**Storage**	One of the advantages of hydrogen, is that it can be stored (similarly to electricity in e.g. Thermal Energy Storage). While the costs for hydrogen storage are currently high for it to be economic, once this option becomes economically attractive, hydrogen can be distributed continuously in pipelines to support a reliable supply of renewable energy.
Side effects	**Energy efficiency losses**	Renewable hydrogen is produced by water electrolysis using electricity produced from renewables. Electrolyser systems today can achieve 70% efficiency, meaning that there is an energy loss for every unit of hydrogen produced from electricity.[81] Technology is advancing and further improvements in the electrolysis electrical efficiency could be achieved. However, this is currently a challenge for production, making hydrogen a non-competitive option.
	Safety risk	Hydrogen is a small, light gas that requires special equipment and procedures due to its ability to diffuse into certain materials, increase the chance of pipe failure, and escape easily through sealings and connectors. Its high flammability, broad ignition range, and low ignition energy make it challenging to handle safely, and detecting leaks is difficult due to its lack of colour and odour. Compared to other energy carriers, protocols for safe handling and refuelling infrastructure for hydrogen remain complex and unfamiliar, requiring more standards and regulation if it were to be used widely in the energy system.

Implementation

These are the most common steps to switch to green hydrogen

→ **Identify hydrogen sourcing strategy**
Identify whether on-site generation via electrolysis or offsite procurement is the most feasible sourcing strategy. This selection may depend on local infrastructure e.g. neighbouring industrial clusters investing in hydrogen hubs, in addition to cost.

→ **Adapt existing infrastructure or install new technology**
Upgrade the existing boiler systems to ensure safe and efficient hydrogen utilization, or replace conventional fuel-powered boilers with new 'hydrogen-ready' or 'hydrogen only boilers'.

→ **Commission boilers**
Perform initial start-up procedures, testing the boilers for proper operation and verifying their performance according to the design specifications. Complete necessary adjustments to optimize use.

Key challenges/hurdles	Potential solutions
High costs Besides energy prices, the setting up of transport and storage infrastructure is associated with **significant cost.**[82] **Lack of expertise** Not all organizations are equipped with the experts necessary to tap into the full potential of hydrogen. This is especially an issue given low maturity levels and the need to create new hydrogen transport and storage infrastructure. **Need for renewable capacity** the deployment of hydrogen for the decarbonization of industry and transport will require the deployment of renewable capacity at scale. IRENA predicts that in a net-zero scenario, in 2050 about 23% of the 90,000 TWh/year of global electricity production would be dedicated to hydrogen production.	**Partner with industrial clusters** Partnering with industrial clusters for the development of a hydrogen hub may help reduce distribution costs. **Develop internal expertise** To ensure effective application of hydrogen in the production process, companies can recruit experts in hydrogen application either directly or hire experts to train the existing workforce.

Action 6: Adopt BECCS technologies

Summary

Product category & value chain

Engineered wood products value chain

Forest production → Processing → Manufacturing → Use → End of life

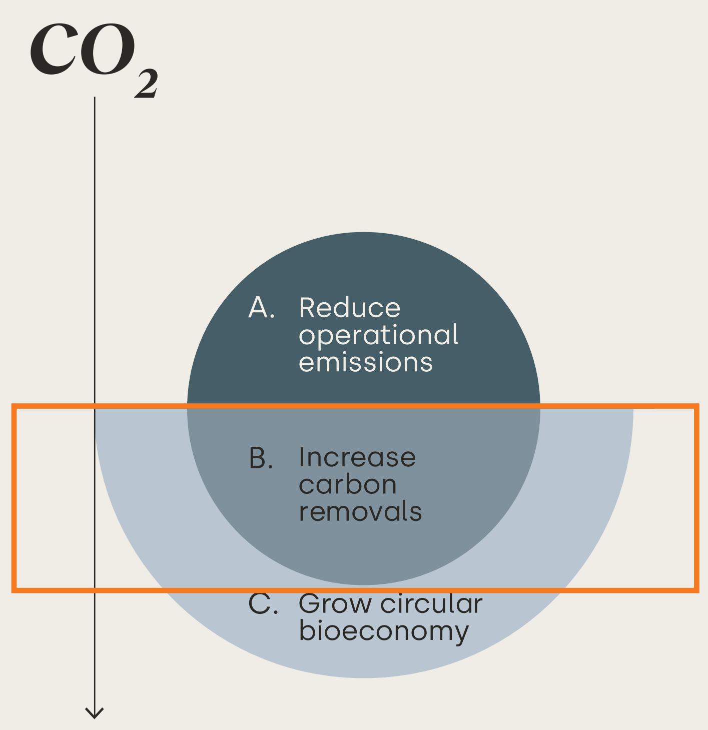
Consumer Packaging value chain

Forest production → Processing → Manufacturing → Converting → Use → End of life

Cellulose based textile value chain

Forest production → Processing → Manufacturing → Textile making → Use → End of life

Forest sector 3 levers of impact



Level of maturity

MEDIUM TO HIGH

Large prototypes have been validated, larger scale deployment is yet to be achieved

Some carbon capture technologies achieved maturity (TRL 5-9)

Emission abatement potential

HIGH

Nearly 100% of biogenic emissions from combustion can be removed

Short-term economic feasibility

MEDIUM TO HIGH

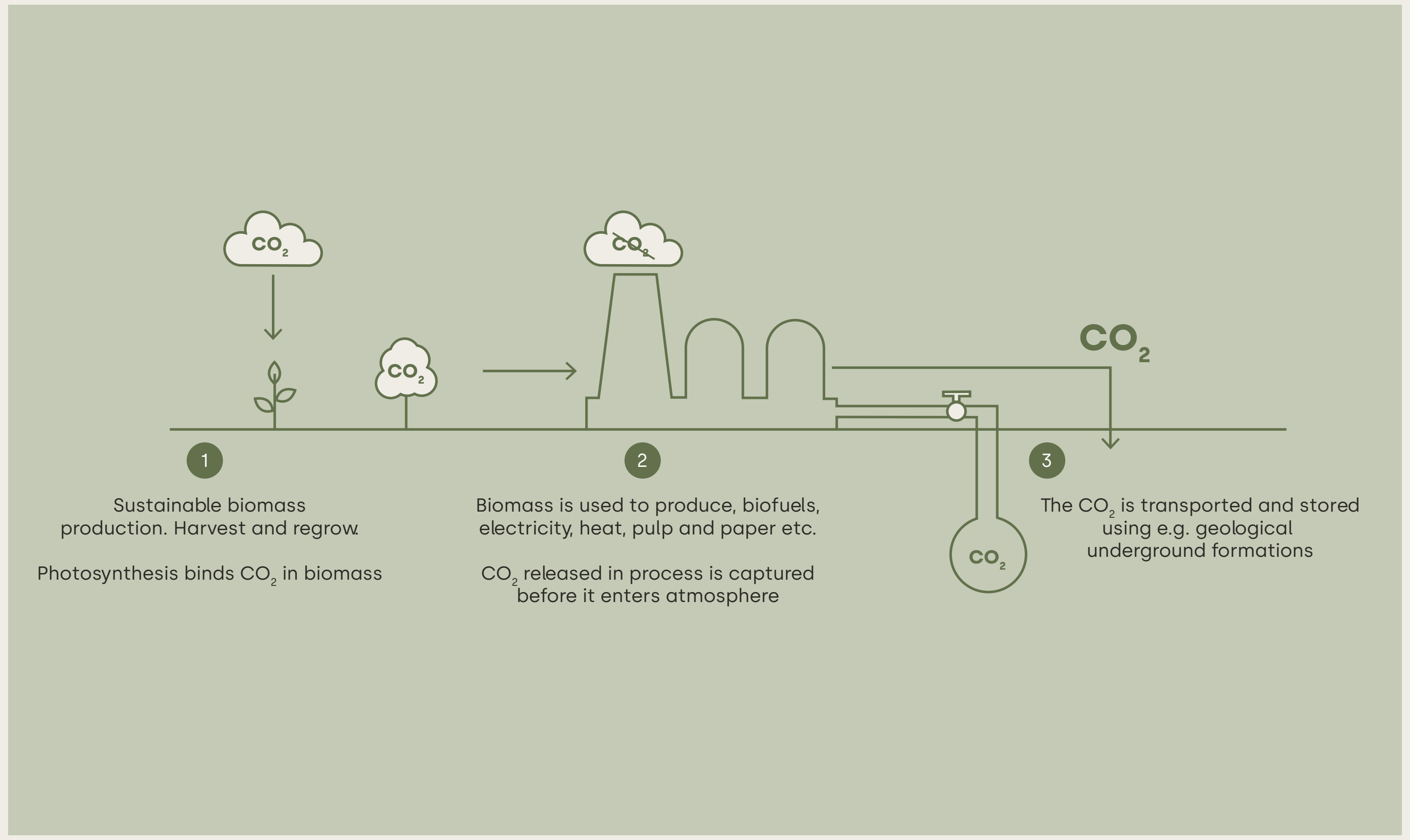
Abatement cost : 125-250 EUR/tCO2
Excluding potential revenues from carbon credits or others

Overview of the solution

Most IPCC scenarios rely on carbon removal technologies to achieve the Paris Agreement's objectives. Bioenergy with carbon capture and storage (BECCS) is typically considered to be a particularly significant option. As the pulp and paper industry is the largest industrial consumer of biomass, there are many large point sources of biogenic GHG emissions that could be captured.

Bioenergy with carbon capture and storage (BECCS) involves any technology through which biogenic CO_2 emissions produced (from biomass combustion, as well as from gasification, fermentation or any other process causing biogenic emission release) are captured and permanently stored, for instance in a geologic formation.[83]

Figure 1: How BECCS works



Source: McKinsey

There are several technologies to capture biogenic carbon, which can be divided into:

→ **Pre-combustion capture,** when CO_2 is removed from a gas mixture before combustion. This technology can only be applied in the mills using **black liquor or biomass gasification** or with lime kilns using biomass gasification.

→ **Post-combustion capture,** when CO_2 is separated from exhaust gases created by burning fuels. Many technologies exist, but the most used one is capture through chemical absorption, using solvents such as amines, monoethanolamide (MEA) or aqueous ammonia.

→ **Oxy-fuel combustion,** a process that reduces fuel consumption by burning fuel using pure oxygen (or a mixture of oxygen and flue gas) instead of air, can also be used for carbon capture by removing the water vapour from the flue gas rich in CO_2 it produces and storing this gas after purification and dehydration.[20, 84]

BECCS can be implemented to capture biogenic emissions from the manufacturing process in the pulp and paper mill, as well as to capture emissions released into the atmosphere at forest products' end of life. In the pulp mill specifically, BECCS can be implemented at multiple points, given that there typically are multiple CO_2 sources. In a mill producing kraft pulp, **these are often found in the recovery boiler, the lime kiln, and the biomass boiler.** [85] However, it will likely not be economical to apply carbon **capture to all potential sources**.[85]

Following the capture process, the biogenic carbon-dioxide is stored. Plants can store the biogenic CO_2 directly underneath the plant, otherwise the biogenic CO_2 has to be transported. In this case, it is purified and pressurized to transform it into the liquid form, as to make the transportation more efficient, since liquified CO_2 is much denser and requires less volume than gaseous form. After liquefaction, the carbon dioxide is stored in buffer tanks, and is then shipped to the final storage site through multiple modes – barge, pipeline, ship, train or road.[86] Captured CO_2 is injected into naturally occurring porous rock formations, for example, unused natural gas reservoirs, coal beds that cannot be mined, saline aquifers, or deep ocean injection.

Usage

Although several carbon capture technologies exist and integrating carbon capture into the production of pulp and/or paper was found to be technically feasible, technologies are mostly in the development stage with limited utilization in relevant environments (TRL 5), while others (such as amines for post-combustion capture) are much more mature and utilized (TRL 9). Globally, as of 2022, there are around 20 BECCS plants currently operational or planned, varying by type, capacity, and costs, as well as industries where the technology is used: cement, waste and energy and power, and some scattered applications in the pulp and paper industry in Sweden and Canada.

Climate and business impacts

Climate impacts	
Targeted emissions sources	Capture of biogenic carbon with BECCS has the potential to permanently remove or remove for longer periods, CO_2 from the carbon cycle.
Emissions abatement potential	The pulp and paper industry holds high potential to leverage carbon capture technologies to significantly mitigate emissions, as up to 75% of emissions from the pulp and paper industry arise from biomass combustion onsite, particularly for chemical pulping plants. These biogenic emissions are considered carbon neutral and can largely be removed through BECCS. Studies estimate that BECCS wider deployment in Europe could help sequester up to 60 $MtCO_2$, of which 20 $MtCO_2$ is just in Sweden.[20] The carbon efficiency of CCS technologies (i.e., the net carbon it captures) vary depending on the type of technology adopted and the type of flue gas, although most current technologies can achieve up to 90-95% efficiency in terms of carbon sequestration. However, the overall impact on the pulp mill emissions will vary depending on the energy sources and configuration. Studies in Swedish pulp and paper mills, with bioenergy demand ranging between 3-5.3 GWh/year, found that the overall potential for emission reductions from BECCS application would range between 53-66%.[88] Additionally, trade-offs must be made between carbon sequestration efficiency, energy consumption and costs.[83]

Climate and business impacts Continued

Business impacts	
Benefits	
Utilization of carbon credits	Companies adopting BECCS can increase revenues by obtaining carbon credits for the sequestered carbon. Currently, carbon credits can be exchanged in voluntary carbon markets. However, compliance carbon markets may soon be able to accept credits from technology-based carbon removals.[70] Should carbon not be stored, as in the case of the carbon being sold to synthetic fuels producers, players implementing BECCS could still benefit from revenues derived from the sale.
Other positive considerations	The distance to a storage location or CCS hub is a crucial consideration for maximizing the economic profitability of BECCS. The greater the distance to storage site, the higher the costs for the transportation of the liquified carbon-dioxide. Some pulp mills may have a relative advantage over others due to their location. For instance, in Europe, mills with proximity to the North sea may benefit from accessible storage potential, whereas in the southern US, projects are more likely to consider land storage. Pulp mills that are less conveniently located can still benefit from carbon capture by selling the liquified biogenic carbon-dioxide to producers of synthetic fuels, such as methanol. Although this option may not provide as much value as carbon sequestration and selling carbon credits on the market, it may still be a favourable option, as the monetization of carbon removals is uncertain and occurs in relatively illiquid new markets.
Costs	
Investment required	As most BECCS projects are either under development or at the prototype stage, capital and operating costs may be subject to strong variations over time. Capital costs of BECCS technologies currently range between 19-22 EUR/tCO_2 depending on the type of technology and capacity.[62] Initial capital costs vary depending on whether the plant is already in place (as in the case of pulp mills) or if it is constructed from scratch (as for energy production purposes). For instance, the investment to incorporate BECCS in the Saint-Félicien Pulp Mill in Canada was around 8 million EUR (with a target to remove 30tCO_2/day), while other projects in the energy sector cost up to 450 million EUR.[89]
Operating costs	Operating costs (excluding transport and storage) are estimated to range between 30-90 EUR/tCO_2, as they vary based on energy prices, which is the main driver of BECCS costs.[90]
Indicative abatement cost	Studies suggest effective **costs** of carbon removal for BECCS range between 125-250 EUR/tCO_2 which are expected to decrease to 50-160 EUR/tCO_2 when deployed at scale by 2050.[58] Other sources indicate lower costs, specifically for the paper and pulp mill, ranging **between 40–90 EUR/tCO_2**.[85] Furthermore, the estimated abatement costs currently do not factor in the potential profits that could be generated from selling the sequestered carbon as either carbon credits or to markets and producers. If such additional revenues were taken into account, BECCS would appear a **cost competitive option** for the forest sector.

Potential co-benefits and side effects

Co-benefits	**Energy generation coupled with carbon removal**	BECCS technologies can also be used to couple energy generation from biofuels and carbon removal technologies to ensure both the supply of clean energy and climate change mitigation benefits.
Side effects	**Trade-off between biofuels and land use**	While most IPCC studies acknowledge the great potential of BECCS, they also warn of potential adverse environmental socio-economic impacts, as significant usage of BECCS would require a large amount of biomass. These potential drawbacks include changes to land use patterns that may increase GHG emissions, pressure on water resources, soil health, air and water pollution, and pressure on food availability and costs.[91] As a bioenergy, BECCS is only considered sustainable when the sourced biomass is grown sustainably or based on waste or residues.[92] Competition with other forms of land use and other external impacts should be taken into consideration and avoided when relevant. The EU Commission's Renewable Energy Directive's sustainability criteria for bioenergy encourages companies to source bioenergy from feedstocks with low indirect land use change risk and to minimize the use of whole trees and food and feed crops.[93] However, these concerns can be mitigated when applying BECCS on top of the pulp and paper process, because BECCS is used as a side stream to producing materials, and not simply for the sake of storing carbon. This makes the pulp and paper industry well suited for BECCS.
	Increased energy demand on site	The carbon capture process requires steam and electricity and may require up to an additional 25-30% of additional fuel and additional electricity consumption. Carbon capture will increase the demand for biomass or other energy sources, potentially resulting in further costs.
	Carbon leaks and safety	There is a small risk that carbon sequestered into geological formations could leak out of the underground reservoirs and pollute air or taint nearby water supplies. However, geological storage has been proven to have low levels of leakage, if best practices are followed.[70] Tremors may also occur due to the build-up of pressure underground, known as induced seismicity. However, such risks can be minimized by injecting CO_2 into soft sedimentary rock formations, like shale or sandstone, as these are less prone to causing earthquakes.[94]

Implementation

These are the most common steps to adopt BECCS technologies:

→ **Select the appropriate equipment and process**
The company must decide what type of technology to use and at which stage of the production process (or multiple, if applicable). This should be informed by existing processes (e.g. pre-combustion may be appropriate for a mill using black liquor), an assessment of technical feasibility and cost.

→ **Adapt existing infrastructure and processes**
Upgrade the existing operations by retrofitting BECCS infrastructure and adapt current production process, as appropriate, to use bioenergy and capture carbon, or establish new pilot mills fitted with BECCS technology.

→ **Ensure adequate measurement and verification of captured carbon**
The issue of carbon credits from BECCS may require a partnership with project developers and carbon credit verification organizations with expertise in the measurement of negative emissions, as well as in the monitoring, verification and issuance process.

→ **Set up a CO_2 value chain**
Storing the captured carbon requires setting up a CO_2 network or a connection with an existing CCS hub.

Key challenges/hurdles	Potential solutions
Uncertain monetization of removals The main carbon credit standards are still in the process of developing carbon accounting methodologies for the issue of carbon credits from technology-based removals like BECCS.[95] Moreover, current climate change mitigation policy frameworks like the EU ETS currently do not provide incentives for negative emissions.	**Partner with carbon credit certification schemes** This may allow organizations to better understand emerging guidelines for the monitoring of captured emissions and issuance of BECCS carbon credits. Furthermore, partnerships may offer an opportunity to support the establishment of guidelines, ensuring the potential to monetize the application of BECCS in the industry.
Evolving policy landscape Related policies are still in early development.	**Develop industry partnerships** Organizations could partner with technology providers and governments to act as pilot projects, which may provide access to equipment at a reduced rate and an opportunity to shape technology development to ensure it is fit for industry purpose. Additionally, partnerships with industrial clusters can help establish a lower cost transport and storage network.
First mover challenge There are few incentives for industrial actors to be first movers and bear the high risk and infrastructure costs associated with setting up a CO_2 transport network.	

Action 7: Maximize waste recovery technologies in the pulp and paper mill: deep dive on black liquor gasification

Summary

Product category & value chain

Engineered wood products value chain

Forest production → Processing → Manufacturing → Use → End of life

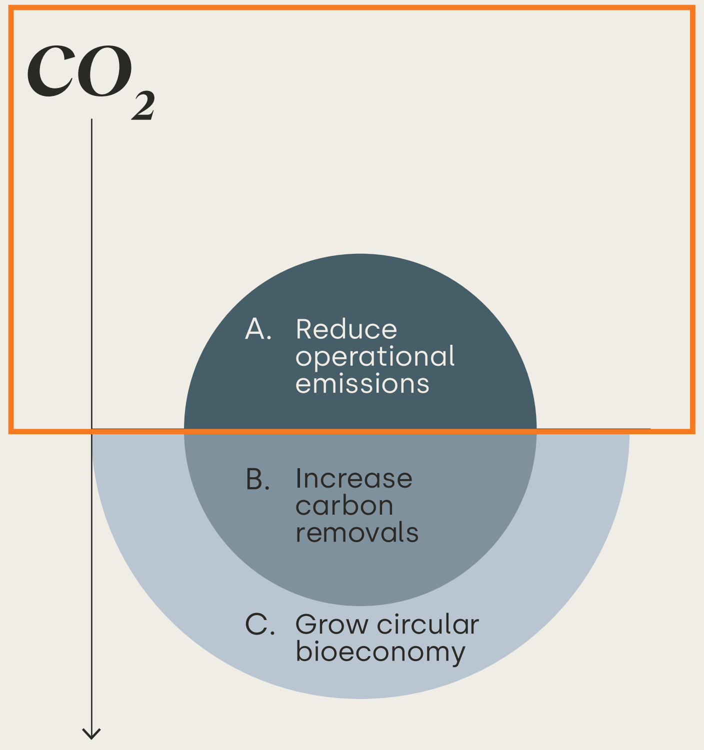
Consumer Packaging value chain

Forest production → Processing → Manufacturing → Converting → Use → End of life

Cellulose based textile value chain

Forest production → Processing → Manufacturing → Textile making → Use → End of life

Forest sector 3 levers of impact



Level of maturity

LOW TO MEDIUM

Prototype proven in test and conditions
and in conditions to be deployed. (TRL 4/5)

Emission abatement potential

LOW TO HIGH

Depending on the configurations, BLG
could reduce 3 to 100% of the lime kiln emissions

Short-term economic feasibility

LOW

CAPEX : 65-230 million EUR
depending on the configuration

Abatement cost : 500-700 EUR/tonCO2, when considering
the revenues from electricity or biofuel safe

Overview of the solution

Black liquor gasification (BLG) is a process to recover energy from black liquor's organic content, using a gasification process. In a BLG system, the recovery boiler is replaced with a gasification plant where the black liquor is converted to a synthesis gas. Black liquor is a by-product of the kraft process, in which pulpwood is converted into paper pulp by removing lignin and hemicellulose constituents to free the cellulose fibers. Black liquor has a **high organic content,** with an approximate energy content of 14 MJ/kg dry solids, which is about half of the energy content of 1kg of coal equivalent. Current black liquor handling uses a recovery boiler to recover the energy and chemicals from black liquor. However, even though the traditional recovery process has worked well, it also has several disadvantages, such as low efficiency (due to black liquor's relatively high water content, which limits combustion efficiency), as well as smelt-water explosions and sulphur gas emissions.

In a BLG system, the black liquor is fed into a gasification plant, where a pressurized gasifier makes it evaporate in a high temperature and high pressure reactor. The black liquor gasification generates a so-called 'syngas'. This is separated from the inorganic smelt and ash, which are cooled in the quench zone below the gasifier, where it dissolves to form green liquor in a manner similar to the dissolving tank of a recovery boiler. In the meantime, the hot syngas is also rapidly cooled and quenched using water or other cooling agents. The heat released as the water vapor in the syngas condenses is used to generate steam. Additionally, the condensation process removes tar and other compounds from the gas. The result is a nearly sulphur-free synthesis gas consisting of mostly carbon monoxide, hydrogen and carbon dioxide.

Moreover, different BLG technologies can be applied to recover black liquor and transform the syngas into other products:

→ **Renewable biofuels**
The synthesis gas produced from gasification can be used to produce biofuels such as DME (dimethyl ether), methanol, chemicals, hydrogen, ammonia, synthetic natural gas or synthetic diesel fuels (e.g., FT diesel). This is a good option given the growing interest in finding cheap and efficient ways to produce CO_2 - neutral automotive fuels.

→ **Electricity**
Generating electricity from black liquor is possible, adopting a Black Liquor Gasification Combined Cycle (BLGCC), a system that uses the synthesis gas to fire a gas turbine, in which power is generated.

Overview of the solution Continued

Box 1: Maximizing waste recovery: other waste streams and recovery pathways

The adoption of technologies that can recover energy from waste can lead to higher resource and energy efficiency, while helping the forest sector to reduce emissions. In fact, pulp and paper mills generate energy-rich biomass as waste in many stages of the process, such as in wood preparation, in pulping and paper making, and through the wastewater treatment. The major sources of biomass in the pulp and paper mill, and the associated energy-recovery methods, include those presented below:

<table>
<tr><th>Waste stream</th><th>Potential solutions</th><th>Recovery method</th></tr>
<tr><td>Wood residues and other biomass</td><td>Wood residues and other biomass (e.g. bark, branches, leaves) are left from the chemical and semi-chemical pulp processes and mechanical pulp manufacture.</td><td>Recovered in biomass boilers to produce energy or in other processes.</td></tr>
<tr><td>Primary sludge</td><td>The primary sludge is generated after removal of suspended solids during primary clarification, while the secondary sludge is the residue left after the biological treatment of the wastewater, where microorganisms are used to reduce the dissolved organic matter in wastewater. Primary sludge has comparably far more biomass, due to the presence of large proportion of woody and other organic materials.</td><td rowspan="2">Recovery through combustion, digestion from anaerobic bacteria or pyrolysis, to either recovery energy or recover materials for land applications (e.g. agriculture, silviculture, composting), or for material applications (e.g. cement, bio composite).</td></tr>
<tr><td>Secondary sludge</td><td>Secondary sludge also contains residual cellulose, hemicellulose, lignin, chemical components and micro and macronutrients. However, the high water content means that it is relatively more difficult to de-water the sludge and recover energy.</td></tr>
<tr><td>Paper sludge / de-inking sludge</td><td>De-inking sludge is produced form the recycling of paper. It contains fibers, inorganic compounds such as ink particles (color pigments), de-inking agents, adhesive components and fillers. The heating value is low, and the high moisture of the sludge affects its ability to burn efficiently.</td><td>Paper / de-inking sludge can be recovered for energy (although very few mills incinerate paper sludge in their boilers as fuel) or for production of high grade biofuels and bio-based chemicals through biological recovery or thermal treatment (e.g. gasification).</td></tr>
</table>

Usage

The pulp and paper industry does not presently use BLG technology, despite its development and operation in pilot plants in the North of Europe since the early 2000s. The technology was deployed in several plants in small, commercial, atmospheric, low temperature BLG units, meaning BLG was proven in test conditions but not deployed at larger scale (TRL 4/5). Although pilot projects have demonstrated viability, funding shortages and political disinterest led to the closure of these projects and the companies leading them (e.g., Coskata, Chemrec, Choren, Battelle, Range Fuels, TPS, and others). Despite this, the patented technologies remain potentially available.

Recently, there has been increased interest in reviving BLG within the industry due to several factors. Firstly, when thinking about replacing an old recovery boiler, implementing a BLG plant could provide higher future profits compared to installing a new recovery boiler. Secondly, the growing demand for biofuels and hydrogen could make the economics of BLG more favourable than when it was previously trialled.[96, 20, 97] However, higher estimated capex compared to recovery boiler systems and reservations to spend capex on new technology may continue to limit the full scale implementation of BLG at the point of recovery boiler replacement.

A potential step forward for BLG could come from implementing a hybrid system, where a small scale auxillary BLG system is installed additionally to the recovery boiler. In fact, in the traditional kraft recovery process, the boiler recovers energy from dissolved organic material and to regenerate the cooking chemicals. Without the recovery cycle, the process would be both economically and environmentally unfeasible. However, pulp mills can often be bottlenecked by black liquor, either due to the content and impurities of the black liquor, or due to the design and capacity of the boilers. In this scenario, the existing pulp mill, delayed by its recovery boiler, but with ample capacity in other process steps, would add black-liquor processing capacity in the form of a small BLG line (~10-20% capacity of the recovery boiler).

The major advantage of this set-up, besides additional pulp volumes, would be to use the flue gas from the gasification process to heat the lime kiln, reducing, or even eliminating, one of the few remaining non-biogenic sources of CO_2 in modern pulp mills.

This approach would allow BLG to be phased in gradually, without forcing companies into an all or nothing decision at the end of boiler life. As BLG technology is refined trough these small-scale implementations, and as the economics of biofuels evolve, this may lead to the adoption of BLG-only black liquor systems.

Climate and business impacts

Climate impacts	
Targeted emissions sources	Black liquor gasification could help abate emissions in different ways: → By enabling additional energy generation in the pulp mill, increasing resource and energy efficiency, reducing the fuels input into the pulping and paper making process or increasing generation of renewable biofuels and electricity for the grid. → By reducing emissions from the lime kiln.
Emission abatement potential	Estimating the decarbonization impact of black liquor gasification remains challenging. Research is relatively limited and there is no scientific consensus. The abatement potential for the industry depends on whether the energy produced is consumed within the pulp mill or sold externally to the grid or market: **On site** If BLG is used to transform the syngas into biofuels, this may require additional energy, which can increase emissions. The net impact on GHG emissions on site depends on the energy sources used in the pulp mill (e.g. if predominantly biomass and clean energy were used, emission reduction will be far less). Using BLG to decarbonize the lime kiln could achieve between 3-100% of emissions reductions, **depending on the mill type**. Additionally, combining black liquor gasification with carbon capture and storage can lead to even greater emission reductions.[98 99] **Externally** When biofuels produced are used outside of the mill, they can substitute fossil fuels in other sectors, such as transportation, which could substantially reduce GHG emissions in these sectors. Depending on how efficiently biofuels are used by the buyers, abatement potential can be higher (e.g. hydrogen is used in the transportation sector, which has higher efficiency fuel cells).

Climate and business impacts Continued

Business impacts	
Benefits	
Revenue-generating opportunity from energy production	The introduction of BLG technology has the potential to generate an additional source of revenue for pulp mills. This is because it offers the opportunity for more efficient conversion of the liquid by-product into biofuels or biochemicals, rather than simply being burned for heat production. By increasing on-site energy production, pulp mills can also sell energy to the power grid, positioning them as suppliers of renewable fuels in the future energy system.[100] The use of BLGCC can increase energy recovery in the pulping process and double power production at the mills, with the excess electricity or other biofuels being sold to the power grid or other players.[101] Studies on BLG installation found potential revenues of EUR 70-80 million per year from the sale of either electricity or other biofuels (DME, hydrogen) from one plant.[102, 103]
BLG can be integrated with carbon capture and storage	The BLG system can be integrated with carbon capture and storage technologies, which can help pulp mills achieve even greater emission reductions while benefitting from the increased revenues from selling produced biofuels or electricity.
Simple logistics	Another advantage of implementing black liquor gasification is the fact that no additional distribution system is required, given that the raw material for fuel production is handled within the boundaries of the pulp and paper plant.
Diversified energy sources	Pulp mill economics become less sensitive to pulp prices when diversified with another product.[100]
Costs	
Investment required	BLG **is two to three times as expensive** in capital costs relative to a conventional recovery boiler. The capital costs for BLG were estimated to range between 65-230 million EUR depending on the different end use configurations: the lower bound is for a hybrid configuration, where the BLG plant is complementing the recovery boiler.[102]
Operating costs	Theoretical studies suggest operating costs for the hybrid BLG system could be around 60 million EUR/year, where about half of the costs are for heat production for the gasifier, and about a third are for the purchase of the black liquor itself. In fact, the configuration in this theoretical study is so that the mill must purchase additional black liquor, either for the gasification or, in a hybrid configuration, to be burnt in a recovery boiler to supply steam to the various **processes in the mill**.
Indicative abatement cost	There are only studies on abatement costs for the hybrid configuration of the BLG system, and only considering the abatement potential within the boundaries of the pulp mill. If potential revenues from selling electricity or biofuels are factored into the calculations, the indicative abatement cost ranges between 500-700 EUR/tCO_2e. Opportunities exist to couple gasification with carbon capture, thus reducing costs. However, excluding revenues from the equation would result in significantly higher abatement costs, ranging between 5,000-8,000 EUR/tCO_2e. This is due to the fact that the abatement potential of the BLG system is limited in absolute terms (excluding biogenic emissions, it can reduce emissions from the lime kiln by 4,000-10,000 EUR/tCO_2e depending on the configuration) relative to very high operating costs (~yearly 60 million EUR). The BLG system's limited abatement potential in absolute terms and high operating costs offers low short-term economic feasibility as a solution for decarbonizing the pulp mill only. However, this does not imply that it is an ineffective solution overall. The system's ability to generate green electricity and renewable biofuels has the potential to yield substantial revenue for the mill and contribute to decarbonization beyond the mill's scope, providing a lever for mitigating fossil fuel emissions and climate change.

Potential co-benefits and side effects

Co-benefits	**Reduce delays in the black liquor recovery process**	In the hybrid system, black liquor gasification could reduce the excess amount of black liquor that needs to be handled, thereby enabling higher productivity on top of reducing GHG emissions.
Side effects	**Additional investments in steam system**	Additional steam system requirements for pulp (or paper) drying may be needed due to the BLG's lower output of high temperature steam, however this could be overcome by additional biomass steam generation, lower steam demand through steam system efficiency increase and/or implementation of heat electrification e.g. heat pumps powered by green electricity.
	Additional lime demand	The calcium (lime) balance of the whole pulp mill system must be carefully studied as research suggests a lower recover of chemicals from green liquor when using BLG. Additionally, the gasification process results in more sodium in the green liquor and increased demand for lime. Estimates suggest a 16-25% additional lime demand in BLG compared to recovery boilers.[104] However, in a hybrid system, where 80-90% of black liquor is still processed by the recovery boiler, this loss would drop to only 1.6-5% of total increased lime demand.

Implementation

These are the most common steps to implementing black liquor gasification in the pulp mill:

→ **Identify and select suitable technology**
Identify and select a suitable black liquor gasification technology that aligns with the mill's requirements. There are several gasification technologies available, such as entrained flow gasification, fluidized bed gasification, or indirect gasification. Suitable technology can be selected based on factors such as feedstock characteristics, desired gas composition, system efficiency, and environmental performance. Given the unique circumstances of each pulp and paper mill, companies may benefit from engagement with engineering experts.

→ **Adapt existing infrastructure**
Determine and carry out any modifications or additions necessary for implementing black liquor gasification. Gasifiers, gas cleaning systems, syngas utilization equipment, and other ancillary systems may need to be installed or upgraded.

→ **Install and commission the plant**
Execute the construction phase based on the technology's design. Coordinate with contractors and vendors to ensure correct installation of equipment and systems. Following construction, conduct thorough testing and commissioning to verify the functionality and performance of the black liquor gasification plant.

Key challenges/hurdles	Potential solutions
Low maturity of technology Black liquor gasification technologies are still in the initial stages of maturity (TRL of 4-5), which complicates their implementation. **Issues with quality of black liquor** The availability and quality of black liquor, the primary feedstock for gasification, can pose challenges. Also, the composition of black liquor can vary depending on the pulping process and wood sources, which may impact gasification performance.	**Invest in R&D** Continued research and development efforts are crucial for improving black liquor gasification processes. These efforts should focus on developing innovative gasification technologies, advanced materials, and more efficient and cost effective gas cleaning and conditioning techniques. Collaborative research partnerships between industry, academia and government institutions can drive innovation in this field. **Engage with academia to identify appropriate black liquor sources** Industry engagement with researchers to test how different compositions of black liquor affect gasification performance can help establish high quality black liquor sources and develop a plan for their supply.

Action 8: Adopt breakthrough technologies to increase energy efficiency in pulp and paper making

Summary

Product category & value chain

Engineered wood products value chain

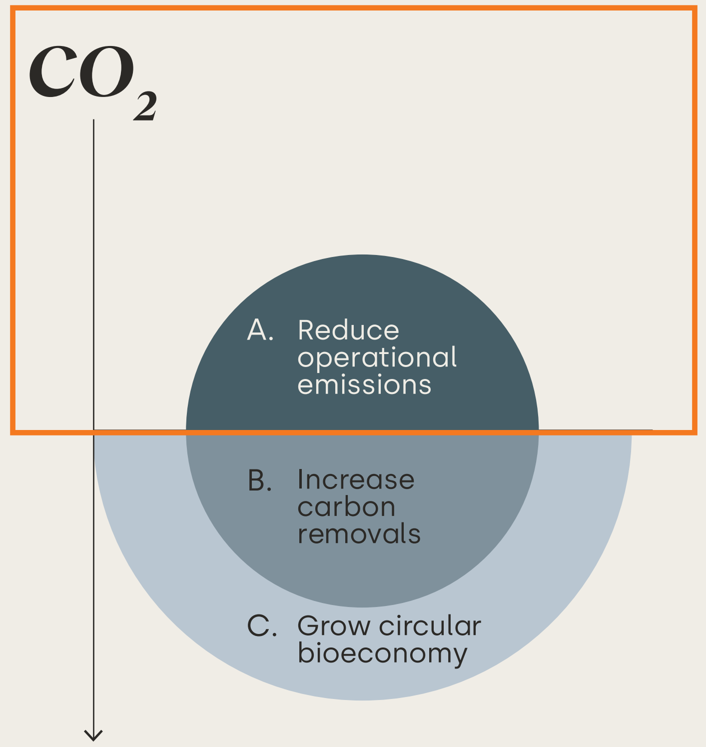
Forest production → Processing → Manufacturing → Use → End of life

Consumer Packaging value chain

Forest production → Processing → Manufacturing → Converting → Use → End of life

Cellulose based textile value chain

Forest production → Processing → Manufacturing → Textile making → Use → End of life



Level of maturity

LOW TO HIGH

Level of maturity varies depending on the technology (TRL 3-9)

Emission abatement potential

LOW TO MEDIUM

Emission abatement ranging between 11% and 20%

Short-term economic feasibility

LOW TO HIGH

CAPEX : EUR 5-20 million depending on the configuration

Overview of the solution

The production of paper involves an energy intensive process, with paper drying consuming the most energy. Mills require low-, medium- as well as high-temperature heat from various sources, depending on the type of process (e.g., mechanical or chemical pulping, integrated and non-integrated mills), the equipment, as well as on the cost of the energy source (as mills will likely favour the cheapest and most readily available). In addition to enhancing heat recovery, it is vital to adopt technologies that are more efficient than conventional methods in order to reduce GHG emissions from fuel combustion, and can reduce the energy inputs required for each step.

Numerous technologies can help increase energy efficiency and decrease energy demand, particularly when combined with incremental process improvements, including the implementation of end-to-end process digitization and advanced analytics (e.g. advanced analytics set point optimization).[105] *Table 1* presents the top emerging technologies that were selected based on their abatement potential across all manufacturing stages, from pulping to paper drying. Additional levers that can increase energy efficiency in the mill through heat recovery are described in *Action 3, Box 1: Further heat recovery technologies for pulping and paper making.*

Table 1: Overview of the selected key technologies to increase energy efficiency in paper making *(heat recovery technologies can be found under Action 3)*

Process step	Technology	Description
Pulping	High efficiency refiner	A high efficiency refiner is a machine used in the papermaking process to refine the pulp and improve its properties. Installing a high efficiency refiner with new disks and design makes it possible to reduce the number of refiners in operation, and therefore energy consumption.
	High efficiency pulper	A high efficiency pulper combined with a new rotor design could provide more efficient pulping, reducing energy consumption.
	Enzymatic treatments	Pre-formed enzymes are employed during the pulping process to pretreat lignocellulosic biomass before the production of pulp.
Forming	Turbo blower pump	A turbo blower pump is a high efficiency vacuum system technology. By replacing conventional liquid ring vacuum pumps, it allows for savings in energy consumption.
	Double dilution headbox	A double dilution headbox is a component used in papermaking machines to evenly distribute a diluted paper pulp slurry to form a uniform sheet of paper. The double dilution headbox uses two stages of dilution to achieve a more consistent and uniform distribution of fibers and reduces the flow passing through the screen and therefore the energy consumption.
Pressing	Shoe press	A shoe press is a type of paper press used to remove water from the paper web in the papermaking process. Installing a shoe press leads to improvements in dewatering: it increases the paper dry content before the dryer section and therefore the overall energy consumption required to dry the paper.
Drying	Steel drying cylinders / Yankee	Steel drying cylinders enable improved heat transfer in the dryer cylinders due to a thinner shell. This makes the drying process more efficient and can achieve significant energy savings.
	Electromagnetic induction steel drying cylinder / Yankee	Using electromagnetic induction instead of steam energy to dry the paper reduces steam consumption in the drying paper process to zero. This allows for heat to be replaced by green energy.
Overall energy efficiency	Variable frequency drives	Instead of using a traditional "on/off" system, variable frequency drives optimize the energy consumed by motors by adjusting speeds to match load requirements.
	Online energy management system	These online systems use advanced analytics, real-time data monitoring and process control to analyse energy use and identify improvement opportunities, fine-tune and optimize the existing system energy use, and reduce the variability of energy consumption. They also enable to make decisions as to when to use green power generation instead of the grid.

Source: McKinsey

Usage

Several of these technologies have already reached an advanced level of maturity in the industry, while some have recently emerged and are still at early stages of testing *(see Table 2)*. Still, there are several pulp and paper mills where even mature technologies are not yet implemented or installed, which gives them the opportunity to reduce their CO_2 emissions significantly (e.g. shoe presses only are installed in 55% of paper machines worldwide, despite their wide scale demonstration of efficiency).

For some technologies such as the shoe press or steel drying cylinders, installation may require major rebuilds, including the building which houses the paper machine, that would need to be stopped for months, leading to revenue loss.

Table 2: Maturity level of the key selected technologies to increase energy efficiency in pulp and paper making

Section	Technology	Maturity (TRL)
Pulping	High efficiency refiner	Medium: 7-8. The solution is working in expected conditions or has gone through commercial demonstration.
	High efficiency pulper	Medium: 7-8. The solution is working in expected conditions or has gone through commercial demonstration.
	Enzymatic treatment	Medium/high: 7-9. The solution is already commercially available, although some enzymatic treatment technologies are being tested and demonstrated. The technology requires further integration to ensure competitiveness.
Forming	Turbo blower pump	High: 9. The solution is commercially available, though it needs further improvement to be stay competitive.
	Double dilution headbox	Medium: 5-6. Some prototypes have been proven at scale in conditions, but still need to be deployed.
Pressing	Shoe press	High: 9 (medium for tissue paper: 7-8). The solution is commercially available, although maturity is lower for tissue paper products.
Drying	Steel drying cylinders / Yankee	High: 9. The solution is commercially available but needs further improvement to be stay competitive.
	Electromagnetic induction steel drying cylinder / Yankee	Low: 3-4. Some early prototypes haven been proven to work in test conditions.
Overall energy efficiency	Variable frequency drives	High: 9. The solution is commercially available but needs further improvement to be stay competitive.
	Online energy management system	Medium: 5-6. Some prototypes have been proven at scale in conditions, but still need to be deployed.

Climate and business impacts

Climate impacts	
Targeted emissions sources	Adopting technologies for increased energy efficiency targets emissions due to fuel combustion as well as those due to use of electricity on site, steam, heating and cooling.
Decarbonization impact	The application of these technologies can achieve substantial energy efficiency gains and reduce GHG emissions. **Adopting these technologies would lead to a 11-20% reduction in emissions.**[62] Given this range, each technology contributes to a different extent, as shown in *Table 3*.

Table 3: Emissions reduction potential of some technologies to increase energy efficiency in pulp and paper making

Section	Technology	Emissions reduction potential
Pulping	High efficiency refiner	Low
	High efficiency pulper	Low
	Enzymatic treatment	Medium
Forming	Turbo blower pump	Medium
	Double dilution headbox	Low
Pressing	Shoe press	High
Drying	Steel drying cylinders / Yankee	High
	Electromagnetic induction steel drying cylinder / Yankee	High
Overall energy efficiency	Variable frequency drives	Medium
	Online energy management system	High

Business impacts	
Benefits	
Reduced costs through energy savings	Multiple technologies enable energy savings, which could lead to reduced operational costs.
Costs	
Investment costs	A typical project to reduce emissions, which includes the above-mentioned technologies, **could cost about 5-20M EUR**.
Operating costs	Some of these technologies are still emerging and others only available from 1-2 OEMs, who do not publicly disclose operating costs. Furthermore, the business case for implementing these technologies will be highly depending on current and future fuel mix and prices, therefore companies are recommended to do 'their own due diligence'.
Indicative abatement cost	Abatement cost cannot be estimated due to the absence of operating costs estimates today.
Economic feasibility	The **economic feasibility** varies for each technology. Less mature technologies are likely to have low short-term economic feasibility despite their potential for significant emission reduction. The technology with the highest economic feasibility is typically used for forming, pressing and improving overall process energy efficiency.

Potential co-benefits and side effects

Co-benefits	**Increased production speed**	The adoption of some technologies like shoe press and steel cylinders makes it possible to increase paper production speed. However, the opportunity to sell the additional volume will also depend on the market situation.
Side effects	**Loss of revenues during installation time**	For some technologies, the machines would need to be stopped for months during installation because of major rebuilds, which could create a revenue loss and other inconveniences during this time.

Implementation

These are the most common steps to adopt breakthrough technologies to increase energy efficiency in pulp and paper making:

→ **Assess requirements**
Forest companies should conduct a comprehensive energy assessment of the paper making process, which involves analyzing energy consumption patterns, identifying energy-intensive processes, and assessing opportunities for improvement through process optimization or the adoption of new technologies.

→ **Select appropriate technology**
Based on the comprehensive energy assessment, organizations should select technologies appropriate to the specific mill, considering factors such as cost, mill size and potential energy efficiency savings.

→ **Install/upgrade equipment and processes**
Replace outdated or energy-intensive equipment with more efficient alternatives. Install state-of-the-art technologies, such as high efficiency refiners and pulper, optimized drying technologies, and energy efficient motors and drives

Key challenges/hurdles	Potential solutions
Impact on final product quality and requirements Energy efficient technologies can have a negative impact on the features and qualities of the product, which may disincentivize adoption.	**Suitability assessment** Individual companies should assess each technology to ensure that product quality can be improved or maintained with the adoption of the technologies. Use of multi variant advanced analytics models will help fine tune recipes and process parameters to maintain product quality.
Disruptions to production Some technologies may require significant implementation time, creating costly disruptions to production.	**Plan installation/implementation to minimize production disruptions** Implementation of abatement measures can be planned to minimize operational disruptions, for instance by grouping the major rebuild items and planning minor interventions during scheduled maintenance or downtime.
Current limited premium on low carbon paper products When consumers are willing to pay a premium for low-carbon products, this can serve as a significant incentive for producers to adopt energy-efficiency technologies. In the context of paper products, consumers' willingness to pay a premium is limited today, and producers may not readily perceive the motivation for change.	**Carry out cost due diligence and capture future premium** As demand for low-carbon paper products is expected to increase, McKinsey experts estimate that a 6-7% premium will emerge on low-carbon paper products. Furthermore, paper makers can carry out a cost due diligence on the above-mentioned decarbonization technologies. Most are already NPV positive today, and, depending on the region, regulation incentives, cost of energy, etc., technologies could be even more economically attractive.
First-mover challenges for low-maturity technologies While most of the technologies have a medium to high maturity level (i.e. most have TRL above 7), a few are still in the earlier stages of development. In these instances, producers may encounter challenges associated with being early adopters, including issues like limited access to information, high capital investment, technological uncertainty, integration complexities with existing systems, limited vendor support, and difficulties in navigating the regulatory and policy landscape. In such a context, particularly smaller organizations may be reluctant to move forward in implementing new measures.	**Invest in R&D, and partner with research institutions and equipment suppliers to refine existing technologies and develop new breakthroughs** Further energy efficiency gains may require development of improved technology or better methods of applying technology to the current manufacturing process. Given the low maturity of some of the technologies, paper makers can engage with suppliers to co-invest into these initiatives.

Action 9: Increase adoption of forest products for construction

Summary

Product category & value chain

Engineered wood products value chain

Forest production → Processing → Manufacturing → **Use** → End of life

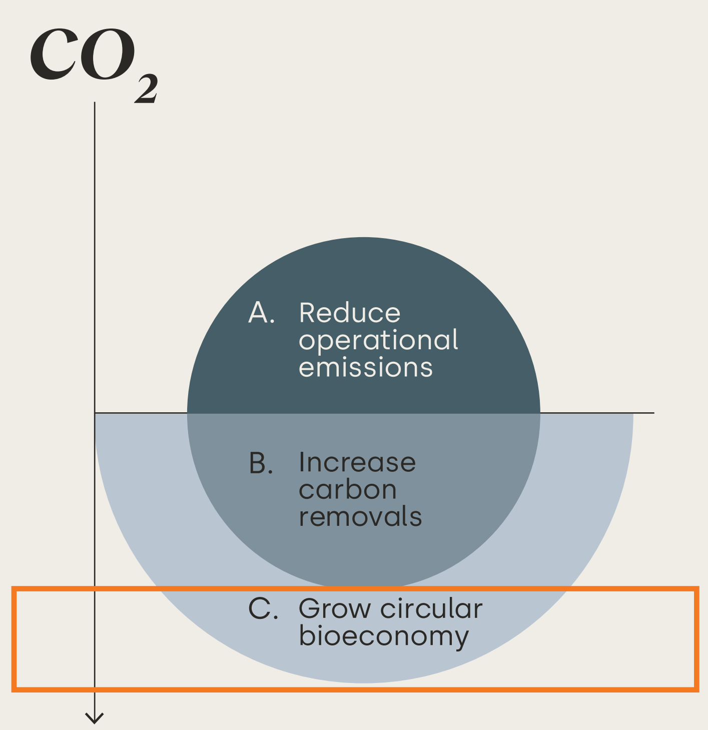
Consumer Packaging value chain

Forest production → Processing → Manufacturing → Converting → Use → End of life

Cellulose based textile value chain

Forest production → Processing → Manufacturing → Textile making → Use → End of life

Forest sector 3 levers of impact



Level of maturity

HIGH

High maturity, stability achieved (TRL 11)

Emission abatement potential

MEDIUM

20-30% emission reduction for a building

Short-term economic feasibility

HIGH

CAPEX : 470-860 EUR/m^2

Abatement cost : 50-90 EUR/tCO_2

Overview of the solution

The forest sector can help mitigate GHG emissions from the built environment by promoting the use of solid wood and engineered wood products in construction. The built environment is responsible for approximately 40% of global energy-related carbon emissions,[106] and a third of these are associated with materials and the construction process, or embodied carbon, primarily linked to concrete, steel, aluminium and plastic.

Scaling up the use of sustainably sourced wood products, such as solid wood and engineered wood products *(see Box 1)*, can result in significant emission reductions in the built environment under the right conditions, and as part a **broader set of decarbonization actions**,[107] Manufacturing of wood products is less energy-intensive than traditional concrete and steel buildings. Also, the overall carbon footprint of buildings can be further improved through reused and recycling at the end of life.[14, 18] In addition to the climate benefits, solid and engineered wood products offer a wide range of benefits, including ease of installation, high strength-to-weight ratio, aesthetic features and more *(see Potential co-benefits section)*. It should be noted that the climate benefits of substituting traditional materials such as concrete and steel with wood products can vary and should be assessed on a case by case basis.

Usage

Solid wood has a long history of use in the construction sector, as well as more innovative engineered wood products that are also linked to very high maturity levels (TRL 11). The market for wood-based construction materials is growing, as well as the global production capacity of cross-laminated timber that increased at a rate of 10% between 2019-2020 due to the addition of large scale production facilities. This growth is projected to continue at a steady rate over the next years.[108]

Despite the growth prospects, the adoption of wood products in the construction sector is hindered by low awareness levels related to their benefits over more traditional building materials. The perception that wood products have limited structural performance, fire resistance and durability is also still widespread, despite studies demonstrating the opposite.[109, 110] The forest sector currently faces a unique widow of opportunity to champion wood as a key action for decarbonizing the construction sector, as steel, cement, and other structural materials continue their decarbonization. Increased evidence of buildings using wooden structures, and more architects trained to adopt these products will contribute to overcoming these barriers to adoption.

Box 1: Engineered wood products: Trends in different product categories

Engineered wood products are wood products that are made by binding together fibres or boards of wood with adhesives. They are designed to respond to a particular specification, for instance, flooring or pillars.

Category	Product		Description[111]	Key trends[112]
Structure and beams	Cross-laminated timber (CLT)		Multiple layers of solid saw lumber are glued perpendicularly for strength. It is very flexible in thickness and good for isolation.	CLT is a growing niche to replace concrete in floor and walls.
	Wood joists (I-joists)		I-shaped wood product that resists bending stress and carry heavy loads with less wood than a solid lumber joist.	This product is mature and already widely used for structural use in floor and roofs.
	Laminated strand and veneer lumber (LVL)		A very strong material, but with strength in only one direction because all veneers have grains going in the same direction.	LVL has potential to replace concrete structures in framing.
	Glulam		Multiple layers of dimensional lumber are glued together, with all grains running parallel to the longitudinal axis. It can also be produced in curved shapes.	This is a mature product, with the largest demand in Europe. It is used in load bearing structures such as bridges or canopies.
Wood panels	Particle and ibreboards, including Oriented Strand Board (OSB)		Wood strands and flakes are combined with adhesives and compressed in wide mats.	Large commoditized market for construction. OSB is mainly used for flooring, roof decking and wall sheathing in family housing.
	Medium/High Density Fibreboards (MDF & HDF)		Used in non-structural applications. Made from hardwood and softwood pieces broken down into fibers and pressed together at high temperatures to provide a smooth surface with high durability.	So far, MSF is used mostly for furniture and not construction, despite its appealing properties such as density and low cost.
	Plywood		Thin cross-laminated veneer layers glued together, with grain direction is alternated from layer to later to maximize strength and stiffness.	Usage is growing in Asia, for instance for furniture, floors, ceilings, doors.

Climate and business impacts

Climate impacts	
Targeted emissions sources	The use of wood in construction, whether in the form of solid wood or engineered wood products, contribute to reducing GHG emissions associated with building materials and construction (embodied carbon). It also contributes to avoided emissions related to the substitution of higher carbon construction materials with wood.
Emissions abatement potential	**Carbon storage** In addition to GHG emissions reduction from embodied carbon, wood products also contribute to carbon storage. An estimated 50-70% of the carbon sequestered in the original tree is stored in wood products for the duration of their lifetime,[113] representing approximately 700-800kg CO_2 per cubic meter.[114 115 116] However, it's important to remember that when a wooden building is demolished, the stored carbon is released into the atmosphere, unless specific measures are taken, such as converting it into biochar or using CCS facilities. Addressing the end-of-life scenario is crucial also for players in the construction sector to be able to claim the carbon sequestration benefits, although different rules may apply depending on the local regulation or certification standard. **Avoided emissions** Around 20-30% of the construction emissions of **a building** could be avoided by substituting higher carbon building materials (e.g. cement, steel and aluminium) for wood, which is associated with lower embodied carbon emissions.[117]

Business impacts	
The overall costs for constructing buildings with wood products can range from 20% less to 26% more than traditional options.[117 119]	
Benefits	
Reduced operating costs	As wood is lighter than steel and concrete, less energy is required during the transportation phase and manipulation of wood at the construction site (although this varies across applications). Lower operational costs are associated with the use of wood products (particularly due to lower maintenance costs), particularly when coupled with modular conception. This can reduce the overall cost of buildings by up to 20%.[120] Additional savings can be made through reduced labour costs, as wood based units can be built up to 50% more rapidly, compared to traditional buildings,[117] and up to 75% less workforce is required to build simple structures.[121]
Costs	
Investment costs in building materials	Depending on the type of product, prices can be slightly lower or higher compared to traditional construction materials, such as steel and concrete (which prices range from 410-750 EUR/m^3).[122 123] For instance, glulam beams can cost ~400-600 EUR/m^3, while CLT prices range from 450-900 EUR/m3.[124 125] Ultimately however, the costs of wood-based products for construction depend not only on the type of product, but also on the performance characteristics, the country and local market size, and the deals in place with manufacturers.
Indicative abatement cost	The abatement cost for the increased use of wood in construction, such as cross-laminated-timber, is estimated to be 45-90 EUR/tCO_2,[117] though it may be significantly more. Cost varies depending on regional prices of wood, concrete and steel, and the quantity of wood used in a structure to replace a given quantity of steel or concrete.
Overall, increasing the adoption of wood products can create opportunities for savings, driven by reduced construction time and reduced transportation costs, although material costs may be higher than in conventional buildings. Training workers so they can handle these products efficiently will be vital to realizing the full potential of savings that could offset these costs. The expected increase of carbon prices on steel and cement industries could also make wood products more competitive compared to traditional construction materials, which are expected to become more costly if emissions are not abated.	

Box 2: Reducing emissions from glue in engineered wood products

Although solid wood and engineered wood products are generally more environmentally friendly compared to traditional construction material, the manufacturing is an emission hotspot in the value chain, and decarbonizing the manufacturing of engineered wood products is key to further improve their potential in the construction sector. A relevant proportion of GHG emissions in the manufacturing of engineered wood products is due to the use of glues and adhesives used to join together the components of engineered wood products. There is an opportunity to decarbonize through breakthrough technologies, such as biobased glues fabricated from lignin, which can substitute petroleum-derived glues. These types of products are currently under development and their large scale application will require further technical improvements (e.g. in water resistance and for bonding strength). However, they represent an appealing decarbonization opportunity to help progress the forest sector towards net-zero while unlocking further commercial opportunities and improving resource efficiency.[118]

Potential co-benefits and side effects

Co-benefits	**Reduced water consumption in production**	Mass timber production requires 30 times less water per cubic meter than reinforced concrete, which represents an additional sustainability benefit.[126]
	Improved energy efficiency in buildings	Buildings using CLT tend to have better energy efficiency in mild climates compared to ordinary buildings due to mass thermal effects balancing heat gains and losses.[127]
	Seismic resistance	Wood-engineered products were found to have a higher seismic resistance, a valuable characteristic in earthquake prone regions.[128]
Side effects	**Material properties**	While wood products are widely used in construction due to their sustainability, affordability, and aesthetic appeal, they are not without their downsides, especially in terms of structural properties. One significant drawback is their vulnerability to decay, pests, and fire when not properly treated or maintained. This vulnerability can be more pronounced in humid environments, potentially leading to structural integrity issues and necessitating costly repairs or replacements. Additionally, wood products typically have lower load-bearing capacity, limiting their suitability for high-rise buildings or in seismic regions.[126] From a technical standpoint, wood-based products cannot entirely replace traditional construction materials like steel and concrete. For instance, most new buildings will require concrete foundations, and wood may not be suitable for **certain architectural designs**. This means that the emission reduction potential of wood products is inherently tied to these limitations and the advancements in product and architectural design.
	Environmental and social risks	Where there is a lack of regulatory and voluntary control mechanisms, there is a risk of exacerbated environmental and social risks associated with timber production and harvesting, if implemented unsustainably. Increase in demand may lead to an increased risk of forest conversion and degradation, without appropriate safeguards. It can also present social and economic implications for local communities, as land tenure conflicts are common in some regions.[129] However, many of these risks can be mitigated by using sustainable forest management practices, investing in assurance through forest certification programs, and improving forest management regulation and oversight from governmental bodies.

Implementation

The forest sector can support the transition to a low carbon economy by promoting the use of wood products in the construction sector. These are the most common steps that organizations can take to increase the adoption of wood products in construction.

Steps for construction companies

→ **Assess structural requirements**
Before incorporating wood products into construction projects, assess the structural requirements of the construction project. Structural engineers and architects will determine which wood products can meet structural considerations, such as necessary load-bearing capacities.

→ **Identify and engage with suppliers that apply the highest standards of sustainable forest management**
Companies should prioritize sourcing wood that is certified by globally recognized forest certification systems such as FSC, PEFC and SFI. These certifications verify that forest management practices meet stringent environmental, social, and economic criteria, ensuring the production of sustainable and responsibly sourced wood for construction.

→ **Build long-term relationships with suppliers**
Building relationships with suppliers who specialize in forest products will help construction companies access a wider range of materials and co-develop customized solutions.

Steps for forest companies

→ **Harvest suitable trees, and invest in technology for improved processing**
Forest companies can harvest trees that possess desirable characteristics for construction, such as straight grain, strength, and density. They can also invest in optimizing wood processing methods. This includes utilizing modern sawmilling techniques, drying technologies and manufacturing processes to produce consistent and high quality wood products suitable for construction.

→ **Collaborate with downstream partners**
Forest companies can collaborate with other stakeholders in the value chain, including architects, engineers, builders, and manufacturers. This collaboration fosters knowledge sharing, promotes innovative design and construction practices, and ensures the availability of wood products that meet industry requirements.

Key challenges/hurdles	Potential solutions
Lack of incentives and regulation Worldwide, there are few financial incentives for the construction sector to use wood products in construction. Furthermore, stringent low carbon building standards are only just emerging in leading countries. **Uncertified timber products** The absence of certification for some timber products may disincentivize their adoption in the construction sector in regions that present higher risks. **The absence of a broadly recognized and credible accounting framework for avoided emissions** This has so far disincentivized forest companies from quantifying or disclosing avoided emissions from their product portfolios to capture additional value from the climate-related benefits of wood products.	**Promote the benefits of using wood products** Raise awareness among architects, engineers, builders, and other stakeholders on the renewable nature, carbon sequestration potential, energy efficiency, versatility and design possibilities associated with the use of wood. **Support research and education** Invest in research initiatives and support educational programs focused on sustainable wood construction, such as research projects, scholarships and fellowships that advance knowledge in wood engineering, design and construction. **Engage with policymakers to promote incentives for the use of wood products** Engage with government agencies, policymakers, and industry associations to advocate for financial incentives, grants, or tax benefits to create favourable economic conditions for wood-based construction projects. Explore partnerships with financial institutions to develop specialized financing options for sustainable construction projects using forest products. **Engage with carbon accounting organizations to develop an accounting framework** Co-developing a framework can provide clarity around disclosure of avoided emissions associated with product portfolios, potentially stimulating demand among construction companies with decarbonization targets.

Action 10: Promote and lead on recycling and sorting technologies for paper products and textiles: deep dive on sensor-based technologies and textile recycling

Summary

Product category & value chain

Engineered wood products value chain

Forest production → Processing → Manufacturing → Use → End of life

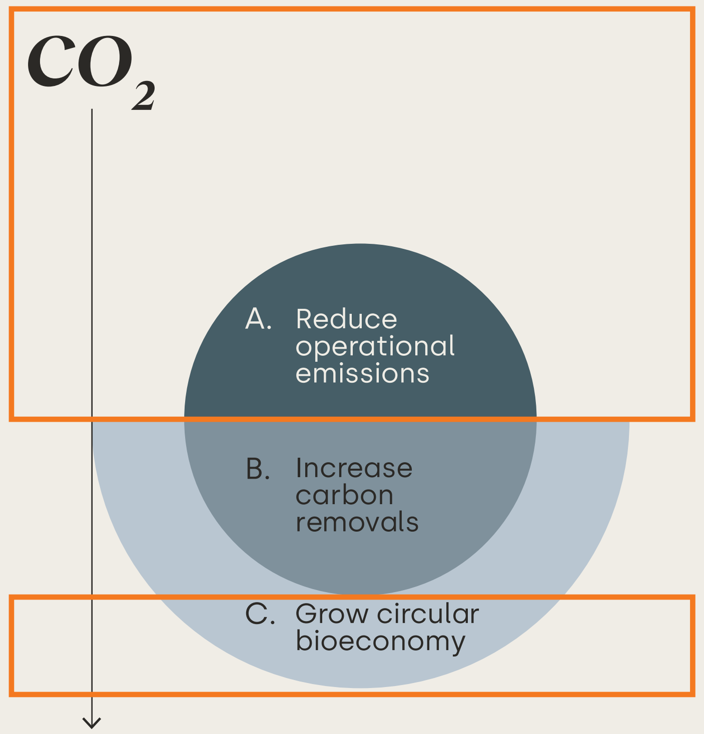
Consumer Packaging value chain

Forest production → Processing → Manufacturing → Converting → Use → End of life

Cellulose based textile value chain

Forest production → Processing → Manufacturing → Textile making → Use → End of life

Forest sector 3 levers of impact



Level of maturity

MEDIUM TO HIGH

First of a kind commercial, Commercial adoption in relevant environments (TRL 8-9)

Emission abatement potential

MEDIUM TO HIGH

Depends on technologies, practices adopted, and the material recycled (30-90%)

Short-term economic feasibility

MEDIUM TO HIGH

Based on type of technology and practice adopted

Overview of the solution

The recycling of paper products and cellulose-based textiles faces several challenges that hinder their reuse. For paper products, collection and recycling is a well-established practice, with a collection rate of 80% and a recycling rate of 60%. However, several production processes could lead to contamination, presenting significant challenges to achieving higher recycling rates. Examples of such processes where different paper grades need to be sorted and separated include disposing waste into single waste bins and collecting streams collectively (instead of separately). This can be challenging for the sector as sector, fabrics with multiple types of fibers are difficult to sort, and the process is reliant on manual labor, leading to low recycling rates. Additionally, recycling technologies often do not produce fibers of sufficient quality for textile applications. To increase the overall recycling rate of paper and textile products, potential solutions include improving product design to facilitate recycling, increasing the capacity to integrate recovered paper into manufacturing processes, and sorting technologies for mixed waste management. The latter solution holds particular promise for achieving higher recycling rates *(see below)*.

→ **Sorting technologies (for paper and textiles)**

Sensor-based technologies have shown high potential for sorting paper and textile products. For instance, near-infrared technologies, such as hyperspectral imaging and visual spectroscopy use sensors and infra-red to detect material composition and colors. They can even employ artificial intelligence through algorithms and machine learning to continuously improve sorting performance. Through high yield and purity sorting, mixed paper can be effectively used. These optical sensors have proven to be particularly effective, with some infra-red methods achieving 100% accuracy in polymer material detection and classification (also by color), and may be able to scan up to one garment per second.[130 131]

Beyond this, through digital watermarking, imperceptible codes can be applied on packaging, which can be detected by high resolution cameras. Packages can then be sorted into different streams more efficiently, due to the information embedded in the code (e.g. material composition). Similar initiatives exist, such as including information in the bar codes for paper packaging or using a 'digital passport' for clothes.[132]

For textiles, adding disassembling microwave technologies to the sorting process could be also helpful: these technologies use microwave radiation to remove labels from clothes and fasten the preparation of textiles for the recycling process.[133]

→ **Textile recycling technologies**

Textile recycling technologies fall into four primary technology categories *(see Table 1)*. These differ in terms of energy efficiency and their ability to maintain or restore virgin quality of textiles. Typically, there is a trade-off between the ability to return to virgin quality and energy efficiency, which are counter-correlated. This creates challenges in producing high quality materials through recycled textile waste in an energy (and cost) efficient way.

Table 1: Technologies to improve textile recycling

Process step	Description
Mechanical recycling	Mechanical recycling uses physical forces such as cutting and grinding to convert textiles into usable fibers. It is a commercially proven, low energy and cost-efficient recycling method. This technology currently faces the challenge of the quality degradation of recycled fibers with a fiber-length reduction of up to 30 to 40%, limiting its application and potential for upcycling. However, companies are exploring higher quality mechanical recycling and other innovative solutions.
Soft mechanical recycling	Soft mechanical recycling is a process that maintains fiber length thanks to an innovative production line. The longer fiber length minimizes losses from the subsequent spinning process, overcoming the typical challenges of mechanical recycling.
Thermo-chemical recycling	Thermo-chemical recycling uses gasification to produce syngas through the partial oxidation reaction of polymers, and is compatible with all forms of fibers. Thermo-chemical recycling as a core technology exists at a commercial scale, however, this technology needs some adaptation or development for the treatment of textile waste.
Chemical recycling	Chemical recycling is a broad category of multiple distinct technologies that use chemical processes to break down fibers to the polymer or monomer level. Chemical recycling targets a broad set of fiber types including synthetic cellulosic fibers.

Usage

Sensor-based sorting technologies
Have reached a decent level of maturity for improved sorting in the textile recycling industry, with some companies already selling machines to aid in this process (TRL 9).

Textile recycling technologies
Are used to varying degrees depending on the method and on the type of fiber. The majority of the technologies are still in the demonstration stage, requiring further development to increase the quality of the outputs while reducing costs (TRL 6-8).

Currently, the use of both sorting and recycling technologies is limited because of the high capital investment required and the lack of incentives in market pricing for recycled products. In fact, it is often more convenient and cost-effective for manufacturers to purchase virgin materials or to ship waste to other regions of the world. For instance, in the Netherlands, 55% of textile sorting takes place abroad.[134]

Climate and business impacts

Climate impacts	
Targeted emissions sources	By promoting the adoption of innovative technologies for improved sorting and recycling of paper products and textiles, the forests sector can reduce emissions from both the end of life – emissions due to products being discarded in landfills or combusted without energy recovery – as well as by increasing resource efficiency, therefore avoiding GHG emissions associated with the production of virgin fibers.
Emissions abatement potential	Adopting sensor-based technologies and therefore increasing the recycling rate of paper products can reduce emissions of paper products by an **estimated 30%**.[135] This is however dependent on the energy and resource efficiency of each mill, as those with high efficiency can produce lower emission products from virgin fibers compared to those using recycled fibers.[136] For textile recycling, mechanical recycling technologies, for example, offer a 60 to 90% GHG emissions reduction, as mechanically recycled fibers also avoid emission-intense, post-material processing, which saves more GHG emissions. Chemical pulping recycling of cellulose-based textiles has a lower potential to reduce GHG emissions compared to virgin fibers and the magnitude of the savings varies widely in different estimates and is still the subject of scientific evaluation.[137] However, and despite the emission reduction potential, many textile recycling technologies cannot yet prevent a loss in fiber quality. The 'downcycling' of fabric and fibers ultimately limits their market and therefore the potential for emission abatement.

Table 2: Estimated cost ranges of some textile recycling technologies at maturity

Technology	Investment required (EUR/t output)	Operational costs (EUR/t output)	Cost and quality trade-offs
Mechanical recycling	30-90	200-800	Mechanical recycling is among the most cost-competitive techniques, although fiber degradation may be a limiting challenge.
Soft mechanical recycling	330-360	2,800-3,500	Although more expensive than traditional mechanical recycling, the higher quality output of this method presents greater revenue potential, which can offset the higher costs.
Thermo-mechanical recycling	100-120	400-850	Cost competitive, although current use is limited due to strict feedstock purity requirements.
Chemical recycling	200-700	750-1,900	Relatively expensive but benefiting from high-scale efficiencies and high-value fiber output.

Source: McKinsey[137]

Business impacts	
Benefits	
Opportunity to increase revenues due to growing demand for recycled products	Consumers are increasingly demanding sustainable products. For instance, searches for sustainable fashion brands increased by 600% between 2016 and 2020. There is a business case for recycling paper packaging and textiles: if scaled, recycling of textiles could create a global USD $6-12 billion pool of value by 2030.[137]
More efficient processes in paper mills	Optical sensors can help improve energy efficiency in paper making. In fact, recovered paper sorting automate recycled feedstock sorting and deliver a more efficient deinking process that leads to electricity and steam savings of 16% and 30% respectively, and a reduction of 20% in material loss compared to a typical plant.[20]
Costs	
Investment required and operating costs	**Sensor-based sorting technologies** Optical sensors machines optimized with artificial intelligence could cost between 200,000-570,000 EUR depending on the type of technology installed (e.g. X-ray).[62] **Textile recycling technologies** The costs of recycling textiles vary based on the recycling process used, ranging from 30-120 EUR/t output for mechanical recycling to 200-700 EUR/t output for chemical recycling. Operational expenses make up most of the recycling costs, with soft mechanical recycling costing up to 3,500 EUR/t output. Despite the high costs, soft mechanical recycling yields high-quality output and potential for greater revenue. Table 2 demonstrates a trade-off between cost and quality among available recycling technologies.
Indicative abatement cost	In the textile industry, it is estimated that it would cost around 130 EUR/ton CO_2e to increase the end-of-use recycling by 15%.[138] Paper recycling abatement costs are estimated to be lower, with some estimates reporting net savings due to recycling: -77 to 18 EUR/ tCO_2e.[139, 140]

Potential co-benefits and side effects

Co-benefits	**Environmental and health benefits from increased resource efficiency**	Increased resource efficiency would enable to reduce pressure on the environment, from water resources to land-use. Additionally, recycling textile can reduce the need for chemicals that may have harmful effects on human health.
	Employment benefits	Increasing sorting and recycling can have beneficial impact on employment, given that these processes would have to be largely scaled up and will create jobs for both the scale up of infrastructure and the process itself. Estimates found that around 15,000 new green jobs could be created in Europe by 2030 due to textile recycling (though impacts on employment in other regions should also be considered).[137]
Side effects	**Fiber quality deterioration**	Many of the existing technologies for textile recycling are currently not able to prevent the deterioration of fibers. It is therefore necessary to complement recycled fibers with higher quality alternatives as a supplement for creating new yarn, increasing resources needs. Additionally, downcycling restricts the application of the fabric in clothing and textiles. Lower quality fibers might also lead to less durable products with a shorter lifespan. All these variables reduce the market and the value of recycled fibers and can create a competitive disadvantage. Nevertheless, the landscape is not devoid of remarkable technological progresses and successes, as start-ups and companies piloting innovative technologies are yielding encouraging outcomes.[131]
	Recycling trade-offs: environmental footprint	Recycling – paper or textiles – may not be the most environmentally sustainable option. Firstly, recycling, particularly for certain textiles and processes, can be very energy intensive, increasing emissions if the process is not powered by renewable energy. Additionally, large-scale textile recycling would require extensive chemical processing of mixed fiber fabrics, which can cause further GHG emissions and hazardous discharge to water systems. Given that dyeing textiles presents significant environmental challenges, the recycling process could therefore inadvertently create additional risks. Furthermore, the degradation of fibers requires the incorporation of new virgin fibers to produce new fabrics. However, recycling facilities (in developing countries) are often located at a significant distance from the textile manufacturing sites (in emerging economies). The transportation between these facilities results in substantial emissions, increasing the environmental footprint of textile recycling.
	Textile recycling and green claims	To minimize undesired trade-offs, it is important for brands to adequately emphasize the importance of reusing items before recycling, and implement the necessary measures to guarantee that recycling takes place. To satisfy a growing demand from consumers for recycled fibers, brands might be inclined to increase the share of recycled polyester from recycled plastic bottles, for example. This approach can inadvertently introduce readily recyclable plastic bottles into a supply chain where recycling technologies are still in the early stages of development, thereby reducing the emission abatement potential from plastic bottle recycling.

Implementation

These are the most common steps for paper manufacturers and textile producers to adopt sensor-based technologies and textile recycling.

→ **Assess requirements**
Conduct an assessment of existing recycling rates for products, recycling rates at owned facilities and use of recycled materials. Establish targets for the use of recyclable materials and corporate recycling rates, based on regulatory requirements, environmental targets and local infrastructure available to support recycling.

→ **Evaluate potential to increase recycling rates and use of recycled materials**
Identify new or existing products that could be manufactured either using materials that can be recycled for other purposes or produced directly using recycled materials, considering factors including product quality requirements and possibilities created by use of new sorting technologies. Additionally, identify opportunities to increase recycling of existing manufacturing waste.

→ **Adapt existing infrastructure, processes and product design**
Increasing recycling rates and use of recycled materials may require changes to the production process or modifications to existing machinery. Changes in product design can also reduce waste and increase the use of recycled materials.

→ **Collaborate with recycling partners**
Establish agreements with new partners sorting waste using sensor-based technology and encourage existing partners to adopt these technologies. Coordinate on a schedule for collection and transportation of: a) recycled materials to the manufacturing facility for reuse in the production process and b) the organization's waste to be sorted and recycled by the recycling facility.

Implementation Continued

Key challenges/hurdles	Potential solutions[137]
Varying sorting and collection rules Varying sorting and collection rules: One of the most pressing challenges faced by multi-national organizations is the differences in the sorting and collection rules in different jurisdictions. If collection rules are not varied and unspecific about the separation of different types of waste, it is hard to develop a coordinated recycling strategy and more advanced and costly technologies may be required to actually sort the waste for recycling. **Inconsistencies in regulations around recycling and use of recycled inputs** This hinders the recycling process, as some regulations mandate the need to recycle but prohibit the use of recycled paper. The EU Commission has for instance adopted legislation restricting the type of input waste that can be used for food containers. The legislation also mandates the use of suitable technologies for recycling waste.[141] This creates uncertainty for companies around which materials they can recycle for reuse. **Lack of infrastructure** Rules for sorting and collection also determine the available infrastructure in different jurisdictions. Less stringent collection rules often lead to a lack of appropriate infrastructure for sorting or collection. **Packaging and material design** Design of packaging of products (e.g. coating to preserve functionality of packaging) can make it challenging to recycle as the coating cannot always be removed. **Challenges in measurement of Scope 3 impact** Forest companies are disincentivized to invest in these solutions due to challenges inherent to scope 3 accounting. **Lack of scale in operations** Recycling facilities are generally large-scale projects requiring long-term investment. Critical scale across the value chain is required to provide sufficient feedstock for the necessary fiber-to-fiber recycling technologies to operate at scale. A lack of wide-spread adoption of recycling, may prevent recycling technologies operating at scale.	**Design for recycling** Manufacturers should follow a 'design for recycling' approach that helps them to prioritise materials which can be recycled following use. There are general guidelines available for different steps of manufacturing by various organizations, e.g. 4evergreen – a cross-industry alliance of over 100 members provides guidelines for fibre-based packaging.[142] **Collaboration across the value chain** Addressing the key challenges in recycling necessitates a strong emphasis on collaboration between forestry companies, technology providers and recycling centres. The industry must also actively collaborate to establish ambitious recycling targets and diligently work towards achieving them, thereby ensuring the complete scalability of recycling operations. Coordinated support from forestry companies for advanced recycling technology can provide the necessary scale to establish the required infrastructure. **Engagement with public policymakers:** Forestry companies can engage with governments to establish consistent regulation that encourages recycling, e.g. through restrictions on the export of unsorted waste and financial incentives to use recycled materials. Additionally, establishing national and industry level recycling targets and education programs can grow the circular economy. technologies could be even more economically attractive.

Appendices

Appendix A

Non-exhaustive list of enabling policies such as public investment and subsidies, as well as other regulations and standards related to the net-zero transition. The list is ordered by county, and tied to corresponding decarbonization action(s).

Public investment & subsidies		
Jurisdiction	**Policy**	**Enabled Actions**
Australia	In October's 2022-23 budget, the federal government allocated AUD 62.6 million for small and medium-sized businesses for implementation of measures such as energy use monitoring, replacing existing gas boilers with more efficient technologies, if it reduces energy bills.[143]	Action 4 (electric boilers)
	Firms that use negative emissions technologies, such as BECCS, are subsided depending on the amount of emission reduction and the technology used.[66]	Action 6 (BECCS)
	In 2021, Australia launched Recycling and Clean Energy National Manufacturing Priority Road map, providing co-funding to products that enable recycling or use recycled feedstock.[144]	Action 10 (recycling)
Belgium	VAT reduction from 21% to 6% on heat pumps purchases.[145]	Action 3 (heat pumps)
Canada	The government invested 56 million EUR (83 million CA$) to enable innovative forestry products still in the development phase to reach commercialization.[146]	Action 1 (enhanced removal and emissions reductions) and 9 (forest products for construction)
	In 2021, Canada announced an investment tax credit for Carbon Capture Utilisation and Storage projects. A 50% tax credit will apply for investment in BECCS equipment from 2022 to 2030.[147]	Action 6 (BECCS)
Denmark	The Business Pool 2022 grant covered 50% of the purchase of a heat pump or heat recovery system by a company.[148]	Action 2 (absorption systems) and 3 (heat pumps)
European Union	The EU Common Agricultural Policy (CAP) offers financial aid to member countries, which can finance forest-related initiatives to preserve the forest, enhance its ability to withstand climate change and to provide ecological services. CAP also promotes investments, innovation, and trainings that can boost the rural economy.[149]	Action 1 (enhanced removal and emissions reductions)
	REPower EU incentivizes heat pump deployment, with a target of 10 million new heat pumps installed by 2027 and 30 million by 2030.	Action 3 (heat pumps)
	The EU will invest 180-470 billion EUR by 2050 in renewable hydrogen through the 2020 Hydrogen Strategy.[150]	Action 5 (alternative fuels)
	The EU announced it would invest 1.8 billion EUR towards seventeen large scale innovative clean tech projects. Two of the projects were BECCS-related: waste-to-energy in Sweden and the cement industry France. The fund will provide 38 billion EUR of support for low carbon technologies between 2020 and 2030.[151]	Action 5 (alternative fuels) and 6 (BECCS)

Appendix A Continued

Public investment & subsidies		
Jurisdiction	**Policy**	**Enabled Actions**
European Union	The 2020 Renovation Wave policy from the European Commission plans to promote carbon sinks in construction, including the use of sustainably sourced wood.[152]	Action 9 (forest products for construction)
France	From 2022, 100 million EUR will be allocated in grants for purchases of heavy industrial vehicles running on electricity or hydrogen.[153]	Action 5 (alternative fuels)
Germany	The government invested 700 million EUR to develop sustainable forest management and digitalization in forestry.[146]	Action 1 (enhanced removal and emissions reductions)
Germany	Subsidies for energy and resource efficiency in commercial enterprises that can cover up to 55% of the initial cost of the heat pump, and up to a ceiling of EUR 15 million per project.[154]	Action 2 (absorption systems) and 3 (heat pumps)
Germany	The 2021 German Development and Resilience Plan includes an investment of 20 million EUR in the development of climate-friendly construction with wood.[155]	Action 9 (forest products for construction)
India	In 2023, the Government of India approved 2.4 billion USD (197 billion INR) towards National Green Hydrogen mission that aims to incentivise the commercial production of green hydrogen.[156]	Action 5 (alternative fuels)
Japan	Japan's 16 bn USD Green Innovation Fund includes projects in Hydrogen and CCS in industry, as well as research in the use of timbre for high-rise buildings.[157]	Action 5 (alternative fuels), Action 6 (BECCS), Action 9 (forest products for construction)
	In 2023, Japan announced it would implement a Contracts-for-Difference-style scheme that would subsidize the difference between the price of green and grey hydrogen.	Action 5 (alternative fuels)
Lithuania	The 2021 National Resilience and Recovery Plan of 457 million EUR includes subsidies for businesses to use wood materials in buildings.[158]	Action 9 (forest products for construction)
Malaysia	In 2023, the Malaysia Government proposed a tax incentive for CCS to limit CO_2 emissions. The proposed mechanisms provide companies an Investment Tax Allowance of 100% for 10 years as well as import duty exemption on the equipment.[143]	Action 6 (BECCS)
Netherlands	The Energy Investment Allowance provides tax deductions based for purchases of heat pumps or some heat recovery systems by a company.[159]	Action 2 (absorption systems) and 3 (heat pumps)
	In 2020, the scope of the previous subsidy scheme, SDE+, was broadened from renewable energy production to other CO_2 emission reduction measures such as electric boilers within the SDE ++ scheme.[159]	Action 4 (electric boilers)
United Kingdom	The BEICS Net-Zero Innovation Policy provides 60 million GBP for carbon removals, including BECCS. 23 winners received a share of 5.6 million GBP, and 15 of those progressed to phase two to get a share of the remaining 54.4 million GBP.[160]	Action 6 (BECCS)

Appendix A Continued

United States	The US Inflation Reduction Act (2022) provides a tax rebate of green hydrogen worth up to USD $3/kg for the first ten years of operations, up to 2032.[161]	Action 6 (alternative fuels)
	The 2022 Inflation Reduction Act expanded the 45Q tax credit, which provides a USD 60 tax credit per ton of CO_2 used and USD 85 per ton of CO_2 stored.[83]	Action 6 (BECCS)
Other regulations and standards		
Jurisdiction	**Policy**	**Enabled Actions**
Brazil	The PotencializEE program offers training for industrial energy efficiency experts to help facilities identify clean and efficient technologies such as heat pumps.	Action 2 (heat absorption), 3 (heat pumps), and 4 (electric boilers)
California	The California Low Carbon Fuel Standard (LCFS) aims at reducing the fuel mix carbon intensity through carbon credit trading.[162]	Action 5 (alternative fuels)
Canada	The Canadian Clean Fuel Standard will require a 13% reduction in carbon intensity of liquid fuels by 2030 compared to 2016.[163]	Action 5 (alternative fuels)
China	In 2022, the Chinese government laid out Hydrogen Industry Development Plan, a medium-and long term development plan for hydrogen focusing on hydrogen for transport as well as its use in different industries.[144]	Action 5 (alternative fuels)
European Union	The EU has implemented an Emissions Trading System as a main pillar of its decarbonization strategy.	Action 2 (heat absorption), 3 (heat pumps), 4 (electric boilers), 5 (alternative fuels), 6 (BECCS) and 8 (breakthrough efficiency technologies)
	In 2018, the EU adopted a circular economy package that will for the first time ensure that textiles are collected separately in all member states, by 2025 at the latest.	Action 10 (recycling)
South Africa	In 2021, South Africa's Extended Producer Responsibility legislation made EPR mandatory for all packaging producers.[164]	Action 10 (recycling)
Sweden	In 2021, Sweden announced a state reverse auction scheme for BECCS.[165]	Action 6 (BECCS)
United Kingdom	Since 2015, businesses have been required to separate recyclable materials from other waste, followed often by separate collections for general waste.[166]	Action 10 (recycling)

Appendix B

Underlying assumptions linked to the abatement potential estimations, tied to relevant decarbonization action.

Decarbonization Action	Assumptions linked to the abatement potential
Action 1: Implement measures to increase carbon removals and reduce emissions in sustainable working forests	1a and 1b i.e., abatement from electric tractors and nitrification inhibitors. The two key drivers of GHG emissions in forest production are fossil fuels used for harvesting equipment and CO_2 land emissions from fertilizer and controlled burns. Together, they could represent 50% of total emissions, hence abatement from electric tractors could apply to 25% of the forest production step of the value chain, and abatement from nitrification inhibitors could apply to the remaining 25%.[167]
Action 2: Adopt heat recovery technologies in the sawmill: deep dive on absorption systems	Abatement applies to wood drying which can be responsible for 60-80% of emissions in the sawmill. Mid-point of 70% used for estimation.[12]
Action 3: Adopt heat recovery technologies in the pulp mill: deep dive on heat pumps **Action 4: Switch to industrial electric boilers** **Action 5: Switch to low-carbon fuels**	Abatement applies to around 30% of the manufacturing stage of the value chain: as the industry uses 60% biofuels, it still uses 40% fossil fuels In addition, if indirect emissions account for ~20% of the total (conservative estimate), direct fossil fuel emissions account for 40%*80% = 32%.[19]
Action 7: Maximize waste recovery technologies in the pulp and paper mill: deep dive on black liquor gasification	Lime kiln emissions account for 14% of emissions in the pulp production process.[168]
Action 8: Emerging pulping and paper making technologies to increase energy efficiency (e.g. innovative technologies for paper drying and pulping)	Abatement is assumed to apply to 60% of manufacturing. The papermaking process is the most energy intensive process across the value chain, followed by pulping. Together they make up most emissions in manufacturing. However, the pulping process uses mostly biomass, which means that energy efficiency could apply to above 50% of emissions of the process.[169]
Action 10: Promote and lead on recycling and sorting technologies for paper products and textiles: deep dive on sensor-based technologies and textile recycling	A 60% paper recycling rate and a 17% textile recycling rate are assumed (GDP-weighted average of 26% Europe, 15% in China, 12% in the US).[170]

Appendix C: Glossary

Term	Definition
Abatement cost	Measure of the costs associated with abating one ton of GHG emission (EUR/ton CO_2e abated). The lower the abatement cost, the cheaper it is to reduce emissions, and therefore the more attractive the decarbonization action.
Anthropogenic removals	Refer to the withdrawal of GHGs from the atmosphere as a result of deliberate human activities. These include enhancing biological sinks of CO_2 and using chemical engineering to achieve long-term removal and storage. Carbon capture and storage (CCS) from industrial and energy-related sources, which alone does not remove CO_2 in the atmosphere, can reduce atmospheric CO_2 if it is combined with bioenergy production (BECCS).
Bioenergy	Energy derived from any form of biomass or its metabolic by-products. (IPCC)
Biomass	Living or recently dead organic material. (IPCC)
Carbon capture and storage	A process in which a relatively pure stream of CO_2 from industrial and energy-related sources is separated (captured), conditioned, compressed and transported to a storage location for long-term isolation from the atmosphere. (IPCC)
Carbon intensity	The amount of emissions of carbon dioxide (CO_2) released per unit of another variable such as volumes of a product. (IPCC)
Carbon sequestration	The maintenance of carbon dioxide or carbon in a physical reservoir or medium for a period of time.
Circular bioeconomy	The bioeconomy is the use of biological resources to produce food and feed, products and energy. In a circular bioeconomy, biological resources are renewable, sustainably managed, recovered and reused as much as possible. (WBCSD)
Decarbonization	The process by which countries, individuals or other entities aim to achieve zero fossil carbon existence. Typically refers to a reduction of the carbon emissions associated with electricity, industry and transport. (IPCC)
Economic feasibility	Refers to the ability of a decarbonization action to generate enough revenue to cover its costs and provide a reasonable return on investment. It is assessed based on the maturity level and the abatement cost of each action. Actions with low maturity level (≤ 4) are considered to have low economic feasibility in the short term, given the need to validate and deploy the technology in relevant environments. However, if the abatement cost has already proven to be low, the action is assessed as medium. Actions with medium maturity (TRL 5-8) may have low or medium economic feasibility in the short term, depending on the abatement cost (≤ 250 EUR/tCO_2e). Similarly, the short-term economic feasibility of actions with higher maturity (TRL 9-11) varies depending on the abatement cost (low when < 550 EUR/tCO_2e, medium if cost ranges between 250-450 EUR/tCO_2e, or high if cost lower than 250 EUR/tCO_2e). The thresholds that define the short-term economic feasibility are defined taking into consideration that additional benefit, including revenue generating opportunities, are not monetized and not included in the abatement cost estimates.

Appendix C Continued

Term	Definition
Emission abatement potential	Describes the potential of a decarbonization action to reduce GHG emissions with respect to the counterfactual technology or practice, meaning the technology or practice that is part of the 'business as usual' scenario, or that is substituted or improved with the adoption of the decarbonization action. Emission abatement potential is usually expressed as a percentage, and the higher it is, the higher GHG emission reductions can be achieved: Low = < 15% of GHG emissions Medium = 15-50% of GHG emissions High = > 50% of GHG emissions.
Emission hotspots	The most carbon intensive stage of the value chain in relation to the sum of emissions across all stages of the value chain of a given product category. To identify emission hotspots, each stage was analyzed and assessed based on its emissions intensity relative to the rest of the chain.
Energy efficiency	The ratio of output or useful energy or energy services or other useful physical outputs obtained from a system, conversion process, transmission or storage activity to the input of energy. Energy efficiency is often described by energy intensity. (IPCC)
Fossil fuels	Carbon-based fuels from fossil hydrocarbon deposits, including coal, oil, and natural gas. (IPCC)
Greenhouse gases (GHGs)	Gaseous constituents of the atmosphere, both natural and anthropogenic (human-caused), that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the Earth's surface, by the atmosphere itself, and by clouds. This property causes the greenhouse effect, whereby heat is trapped in Earth's atmosphere. Water vapor (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and ozone (O_3) are the primary GHGs in the Earth's atmosphere. (IPCC)
Net-zero emissions	Net-zero emissions are achieved when anthropogenic emissions of greenhouse gases to the atmosphere are balanced by anthropogenic removals over a specified period. The reduction of emissions should follow science-based pathways that limit warming to 1.5°C, with no or limited overshoot, with any remaining attributable GHG emissions fully neutralized by permanent removals either within the value chain or through purchase of valid offsets. Fully neutralized refers to permanent removal, which needs to take into account the potential of reversal of the emission storage by wildfires, pests, or diseases that cause trees to die and decompose. This definition clarifies that purchasing offsets cannot be a substitute for emissions reductions, but rather is a tool to complete the neutralization process. (IPCC)
Technology Readiness Level (TRL) scale	A common framework that can be applied consistently to any technology to assess and compare maturity across sectors measured through an assessment of their progress and capabilities. The scale originally ranges from 1 when the basic principles are defined to 11 when the technology is mature. (IEA)
Working forest	Forests that are actively managed to generate revenue from multiple sources, including physical goods for sale (such as sustainably produced timber), while maintaining ecosystem services and social values. They are therefore not converted to other land uses. (WRI)

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Disclaimer

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WBCSD's Forest Solutions Group (FSG) is the global platform where leading business in the forest products sector build and share sustainable development solutions. FSG's mission is to grow an inclusive circular bioeconomy that is rooted in thriving working forests. Our member companies span all forested continents and a broad range of forest products such as pulp, paper, packaging, timber, biomaterials, bioenergy and forest asset management. They represent a combined revenue of more than USD $150 billion and 219,931 employees. Together they own, lease or manage more than 20 million hectares of land, of which 98% is third party certified and 24% is set aside for conservation or restoration.

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Our member companies come from all business sectors and all major economies, representing a combined revenue of more than USD $8.5 trillion and 19 million employees. Our global network of almost 70 national business councils gives our members unparalleled reach across the globe. Since 1995, WBCSD has been uniquely positioned to work with member companies along and across value chains to deliver impactful business solutions to the most challenging sustainability issues.

Together, we are the leading voice of business for sustainability: united by our vision of a world where more than 9 billion people are all living well and within the boundaries of our planet, by 2050.

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