



CALiMERO

IMPROVING BIO-BASED INDUSTRIES LIFE CYCLE SUSTAINABILITY

D5.1

Potential solutions to improve the performance

Due date of submission: 30/06/2025

Actual submission date: 30/06/2025



**Funded by
the European Union**

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LIST OF ACRONYMS

BLS	Black liquor soap
CAPEX	Capital expenditure
BAT	Best Available Technique
BMB	BioMass Balance
BREFs	BAT REFeRence documents
CB	Cardboard
CE	European Conformity Certification
CF	Characterisation factor
CTO	Crude tall oil
DLK	Double Lined Kraft
EoL	End-of-life
GHG	Greenhouse Gas
HRR	Heat release rate
JCP	Job creation potential
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCSA	Life Cycle Sustainability Assessment
LDPE	Low-density polyethylene
LHV	Lower Heating Value

LSL	Laminated Strand Lumber
MOO	Multi-objective optimization
OPEX	Operational expenditure
PEF	Product environmental footprint
PEFC	Program for Endorsement of Forest Certification
PEG	Polyethylene glycol
pMDI	polymeric Methylene Diphenyl Diisocyanate
S-LCA	Social Life-cycle Assessment
SRF	Solid recovered fuels
THR	Total heat release
VOCs	Volatile Organic Compounds

PROJECT INFORMATION

Project full title: Industry Case Studies AnaLysis to Improve Environmental Performance and Sustainability of Bio-based Industrial Processes

Acronym: CALIMERO

Call: HORIZON-CL6-2021-ZEROPOLLUTION-01

Topic: HORIZON-CL6-2021-ZEROPOLLUTION-01-06 - Increasing the environmental performance of industrial processes in bio-based sectors: construction, woodworking, textiles, pulp and paper and bio-chemicals

Start date: 1st July 2022

Duration: 48 months

List of participants:

Partner No.	PARTICIPANT ORGANIZATION ACRONYM
1 (Coord.)	Contactica CTA
2	WeLOOP WELOOP
3	European Cellulose Insulation Association ECIA
4	Swedish Environmental Research Institute IVL
5	Neovili NEOVILI
6	Cesefor CESEFOR
7	Luxembourg Institute of Science and Technology LIST
8	Technical University of Denmark DTU
9	Techtera TECHTERA
10	Essity ESSITY
11	BIM Kemi AB BIMKEMI
12	Ereks garment EREKS

DELIVERABLE DETAILS

Document Number:	D5.1
Document Title:	Potential solutions to improve the performance
Dissemination level	PU – Public
Period:	PR2
WP:	WP5
Task:	T5.1 – Identification of potential solutions for sustainability performance improvement
Authors:	Eduardo Entrena Barbero (CTA), María Gallego Fernández (CTA), Tamara Coello (Cesefor), Benjamin Donovan (IVL), Emma Moberg (IVL), Sahar Safarianbana (IVL), Pernilla Cederstrand (Essity), Fredrik Nyhlén (BimKemi), Margarida Vidinha (WeLOOP), Naeem Adibi (WeLOOP), Sajjad Malekzadeh (WeLoop), David Stimm (ECIA), Juho Laaksonen (ECIA), Federico Busio (LIST), Maura Camerin (LIST), Thomas Schaubroeck (LIST), Pauline Guillon (Techtera), Bilgesu Altunkan (Ereks), Pelin Birsén (Ereks), Merlin Alvarado Morales (DTU)
Abstract:	Deliverable D5.1 of the CALIMERO project, identifies and evaluates potential solutions to enhance the sustainability performance of five key bio-based industrial sectors: construction, textiles, woodworking, bio-chemicals, and pulp and paper. Drawing on results from earlier work packages in CALIMERO—including hotspot analyses (WP1), case study definitions, (WP2), methodological innovations (WP3), and multi-objective optimization (WP4)—this report outlines sector-specific solutions aimed at achieving substantial environmental, social, and economic improvements. The analysis integrates insights from literature reviews, BREF documents, stakeholder consultations, and ecolabel criteria to propose practical interventions. The shortlisted solutions will be further testing in Task 5.3 of the CALIMERO project, with the ultimate aim of demonstrating measurable reductions in greenhouse gas emissions and toxicity impacts while improving economic viability. This deliverable represents a step in CALIMERO’s overarching mission to support the transition toward a sustainable and circular bioeconomy.

Version	Date	Description
V1.0	30/06/2025	First draft

Introduction

The CALIMERO project sets out to further improve sustainability in the bio-economy. With such an aim, improved life-cycle methodological approaches (based on the Product Environmental Footprint (PEF) method) will be proposed to evaluate the bio-economy's sustainability performance (mainly in WP3). A holistic approach was followed by integrating these methodological approaches in a framework to simultaneously further enhance a series of pre-established objectives by means of an MOO (Multi-Objective Optimization) framework. In addition to the above, sector-specific potential solutions to improve sustainability will be identified. This report synthesizes solutions researched and developed within the CALIMERO project in five bio-based industrial sectors: (i) biochemicals, (ii) construction, (iii) pulp and paper, (iv) textiles, and (v) woodworking. The solutions presented are then assessed for feasibility and impact to produce a shortlist of sustainability optimization solutions for testing in Task 5.3 *Demonstration of the best solutions for the bio-based industries*.

IMPROVEMENT OF THE SUSTAINABILITY PERFORMANCE IN THE BIO-ECONOMY INDUSTRY

Carbon emitted from the bioeconomy is extracted from biosphere stages in the carbon cycle, offering opportunities to both utilise the properties of the material it is bound in, while also being able to quickly neutralise its climate impact by photosynthesising equal quantities of carbon back into plant matter (Tan & Lamers, 2021). This same biological process is also why bio-based resources are a renewable source of materials and chemical-energy generation (Venkatesh, 2022). With proper management and consideration for the balance between resource harvesting and stewardship, the development of bio-based raw material sources can also have regenerative effects on nature by fostering the recovery and growth of biological ecosystems (UNECE, 2025). The diverse range of applications of bio-based raw materials for developing both intermediary and final products, particularly when subject to industrial refining processes, make them suitable for a wide range of uses in industries (Isikgor & Becer, 2015). Utilisation of biomass and the carbon bound within it to produce long-life material products can also serve to sequester and store carbon in product stocks (Tan & Lamers, 2021). Collectively these characteristics demonstrate the potential for the bioeconomy to secure sustainable supplies of material and energy resources suitable for substituting out and transitioning away from the current fossil-fuel economic system.

Diversity in application and renewability are properties of bio-based raw materials that are necessary for their suitability to substitute fossil-fuel resources, but alone these properties are not sufficient for that purpose. Key to realising the potential of the bioeconomy is in ensuring that the environmental, social and economic costs of bio-based raw material extraction and refinement outweigh those of fossil-based alternatives and are inherently sustainable (Tan & Lamers, 2021). The path to achieving a sustainable bioeconomy involves developing solutions in bio-based value-chains for resource use optimisation and circularity, and for mitigating emissions and associated impacts related to toxicity, social conditions, and economic costs (EEA, 2018).

The CALIMERO project's contribution to developing a sustainable bioeconomy focuses on sustainability performance improvement in the bio-chemicals, construction, pulp and paper, textiles and woodworking sectors. Life-cycle impact assessments were conducted for the operations of industrial partners to CALIMERO, that operate within these sectors, to identify value-chain hotspots in need of sustainability improvements. Hotspots identified (in WP2) in the assessed bio-based sectors provided the basis for scoping case study value-chain processes for which sustainability processes improvement solutions were to be researched and modelled. Novel methodological advancements were presented in WP3 in order to tailor LCSA (Life Cycle Sustainability Assessment) as a method to provide a holistic perspective of sustainability, covering environmental, social and economic impacts that are of particular relevance to, yet underdeveloped for, circular and regenerative bio-based value chains. Some of the case studies were individually subject to an MOO analysis to assist identifying beneficial combinations and nuanced configurations of solutions. The process assessed

how to implement that solution in a way that achieves net maximum benefit for net minimum costs between trade-off across all selected environmental, social and economic parameters (i.e., Pareto efficiency). This report will demonstrate how each of these stages in the CALIMERO project has revealed potential sustainability solutions in the targeted bio-based sectors. In addition, this document details how bio-based sector specific reviews of academic and clean technology literature (e.g., BREF documents), ecolabel criteria and expert stakeholder consultation build on results from earlier CALIMERO WPs, to search for, assess and select sustainability improvement process solutions.

AIM AND OBJECTIVES

The main aim of this report is to identify potential solutions to improve the sustainability performance of the case studies addressed in the CALIMERO project (**Table 1**) in order to achieve the following objectives:

- Make use of WP1 (Challenges related to bio-based sectors) in relation to the hotspots analysis of most impactful industrial processes (i.e., Task 1.2) per each one of the 5-target bio-based sectors in the CALIMERO context.
- Take advantage of the descriptions of the case studies and the simulation processes carried out in WP2 (Analysis of case studies from the target bio-based sectors).
- Putting into practice the methodological advances developed in WP3 (Toolbox/methodological development for the LCSA of bio-based sectors).
- Apply the MOO framework available in WP4 (Framework for the sustainable optimization of target bio-based sectors).
- Comply with the targets established in the Grant Agreement of the CALIMERO project (a 25% reduction in both greenhouse gas emissions and toxicity impacts, and a 15% increase in the internal rate of return for proposed solutions over a 5-year period.), apart from those depicted per each bio-based sector (see **Table 1**).

#	Case study		Bio-based sector		Industrial partner	Academic partner	Targets to be achieved
1	Cellulose insulation	Construction	ECIA	WELOOP			- GHG emissions < 20-30% - Renewable energy share > 25-40% - Use of alternative additives to reduce fossil resources
2	Washing process	Textiles	Ereks, TECHTERA	LIST, NEOVILI			- GHG emissions < 25% - Toxicity < 25% - Increase the circularity performance by considering design requirements in the optimization
3	Washing after desizing	Textiles	Ereks, TECHTERA	LIST, NEOVILI			
4	Washing after bleaching	Textiles	Ereks, TECHTERA	LIST, NEOVILI			
5	Wood panels production	Woodworking	CESEFOR	CTA			- GHG emissions < 25% - Waste generation < 20% - Toxicity < 25%
6	Steam production from wood waste	Woodworking	CESEFOR	CTA			
7	Ester production	Biochemicals	BIM Kemi	IVL			- GHG emissions < 25% - Occupational health and safety risk < 25%
8	Forestry	Pulp and paper	Essity	IVL			- GHG emissions < 25% - Waste generation < 20% - Toxicity < 25%
9	Tissue production	Pulp and paper	Essity	IVL			

Table 1 Descriptions of the case studies addressed in CALIMERO and sector specific sustainability targets

REPORT STRUCTURE

First, a series of brief descriptions of the CALIMERO case studies, main hotspots, industrial processes simulated, methodological improvements considered in terms of LCSA, apart from the way the MOO framework is applied, are provided for each bio-based sector as a way of contextualization: construction (**Section 2.1**), textiles (**Section 2.2**), wood-working (**Section 2.3**), bio-chemicals (**Section 2.4**) and pulp and paper (**Section 2.5**) industries. Later, this information will be taken into account in the search for solutions to improve sustainability performance, complemented by a literature review of scientific papers and other documents of particular interest, such as BREFs or other ecolabel criteria. Lastly, an overview of the list of solutions identified and the general conclusions obtained are summarized in **Section 3**. On the other hand, the identified solutions will be further implemented measuring the level of improvement achieved in T5.3 (Demonstration of the best solutions for the bio-based industries) with the goal of elaborating a series of recommendations and guidelines in T5.5 (Guidelines and recommendations for the sustainable development of target bio-based industries). An infographic description of the roadmap to be followed is shown in **Figure 1**.

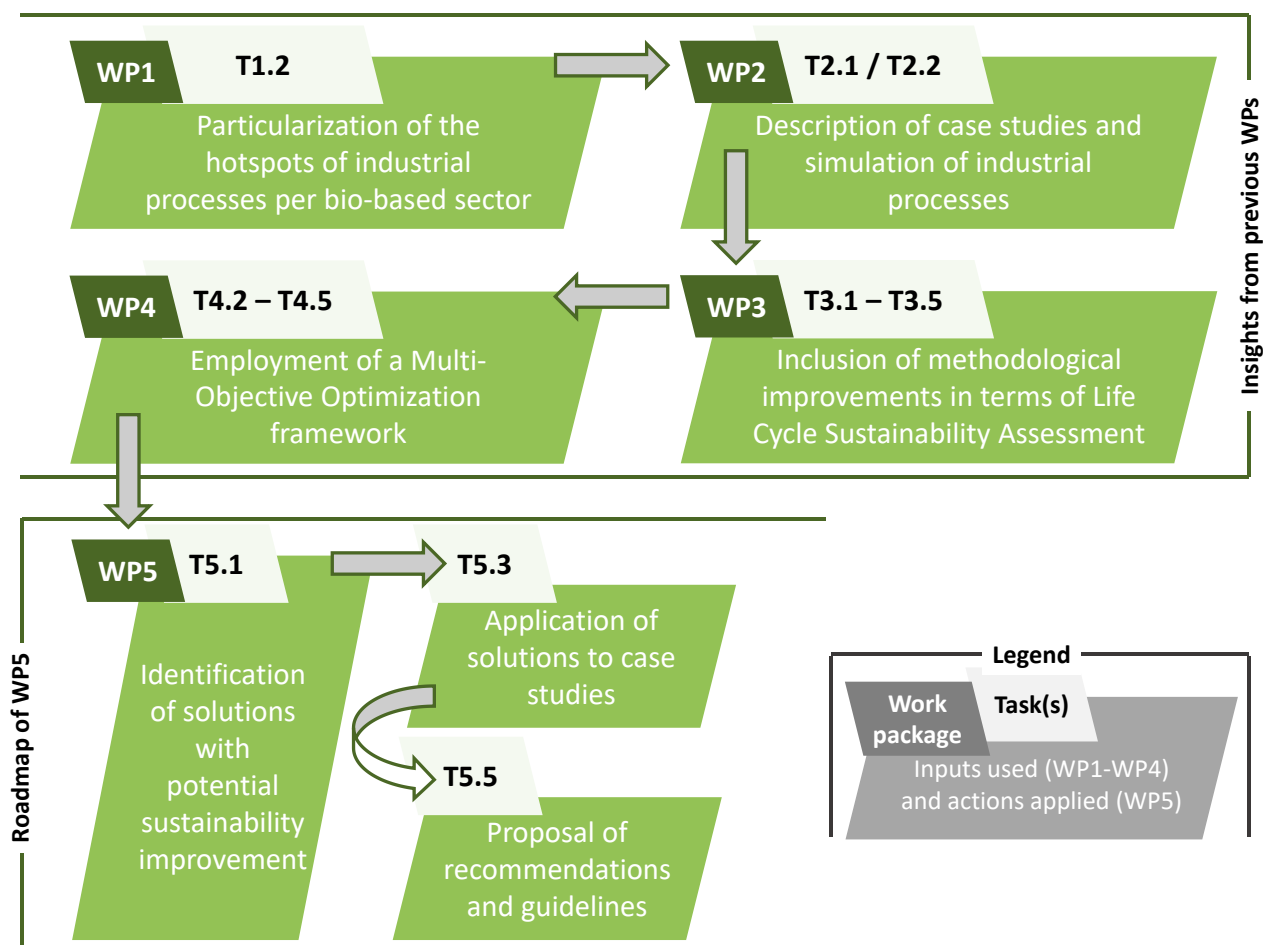


Figure 1. Roadmap followed to identify and subsequently apply solutions with potential to improve sustainability in the context of the CALIMERO project.

Solutions with Sustainable Improvement

Potential of Target Bio-based Sectors

1 CONSTRUCTION

1.1 Contextualization

1.1.1 Case Study Description

In the CALIMERO project, the construction industry is represented by two key partners: WeLOOP and the European Cellulose Insulation Association (ECIA). WeLOOP is responsible for conducting the Life Cycle Sustainability Assessment (LCSA), while ECIA, as an industrial partner, provides primary data for the cellulose insulation case study and contributes its sector expertise. To support the study, sixteen cellulose insulation manufacturers, all ECIA members, were contacted, and a case study on the production of loose-fill cellulose insulation was analysed.

The case study assessed the sustainability performance of loose-fill cellulose insulation products in the European context, considering the three sustainability pillars: environmental, social, and economic. The analysis covered sixteen commercially available products from multiple manufacturers, representing a broad geographical segment of the European cellulose insulation market. The studied system included the full production process as shown in **Figure 3**, from raw material extraction and processing to product installation and end-of-life (EoL) treatment. The primary raw materials, recycled newspaper, mineral additives, and packaging are transported from suppliers to production sites, where the newspaper is sorted to remove foreign objects such as staples, clips, and plastics. The cleaned material is then shredded into small pieces, with any remaining impurities being reintegrated into the process. During the milling stage, flame retardants and mineral additives are added, resulting in the final loose-fill cellulose insulation product.

The finished insulation is mechanically compacted and transported to construction sites for installation. Using pneumatic blowing equipment, the compacted cellulose is fed into a blower, where fibres are separated and delivered via an air pressure system without the addition of water or glue (Lopez Hurtado et al., 2016). When properly installed, loose-fill insulation requires no maintenance, repair, or replacement throughout its lifespan. At the end of its service life, the dismantling process is a straightforward reversal of installation, using a hose to extract the insulation from cavities and transport it to an EoL treatment or disposal site. Currently, the predominant EoL scenario for loose-fill cellulose insulation is incineration with energy recovery. In some countries, 100% of cellulose insulation undergoes incineration, while less than 5% is recycled under current practices.

Average Cellulose Insulation Product

Each studied product and manufacturing plant was assessed individually based on the framework outlined in this report. However, due to confidentiality reasons, individual product results are not disclosed. Instead, a representative product is presented, calculated using the weighted average of sales in the European market, as shown in **Figure 2**.

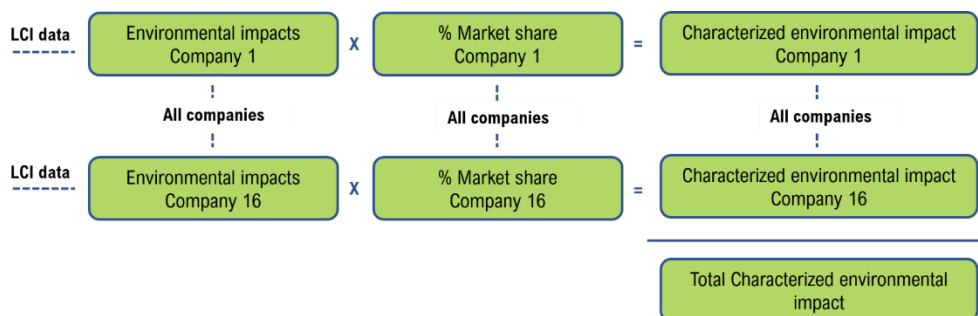


Figure 2 Procedure to calculate the average impact of the cellulose insulation products

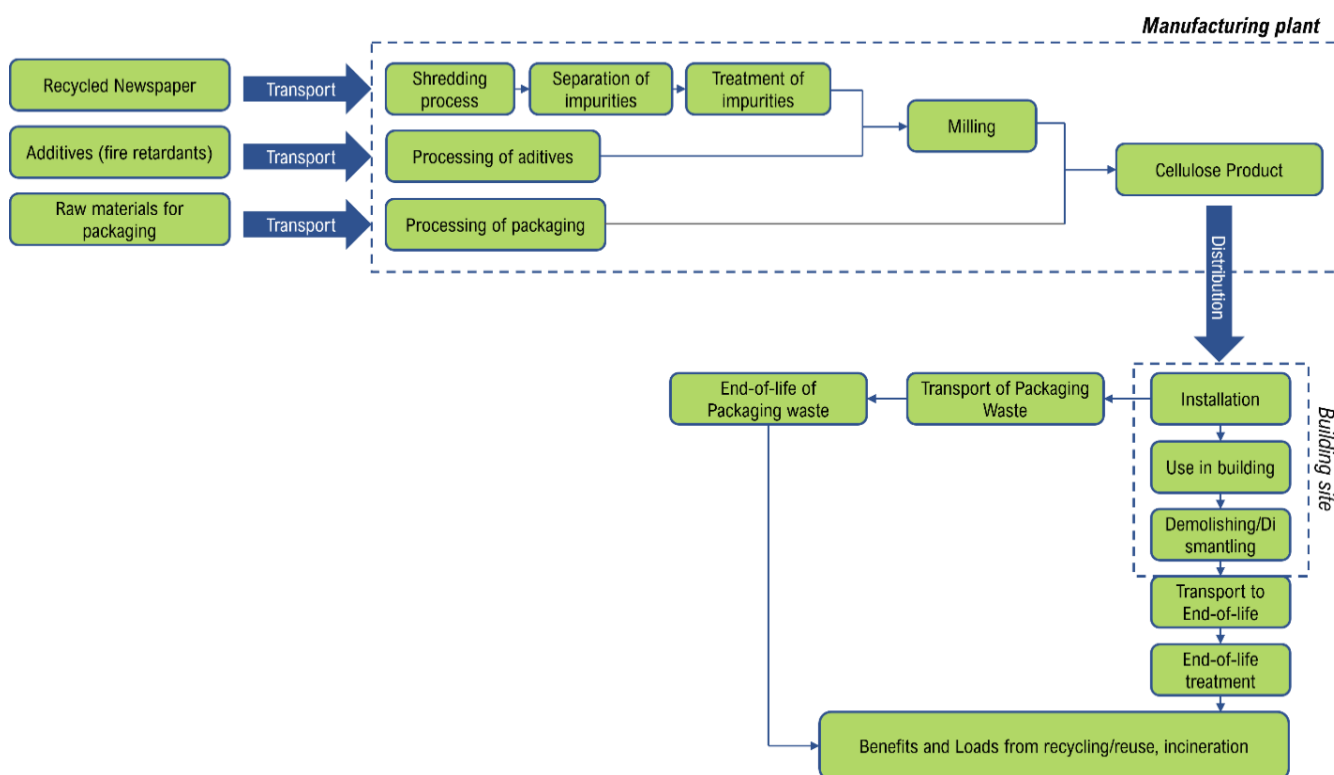


Figure 3 Diagram of the industrial process for the loose-fill cellulose insulation addressed in the construction sector

1.1.2 Case Study Lifecycle Aspects, Impacts and Hotspots

From the sectorial review section in D1.2 which focused in conducting a hotspot analysis of the most impactful industrial processes for the different CALIMERO sectors, the main environmental hotspots for non-woodworking construction processes are linked to climate change, fossil and mineral resource depletion, particulate matter, and acidification. The key contributors to these impacts are material provisioning, including non-bio-based materials (low-alloyed steel, nickel coatings, glass), wood-based semi-products (fibreboard, particleboard), and chemical treatments such as alkyd paints and boric acid. Energy use, particularly electricity

and heat, is another major hotspot, while infrastructure-related impacts can be considered minimal.

Specifically, for the cellulose insulation case study, the LCA results highlight material acquisition and processing as the most significant life cycle stage, primarily due to the production of inorganic flame retardants and mineral additives. These materials contribute to high resource depletion, climate change, and particulate matter emissions. The transport stage is another relevant contributor, with emissions from truck wear and diesel consumption affecting air quality. End-of-life disposal varies by region, with landfilling and incineration impacting fossil resource depletion but also offering potential avoided emissions from natural gas production. While these conventional disposal methods remain predominant, several recycling and recovery options are being explored to enhance circularity in the construction and insulation sector. Although not yet widely implemented, these emerging solutions could play a crucial role in ensuring that insulation products contribute positively to sustainability. Potential end-of-life pathways include:

- **Recovered fibres (e.g., cellulose) being transported** – potentially via specialized trucks with compression or pelletizing systems – for use as a stabilizing agent in asphalt
- **Boron-impregnated fibres** undergoing pyrolysis to produce biochar, a fertilizer that supplies plants with essential boron nutrients
- **Recovered fibres** being reintroduced into the production line and recycled into new insulation materials
- **Recycling of fibres** to produce renewable solid fuels, reducing reliance on fossil-based energy sources

A cross-analysis with sector-wide data confirms that chemicals and additives used in construction, including insulation, significantly contribute to environmental hotspots. While bio-based materials generally have lower environmental impacts than metals and coatings, the necessary use of additives (e.g., adhesives, flame retardants) can considerably influence their impact profile. Future improvements should focus on developing bio-based alternatives for these additives to enhance sustainability in the construction sector.

1.1.3 Industrial Processes Simulated

The case study focused on cellulose-based insulation and aimed to find the optimal formulation of the final product by minimizing specific performance criteria. These criteria included the heat release rate (HRR) and total heat release (THR). In the context of insulation materials and fire safety, HRR and THR are key parameters used to assess the resistance of those materials to fire. HRR is the rate at which a material releases heat during combustion. THR also is the cumulative heat energy released as the material burns over a period. Data on various insulation material formulations was provided by ECIA (see D2.2 Appendix).

As a first step in the modelling approach, a set of data-driven models was developed using the datasets provided by ECIA. Each model connects a group of input variables (predictors: NP, CB, A1, A2, A3, A4) to an output variable (either THR or HRR). The models were generated using MATLAB Stepwiselm function, and the resulting models (along with their statistical details) are presented in D2.2 Appendix.

1.1.4 MOO Framework Analysis

In WP4, a multi-objective optimization (MOO) study was conducted to optimize the formulation of cellulose-based insulation materials, with a focus on minimizing key performance metrics, specifically HRR and THR. The study used a systematic approach to evaluate various material compositions and their thermal behaviour under different conditions. A series of experimental tests and simulations were carried out to assess the impact of

different additives and fibre compositions on fire resistance and overall insulation performance.

The optimization process involves analysing the trade-offs between fire safety, thermal efficiency, and material cost-effectiveness. In addition, the environmental impact of various formulations was considered, including factors such as carbon footprint and recyclability potential. The ultimate goal is to develop an insulation material that not only meets stringent fire safety regulations but also maintains high energy efficiency and sustainability.

Following the study, it was possible to determine optimal proportions of components for production, based on the presence or absence of a specific component, in this case, cardboard (CB). Four different mineral additives (A1, A2, A3 and A4), whose names remain confidential in the report but are known among cellulose insulation producers, were evaluated. Combinations with other inputs, such as newspaper and cardboard, were also explored.

Overall, the results highlight the importance of considering a broad range of objectives when selecting the optimal solution. Certain formulations may excel in one or more objectives but perform less effectively in others. Therefore, the trade-offs between THR and HRR, environmental impacts, material and energy resource usage, and operational costs (OPEX) must be carefully balanced to identify the most sustainable and cost-effective solution for the construction sector.

The work developed in the MOO study focused on analysing the mineral additives and cellulose sources currently used in the industrial processes, specifically waste newspaper and cardboard-rather than exploring future bio-based alternatives for replacing these additives. The aim was to identify the most optimized solution based on existing industry practices.

1.2 Search for Sustainability Performance Improvement Solutions

1.2.1 Solutions From Contextualization Review

The end-of-life (EoL) management of cellulose insulation products involves several solutions aimed at improving sustainability and reducing environmental impact. Traditional disposal methods include landfilling as a non-hazardous material and incineration with energy recovery, while industrial composting allows for organic decomposition into a finished compost product. To enhance circularity, recycling recovered cellulose fibres presents multiple opportunities. They can be used as stabilizing agents in asphalt, preventing binder separation during asphalt production (Antrocel, 2025.; Masri & Baqadeem, 2023, Climatizer, 2020; Makron, 2025; Termex, 2020) or processed back into the production line to be reused as insulation (Duboc et al., 2019; ISOCELL, 2024; Duboc et al., 2021). A promising end-use is the potential application of recycled fibres in the fertiliser industry in the form of biochar. Using biochar recycled from end-of-life products such as organic waste from cellulose insulation presents significant environmental and agricultural advantages (Refer to section 2.1.3 for more information). Biochar can be produced by subjecting boron-impregnated cellulose insulation fibres to pyrolysis. The biochar serves as a slow-release fertilizer by providing boron as a key nutrient for plants (Government of British Columbia, 2015; LRA Toulouse, 2022). Another recycling route involves processing fibres into solid recovered fuels (SRF), which can be used as a renewable energy source (Čespiva et al., 2025).

In addition to EoL strategies, several possible industrial solutions have been identified. One key approach is reducing the share of mineral additives in cellulose insulation to minimize resource depletion and overall environmental impacts. An alternative could be substituting mineral additives with sulphates derived from mining by-products, creating a more circular use of resources or considering bio-based additives. On the production side, shifting to renewable electricity and using electric lift trucks can reduce the carbon footprint of manufacturing processes although these aspects are not among the hotspots of the construction sector in

terms of climate change.

A complementary strategy to improve sustainability in cellulose insulation lies in optimizing raw material sourcing. While most recovered cardboard is recycled back into packaging, redirecting clean, untreated cardboard to insulation manufacturing presents environmental advantages. Cardboard in EU economy is an abundant raw material. Most of the products imported into the EU are shipped with packaging which can be valorised to produce products like thermal insulation. Recycling of cardboard to thermal insulators with mechanical processes has lower environmental impacts when compared cardboards-to-cardboard recycling processes. Moreover, insulation applications extend the service life of fibres, potentially up to 50 years in buildings (CEN EN 16783:2024 - TC88), offering a long-term carbon storage. In this way, using cardboard in insulation not only diverts material from incineration but also enhances the life-cycle efficiency and circularity of the fibre itself (Belle et al., 2024; Secchi et al., 2016).

Further optimizations focus on improving packaging sustainability by incorporating a high percentage of low-density polyethylene (LDPE) pellets, reducing both material use and weight. Additionally, the compaction rate of insulation material is being optimized to enhance transport efficiency. Transportation distances for collection and distribution can also be reduced, lowering emissions and energy consumption.

1.2.2 Solutions From Experts and Stakeholder Dialogue

Substitution or reduction of mineral additives solutions

The production of cellulose insulation from recycled paper inevitably involves handling fibrous materials and paper dust. From a technical standpoint, a small quantity of fire retardant is essential during the fiberizing process to maintain fire safety, particularly due to potential contact with hot metal particles, such as staples or other metallic contaminants in the paper feedstock.

Most cellulose insulation producers rely on powder form additives, although some systems can accommodate liquids. Retrofitting facilities to dose liquid additives is technically feasible but involves significant investment and added complexity in terms of storage, handling, and dosage calibration. For powder dosing, various delivery systems are employed, such as small feeders, chemical pulverisers, and gravity-fed or air-blown setups into fiberizers or chemical blenders. Typically, two chemicals are dosed separately into the mill, although blending can also be outsourced. The number and type of additives influence storage requirements, logistics, and feeding mechanisms.

Processability is a critical factor in identifying suitable alternative flame retardants. Many promising candidates fail due to issues like caking from atmospheric moisture or excessive abrasiveness, which accelerates wear on fiberizing equipment and increases maintenance costs. In the ongoing search to replace boron-based additives, cellulose manufacturers, often in collaboration with additives suppliers, have conducted extensive testing. Some companies have tested over 250 chemical combinations over the last decade, identifying 30-40 with potential viability. However, high-performing alternatives often entail higher material costs, which could impact the economic competitiveness of cellulose insulation.

Manufacturers are also increasingly aware that additive content influences the product's environmental footprint. This was notably highlighted in the context of the European PEF (Product Environmental Footprint) project, where the additives used in cellulose insulation were linked to the highest global warming potential (GWP) within the production stage (PEF Thermal insulation products in building, Screening core report, Dec 2025). Despite this, the remainder of the production process remains environmentally efficient, since it uses waste-based raw materials, involves a dry, electrified mechanical process, requires low energy input and operates without water, heating, or drying. Over the past two decades, European producers have successfully reduced borate content from approximately 15% to 3-5%. A comparable environmental assessment of

alternative additives remains necessary to validate their long-term benefits.

Exploration of bio-based alternatives is ongoing. Although early trials with lignin did not yield practical outcomes, there is emerging potential in other natural compounds. For instance, the BIOSUOJA project, a collaborative between Aalto University and XAMK, investigated bio-based flame retardant for wood substrates and identified promising materials for use in construction. Parallel research from the Fraunhofer Institute (ScaleAmP project) has focused on phytic acid-based flame retardants derived from maize soaking water, which shows potential for application in Biocomposites and wood-plastic composites.

Additives directly influence the functional performance of cellulose insulation. Fire resistance is evaluated using standards such as EN 15101-1:2013 and EN ISO 11925-2 for ignitability (small burner test), and EN 13823 for large-scale fire behaviour (SBI test). Mould resistance testing is conducted under ETA EAD 040138-01-1201 or the newer EN 17886:2024, requiring laboratory assessment under controlled humidity and temperature for four weeks. Corrosion testing is governed by EN 15101-1:2013 (Annex E), although its relevance to insulation use is contested. Finally, emissions testing under EN 16516:2017+A1:2020 ensures compliance with indoor air quality regulations, which vary by EU member state.

Historically, borate-based additives have shown strong performance in fire resistance and mould suppression and have passed corrosion standards. However, regulatory shifts, such as REACH restrictions on inorganic ammonium salts, have limited the use of certain traditional flame retardants. This regulatory landscape underscores the urgency of developing viable, non-toxic, and sustainable alternatives for cellulose insulation additives.

Newsprint vs Cardboard as Secondary Raw Materials

A survey conducted among ECIA partners provided valuable insights into the feasibility of substituting newspaper with cardboard as a raw material in loose-fill cellulose insulation. Based on the inputs obtained, cardboard can partially replace newspaper from a technical standpoint without requiring major production adjustments. In the United States, some manufacturers have already successfully transitioned to using only cardboard. However, in Europe, this substitution is expected to remain partial due to considerations of product performance, economic viability, environmental impact, and regulatory compliance. Also, some production technology renewals will be necessary.

The shredding equipment required depends on the size of the cardboard used. Box cuttings and trimmings from large sheets of cardboard, known as DLK (Double Lined Kraft) in North America, are considered the cleanest source and can be used in most existing production lines. In contrast, OCC (Old Corrugated Containers), which consist of larger pieces, specialized shredders capable of handling large sheets are required.

One challenge identified is ensuring a clean and consistent cardboard supply. Tape can impact the production process of cellulose insulation, and the primary solution is sourcing sufficient quality cardboard alongside of developing separation technologies. The need for improved separation technologies to remove tape and other contaminants has been emphasized as a key factor for successful implementation. However, some North America producers specifically identified fibre-reinforced tape as significant issue. This is due to the difficulty in separating it from the cardboard matrix, its potential to disrupt processing equipment, and the risk of introducing non-cellulosic contaminants that could compromise the structural integrity and thermal performance of the final insulation product.

Beyond contamination concerns, the survey also examined the broader impact of cardboard substitution on material properties. Using cardboard instead of newspaper leads to a slight increase in dust generation, which, while not a critical issue, may require enhanced dust management strategies in both production facilities and application sites. A reduction of 25-30% in metal contamination (from staples in newspaper) is expected,

simplifying processing, and improving overall material purity. Additionally, initial VOC testing with a 15% cardboard mixture showed a minor exceedance of aliphatic compounds limits regarding strict eco-labels requirements, indicating a need for further optimization.

Key performance indicators, such as bulk density and thermal conductivity (λ -value), remain within acceptable ranges when up to 25-30% cardboard is introduced. Some manufacturers observed slight variations in λ -values, suggesting that careful formulation adjustments may be necessary to maintain optimal insulation performance. No significant impacts were observed regarding mould resistance, corrosion, or processability, apart from dust-related considerations. Notably, in North America, some manufacturers successfully use as much as 95% cardboard without major issues. While energy consumption may have increased slightly, density, R-value (thermal resistance), and chemical loading remain comparable to cellulose insulation made with newspaper.

From an environmental perspective, the reuse of cardboard in insulation manufacturing offers notable sustainability benefits by extending the material's lifecycle and diverting it from incineration or landfilling. Industry stakeholders widely recognize cardboard as the most viable and economically feasible alternative to newspaper, with several producers actively testing ways to optimize its integration into cellulose insulation production. In North America, the shift toward cardboard is expected to continue, primarily due to its availability and lower cost compared to newspaper. In some remote regions, manufacturers have already transitioned to cardboard due to a lack of newsprint supply, with no reported customer complaints. At present, no other bio-based materials have been identified as being as easily and economically substituted for newspaper in insulation production as cardboard.

1.3 Selection of sustainability performance improvement solutions

To improve production sustainability, recyclability and reusability of loose-fill cellulose insulation, three potential strategies have been identified:

- 1) **Replacement or reduction of mineral additives with biobased alternatives for lowering the environmental impact of cellulose insulation production:** These additives typically account for a high share of the product's environmental footprint. However, any substitution must ensure that the insulation maintains its fire-retardant and anti-mould properties, which are essential for performance and regulatory compliance.
- 2) **Biochar end-of-life treatment insulation fibres using pyrolysis:** An alternative end-of-life pathway for boron-impregnated cellulose insulation fibres involves pyrolysis, producing biochar that can be utilized as a slow-release boron fertilizer. This approach supports circular material flows and contributes to agricultural boron supply while mitigating potential groundwater contamination risks.
- 3) **Partial substitution of waste newspaper with cardboard as the primary feedstock for cellulose insulation production:** Using waste cardboard offers a viable and economically advantageous alternative to using waste newspaper for producing cellulose insulation. This strategy extends the lifecycle of cardboard, likely reduces CO₂ emissions by diverting material from incineration and has demonstrated promising feasibility in existing cellulose insulation production processes.

1.3.1 Literature Review Assessment of Biochar and Additives Solutions

An alternative end-of-life scenario for cellulose fibre insulation materials is their potential application in the fertiliser industry in the form of biochar. Using biochar derived from the recycling of end-of-life products,

particularly organic waste such as cellulose insulation, presents significant environmental and agricultural advantages. Biochar production sequesters carbon, helping to mitigate climate change by storing carbon in a stable form in soils for centuries (Lehmann & Joseph, 2015; Woolf et al., 2010). It also reduces the volume of waste going to landfills, decreasing methane emissions and pollution (UNEP, 2021). When applied to soil, biochar improves water retention, nutrient availability, and microbial activity, which can enhance crop yields and reduce the need for chemical fertilizers (FAO, 2019; Lehmann & Joseph, 2015).

From an economic and sustainability perspective, converting waste into biochar supports circular economy principles by turning low-value waste into a valuable resource. This not only creates new revenue streams but also lowers input costs for farmers by improving soil health and reducing irrigation needs (Woolf, D. et al., 2010, International Biochar Initiative, 2022). Additionally, biochar can be used in various industrial applications such as water purification and building materials, broadening its utility and making it an innovative solution for both waste management and sustainable development (International Biochar Initiative, 2022).

This recycling scenario is even more significant for cellulose and other boron-impregnated insulations due to its potential to fulfil boron requirements in agricultural applications. Boric acid is also used as a fire retardant in fibre insulation. This solution therefore can optimize recyclability and reusability at end of life by providing a pathway to reuse the boron content.

For this recycling scenario, the insulation is first pelletized then charred in a pyrolysis furnace to produce biochar which will be used as a fertilizer. This pyrolysis process scenario has been adopted from research on fertilizer from boron impregnated cellulose insulation based in Austria (Duboc et al., 2021).

Boron has been listed as a critical raw material (CRM) in the European Union (EU) since 2014 (Regulation EU 2024/1252). Currently, the major applications of boron are in glass (70%), fertilisers (12%), frits and ceramics (11%) (Duboc et al., 2021). Boron is an important micro-nutrient required by plants. One of the common boron fertilizers currently employed in the agriculture industry is Borax (Government of British Columbia, 2015). Therefore, transforming recycled insulation fibres as fertilizer could potentially serve as a substitute for this boron source. The Pyrolysis of insulation fibres results into production of Boron containing biochar (B-biochar).

An additional benefit of this recycling is that the biochar produced exhibits the properties of a slow-release fertiliser (Duboc et al., 2019). While Borax usually has an increased risk of leaching, experimentation on B-biochar fertilizer has shown no risk of contamination can be expected on groundwater bodies (Duboc et al., 2019). The only thing to consider is the presence of polycyclic aromatic hydrocarbons (mainly naphthalene), which can be controlled through appropriate process parameters (Duboc et al., 2019). Since this occurs post-use, it does not interfere with the insulation's performance during its lifecycle.

1.3.2 Literature Review Assessment of Waste Newspaper vs Cardboard Solutions

The substitution of waste newspaper with end-of-life (EoL) cardboard in the production of loose-fill cellulose insulation presents a promising innovation in sustainable construction. Both materials are cellulose-based and recyclable, but EoL cardboard, has become increasingly prevalent in waste streams due to the growth in e-commerce and packaging use. As the availability of waste newspaper declines with the digitalization of media, cardboard emerges as a more abundant and accessible raw material. This transition contributes to reducing landfill disposal, incineration, or the export of waste from EU countries (CEPI, 2024).

Recent statistics from the Confederation of European Paper Industries (CEPI) highlight a notable discrepancy between the declining use of newspaper and the increasing role of packaging materials like corrugated cardboard. In 2023, newsprint production in Europe dropped by 19.3%, and its consumption declined by 20.6% compared to 2022. In contrast to the declining availability of waste newspaper, containerboard, the primary

component of corrugated cardboard, remains a dominant and resilient material within the paper and board sector. In 2023, containerboard production in Europe reached 30.9 million tonnes, confirming its widespread presence in the waste stream. It also achieved a recovery rate of 95.4%, the highest among all paper grades, demonstrating the effectiveness of existing systems for collecting and processing this material (CEPI, 2024).

While most recovered cardboard is recycled back into packaging, the consistently high volumes of available and well-sorted end-of-life cardboard present a compelling opportunity for repurposing the material into cellulose insulation, a fundamentally different application. In 2023 alone, the containerboard sector accounted for 29.4 million tonnes of recycled paper use, representing 66.9% of all recovered paper inputs. This scale of recovery infrastructure ensures a stable and accessible supply of clean, fibrous material, making end-of-life cardboard a practical and resource-efficient substitute for newspaper in the production of loose-fill cellulose insulation (CEPI, 2024).

Technical studies reinforce the material viability of recycled cardboard for insulation, yet there is no direct comparison of cardboard or paper-based insulation boards performance. Secchi et al. (2016) demonstrated the performance of several cardboard-based insulation designs and identified the most effective as a sandwich panel made from two honeycomb cardboard layers filled with cellulose fibres. This configuration showed acoustic performance, and favourable environmental impacts, with a 10% lower cumulative energy demand and 34% lower greenhouse gas emissions compared to traditional gypsum boards, further validating the ecological advantages of substituting newspaper with cardboard in insulation applications (Secchi et al., 2016). Comparing the studies mentioned before, with the industrial data from ECIA partners, one can conclude on the advantages of the cardboard versus paper. This statement will be double checked once the studies of T5.3 are conducted and will be reported in their corresponding deliverables.

Further considerations support this substitution. Although the study by Belle et al. (2024) does not offer a direct LCA-based comparison between newspaper and cardboard derived cellulose insulation, it provides qualitative insights into the respective recycling processes. Cardboard typically does not require deinking, an energy and chemical intensive step necessary for white fibres in newspaper recycling. These could lead to lower reject rates compared to similar paper recycling processes involved with de-inking (Belle et al., 2024). The absence of deinking also minimizes the risk of process contaminants like inks that are more prevalent in graphic papers. These factors suggest that cardboard not only offers material feasibility but also environmental efficiency advantages over waste newspaper in insulation manufacturing (Belle et al., 2024).

From a broader perspective, Lisowski and Glinicki (2023) highlighted the potential of biomass-derived insulation materials to support EU decarbonization targets. Their review emphasized that many of these materials, including recycled cardboard, consistently achieve thermal conductivity values below $0.1 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, (The values below 0.1 are classified as a moderate performance) and have similar performance compared to petrochemical-based alternatives. The shifting landscape of waste streams further favours the use of cardboard. With digital media reducing newspaper circulation, the supply of recyclable newsprint is waning. In contrast, CEPI data show that corrugated and kraft grades made 62.9% of all paper for recycling grades utilized in 2023, and their collection remained high at 51.6 million tonnes, of which containerboard represented a significant share (CEPI, 2024).

1.3.3 Ecolabels Assessment of Identified Solutions Performance

Ecolabel Identification and Selection Process

Given the absence of BREF documents specific to the construction sector, eco-labels have been considered within this report, as a means of identifying viable sustainability solutions. However, the adoption of eco-labels presents several challenges that must be carefully considered. One of the most significant barriers is the cost of implementation, particularly for small and medium-sized enterprises (SMEs). Additionally, the complexity of certification, requiring frequent revision demands, and lengthy validation procedures can deter companies from pursuing eco-labels, limiting their widespread adoption. These concerns, frequently discussed during the development of this deliverable and among industrial actors, highlight the importance of finding a balanced approach that upholds credibility while making certifications processes more accessible.

Due to the extensive range of existing eco-labels, a selection process (**Table 2**) was undertaken based on expert input to identify the most relevant labels for in-depth analysis within the scope of this deliverable. To support this process, ECIA conducted a survey with its members to gain insights on key criteria. The eco-labels were initially classified according to their application scope: product-based versus building-specific labels. Given the focus of the preceding case study on the production of loose-fill cellulose insulation, which does not relate to a specific building application (e.g., walls, attics, or floors), it was determined that product-related eco-labels would be more relevant. Labels specific to buildings, which are often contingent on national standards, were thus excluded from further consideration, within this study.

To ensure a comprehensive representation of eco-labels across Europe, an effort was made to include labels that are prominent in various European regions. This led to the identification of the following eco-labels, which were selected based on their regional significance and recognition:

- **Northern Europe:** Nordic Swan Ecolabel (Denmark, Finland, Iceland, Norway, Sweden)
- **Northern Europe:** Byggvarubedömningen (Sweden)
- **Central Europe:** Österreichisches Umweltzeichen (Austria)
- **Central Europe:** Nature Plus (Germany)
- **Western Europe:** Label Produit Biosourcé (France)

This selection was subsequently validated by ECIA partners, ensuring that the chosen labels provide a broad representation of eco-labelling system across different European regions and encompass the main difference among eco-labels criteria and assessment methods.

Eco-Label	Country	Link
Natureplus (label)	Germany	https://nplusr.ampad-app.de/public/guidelines/en/0107.pdf
Byggvarubedömningen	Sweden	https://byggvarubedomningen.com/media/1yifbykg/criteria-73.pdf
SundaHus	Sweden	https://www.sundahus.se/
QNG (seal)	Germany	https://www.nachhaltigesbauen.de/
EMICODE®	Germany	https://www.emicode.com/en/
Nordic Swan Ecolabel	Denmark, Finland, Iceland, Norway, Sweden	https://svanemerket.no/krav/the-nordic-swan-ecolabel-environmental-requirements-for-houses-and-other-buildings/
EU Ecolabel	EU	https://ec.europa.eu/environment/ecolabel/
pure life	Germany	https://www.purelife.de/
Cradle to Cradle	Global	https://www.c2ccertified.org/

eco tested product	Germany	https://www.ecotest.de/
Sentinel Haus	Germany	https://www.sentinel-haus.eu/
Assessment system for sustainable building (BNB)	Germany	https://www.bnb-nachhaltigesbauen.de/
BREEAM	Germany, Global	https://www.breeam.com/
DGNB (seal)	Germany	https://www.dgnb.de/en/
Leed (seal)	USA, Global	https://www.usgbc.org/leed
eco-bau label	Switzerland	https://www.eco-bau.ch/
Ökotest	Germany	https://www.oekotest.de/
Indoor Air Comfort Eurofins	Global	https://www.eurofins.com/
Blue Angel	Germany	https://www.blauer-engel.de/en
Greenguard	Global	https://www.ul.com/resources/ul-greenguard-certification-program
RAL Gütezeichen	Germany	https://www.ral-guetezeichen.de/
Label produit biosourcé	France	https://www.batiment-biosource.fr/wp-content/uploads/2020/12/200805-Referentiel_label_produit_biosource.pdf
French regulation on COV emission	France	https://www.ecologie.gouv.fr/politiques-publiques/etiquetage-produits-construction
Label Bâtiment Bas Carbone	France	https://www.batimentbas carbone.org/
HQE Bâtiment Durable	France	https://www.certivea.fr/
HQE Label Bâtiment Biosourcé	France	https://www.certivea.fr/
Österreichisches Umweltzeichen	Austria	Wärmedämmstoffe aus nachwachsenden Rohstoffen

Table 2 List of collected eco-labels relevant for cellulose insulation products, 25 European labels and 2 labels with a global scope. Six eco-labels (green) were analysed for this deliverable. (The choice was made from a survey of eco labels. ECIA decided that the chosen labels are the most important and should represent the landscape of Europe for cellulose insulation.)

Ecolabel Qualifying Criteria Relating to Identified Solutions

1. Reduction of Mineral Additives/Substitution with Biobased Alternatives

The substitution of mineral additives with biobased alternatives presents challenges across multiple ecolabels due to its influence on key material properties such as fire resistance, thermal conductivity, and mould resistance. Since mineral additives typically represent the highest share of environmental impact in the production of loose-fill cellulose insulation, their replacement with bio-based options is highly relevant but must maintain critical performance attributes.

Natureplus®: Compliance may be affected due to strict requirements regarding fire resistance (EN 13501-1, at least Class E), thermal conductivity (≤ 0.1 W/mK, ISO 10456), and mould resistance (Category 0, EN ISO 846). Mineral additives are permitted as flame retardants, and their replacement with biobased alternatives might not be allowed under current standards.

Nordic Swan Ecolabel: The ecolabel requires insulation materials to meet fire safety and durability standards. Substituting mineral additives could alter fire resistance and moisture management, requiring extensive testing.

Byggarubedömnigen (Sweden): This ecolabel evaluates chemical composition and environmental impact. Substituting mineral additives with biobased ones may require additional assessment to ensure compliance with restrictions on hazardous substances, particularly regarding fire retardants and biocides. Alternative additives must not introduce harmful emissions or compromise product durability. Further evaluation may be necessary to ensure long-term performance aligns with its sustainability criteria.

French COV Regulation: Biobased additives could introduce new VOC emissions, impacting compliance with emission thresholds ($\leq 10 \text{ mg/m}^3$ at 3 days, $\leq 1 \text{ mg/m}^3$ at 28 days).

Österreichisches Umweltzeichen: Ensuring compliance with a thermal conductivity limit of $\lambda \leq 0.065 \text{ W/mK}$ may be challenging with new biobased components.

Label Produit Biosourcé: Since the ecolabel focuses on biobased content, this solution could align with its criteria, but its impact on fire resistance and emissions would require further assessments.

2. Pyrolysis of Boron-Impregnated Fibres for Biochar Fertilizer

The pyrolysis of boron-impregnated cellulose fibres as a means of producing biochar fertilizer introduces both opportunities and constraints within ecolabel frameworks. While this end-of-life pathway offers a sustainable recycling route by leveraging the boron content for agricultural benefit, it also raises concerns related to the handling and environmental fate of boron compounds. Given that boric acid is commonly applied as a fire retardant in fibre insulation, its transformation and potential leaching in soil applications must align with ecolabel criteria for toxicity and nutrient runoff, which may limit or condition its acceptance.

Natureplus®: As this process does not alter the insulation's functional stability, composition, or emissions during use, it remains compliant with ecolabel standards.

Nordic Swan Ecolabel: No restrictions on disposal methods suggest that this approach does not conflict with certification.

Byggarubedömnigen (Sweden): While this ecolabel does not regulate end-of-life disposal methods directly, it considers the environmental impact of materials. The process of pyrolysis may need to ensure that no hazardous by-products, such as excessive levels of polycyclic aromatic hydrocarbons (PAHs), are introduced. The sustainability benefits of biochar may also need to be weighed against potential emissions from the pyrolysis process.

French COV Regulation: The regulation assesses VOC emissions during the insulation's use phase, meaning pyrolysis does not affect compliance.

Österreichisches Umweltzeichen: Since the material performance remains unchanged until disposal, this process does not impact ecolabel criteria.

Label Produit Biosourcé: While this solution does not affect insulation certification, biochar's agricultural application may require compliance with separate regulations.

3. Substitution of Waste Newspaper with Cardboard as the Main Raw Material

Replacing waste newspaper with cardboard could enhance sustainability by giving cardboard a second life. However, it poses potential challenge related to classification, fire resistance, and emissions.

Natureplus®: The ecolabel mandates a minimum of 85% recycled newspaper (EN 643 group 2.01). Since cardboard does not meet this definition, certification compliance may be affected unless exemptions are granted. This indicates that a full replacement of waste newspaper with cardboard wouldn't be possible, but a partial substitution is recommended.

Nordic Swan Ecolabel: Substitution must meet material requirements, and further testing may be necessary to validate insulation properties, particularly regarding fire resistance and durability.

Byggarubedömningen (Sweden): The use of cardboard may need to comply with chemical content criteria, particularly regarding adhesives and coatings. If cardboard introduced new substances such as chlorine-based inks or synthetic adhesives, it may not meet the ecolabel's low environmental impact requirements. Additionally, the recyclability and processing of cardboard within the insulation industry may require further evaluation to ensure compliance with sustainability goals.

French COV Regulation: Cardboard may introduce new VOC emissions due to adhesive, inks, or coatings, which may need to remain below regulatory thresholds to maintain certification.

Österreichisches Umweltzeichen: The impact on thermal conductivity, density, and overall environmental footprint (e.g., global warming potential) may need to be assessed, as variations in raw material composition can influence these factors.

Label Produit Biosourcé: The impact on bio sourced material classification may require further evaluation to determine whether the change aligns with the ecolabel's requirements.

Summary of Ecolabel qualifying criteria relating to identified solutions

Each sustainability solution may have implications for ecolabel compliance. While the pyrolysis solution appears to be the least challenging to implement, replacing mineral additives or newspaper may require rigorous testing to ensure continued compliance with fire safety, thermal performance, emissions, and material composition requirements. The potential to improve the environmental impact of loose-fill cellulose insulation through these solutions is significant, but modifications must be carefully assessed to balance sustainability benefits with regulatory and performance criteria. Manufacturers should conduct extensive validation before implementing these changes to ensure continued certification under relevant ecolabels.

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2 TEXTILES

2.1 Contextualization

2.1.1 Case Study Descriptions

The textile sector in the CALIMERO project was represented by the two industrial partners Ereks and T.I.L. and sustainability assessment performed by the academic partner LIST. T.I.L. provided primary data to perform the LCSA and the process optimization modelling performed by LIST, while for Ereks only the LCSA was conducted.

Ereks Case Study:

Ereks is a denim garment manufacturer, which uses fabric purchased from external suppliers. The focus of the study was limited to the so-called finishing step of garment production, specifically the garment washing process. Two case studies were evaluated. The first is the conventional denim jeans washing technique that uses pumice stone in acid washing; the second is the use of a synthetic based reusable stone to replace pumice stone.

The washing process steps are the same for both case studies; the main differences are associated with the stones used and the type and quantity of chemicals used. The washing process (**Figure 4**) consists of several consecutive steps: garment loading, desizing, rinsing, pumice stone loading, mid-process, pp-spraying, after pp spraying, rinsing, softening, spinning and drying. The two washing processes are the same apart from the step denominated “after pp-spraying” which is not performed when using the synthetic stone. The studied system also includes the wastewater treatment plant located on the production site which receives the washing process effluents and that recycles the water from the effluents back in the washing process at a 90% rate.

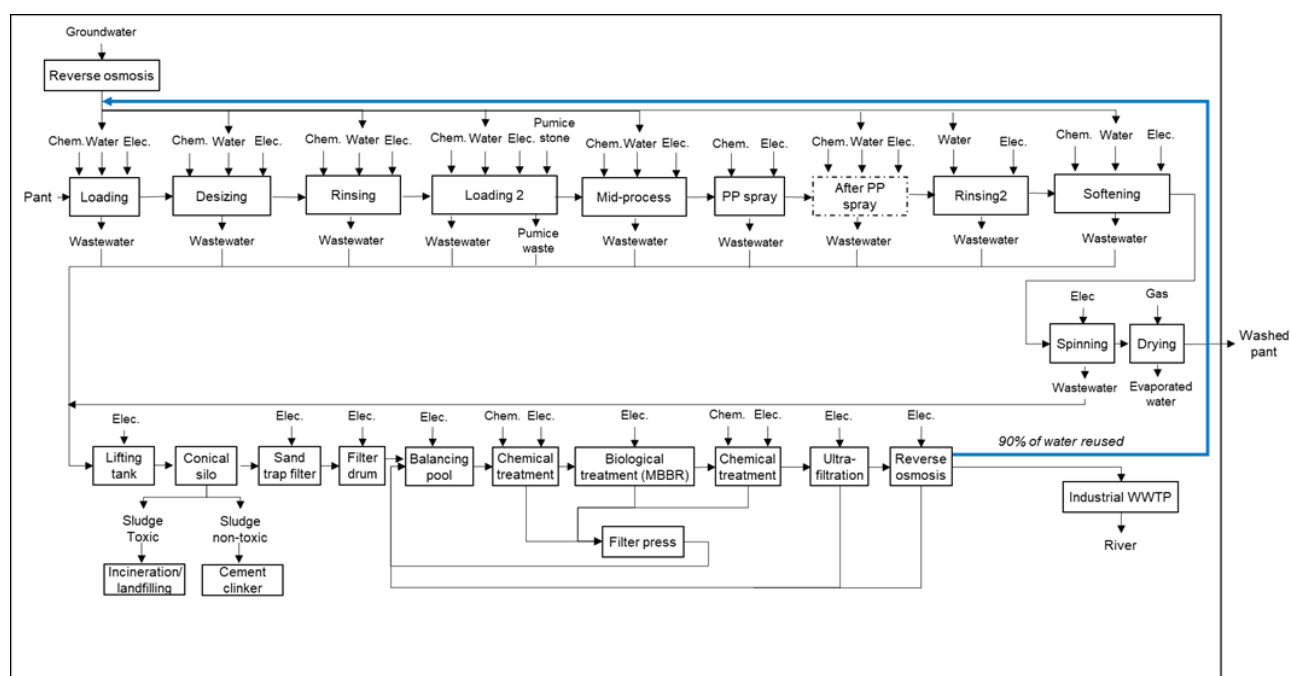


Figure 4 Ereks washing process (dashed unit process applies to pumice stone wash only). Blue line is the reused treated wastewater

The washing and wastewater treatment processes consume electrical energy which is sourced from the grid and some natural gas consumed by the drying step. Additional input materials are the chemicals used during the washing process and the stones. Finally, for the pumice stone washing, a sludge solid waste is generated which is sent for disposal and 10% of the treated effluents are released from site.

Pumice stone is supplied from mining sites available in Turkey and is transported to the production site at a regular frequency. Pumice stone is a short-lasting material since it can be used for only two washing cycles before becoming unusable. The synthetic based reusable stone is a polypropylene based material manufactured in Turkey which can be reused for up to 3000 hours of washing cycles and that is recycled back into the same product at the end of its lifespan. The main benefits are associated with its longer durability and reusability which reduces the supply associated transport and its consumption rate. Moreover, it avoids the mining activity required for the pumice stone and because it does not degrade during the washing process, it does not generate sludge waste. Ultimately, the use of the synthetic stone allows for changes in the type and quantity of some chemical auxiliaries with changes in potential toxicity effects associated with the release of chemical substances contained in the process effluents.

T.I.L. Case Study:

Teintures et Impressions de Lyon (T.I.L.) is a French company specializing in textile finishing processes, including bleaching, dyeing, and printing of yarns and fabrics. Two processes were of interest in the CALIMERO project, the first called “M50 washing after desizing” and the second “M30 washing after bleaching”. Both of them were investigated for the LCSA assessment in CALIMERO WP2 (see deliverable D2.1), but only the first one was of interest for the optimization of WP4 (see deliverable D4.2).

Process “M50 washing after desizing” aims to remove the sizing agents present on the cotton woven fabric and is the first wet finishing step in textile processing. In the case of T.I.L., cellulose is the size that is present on the fibers to allow for further processing such as printing and makes use of the “Starwash Evo” machine, which offers an ideal washing solution for synthetic and natural fibers (MCS, 2024). The desizing process is a necessary step to perform before applying any treatment/colour on a woven textile, cotton in particular. Indeed, sizes such as starch are applied on the warping yarns to make them more resistant to friction during the weaving process. The method chosen for desizing depends on the type of sizing agent used, which can be either water-insoluble or water-soluble. Additional auxiliaries are added to the sizing mixture when treating specifically cotton yarns: antistatic agents, de-foaming agent or wetting agents for example. Normally M50 process requires rinsing water and detergent addition; nonetheless, when the sizing agent is water-soluble, repeated washing with high-temperature water (80–95°C) and good agitation can help remove remaining size particles without any chemical addition. This last case applies to the process under investigation at T.I.L.. Indeed, T.I.L. desizing process uses amylase, an enzyme to remove the non-soluble starch present on the textile and a wetting agent to make sure the enzyme penetrates the fibres. Consequently, The M50 process aims to remove the wetting agent and the maltose, a water-soluble sugar obtained via the action of the enzyme on the starch.

Cold water is supplied by the network and feeds the washing tank, where the fabric is inserted and removed by an automated snare drum. The water within the tanks is heated to 95°C by a steam network linked to a boiler. This specific temperature is maintained to ensure that the compounds (e.g. starch for M50) dissolves in the water and to optimize the washing process’s effectiveness. Following these steps, the fabric is wound around a heated cylinder to dry, and subsequently around a cooled cylinder to lower its temperature. This comprehensive process ensures the fabric is thoroughly cleaned and prepared for further use. Finally, the used water is directed to the wastewater treatment of the whole plant, that is not included in the system boundaries as the company utilises a single central treatment unit for the collective wastewater of all processes.

Consequently, they don't have data regarding the wastewater composition at the end of process M50.

A schematic representation of process M50 is shown in [Error! Reference source not found.5](#).

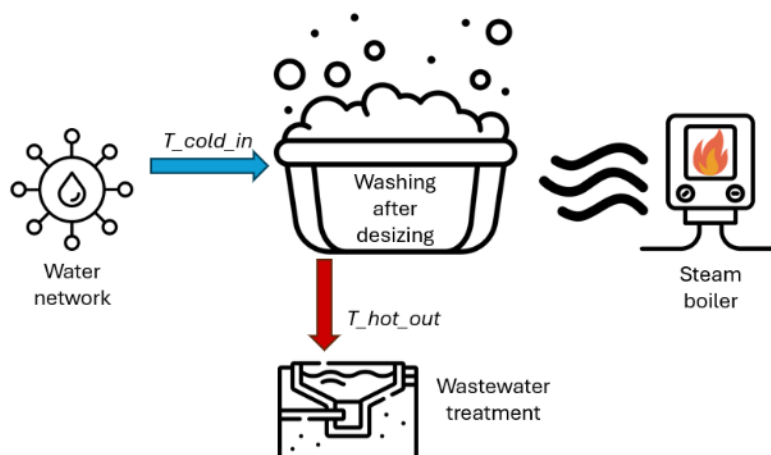


Figure 5 Schematic representation of process “M50 washing after desizing” at T.I.L.

Process “M30 washing after bleaching” is crucial to remove residual chemicals and impurities from the fabric. At T.I.L., this process is performed in the same device used in M50, “Starwash Evo”. The bleaching that happens beforehand is the process of removing natural colour, impurities, and any remaining sizing agents from the fabric, with chemicals like hydrogen peroxide (H_2O_2) with a stabilizer plus sodium hydroxide, a wetting agent and persulfate to increase the oxidizing effect ($NaClO$). Therefore, in the washing process afterwards, it is required to use hot water to rinse the fabric, with the addition of acidic neutralizing agents and detergents or surfactants.

The process' system boundaries are the same identified for M50 and can be seen in [Error! Reference source not found.4](#) above. The same reflections on the wastewater treatment are applied. For the bleaching process done by padding before the M30, there are different chemicals used. The process begins with the addition of H_2O_2 and a stabilizer to control the decomposition of H_2O_2 , followed by the addition of a wetting agent for core treatment. A persulfate is then introduced to enhance the oxidizing effect, along with sodium hydroxide. This mixture undergoes cold impregnation for 18 hours, during which time the H_2O_2 is completely decomposed. The M30 process is then used to remove the remaining chemical residues, including the sodium hydroxide, which is the most challenging to eliminate.

Since the washing processes M50 and M30 are highly dependent on the preceding steps, specifically the desizing and bleaching processes, the search for and selection of sustainability improvement solutions will also include these earlier stages. As such, the scope will be broadened to consider the processes as “desizing and washing after desizing (M50)” and “bleaching and washing after bleaching (M30).” In fact, achieving a more sustainable washing process with reduced water, energy, and time consumption may require analyzing and identifying improvement opportunities in the processes immediately preceding the washing stages.

2.1.2 Case Study Lifecycle Aspects, Impacts and Hotspots

Ereks Case Study:

From the sectorial review part in D1.2, the main environmental hotspots for textile manufacturing are identified as air and water emissions, soil pollution, depletion of resources and land use impacts. The main environmental impacts are climate change, soil and water acidification, particulate matter generation, water use, resource use and freshwater ecotoxicity. Energy consumption, chemical treatments and consumption of materials are the main sources of impact. The textile sector is overall burdened by social issues, in particular regarding the supply chain in developing countries. Amongst the main hotspots identified for the sector there are collective bargaining, wages, toxic and hazards, injuries and fatalities, conflicts, corruption and health and safety. A detailed SLCA evaluation of textile products is, however, still limited.

Specifically, for the Ereks case studies, according to the LCA results, the main environmental burdens are associated to the pumice stone washing, pp-spraying is the step contributing the most to all environmental impacts categories followed by the wastewater treatment process and the pumice stone loading step. PP-spraying shows major impacts in terms of ecotoxicity, ionising radiation and minerals and metals resource use. For the wastewater treatment process most impacts are due to the emissions of treated effluents, disposal of pumice sludge and energy consumption for the wastewater treatment plant. Specifically, the release of treated effluents has impacts in terms of freshwater eco-toxicity. For the pumice stone loading, most of the impacts are linked to the supply of pumice stone.

For the synthetic stone, pp-spraying, wastewater treatment and mid-process steps are the main process hotspots, but this shows a 76% overall impacts reduction compared to the pumice stone washing. Once again, the main impacts are associated with the use of the pp-spraying chemical which generates impacts in terms of land use, ionising radiation and marine eutrophication. For the wastewater treatment process, the highest source of impacts is due to the energy consumption, followed by the release of treated effluents. For the mid-process most of the impacts are linked to the supply of the chemical used in this step, which is not present in the pumice stone washing process.

T.I.L. Case Study:

From the LCA results of process M50, the highest burdens of the process were carried by the natural gas consumption used for the steam production in the boiler, the combustion process, the electricity demand and the water discharged with its relative treatment process, in each category. The water supply from the network and the Starwash machine production had negligible impacts. As concerns the water evaporation, it's negligible in all impact categories with the exception of the water use. Concerning process M30, in addition to the use of natural gas and the combustion process, the key impact drivers also include caustic soda solution, the use of soap, and to a limited extent the addition of acetic acid solution.

Additionally, social and economic impacts were also assessed to complete the LCSA. The chosen social indicator was Job Creation Potential, such as the potentiality for a process to generate work in its life cycle. The company provided the direct worker hours of the employees involved in the process, while the indirect worker hours (background data) were defined through PSILCA database, version 3. The results showed that process M30 has a slightly higher potential of employment, 1.47 jobs, in comparison to process M50, 1.23 jobs. The workers hours were compared to the hours worked in a full-time job annually works in France.

Finally, a simplified version of Life Cycle Costing and the other economic indicators was performed. The results show that the highest LCC is associated to the process M30. The result is expected, as the Starwash machine works for the 54% of the time for the process M30. Moreover, process M30 required the addition of some chemicals (caustic soda, acetic acid, soap), which corresponds to extra costs. Both processes return a positive value of the cashflow at the year 20. Process M30 is the one that provides the highest Net Present Value (5.78

times higher than that of process M50), with the Levelized Cost of Production consequently higher. The Internal Rate of Return is at 6% for process M50, and reaches 11% for the second process. Considering that the process M30 is consuming more resources overall, its associated Environmental Externalities are higher (119.18 €/FU versus 86.18€/FU).

2.1.3 Industrial Processes Simulated

T.I.L. Case Study:

The process simulation was performed in ASPEN-Plus software for process M50, in steady-state mode. The model is detailed, and it includes the valves for the water supply control of their regulation system and the overflow ducts. The initial model also includes the old heat exchanger that T.I.L. had originally installed. Nonetheless, the device was not properly dimensioned for the heat duty, so it is not actively used during the processes. In the simulation, corn starch was used as the starch material, as it is one of the most used textile sizing agents, and the choice was confirmed by T.I.L.. The properties of the agent were thoroughly investigated to accurately model starch behaviour in aqueous solutions (see deliverable D2.2). The Flory-Huggins model was applied to describe the solubility of starch in water, with interaction parameters obtained from open literature. Furthermore, the molecular structure of corn starch was analysed in detail using data retrieved from the PubChem database. This meticulous characterization of starch was instrumental in the subsequent solubility analysis. The model will be updated to incorporate the results of the optimization tasks, as outlined in T5.3.

2.1.4 MOO Framework Analysis

T.I.L. Case Study:

Based on the results of WP2, process M50 was selected as of interest for the process optimisation, as the LCA investigation brought to the attention the significant impact related to natural gas extraction and combustion in the boiler. Additionally, the LCC highlighted the OPEX expenses related to the purchase and consumption of the natural gas. Therefore, a potential improvement could be reached if the boiler consumption is decreased, nonetheless the social repercussions on the job creation potential are not clear, as there would be a decrement of employment for people that work on the gas supply network.

The installation of a heat exchanger is suggested as a solution, according also to the expressed need and interest of the T.I.L. company. The multi-objective optimization has the main purpose of identifying the best heat exchange area to ensure that the heat demand is covered, reducing the use of the boiler. Nonetheless, the impacts related to the production and installation of a new device, under the environmental, economic and social perspective, must be considered. In the process, the energy was identified as the only feasible variable of optimization. This is because process M50 is restricted in scope and infrastructure. Indeed, the process requires only water supply, which doesn't carry significant impact under any indicator, and heat to remove the starch. As explained above, the wastewater treatment was not part of the system boundaries, thus any information about that process and its improvements was not part of the scope of the project. Consequently, the optimization definition is strictly focused on the energy domain. Water recirculation is not a feasible option, as the preceding step is the desizing process itself. This involves the addition of enzymes and wetting agents that adhere to the textile and are subsequently removed in process M50. Therefore, clean water is necessary to ensure effectiveness of the cleaning.

Typically, multi-objective optimization requires a custom algorithm due to the high complexity and large number of parameters involved. However, a simpler approach can be sufficient due to the limited scope, e.g. of only three parameters in the subsequent case study. Calculations can even be performed in Excel, as done for this integration, where the simplicity of the problem justified the use of this software. Therefore, LIST has worked

out an optimization approach in this context in Excel. In this case, the optimization occurs by having the process-model together with its impact scores for Life Cycle Costing (LCC), Life Cycle Assessment (LCA) and Social Life Cycle Assessment (S-LCA) be calculated in Excel. This is done for various scenarios, for which the (sub)optimal one(s) is/are then selected. The term (sub)optimization is used to indicate that the scenario definition follows a discrete number of possible design alternatives, depending on the relevant technical constraints of the case study. This leads to the optimization definition not by continuous selection and intermediate values consideration, meaning that the technical optimal solution could fall in a scenario not included. Consequently, the optimization method as well consists in a stepwise/discrete epsilon constrained approach. In other words, a priority list is set up for all life cycle impact indicators, and then for each indicator a space of (sub)optimal parameters is selected for these based on constraints and optimal targets. The feasibility of this solution depends on the specific case. Additionally, Excel's data visualization tools enabled a clear analysis of trade-offs between objectives, making it an effective choice for small-scale optimizations without the need for complex algorithms.

The primary goal was to integrate an appropriately sized heat exchanger into the process to harness heat recovery from the washing water. Error! Reference source not found.6 presents a schematic overview of the process. Several scenarios were defined, beginning with the techno-economic design of the heat exchanger. The logic was that while a larger heat exchanger would be more expensive, it would also enable greater heat recovery. This is linked to the operation of a gas boiler within the system to supply any remaining heat requirements.

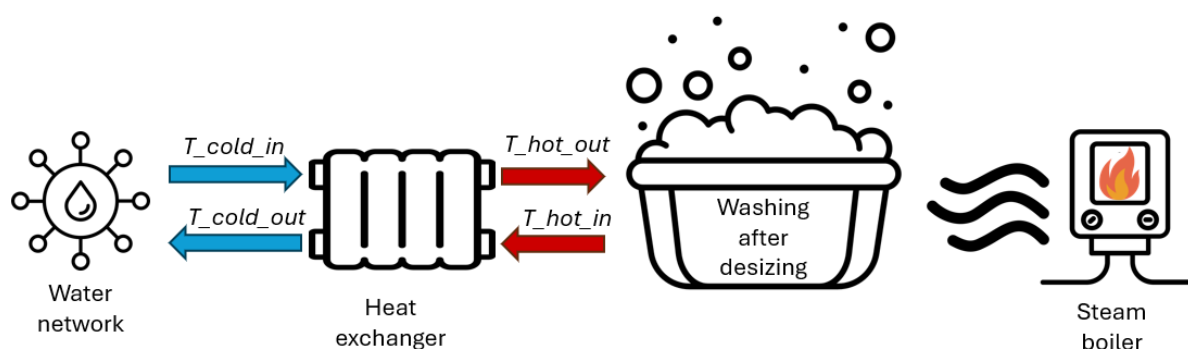


Figure 6 Schematic representation of process "M50 washing after desizing" at T.I.L., after optimization

This task required optimizing not only based on thermodynamic calculations to determine the most effective heat exchange area but also on environmental and social indicators. As mentioned, Life Cycle Costing (LCC), Life Cycle Assessment (LCA), and Social Life Cycle Assessment (S-LCA) was used for this purpose. The economic indicator used was LCC, accounting for OPEX and CAPEX, but adjusted to a one-year timeframe. For the social indicator, Job Creation Potential (JCP) was considered, while the environmental impact was assessed using the single score approach.

The first step consisted of a technical calculation of suitable dimensions for the heat exchanger to supply part of energy need. 11 potential heat exchanger areas were defined, with the logic that an incremental area will consequently lead to a reduction of the boiler use. Afterwards, the influence of the combined use of boiler and heat exchanger was investigated for all the potential heat exchanger's dimensions, in all the 3 indicators (LCC, LCA, S-LCA). Concerning the economic indicators, the LCC indicator was calculated, including CAPEX and OPEX for all scenarios, and then referred to one unique year.

Concerning the LCA, a single score environment footprint was calculated for each design alternative, considering the impact of the new device's production and recycling, and the combined use of the boiler. With

the same approach, S-LCA was considered calculating the JCP related to greater device production and the consequent decrement of jobs related to the natural gas network management. Finally, the optimal result was identified using the epsilon-constraint approach, which consists of defining an acceptance threshold for each parameter and identifying acceptable ranges. Once these boundaries were established, a priority order for applying the constraints was determined, with the first constraint applied having the greatest influence. In this specific case, priority was given to the social opportunities, followed by economic constraints and finally environmental ones.

More information about the MOO framework and the application in the case Studies are available in D4.2.

2.1.5 LCSA Methodological Improvements Considered

Ereks Case Study:

Given the number of toxic chemicals used for the denim garment washing, it is important to quantify their emissions to the environment for a comprehensive evaluation of the process's potential toxicity impacts. For this, the chemicals consumed must not only be quantified as mass emitted but also their impact in terms of ecotoxicity and human toxicity characterized via a specific characterization factor (CF).

As part of the methodological optimisation performed within the CALIMERO project. A new set of CFs have been calculated for all the chemicals used in the Ereks washing process and will be added to the impact assessment method to increase the accuracy of the impact assessment of the effluents released.

T.I.L. Case Study:

During process M30, caustic soda and hydrogen peroxide and acetic acid solution are added with the purpose of degrading the chemicals added in the previous step. As with the Ereks case study it is important to assess the impact of their emissions and impacts in terms of ecotoxicity and human toxicity, through utilising the new CFs. These CFs have been calculated for all the chemicals used in T.I.L. washing processes and will be added to the impact assessment method.

2.2 Search for sustainability performance improvement solutions

Ereks Case Study:

2.2.1 Solutions from Contextualization Review

Following the LCA results, the main sources of impacts can be associated to both the use of large quantities of chemicals, pumice stone and water for the multiple washing steps, ultimately generating large volumes of effluents to be treated. Additionally, the high energy consumption of the overall process contributes to multiple impacts. The change to the synthetic stone addresses all the impacts associated with the pumice stone consumption. Furthermore, the washing performed with synthetic stone, demands less water and requires less chemicals, showing overall positive impacts both in terms of chemicals consumption, chemicals emissions in the process effluents and wastewater treatment requirements.

2.2.2 Solutions from Literature Review

To further identify improvement solutions to the denim washing process, a literature review was also performed. More advanced solutions identified from literature range from more environmentally friendly discoloration techniques to more ecological abrasion methods, with the main objective to offer further improvements for the stone abrasion and potassium permanganate bleaching steps:

1) **Abrasion steps improvements**

Identified solutions to eliminate the negative environmental impacts associated with the use of pumice stone include direct replacement of pumice stone with enzymatic alternatives capable of abrading the fabric surface such as cellulase enzymes (i.e. bio-stoning), or combination of the de-sizing and abrasion washing steps in a single step by using a specific enzyme, thus greatly reducing water and energy demand (Colomera and Kuilderd 2015; Kamppuri and Mohmood 2019). Other techniques such as waterjet fading aim at completely removing chemicals and stones to obtain the faded look, by using only high-pressure waterjet from a closed loop water recycling system. Laser fading techniques go a step further by operating in totally dry conditions. A CO₂ laser fading method is considered the most efficient type and the one generating the best results and represents a valid alternative to the conventional wet treatment with stone washing and bleaching (Tarhan and Sariisik 2009; Chi-Wai Kan 2014; Venkatraman and Liauw 2019). Finally, e-flow uses nanobubbles of air formed from air subjected to electromechanical shock, capable of abrading the fabric surface, offering savings of over 90% in chemicals and water consumption and 40% for energy needs (Garcia 2015; Periyasamy and Periyasamy 2023).

2) **Discoloration techniques improvements**

Bleaching is the process to lighten or decolorize the indigo from the denim fabric surface by means of a strong oxidative bleaching agent such as sodium hypochlorite, potassium permanganate and hydrogen peroxide. When sodium hypochlorite is used, hypochlorous acid is formed and residual chlorine that is released either in the effluents or as part of the process vapor emissions, is toxic to both ecosystems and workers. Moreover, to neutralize residual chlorine from the denim fabric and avoid fabric yellowing, thiosulfate, or sodium metabisulfite are used as antichlor agents. The neutralization of chlorine liberates strong gases and sulphur dioxide. Potassium permanganate is also a strong bleaching chemical; it is harmful to the environment and is toxic to workers (Atav et al. 2023).

The use of potassium permanganate generates manganese oxide as brown non-water-soluble deposit, which requires removal with oxalic acid and high temperature washing. Additionally, bleaching causes issues also from the indigo that is detached from the cotton fibers and that is washed away in the effluents. The denim fabric discoloration liberates indigo dye molecules in water which during the wastewater treatment become toxic aromatic amines (Sadeghian and Montazer 2013).

Sustainable bleaching alternatives range from chemical auxiliaries' replacement with more environmentally friendly laccase enzymes (Colomera and Kuilderd 2015) or the use of ozone dissolved in water (Garcia 2015; Sarker et al. 2021), to more experimental techniques using lasers (Atav et al. 2023).

The use of enzymes either as co-adjuvants for the reduction of chemicals usage, or as direct alternative to the use of chemicals or pumice stone for abrasion and bleaching processes, appears to be quite a mature technological solution with several demonstrated commercial applications. Regarding dry-treatment processes, laser technology and e-flow offer commercially available machines as reported by Garcia (2015).

Regarding bleaching, laccase and ozone bleaching represent the most mature technologies to date. Ozone bleaching includes several commercially available production machines with examples reported by Atav et al. (2024) and in Garcia (2015). Commercial solutions for laccase use are reported in Colomera and Kuilderd (2015).

2.2.3 Solutions BREF Documents Review

The Best Available Techniques (BAT) Reference Document for the Textiles Industry Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control) was reviewed for potential technological improvements to reduce Ereks washing process impacts. However, since Ereks production process does not include fabric production but only garment finishing, the BREF document was of limited applicability as this refers mainly to denim fabric production.

Identified alignments with BREF recommendations include:

- The company employs real-time monitoring systems to track and optimize water usage (BAT 10), particularly during denim production's water-intensive washing. Based on BREF guidelines, Ereks has successfully implemented water recycling practices, reusing 90% of its wastewater through advanced filtration systems (BAT 20). This not only reduces the consumption of freshwater but also significantly cuts operational costs.
- In terms of energy efficiency (BAT 11), Ereks has incorporated a heat recovery system that captures energy from process water, cooling systems, and air and reuses it to maintain the necessary production temperatures. This BREF-aligned approach has led to an 11.5% reduction in overall energy consumption. Additionally, by investing in energy-efficient machinery, such as advanced boilers and dryers, Ereks has made substantial progress in minimizing its carbon footprint.
- Following BREF's chemical management protocols (BAT 14), Ereks sources all chemicals used in production from certified suppliers who meet international sustainability standards, such as GOTS, OEKO-TEX, and ZDHC. By optimizing chemical use and applying low water washing techniques, Ereks minimizes its chemical consumption and waste production, further adhering to the best practices outlined in BREF.
- Ereks adopts a circular waste management approach, consistent with BREF's focus on waste reduction (BAT 29). The company recycles production waste such as offcuts, packaging materials, and wastewater, either within the production process or through external certified recycling facilities. This circular approach significantly reduces the environmental impact of waste, aligning with Ereks' broader sustainability goals.

BREF sections reference	Status	Comment
Environmental management system (EMS), and Monitoring and Control of Operational Parameters	Implemented	Ereks has ISO 14001 certification for our Environmental Management System and ISO 50001 for our Energy Management System.
Monitoring and Control of Operational Parameters	Not Implemented / Good to	Ereks has wet treatments, thermal treatments, and machine rate control and can obtain detailed information about its washing process from using the

	Implement: We plan to implement an automatic dosing system for better results.	latest generation of machines. These machines do not however have automatic dosing systems. This part of the process is done manually, and Ereks plans to automate these processes in the future.
Water efficiency Water management plan and water audits	Implemented	Ereks uses the latest technology, low energy, water efficiency implemented machines and has implemented a rain harvesting system. The process is constantly monitored by the washing manager via monitoring outputs at the end of the process. Wastewater is recycled and reused in the process, with a wastewater recycling rate of 90%.
Emission Monitoring	Implemented	Emission measurements are carried out at different production stages. Scope 1 and 2 emissions have been monitored for the last 2 years.
Energy efficiency	Implemented	Ereks ISO 50001 certification ensures a comprehensive Energy Management System. Ereks also has energy-efficient machinery. By installing a heat exchanger system that releases hot air outside during the cooling process, Ereks save 150 cubic meters of natural gas per day. In this way, Ereks does not consume natural gas for heating in the winter, and by using the same hot water in the production processes in the summer, Ereks saves 4000 cubic meters of natural gas per month. Moreover, due to the system innovations in Ereks' heating boilers, the facility's our average daily natural gas usage has decreased by 11.5%. In comparison, Ereks has improved its daily washing count by 20% and reduced its emissions accordingly. Ereks solution is a heat recovery system for dryers, which are one of the most energy-intensive processes, utilizing renewable energy from a solar power plant.
Reuse & Recycle of Water	Implemented	All water and sludge generated during the process is recycled.
Chemical Usage	Implemented	By using the Zero Discharge Harmful Chemicals (ZDHC) Incheck platform and by having BvH3 membership, Ereks chemical management is monitored following certain limits. According to ZDHC, the storage, renewal, stacking, and classification of chemicals at Ereks are carried out per ZDHC and the process is constantly monitored. Ereks has a chemical storage area and its chemicals are organized according to the chemical storage matrix. Materials Safety Data Sheet of chemicals are prepared.

Table 3 BREF solutions applicable to the Ereks case Studies

T.I.L. Case Study

2.2.4 Solutions from Literature Review

As mentioned above, the case studies of T.I.L. are quite limited in scope and complexity. The only flows of the system boundaries for process M50 are those related to water and heat supply as inputs and used water as output. Used water is sent to a collective wastewater treatment unit common to all T.I.L. processes. For this reason, wastewater treatment is located outside the processes system boundaries and cannot be an object of optimization or technique refinement for the scope of this project. Water supply had proved not to have relevant impacts, unlike the energy supply. The sustainability performance improvement solutions will therefore primarily focus on energy valorisation in the washing technique and machine itself. Beyond this, some improvements will also be considered for the desizing process prior to the M50 washing process to provide a more comprehensive vision. Similar considerations apply to the M30 process, that only differs for the chemical addition to the system, that have a significant impact contribution. Some improvements will be considered for the bleaching process that occurs prior to the M30 process.

Based on results from the LCA performed in D1.2, the highest environmental footprint for both processes' is due to natural gas consumption. Impacts from gas supply, combustion in the boiler, the electricity demand and wastewater treatment. M30 is also impacted by caustic soda solution and soap addition, less by acetic acid solution.

To reduce the main impact, it was highlighted that energy optimization is crucial. Proposed improvements are listed below and comprehend good practice not only for installing new performance devices, but also regarding procedural recommendations to enhance equipment efficiency and lifetimes.

2.2.5 Solutions from Literature Review

1) Energy efficiency of the gas boiler

A literature review was performed to find recommendation to improve the energy efficiency related to the use of a gas boiler and heat exchanger.

Concerning the use of the boiler, (Barma et al., 2017) recommended the following attentions:

- **Perform the scheduled maintenance** and cleaning. Poor maintenance of boiler can lose up to 30% of the original efficiency.
- **Install properly sized boiler** for the required heat load.
- **Apply a digital control** of excess air
- **Perform heat recovery** from exhaust gases. About 10–20% of input energy may be lost through high temperature flue gas. This heat can be used to preheat combustion air, boiler feed water within the boiler, or as a driving heat source for other purposes such as an absorption chiller.
- **Use preheated combustion air.**
- **Operate condensate recovery**
- **Improve boiler insulation:** directly to the outer walls of the boiler as well as steam pipes. Any surface above 50 °C should be insulated.
- **Minimize wasted blowdown water**, that is the periodical hot water discharge from the bottom of the seam drum to prevent scale formation during boiler use. For further energy savings, boiler feed water can be preheated by recovering waste heat from blowdown water and approximately 1% improvement on system's efficiency could be achieved.

- **Check the fuel specification:** gaseous fuels with a higher hydrogen content lead to more water vapor formation during combustion. The result is energy loss as the vapor absorbs energy in the boiler and lowers the efficiency of the equipment.
- **Check the operating conditions,** especially ambient temperature and humidity. Ideal conditions at 25°C and 30% humidity.

2) Energy efficiency of a heat exchanger

Concerning the use of the heat exchanger, (Klemeš et al., 2020) recommended:

- **Improve the heat transfer enhancement:** it can be applied both inside and outside of tube walls and focuses on the geometrical design and heat transfer coefficient (HTC). Typical geometries are grooved tubes, converging-diverging tubes, helical tubes, and wavy surface tubes. Enhanced heat exchange tubes effectively enlarge the heat-transfer surface area of tube-sides and promote turbulent flows over laminar. Experiments have proven that HTC could increase by 2–4 times.
- **Execute the periodic maintenance.** Fouling and poor maintenance affect the heat transfer performances. Fouling studies mostly develop correlations for thermal fouling resistance as a function of time, design parameters, and operating conditions.
- **Implement data monitoring** to predict fouling phenomena.
- **Pipes insulation** (as seen in the case of the boiler)

Moreover, in the T.I.L. case study a closed structure around the Starwash machine could help reduce evaporation losses from the washing process. Additionally, steam pipes could be placed above the tanks so that the evaporation's heat will preheat the water-steam network, reducing the gas combustion in the boiler.

3) Optimization of the desizing and bleaching processes before T.I.L. M50 and M30 washing processes

Finally, to improve T.I.L. washing processes, the desizing and bleaching processes done beforehand could be optimized. The desizing and bleaching processes could be improved to obtain a cleaner textile that would subsequently require shorter washing times with fewer chemicals and lower temperatures as well as the potential reuse of washing waste water.

- **Combined desizing, bleaching, and scouring:** Oxidative desizing involves soaking the fabric in a bath containing hydrogen peroxide (H_2O_2), caustic soda (NaOH), stabilizers, and complexing agents, allowing simultaneous desizing, scouring, and bleaching. H_2O_2 , combined with NaOH, facilitates bleaching, while caustic soda ensures effective scouring (Ahmed et al., 2019).
- **Ultrasound for bio-scouring with pectinase:** before doing an enzymatic desizing with α -amylase. It generates shock waves which enhance the action of enzymes on textile materials during scouring which could serve as a pre-desizing. This would lead to lower quantities of water and α -amylase for the desizing leading to cleaner textile during the T.I.L. M50 washing process (Dragana Grujić et al., 2023).
- **Laccase-mediated system pretreatment** to enhance the effect of hydrogen peroxide bleaching of cotton fabric: The use of LMS (laccase-mediator system) pre-treatment is an effective method to enhance the bleaching efficiency of cotton fabric in the hydrogen peroxide bleaching process. The use of laccase leads to a lower hydrogen peroxide dosage, a reduced bleaching temperature about 30 °C lower than in the conventional process and a bleaching duration reduced by 33%. (Liqiang et al., 2011)

- **Plasma pre-treatment after desizing** improves textile processing by modifying fiber surfaces, enhancing bleaching efficiency. It reduces the need for harsh bleaching agents, lowers environmental impact, and improves wettability. The process is energy-efficient, operating at lower temperatures with shorter treatment times, offering a more sustainable alternative to traditional methods. (C.-W. Kan, 2015)

Both the solutions of combined desizing, bleaching, and scouring, and ultrasound-assisted bio-scouring optimize the washing process after desizing by enhancing the removal of impurities before the actual washing step. This reduces the need for excessive rinsing and chemical use while improving process efficiency.

2.2.6 Solutions BREF Documents Review

Some optimization techniques identified in the BREF and BATS for the T.I.L. washing process after desizing are listed below:

1. Design and operation techniques:

- **Perform countercurrent washing:** This technique is relatively straightforward and inexpensive and can be applied for washing after continuous desizing. It is important to note that this method is currently being used for the T.I.L. process. (BAT 10)

2. Water reuse and recycling techniques

- **Use of membranes:** water streams can be filtrated through membranes to reuse it in processes such as cleaning, rinsing or cooling avoiding or postponing the treatment in the wastewater treatment plant.
- **Reuse of treated water in other processes:** Pre-treated water (e.g. via filtration or evaporation) can be reused for rinsing, cleaning, cooling, or processing. Reuse depends on contaminant levels, and streams from multiple on-site units may be combined if quality allows. (BAT 10)
- **Recovery and reuse of water-soluble sizing agents and water:** Hot water desizing allows for the recovery of water-soluble sizing chemicals (e.g., polyvinyl alcohol and carboxymethyl cellulose) through ultrafiltration. The concentrate is reused for sizing, while the permeate is recycled for washing. The permeate could be used during T.I.L. M50 washing process. (BAT 10)

3. Energy efficiency

- **Heat recovery system:** Installing heat recovery equipment on a continuous washer is typically a straightforward yet effective measure, as the inflow of fresh water and the outflow of effluent are balanced, removing the need for holding tanks. However, since the effluent from these machines may contain fibrous material, it is essential to use heat exchangers designed to handle such loads. (BAT 11)

Regarding the recommendations for process optimization, the BREF document highlights the same findings as the literature review, specifically the use of plasma or ozone for desizing, enzymatic desizing, and the combination of desizing, bleaching, and scouring processes. Considering that at T.I.L. desizing, bleaching and scouring aren't done simultaneously, the implementation of such a technique could lead to the optimization of several steps of production. For further details, please refer to the paragraphs above.

Regarding enzymatic desizing, which requires fewer chemicals due to the use of enzymes like α -amylase or pectinase (for water-insoluble sizes) and operates at lower temperatures compared to oxidative desizing, this process is already being done at T.I.L. before the M50 process. (BAT 10)

2.2.7 Ecolabel Considerations

Ereks Case Study:

While Ereks is evaluating the potential of pursuing an Ecolabel certification, the company wants to emphasize its reservations about the comprehensiveness of ecolabels, particularly in denim production and washing facilities. The EU Ecolabel, for example, is primarily focused on chemical usage and fails to take a more holistic approach to sustainability.

Ereks perspective on the EU Ecolabel:

While the EU Ecolabel is widely respected and represents high environmental performance, its scope is limited. The certification revises its criteria every four years to reflect advancements in materials, production processes, emission reductions, and market trends. The Ecolabel, which complies with ISO 14024 standards and is a Type 1 Environmental Label, focuses on lifecycle-based assessments verified by third parties. However, it only addresses chemical use and does not fully capture the broader sustainability context.

A product can meet Ecolabel's Chemical Criteria and still be produced using conventional methods that do not prioritize sustainability in the broader sense. This narrow focus overlooks significant aspects such as resource management, energy use, and waste reduction, which are critical to a sustainable operation. Therefore, while Ecolabel provides value in assessing specific environmental impacts, Ereks believes that for certifications to be genuinely comprehensive, they must evaluate the entire lifecycle—from raw materials to the finished product.

T.I.L. Case Study:

The EU ECOLABEL mostly focuses on the substances used in textile production and doesn't mention the alternative processes having lower environmental impacts. It is quite a restricted view on sustainability as it doesn't take into consideration all the other parameters beyond chemical substances. In T.I.L.'s case, the company already benefits from the STeP label by OEKO-TEX®, which has a broader scope, covering chemical management, health and safety, as well as environmental management.

However, such a framework wouldn't highlight T.I.L.'s efforts in process optimization. T.I.L. is a French textile finisher at the forefront of water management, especially through the implementation of its own wastewater treatment plant leading to an autonomous treatment of its industrial effluents. A label such as the EU ECOLABEL still provides relevant criteria for T.I.L.—particularly regarding the use of chemicals in pre-treatment processes—but does not fully reflect the company's commitment to more comprehensive sustainability strategies.

In conclusion, Ereks and T.I.L. believe a certification system should include a robust methodology that evaluates all sustainability dimensions rather than focusing on one isolated factor. The current scope of the EU Ecolabel does not fully align with our understanding of sustainability. For that reason, we continue to seek more comprehensive ways to assess and communicate the environmental impacts of our operations.

2.3 Selection of sustainability performance improvement solutions

Ereks Case Study:

Based on the insights obtained from the LCA of the two washing processes performed by Ereks, as well as a specific literature review for the denim garment washing, the following solutions have been identified as offering the most effective solutions to reduce the environmental hotspots identified for the garment washing process:

- 1) The synthetic stone is an effective alternative to remove the use of pumice stone for the fabric abrasion step. Replacing the natural pumice stone with the synthetic one shows positive impacts in terms of GHG emissions reduction, due to the lower quantity of effluents generated from its use and consequently the reduced energy consumption for the wastewater treatment. Additionally, the use of the synthetic stone induces a reduction of potential freshwater ecotoxicity impacts, since the washing process requires less chemicals compared to the pumice stone washing. Furthermore, the use of the synthetic stone avoids both the emissions linked to the supply of pumice stone (i.e. mining and transport) and the emissions linked to the disposal and treatment of the pumice stone sludge.
- 2) The use of chemicals required for discoloration techniques represent a process hotspot both in terms of environmental impacts in particular for eco and human toxicity, but also in terms of social impacts to workers occupational health and safety. Alternatives to the use of chemicals for discoloration can be found in the use of ozone dissolved in water with the addition in case of discoloration enzymes, or in the use of laser which goes even further by eliminating the use of water besides bleaching chemicals, or in the use of e-flow nanobubbles which reduces both the use of chemicals and water by over 90%.

T.I.L. Case Study:

- 1) To reduce the toxicity emissions of the bleaching and desizing processes, use laccase enzymes during the bleaching process and amylase for the desizing (bio-desizing already done at T.I.L.) instead of harsh bleaching agents.
- 2) Include plasma or ozone desizing post-treatment before bleaching to reduce the toxicity by reducing the use of bleaching chemicals. This also reduces the use of water for the washing process as the textile has less chemicals on its surface.
- 3) A more global approach to improve the resources circularity and decrease the environmental impacts of the chemical additions for textile washing is proposed from BREF and literature recommendation. The approach consists of incorporating desizing and bleaching processes in a unique process. The incorporation can also be expanded to include scouring. In fact, oxidative desizing involves soaking the fabric in a bath containing hydrogen peroxide (H_2O_2), caustic soda (NaOH), stabilizers, and complexing agents, allowing simultaneous desizing, scouring, and bleaching. H_2O_2 , combined with NaOH, facilitates bleaching, while caustic soda ensures effective scouring. In such a way, three processes are done simultaneously allowing only one washing step and less chemicals.
- 4) As highlighted from the LCSA assessment of WP2, high impacts both in processes M50 and M30 are driven using natural gas boiler in all impact categories. The suggested improvement, coming from the screening of available resources (BREF, literature review) consist in the installation of a heat exchanger to recover the heat from the hot wastewater, before sending it to the water treatment unit. The solution proved to have met the expect results, leading to a reduction >25% of process' carbon emissions, limiting the effects on the Global Warming Potential.
- 5) Perform countercurrent washing to increase the washing effectiveness and reduce the water supply (this method is currently being used for the T.I.L. process). (BAT 10)
- 6) Use of membranes: desizing and bleaching processes (before M50 and M30) could implement more water recirculation. Hot water from desizing could be recovered to extract the water-soluble sizing chemicals (e.g., polyvinyl alcohol and carboxymethyl cellulose) through ultrafiltration. The concentrate can be reused for sizing, while the permeate can be recycled for washing. The permeate could be used during T.I.L. M50 washing process (BAT 10). The strategy is expected to lead in a toxicity reduction, as less chemicals would be used in other steps of production. This would also contribute to CALIMERO's circularity indicator by reusing the water and having a more circular process.

A summary of the proposed selection of sustainability performance improvement solutions is summarized in **Table 4**.

Process steps	Sustainable solution	Process improvement	Case study
Desizing and bleaching	Enzymes for the bleaching (laccase) Enzymes for the desizing (amylase)	Less polluted wastewater for the M30 and M50 Reduces the toxicity	T.I.L
Bleaching before M30	Ozone or plasma bleaching pre-treatment	Reduce the use of bleaching chemicals Less polluted wastewater for the M30 Reduces the toxicity	T.I.L
Desizing and bleaching	Simultaneous processes	Reduce washing steps, reduce chemical consumption, reduce toxicity	T.I.L
M50/M30	Heat exchanger	Energy demand reduction, reduction of GWP	T.I.L
M50/M30	Counterflow washing	Water consumption reduction	T.I.L
M50/M30	Membrane filtration of the wastewater	Water consumption reduction, re-use of concentrate	T.I.L
Abrasion	Reusable synthetic stone	Avoidance of pumice stone consumption. Reduction in chemical consumption. Avoidance of waste generation.	Ereks
Abrasion	e-flow nanobubbles	Reduction of chemicals and water consumption. Avoidance of stone usage.	Ereks
Discoloration	Ozone washing	Elimination of bleaching chemicals	Ereks
Discoloration	CO ₂ laser	Avoidance of bleaching chemicals and water consumption.	Ereks

Table 4 Summary of the proposed selection of sustainability performance improvement solutions for desizing, bleaching and washing after desizing and bleaching processes and for denim garment washing

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3 WOODWORKING

3.1 Contextualization

3.1.1 Case Study Descriptions

The woodworking industry in the CALIMERO project involves the partners CTA and CESEFOR. CTA is the partner responsible for carrying out the LCSA and applying the MOO tool. CESEFOR as an industrial partner, is responsible for providing the primary data of the case studies, apart from giving its industrial expertise. Having contacted several Spanish companies, one of them was selected for two main reasons: 1) the product produced by the company (LSL - Laminated Strand Lumber) was identified as the most interesting from an innovative point of view, since it is a niche product with a higher added value than particleboard, and 2) there was greater availability of process data and a better willingness to collaborate. From this company, two different case studies were analysed: Case study 1, LSL production, and case study 2, steam production from residual biomass.

LSL PRODUCTION: CASE STUDY 1 CONTEXTUALISATION

The first woodworking case study analysed concerns the production of a single product from the family of engineered wood products Lignumstrand®, also known as LSL. This wood product has a fixed length of 8.2 m and a fixed width of 0.62 m, and a thickness that can vary from 30 to 100 mm. LSL is commonly used in the market for technical doors, resistant to fire or noise, bowling alleys, as well as in the construction of prefabricated houses. In the factory, two types of LSL are manufactured: industrial and construction, which represent 85 % and 15 % of the company's sales respectively. The main difference between the two is that the structural LSL used in construction is certified with the CE (European Conformity Certificate) label, so it must undergo an external control to evaluate a series of minimum legal and technical requirements in terms of safety according to Directive 93/68/EEC. In terms of durability, the product is expected to have a service life of 50 years according to the specifications.

According to the production process, this consists of three main stages: (i) sourcing of the raw material, (ii) transportation to the factory, and (iii) production of Lignumstrand®. Firstly, the raw material is harvested from different poplar forests located in two Spanish riverbanks: (1) Ebro, located in La Rioja and (2) Duero, located in Castile and Leon. In addition, these places are located about 200 km from the factory to minimize emissions from wood transportation.

Likewise, harvesting takes place in 14-year shifts, during which the poplars are felled as low as possible. The most common practice today is not to remove the stump, but to leave it and plant the next generation right next to it. On the other hand, it is important to mention that the process is certified with the PEFC (Program for Endorsement of Forest Certification) label, which guarantees compliance with responsible and sustainable forest management practices.

Regarding the production process (**Figure 7**), the first case study starts from the poplar forests, where the wood is harvested as green wood and transported to the plant where it is debarked and chipped. The chips are then sent to a drying and screening process. This process consumes energy from a boiler in the form of electricity and heat to produce chips with a moisture content of approximately 4 %. The wood is then pressed in the form of dry poplar chips and a fossil-based adhesive, in this case a pMDI (polymeric methylene diphenyl diisocyanate) glue, is added, also consuming steam from the boiler for the heating of the press. The pressing time depends on the density and thickness of the final product but is about 5 minutes. The Lignumstrand® is then produced after edge trimming and sanding.

STEAM PRODUCTION FROM BIOMASS: CASE STUDY 2 CONTEXTUALISATION

The second case study (**Figure 7**) focuses on the production of steam from biomass. This biomass includes a 10 % of virgin sawdust (pine or beech) that is purchased outside, and a 90 % of waste biomass from the LSL manufacturing process: fines and poplar chips from both the screening process (free from adhesive) and the trimming and sanding process (which contain adhesive); and chipped waste boards (also containing adhesive). The system for producing steam comprises a biomass silo, which collects all biomass leftovers, and a boiler connected to the silo, where the steam is generated. The generation of steam system requires electricity for the suction and the operation of the entire feed circuit and the boiler. The system does not produce any solid or liquid waste, but emissions to the air result from the operation of the boiler. In addition, it is important to note that the boiler produces sufficient steam to meet the heat demand of the dryer and the press equipment.

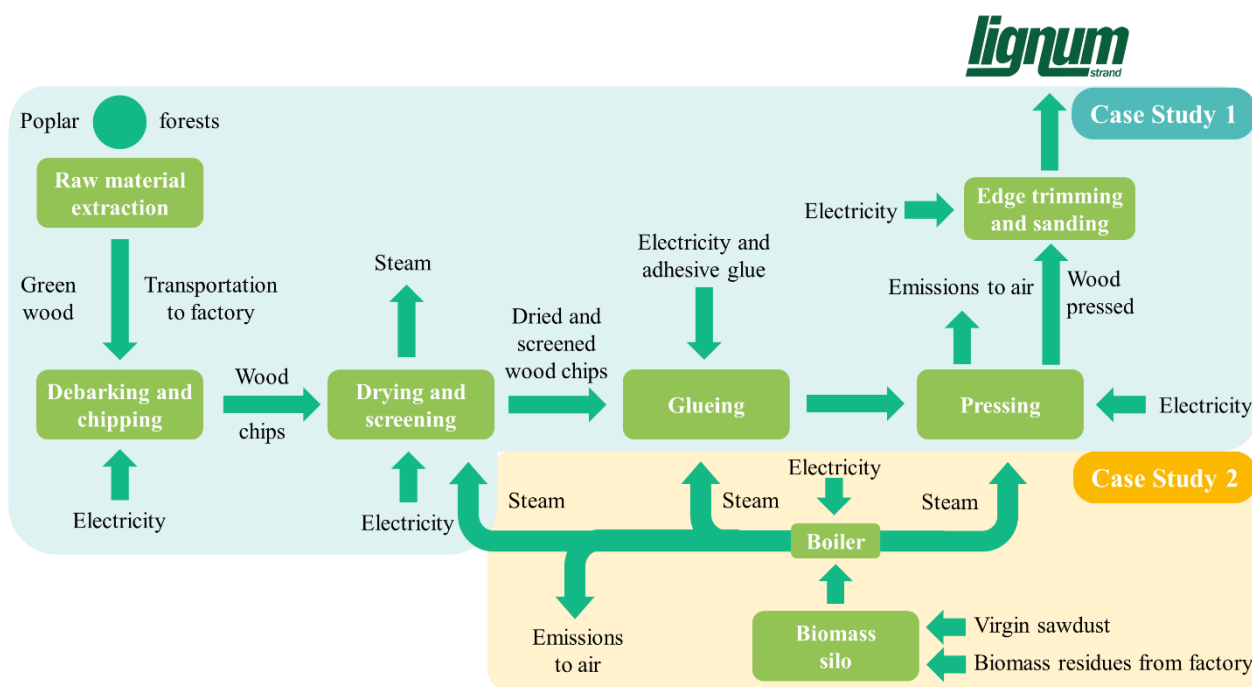


Figure 7 Diagram of the industrial processes for the two case studies addressed in the woodworking sector

3.1.2 Case Study Lifecycle Aspects, Impacts and Hotspots

Taken into consideration the results obtained in D1.2 (“Most impactful bio-based industrial processes”), the most impactful environmental categories (from the PEF method) for the woodworking sector in environmental terms were identified to be climate change, the use of fossil resources, land use, photochemical ozone formation and particulate matter (see Figure 17 in D1.2). Similarly, potential exposure to toxic chemicals and indoor air pollution, as well as injuries and accidents due to lack of safety measures, are usual social risks associated with woodworking. This is due in part to the generation of significant amounts of particles and dust, and to the use of toxic and sometimes carcinogenic chemicals in many woodworking and construction products, such as those that release Volatile Organic Compounds (VOCs), which can adversely affect human health. In that way, workers may be directly exposed to such contaminants. Concerning the economic hotspots of woodworking, those are mainly related to the cost of raw material, workers and adhesive, while energy is not usually seen as an economic concern due to the use of process waste biomass for its production. Energy can, however, be very relevant for the most time-consuming processes (such as pressing and drying processes) particularly in the case of small plants, and for those that do not have a highly optimized production. Consequently, the knowledge gained from the hotspot analysis was used as a reference to select the industrial processes to be simulated, optimised and sustainably improved.

3.1.3 Industrial Processes Simulated

In terms of simulation, each of the woodworking case studies focused on a specific process. For case study 1, the goal was to develop a mathematical model that would predict emissions from the hot-pressing process step based on the composition of the adhesive used and depending on operating conditions. To do this, a set of data-driven models were created. In this sense, each model relates to a set of input variables or predictors (pressing temperature, pressing time, resin content, moisture content, and board density) to an output variable, the emission of interest (e.g., VOCs, methanol, acetic acid, etc.). Additionally, this hot-pressing process was also selected to be optimized by means of the Multi-Objective Optimization (MOO) framework. The above is justified by the fact that it represents one of the main bottlenecks concerning time consumption of the production process. For case study 2, a simulation model was developed for the emissions derived from the combustion unit (i.e., the boiler), which included three different sections: (i) size reduction and drying, (ii) combustion, and (iii) heat recovery and steam generation, simulating the amount of sulphur oxide, methane, or carbon monoxide, among others.

3.1.4 LCSA Methodological Improvements Considered

Based on the methodological improvements achieved in the CALIMERO project in terms of LCSA, the following were selected to be applied in the woodworking sector: ecosystem services impacts, criticality aspects, the time-dependency of the carbon footprint (i.e., dynamic carbon footprint), the inclusion of the refinement of social and economic life cycle assessment methods (i.e., S-LCA and LCC) in terms of Job Creation Potential (JCP) and economic indicators, respectively, in order to address a holistic view of sustainability, apart from the consideration of novel toxicity characterization factors from both ProScale and UseTox methods.

3.2 Search for sustainability performance improvement solutions

Considering the issues highlighted in the contextualization section, a series of sustainability concerns have been identified for the woodworking sector. Based on them, the academic and industrial knowledge of the CALIMERO project partners has served to propose possible solutions for improvement.

The solutions to be proposed have been exclusively focused on the LSL manufacturing process (i.e., case study 1), thus disregarding the sustainability concerns related to the steam production from the biomass silo (i.e., case study 2). This decision was justified by the fact that case study 2 represents less than 20% of the total environmental impacts (see woodworking section in D2.1). The preliminary improvement solutions proposed from the sustainability concerns identified appear collected in **Table 5**.

In this way, these preliminary solutions will be considered as a starting point for further refinement through a literature review and consultation of other documents of interest in this regard, such as BREFs. This section has been divided into two different subsections, depending on the aspect or step to be improved: (i) adhesive for wood boards, and (ii) pressing and drying processes.

Sustainability concerns identified	Preliminary improvement solutions proposed
Use of fossil resources in the adhesive	Employment of a bio-based adhesive
Pollutant and toxic emissions generated during the pressing process	Installation of filters to reduce the associated emissions
	Simulation of the associated emissions to be further optimized
Environmental impacts and economic concerns associated to the electricity employed in the drying process	Upgrading of the equipment used

Table 5 Main sustainability concerns and preliminary solutions proposed for the woodworking sector

1) Adhesive for wood boards

A literature review was also conducted to identify solutions to improve the sustainability performance of woodworking companies. In this regard, recently published scientific reports agree that one of the main concerns for woodworking companies is related to formaldehyde emissions, since this constitutes the main component of the most used adhesives for wood-based panels manufacturing (i.e., urea-formaldehyde, melamine-urea-formaldehyde, phenol-formaldehyde). In addition, these are extracted from fossil resources, apart from having been classified as a type 1 carcinogenic substance (Protano et al., 2021).

Exposure to formaldehyde from wood-based panels starts in the production phase (especially from panel pressing, but also from panels curing and storing) and extends to the use phase. Consequently, current research focuses on the development and implementation of bio-based adhesives aimed at replacing fossil-based counterparts and reducing or eliminating formaldehyde content (Chen et al., 2025).

Bio-based adhesives can be produced from a range of natural resources, such as lignocellulosic compounds, tannins, proteins or sucrose, and have the potential to allow the industry to reduce disposal costs and develop high-value materials (Antov et al., 2020). Additionally, industrial by-products and biological waste, such as discarded fruits and vegetables, dairy by-products like whey, agricultural residues from production and harvest, as well as wood remnants generated during processing, can be used as raw materials in the production process for bio-based adhesives (Arias et al., 2021). Therefore, this approach has the added benefit of valorising waste and reducing dependence on primary resources.

In the CALIMERO project context, pMDI is used for LSL manufacturing. This is a formaldehyde-free adhesive, thus not posing the risk above mentioned. However, isocyanates bring with them their own problems associated with occupational exposure, i.e., they can induce occupational asthma and violently increase asthma symptoms, such as eye, nose and throat irritations, as well as tightness in the chest, bronchitis and severe bronchospasm (Bantolaya Martínez, 2024).

Life cycle studies suggest that bio-based adhesives have significant potential to replace traditional (i.e., fossil-based) adhesives, reducing negative impacts on human health and the environment, providing that extraction processes and modification techniques are improved, and energy-efficient processes are achieved throughout the production chain. However, there are still considerable pitfalls for the large-scale application of bio-adhesives, i.e., they are still not economically competitive and most of them have performance challenges compared to conventional adhesives, such as limited water resistance, lower bonding strength, and high production costs (Calvez et al., 2024). Consequently, the use of bio-based adhesives is currently limited to small-scale applications and pilot plant trials.

At present, the bio-adhesives for board manufacturing that are closest to the market are those developed from

kraft lignin processes. An example of this is Neoligno¹, developed by Storaenso², which, together with Koskisen³, has resulted in the first 100% bio-based board⁴ (to the author's knowledge, no other manufacturing is using Neoligno so far). On the other hand, IKEA claims the use of a corn starch-based adhesive at large scale in one of their plants⁵, however, no detailed information regarding the origin of the adhesive has been disclosed on this. Thus, we can confidently state that the use of bio-adhesives is not at all widespread in the industry, with a lot of secrecy surrounding the success stories. This is the reason why, although they are in fact a promising measure, they are not considered viable for the CALIMERO case studies due to a lack of specific information on their performance and requirements in terms of manufacturing parameters and production line modifications.

On the other hand, emerging technologies, such as binderless panels, are gaining attraction in scientific research. These panels eliminate the need for adhesives by activating the chemical components of the materials used, allowing wood particles to bond through mechanical, chemical, hydrothermal, or biological treatments (Calvez et al., 2024). However, these types of adhesive-free panels are under development and further improvements must be made until their implementation is at an industrial scale.

Notwithstanding, there is an alternative way for assessing the impacts of bio-based feedstocks in existing production processes, this is, the Biomass Balance (BMB) approach proposed by Jeswani et al. (2019). This concept was applied by the authors in a case study involving polymers. In this method, fossil feedstocks are replaced by bio-based alternatives, such as bio-naphtha substituting naphtha, and biogas (bio-methane) replacing natural gas. The quantities of fossil feedstocks and the corresponding amounts of bio-feedstocks required for replacement are calculated through a Material Flow Analysis (MFA). In this sense, it is crucial to consider that some bio-feedstocks may have different carbon content, energy values, or other chemical properties compared to the fossil feedstocks they replace. This disparity can result in either higher or lower requirements for bio-feedstock quantities compared to the fossil counterparts. In such cases, it becomes necessary to account for the equivalent quantities of bio-feedstock. To facilitate this, the use of an equivalent factor based on the Lower Heating Value (LHV) of both fossil- and bio-feedstocks is recommended as an approximation of their chemical properties. This ratio, within the context of the BMB approach, is referred to as the 'chemical value factor' of the feedstock.

2) Pressing and drying processes

Likewise, among the most frequently mentioned strategies for improving the sustainable performance of the woodworking sector, were energy efficiency measures, such as using low-energy machinery and renewable energy sources, optimizing transportation systems, selecting locally sourced raw materials, and certifying wood from sustainable sources, which promotes responsible forestry practices and supports reforestation (Garcia et al., 2024; Iritani et al., 2015; Van den Auwelant et al., 2024).

In this regard, the Best Available Techniques (BAT) reference documents (i.e., BREFs) constitute a cornerstone when referring to collect the most up-to-date or emerging technologies in terms of both energy savings and environmental impacts reduction. Therefore, the BREFs for the production of wood-based panels were also reviewed (Karlis et al., 2016). Based on the abovementioned sustainability concerns (see **Table 5**), the focus was put on those aimed at preventing or reducing air emissions from presses, apart from promoting energy-

¹ [NeoLigno® : Choosing Forest over Fossil](#)

² [Home | Stora Enso](#)

³ <https://koskisen.fi/>

⁴ <https://www.storaenso.com/en/newsroom/news/2022/1/the-first-fully-bio-based-furniture-board-in-the-world>

⁵ <https://www.ikea.com/global/en/newsroom/sustainability/ikea-to-use-bio-based-glue-for-reduced-climate-footprint-230301/>

efficiency profiles in the drying process.

The available techniques in BREFs can be categorized into primary and secondary methods for the prevention and reduction of emissions from presses. These are briefly described below:

Primary techniques to prevent or reduce emissions to air from presses.

- **Selection of resin/adhesive and appropriate press operating conditions:** The adhesive should contain a low level of free formaldehyde. In addition, it is important to optimize press operating conditions based on the resin type, including the correct combination of press time and temperature, to minimize formaldehyde emissions.

Secondary techniques to prevent or reduce emissions to air from presses (and dryers).

- **Wet electrostatic precipitator:** Uses wet scrubbing to remove a portion of organic compounds and dust from waste gas. The waste gas is then passed through an electrical field, where dust particles are captured and collected on electrodes.
- **Bag filters:** Collect dust by passing waste gas through a fabric medium. They are cleaned periodically, and the collected dust can be repurposed as fuel.
- **Electrified filter bed:** Employs electrostatic filtration to remove particulates and, to some extent, condensable organic compounds from the gas stream.
- **Wet scrubbers:** Eliminate dust particles and some gaseous organic compounds by bringing the gas stream into contact with water, utilizing inertial and/or diffusion interception within the water phase.
- **Bio-scrubbers:** Degrade both condensable and non-condensable VOCs adsorbed onto a packed bed containing a bacterial culture through biological oxidation. They also reduce dust through an initial scrubbing step.
- **Thermal oxidation:** Destroys organic compounds by thermally oxidizing combustible materials, converting all carbon present in the waste gas into CO₂.
- **Incineration of press water gases in an on-site combustion plant:** Incinerates collected waste gas from the press after initial dust removal via quenching or wet scrubbing. This process effectively destroys VOCs in the press emissions and contributes positively to the energy balance of on-site operations.

Nevertheless, there are some of these techniques that have proven to be the most suitable to be applied to the reduction of the air emissions coming from the press, which are:

- **Select resins with a low formaldehyde content, apart from controlled operation conditions of the press with balanced press temperature, applied pressure and press speed:** These techniques are focused on the abatement of VOCs, although its applicability may be limited to some factors such as demands for a specific product quality.
- **Wet scrubbing of collected press waste gases using Venturi scrubbers or hydro-cyclones, wet electrostatic precipitators or bio-scrubbers:** these techniques are focused on the reduction of both dust and VOCs, being applicable on a general basis.

- **Post-combustion as the last treatment step after application of a wet scrubber:** These techniques are focused on the reduction of both dust and VOCs, although its applicability may be limited to existing installations where a suitable combustion plant is not available.

Lastly, the technologies for the drying of wood particles and fibres, identified from the associated BREFs for the production of wood-based panels are the following:

- **Bundle dryers:** This type of dryer is composed by the rotatory bundle dryer and the tube bundle dryer. The former can achieve a temperature range exceeding the 200 °C, while the latter has a limited to 160 °C. Conversely, in terms of drying capacity, the tube bundle dryer has a drying capacity between two and ten times higher per tons of wood dried per hour. Both are heated directly by hot gas or indirectly by radiation heat.
- **Drum dryers:** This type of dryers is composed by the single-pass drum dryer and the three-pass dryer. Both can achieve temperature ranges around 400 °C, although in the case of the single-pass drum dryer, this can be exceeded by 50 °C. In terms of drying time, the single-pass drum drying process takes considerably longer, up to half an hour, while the three-pass does it in about 6 minutes. However, the drying capacity is more than doubled (40 and 25 tonnes per hour for the single-pass and three-pass dryers, respectively). As is the case of the bundle dryers, these dryers can be heated directly by hot gas or indirectly by radiation heat as well.
- **Tube dryers:** This type of dryers is composed by the flash tube pre-dryer and the jet tube dryer. They are suitable for production processes that require high operating temperatures (around 500 °C) and short drying times (from 3 minutes to less than 1 minute), with an average capacity of 10 tonnes per hour.

3.3 Selection of sustainability performance improvement solutions

Based on the compilation of information from the contextualisation section, the literature review on solutions to improve the sustainability performance of woodworking companies and the consultation of the related BREFs documents, a number of proposals were made for the specific case of the case studies selected in the CALIMERO project for the woodworking sector.

Use of bio-based adhesives

The BMB approach turns out to be a valuable method for estimating the potential impacts of pMDI as opposed to a bio-based alternative because it offers a rapid and pragmatic solution in scenarios where comprehensive data may be lacking. Then, this method was selected to be applied to case study 1 to know in more detail the advancements in sustainability terms when selecting a bio-adhesive as opposed to other commercial alternatives based on the use of fossil-based resources.

The steps when applying this approach are the following:

1. Estimation of the environmental burdens of the fossil-based adhesive (i.e., pMDI). The LCA of pMDI serves as the starting point, making it essential to collect inventory data for pMDI. In this case, relevant information on the production of pMDI is available in ecoinvent (B_{fossil}).
2. Estimation of the environmental burdens of bio-feedstocks and fossil feedstocks. The pMDI inventory must be carefully reviewed, with a particular focus on tracking feedstocks. Currently, pMDI is derived from aniline, which is produced from benzene. Benzene, in turn, is obtained from naphtha or natural gas through refinery processes. For this approach, it is assumed that these fossil-based feedstocks

are replaced by bio-feedstocks —specifically, bio-naphtha and biogas (bio-methane). Consequently, an LCA should be conducted for each feedstock ($B_{\text{bio-feedstock}}$ and $B_{\text{fossil-feedstock}}$).

3. Quantification of the amount of the fossil feedstock to be replaced by bio-feedstock (a) through an MFA.
4. Evaluation of the equivalent amount of bio-feedstock required. Bio-feedstocks may have different carbon content, energetic value or other chemical properties from the fossil feedstocks to be replaced. This could lead to higher or lower requirements for bio-feedstock quantities compared to the quantities of fossil feedstocks. In such situations, it is necessary to consider the equivalent quantities of bio-feedstocks. For these purposes, an equivalent factor (cv), based on LHV of fossil and bio-feedstocks is used as an approximation of the chemical properties (see **Equation 1**).

$$cv = \frac{LHV_{\text{fossil feedstock (substituted)}}}{LHV_{\text{biofeedstock}}} \quad (\text{Equation 1})$$

5. Estimation of the environmental burdens for biomass balance products (B_{BMB}). Each product is calculated following the **Equation 2**.

$$B_{\text{BMB}} = B_{\text{fossil}} + a \cdot (cv \cdot B_{\text{biofeedstock}} - B_{\text{fossil feedstock}}) \quad (\text{Equation 2})$$

Optimisation of pressing conditions

For the minimisation of both pollutant and toxic emissions from the pressing process of case study 1 and taking into account the findings of the research on the BREFs documents, the application of primary techniques, specifically, the optimisation of the pressing conditions, was chosen to achieve this objective. After simulating the emissions, viable operating conditions were first defined with the industrial partner, who provided a range of values (both for pressing time, temperature and adhesive concentration) that allowed for process optimisation while maintaining product quality, i.e., not compromising the mechanical properties of LSL produced in the factory (see **Table 7**). This information was incorporated into the MOO tool developed in WP4 to find out the optimal pressing conditions for the overall best environmental performance.

Variable name	Unit	Range
Pressing time	s	[260, 300]
Operating temperature	°C	[150, 210]
Adhesive concentration	%	[4.8, 5.2]

Table 6 Name, units and ranges of the variables selected from case study 1 to be optimized for the woodworking sector

Use of wet scrubbers, wet electrostatic precipitators or bio-scrubbers

The use of secondary techniques for emissions abatement in the pressing process was also investigated. For this purpose, we contacted Scheuch⁶, one of the world market leaders in industrial system engineering for clean air with extensive experience in the woodworking industry applications. The range of technologies

⁶ <https://www.scheuch.com/en/>

available from this company goes from bag filters, dry electrostatic precipitators (ESP), wet electrostatic precipitators (WESP) and scrubbers or condensers (last two very appropriate for dryer and press exhaust air cleaning)

Unfortunately, discussions with Scheuch revealed that these technologies are, so far, only used in continuous presses, therefore none of these are compatible with the process in case study 1 which uses a batch press. Batch presses can be “single daylight” or “multi-daylight”, and they produce one or more long boards, in batches, which are subsequently cut to the required length. Although still present in many production plants, batch presses have gradually been replaced by continuous presses, which are generally more efficient (they have considerably lower energy requirements since they do not need to open and close but they remain closed, they have reduced trimming and sanding losses...). Current filtering/scrubbing technologies are designed for continuous presses where emissions are also continuous, and which allow for the installation of the filter/scrubber at a point in the press above the conveyor belt transporting the board, where it is possible to capture these emissions. On the other hand, emissions in batch presses are temporary and punctual (e.g. gases are emitted during the two minutes that the press is closed and then stops), and, above all, because it is extremely difficult to physically capture the emissions in this type of press. Therefore, this alternative had to be excluded.

Drier upgrade

To address the environmental impact and economic concerns related to electricity consumption during the drying process, the hypothetical replacement of the existing dryer with a more energy-efficient technology was assessed.

For this purpose, primary data regarding the feasibility and characteristics of the production process in the selected CALIMERO case study were considered. Additionally, other common factors in technology selection processes were taken into account, including the availability of heat sources, spatial constraints, required processing capacity, emissions and their abatement, as well as total investment, operating, and maintenance costs. The dryer used for the manufacturing of LSL in case study 1 is a continuous dryer in which the strands circulate on top of trays in a drying chamber and are progressively dried by a source of hot air. Nowadays, this type of technology is outdated, and the most common driers are three pass and single pass dryers. Specifically, in the OSB industry—which can be used as a proxy for LSL since both products have a similar particle size and geometry and are primarily used in structural applications—the single pass drum dryer is by far the most common (see **Figure 8**). Consequently, this was the technology selected for potential upgrading. The improvements in electricity consumption and, therefore, the associated economic impact, will be assessed by comparing the technical characteristics of the current and upgraded systems.



Figure 8 Single pass dryer in an OSB manufacturing process

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4 BIO-CHEMICALS

4.1 Contextualization

4.1.1 Case Study Description

For the bio-chemicals industry, a case study was performed together with the industrial partner BIM Kemi with the aim of assessing the environmental impacts associated with their ester production. The chosen functional unit was a production output of 1 kg ester. The scope considered in the study was a cradle-to-gate method starting from resources extraction through to ester production. The chosen system boundaries for the production are shown in **Figure 9**. Economic allocation was addressed for the outputs of kraft pulping and recovery, specifically softwood pulp and black liquor soap.

During the kraft pulping process in ester production, raw materials such as wood chips are subjected to a cooking process where they are treated with an alkaline solution. The process breaks down the lignin in the wood and releases various components, including resinous materials. The resulting mixture is separated into two main fractions: the pulp (i.e. cellulose fibers) and the black liquor. The black liquor contains dissolved lignin, resin acids, and other by-products. The liquor undergoes a recovery process to reclaim the alkaline chemicals used in the pulping process. As part of the recovery process, tall oil is extracted from the black liquor. The tall oil consists of a mixture of fatty acids, resin acids, and other compounds derived from the wood's resinous content. The extracted crude tall oil can undergo additional processing steps to refine its composition and remove impurities.

For Polyethylene glycol (PEG) production, a fossil-based alternative was considered. PEG is synthesized through the polymerization of ethylene oxide, a key monomer derived from either crude oil or biomass. The production process for ethylene oxide varies depending on the feedstock used. Firstly, crude oil is processed to extract ethylene, a hydrocarbon that serves as the primary precursor for ethylene oxide. Then, ethylene is subjected to a process called ethoxylation, where it reacts with oxygen in the presence of a catalyst. This process results in the formation of ethylene oxide.

In the esterification process, PEG as alcohol and tall oil fatty and resinous acids such as carboxylic acid react to produce ester. The esterification process is typically carried out at elevated temperatures to accelerate the reaction, and the equilibrium between reactants and products is influenced by factors such as temperature and concentration. Finally, the ester product will be back to the pulping mills.

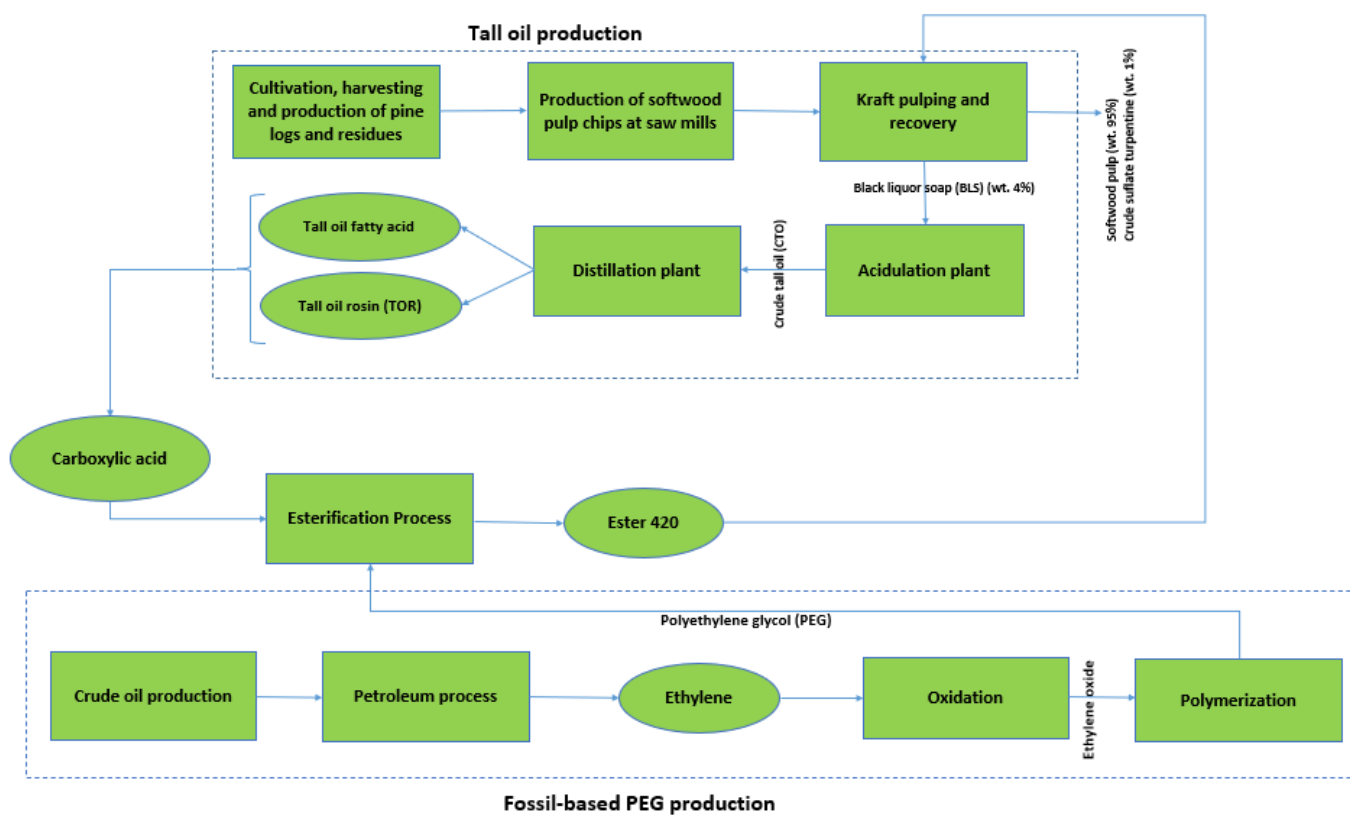


Figure 9 System boundaries for ester production plant, here referred to as 'Ester420'.

4.1.2 Case Study Lifecycle Aspects, Impacts and Hotspots

With regards to biochemicals production, environmental hotspots result from the agricultural phase as well as the use of chemicals and energy-intensive processes that release pollutants into the environment. These pollutants can lead to a range of adverse environmental impacts such as water and air pollution, habitat destruction, and loss of biodiversity. Biochemicals, which are produced from renewable biomass sources, have been promoted as a more sustainable alternative to fossil-based chemicals. However, producing biochemicals on a large scale poses significant environmental challenges. For example, biochemical production processes require large amounts of water, energy, and chemicals, which can lead to the release of GHGs and other harmful pollutants. Additionally, the agricultural practices required to produce the biomass feedstocks can result in land use change, deforestation, and loss of wildlife habitat. To mitigate the negative environmental impacts associated with the production of biochemicals, several strategies can be employed, such as using more efficient production processes, reducing the amount of waste produced, and implementing sustainable feedstock production practices. Additionally, the development of a circular economy approach, where waste products are recycled and reused, can further reduce the environmental impact of biochemical production (Ögmundarson et al., 2020a, 2020b).

The most important and abundant biochemical production in the world and in Europe is bioethanol where about 80% of the production stems from fermentation of food commodities such as sugarcane and corn. The production causes significant environmental burdens. Hence, using of organic wastes and conversion of them to bioethanol can mitigate GHG emissions and waste disposal impacts from agriculture. Therefore, the adoption of environmentally friendly production practices is crucial in ensuring that the transition to renewable biochemicals does not result in the creation of new environmental hotspots (Obydenkova et al., 2022).

Results from the case study analysis of ester production in the BIM Kemi facility (Task 2.1) indicate that the upstream process of tall oil production is the main cause for emissions across various environmental indicators due to chemical processes and energy consumption. The extraction and refining of tall oil involves chemical reactions and treatments that release pollutants, contributing to acidification, human toxicity, and eutrophication. The process is energy-intensive, relying on fossil fuels, which leads to emissions of particulate matter, ozone-depleting substances, and resource depletion. Moreover, results from the case study indicated that PEG production based on fossil fuels is primarily responsible for CO₂ emissions due to the nature of its feedstock and energy requirements. Fossil fuels, such as petroleum and natural gas, are the primary sources of carbon emissions in traditional PEG production. The extraction, refinement, and processing of these fossil fuels release significant amounts of CO₂ and other greenhouse gases into the atmosphere. Additionally, the energy required for these processes often comes from burning fossil fuels, further exacerbating CO₂ emissions. As a result, the entire lifecycle of fossil fuel-based PEG production, from raw material extraction to final product, contributes heavily to the overall carbon footprint.

4.1.3 Industrial Processes Simulated

In D 2.2 in CALIMERO, two case studies were performed related to the biochemicals sector, the first one looking into downstream processing of second-generation bioethanol and the other one focusing on bioethylene production from second generation bioethanol.

With regards to the first case study, the focus was on producing bioethylene with an energy-efficient process from bioethanol produced by their second-generation bioethanol plant. The background scenario considered in this work was the second-generation bioethanol plant-wide simulation model developed by Prunescu et al. (2017) for MELIORA large-scale plant. The model includes pre-treatment, enzymatic hydrolysis, and co-fermentation sections, respectively. The output of the plant-wide simulation model –the fermentation broth coming out from the co-fermentation section –is used as the input for the bioethanol downstream model developed for this case study. The proposed downstream process configuration (**Figure 10**) is based on Bisgaard et al. (2017). In a first step, the beer stripper column separates the solids from the fermentation broth by stripping the product stream with steam. The remaining solids are separated from the beer column bottoms with a filter press and sent for combustion. The remaining solids are separated from the beer column bottoms with a filter press and sent for combustion.

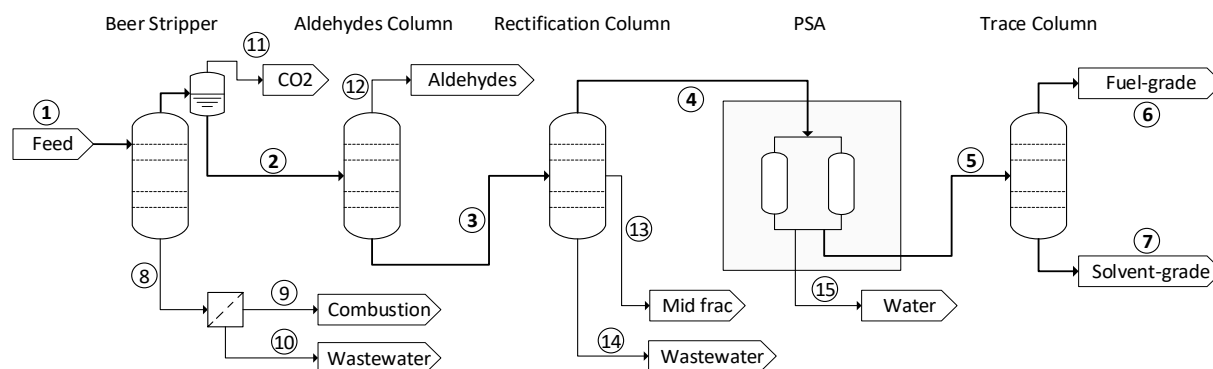


Figure 10 Scheme depicting the downstream process for bioethanol purification

The aldehydes column removes acetaldehyde, 1-propanal, 1-butanal, crotonaldehyde, and ethyl acetate. The main function of the third column, the rectification column, is to further concentrate ethanol up to a distillate with an azeotropic mixture of ethanol and water. The side draw is implemented to remove benzaldehyde, 1-propanol, 1-butanol, 2-butanol (s-butanol), 2-methyl-1-propanol, 2-methyl-1-butanol, and 3-methyl-1-butanol.

The top product from the rectification column is sent to a molecular sieve unit to produce anhydrous ethanol. A fourth column, the trace column, is required to separate the remaining impurities, which are mainly methanol. Thereby, methanol can be separated with ethanol as the top product obtaining a solvent-grade ethanol with a purity of over 99.9 % (w/w) at the bottom.

With regards to the second case study, the focus was on producing bioethylene with an energy-efficient process from bioethanol produced by their second-generation bioethanol plant. The basic process layout of the ethylene process is depicted in Error! Reference source not found..

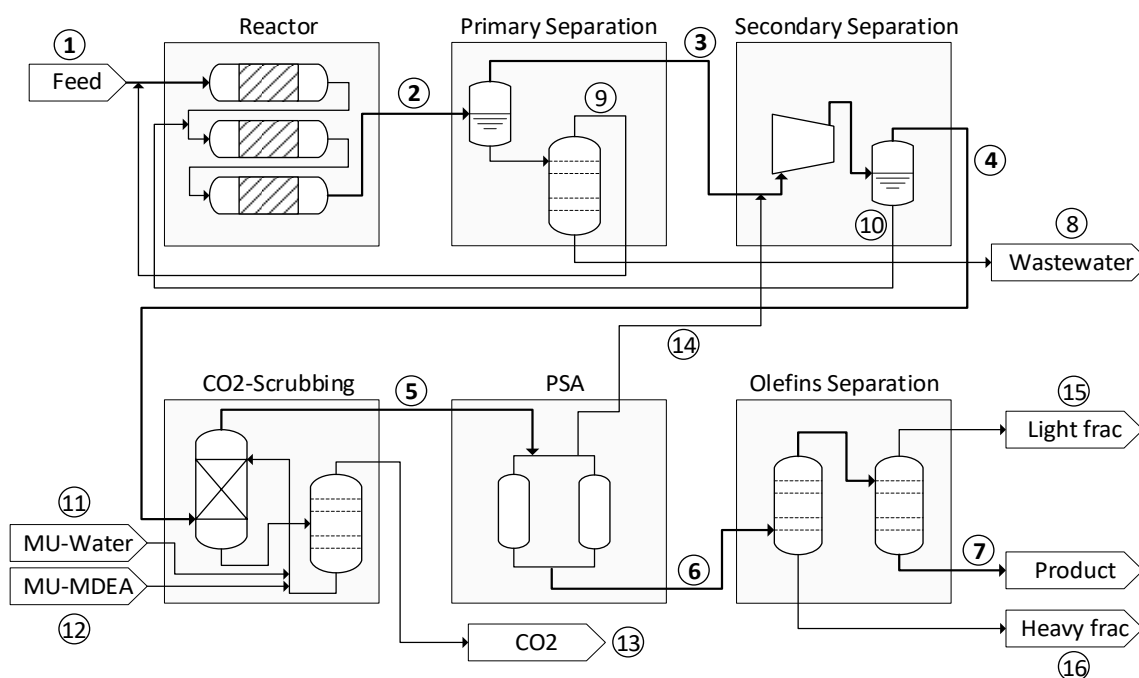


Figure 11 Scheme depicting the ethylene process

In a first step, ethanol is dehydrated to ethylene in a train of adiabatic fixed-bed reactors. Before being fed to the reactor, the ethanol is heated since the dehydration reaction to ethylene is strongly endothermic. As water is produced during the reaction, this is separated in two steps, namely a primary and secondary separation, where the pressure is increased to around 16 bar to further condense the remaining water. Carbon dioxide, a side product of the dehydration reaction, is separated in an absorber column using methyl diethanolamine (MDEA). After that, the remaining humidity is removed using pressure-swing adsorption (PSA) columns followed by a cryogenic olefin separation that removes methane, hydrogen, acetaldehyde, and other impurities to achieve polymer-grade ethylene (high purity, suitable for polymerization).

4.1.4 MOO Framework Analysis

In CALIMERO WP4, one case study was performed focusing on improving the reactor section of a second-generation bioethanol process developed within WP2, aimed at recovering bioethanol through an energy-efficient downstream configuration. Here, ethanol is converted to polymer-grade ethylene using three adiabatic fixed-bed reactors at different temperatures, as described by Bisgaard et al. (2017), from which ethylene is obtained with >99.9% purity.

A detailed process simulation was developed in Aspen Plus to model this reactor train. The system includes three adiabatic reactors (REACTOR1, REACTOR2, REACTOR3) and an intermediate heater. The feed enters at 25.0°C, is preheated, and undergoes exothermic dehydration reactions across the reactors. Mass and energy

balances, reaction kinetics, and thermodynamic models were used to predict temperature profiles and energy demands. This approach supports optimization of the reactor sequence by simulating reaction behaviour and energy flows without physical trials.

In WP4, the framework evaluated five different solutions by analyzing temperature variations, reactor length, and overall environmental and operational performance with results showed in **Table 7** below. Each solution presented distinct characteristics, influencing material stability, energy efficiency, and sustainability.

From an environmental perspective, Solution 5 was found to emerge as the most sustainable option, showing the lowest climate change impact, non-carcinogenic human toxicity, and carcinogenic human toxicity. Solution 2 was also found to perform well, particularly in reducing freshwater ecotoxicity and overall environmental impact, making it a strong competitor. Notably, Solution 3 was found to cause significantly high freshwater ecotoxicity, making it a less desirable choice for environmental sustainability. From an economic standpoint, operational expenditure (OPEX) was found to remain fairly consistent across all solutions, with Solution 1 having the lowest costs, while Solutions 2 and 5 incurred slightly higher expenses. However, since the cost differences were found to be minimal, economic factors are not the primary drivers in the decision-making process.

Objectives	Solution 1	Solution 2	Solution 3	Solution 4	Solution 5
Climate Change (kg CO ₂ eq.)	-70%	-82%	-74%	-76%	-82%
Human Toxicity: Non-Carcinogenic (CTUh)	-15%	-60%	-29%	-38%	-61%
Human Toxicity: Carcinogenic (CTUh)	-15%	-52%	-26%	-33%	-55%
Ecotoxicity: Freshwater (CTUe)	-46%	-75%	-37%	-36%	-28%
Single score (Pt)	-76%	-86%	-79%	-81%	-86%
OPEX (€)	-30%	-27%	-30%	-27%	-27%

Table 7 Solutions identified for the Bio-Chemical case study

4.1.5 LCSA Methodological Improvements Considered

For the update of the case studies in Task 5.3, the biochemicals sector study will focus on assessing all environmental categories previously assessed, i.e. according to the PEF framework. Moreover, the study will cover the socioeconomic indicators of Job creation potential as well as Life Cycle Costing indicators. A specific objective for the biochemicals sector in the CALIMERO project is to reduce occupational health and safety risks by 25%. For this, the case study will apply the methodology of the indicator of Occupational health and safety risks which was developed within the WP3 in CALIMERO.

4.2 Search for sustainability performance improvement solutions

4.2.1 Solutions from Contextualization Review

Based on the work from D 2.1 and D 2.2 within CALIMERO, the following sustainability improvement options have been identified within ester production:

- Reducing the amount of waste produced
- Implementing sustainable feedstock production practices
- Recycling and reuse of by-products and waste
- Use of organic wastes and conversion of them to bioethanol
- Use bio-based inputs in ester production instead of fossil-based substrates
- Design the production process of bio-based PEG to be more energy-efficient and environmentally friendly, relying more on renewable energy sources

4.2.2 Solutions from Literature Review

Potential solutions to reduce environmental impacts associated with the production of biochemicals include the use of more efficient production processes, reducing the amount of waste produced, and implementing sustainable feedstock production practices. Additionally, the development of a circular economy approach, where waste products are recycled and reused, can further reduce the environmental impact of biochemical production (Ögmundarson et al., 2020a, 2020b). The use of organic wastes and conversion of them to bioethanol can mitigate GHG emissions while providing a sustainable and eco-friendly method for waste disposal. Therefore, the adoption of environmentally friendly production practices is crucial in ensuring that the transition to renewable biochemicals does not result in the creation of new environmental hotspots (Obydenkova et al., 2022).

A promising approach to enhancing sustainability in the biochemicals industry involves integrating bio-based raw materials through industrial symbiosis. This was also described for the case of ester production mentioned in the D2.1 report in CALIMERO. One key opportunity is in replacing fossil-based carboxylic acids with tall oil, a by-product of the pulp and paper industry. By utilizing tall oil, the bio-chemical sector not only reduces reliance on non-renewable resources but also strengthens cross-sector collaboration, particularly with the pulp and paper industry. To ensure its suitability for ester production, crude tall oil (CTO) undergoes refining to remove impurities and optimize its composition. This refined bio-based carboxylic acid can then be directly used in esterification, aligning with circular economy principles while reducing environmental impact.

An important part of ester production is the use of PEG, which is conventionally synthesized through the polymerization of ethylene oxide, a process heavily reliant on fossil-derived ethylene. A sustainable alternative is transitioning to bio-based ethylene oxide, which can be produced from bioethanol derived from various biomass feedstocks such as from sugarcane, corn, or lignocellulosic biomass. Additionally, a source of bioethanol could be biowaste from the wood-working industry, which generates significant amounts of residues that can be repurposed for ethanol production. By utilizing these bio-based resources, the production of PEG can significantly reduce dependency on fossil fuels while growing a cross-sectoral synergy between the biochemical and wood-working sectors (Soleymani Angili et al., 2021; Zanon-Zotin et al., 2023).

Additionally, there are alternatives for the production of esters which could be applied at the BIM Kemi facility, in order to make the most of a bio-based, renewable feedstock while improving energy and emission efficiency.

With regards to tall oil production, alternatives include:

- Increase tall oil yield via process optimization: Improve black liquor soap production and separation techniques to maximize crude tall oil (CTO) extraction, reducing the need for additional processing and

energy (Cashman et al., 2016).

- Utilize renewable energy for recovery operations: Replace fossil fuels in tall oil distillation and recovery units with biomass-derived steam, solar thermal, or electrification powered by green energy (Kiss & Smith, 2020).
- Valorize all by-products: Convert remaining lignin and black liquor residues to biochar or biogas, offsetting energy use elsewhere in the mill (Aro and Fatehi, 2017).

With regards to PEG production, apart from using bio-based alternatives as previously discussed, an alternative would be to adopt carbon capture and reuse (CCU) during the ethylene oxidation production. This would entail capturing CO₂ generated during ethylene oxidation and reuse it in other chemical processes (de Faria et al., 2019).

Within improvements for the esterification process, these could include the following alternatives:

- Use catalysts to lower energy demand: Employ solid acid catalysts (e.g., zeolites, sulfonated carbons) or enzyme-based biocatalysts (e.g., lipases) to perform esterification at lower temperatures and pressures, reducing energy use (Shanmugam et al., 2004).
- Switch to continuous processing: Replace batch reactors with continuous flow systems to improve heat integration, reduce waste, and enhance yield with tighter control of reaction conditions (Nyhlén, F., pers. comm., 2024).
- Integrate waste heat recovery: Capture and reuse waste heat from esterification or upstream processes (e.g., ethylene oxide production) to reduce additional heating requirements (Farhat et al., 2022).

Several biochemical substances can be produced from organic waste where a significant example is represented by adipic acid, typically derived from fossil sources. Producing adipic acid through bioprocessing routes appears promising as it not only eliminates N₂O emissions, but also enhances the use of renewable resources such as biomass, instead of fossil feedstocks. Forest residues, primarily composed of branches and tops from commercial thinning, can be considered a promising renewable resource (Aryapratama and Janssen, 2017).

4.2.3 Solutions BREF Documents Review

Within the BAT reference document for the Production of Large Volume Organic Chemicals (Falcke et al., 2017) relevant BATs related to ester production were identified. These include for example process optimization, such as using efficient catalysts which can reduce by-products and enhance reaction yields in esterification processes. Moreover, the BREF document points at techniques for increased energy efficiency such as utilizing heat exchangers for the recovery and reuse of thermal energy within processes, which has the potential to lower external energy requirements. The BREF also points at waste minimization for which solutions include by-product utilization. Specifically, identifying and utilizing by-products within processes or converting them into valuable secondary products can minimize waste generation. Additionally, designing closed-loop systems with processes that recycle solvents and other materials internally can reduce the need for raw material inputs and decrease waste outputs.

Specifically, within the BREF document, BAT solutions for ethylene oxide and ethylene glycols are included, which are used in the production of esters. The BREF document concludes on processes to reduce environmental impacts through process optimization, emissions reduction, and increased resource efficiency.

For example, to reduce emissions of organic pollutants as well as CO₂, the suggested BAT recommends using oxygen instead of air in the process of oxidation of ethylene to ethylene-oxide. Moreover, to recover energy and reduce emissions of organic compounds to air from ethylene-oxide plants, various techniques are recommended such as Pressure Swing Adsorption and membrane separation to recover ethylene from inert gases. Pressure Swing Adsorption works by adsorbing ethylene onto a solid material under high pressure and desorbing it at lower pressure for reuse or recovery. Other options include catalytic oxidation of off-gases to reduce emissions of volatile organic compounds (VOCs), and thermal oxidation of off-gases as an alternative technique for VOC abatement.

Within measures to improve energy efficiency, the recommended BAT suggests using heat exchangers for recovering heat from process streams and reducing the need for external energy sources. Finally, to reduce waste and emissions, it is recommended to implement an effective waste management system, which includes recovery and reuse of by-products and residual streams, as well as treatment of waste to reduce environmental impact before disposal or discharge.

4.3 Selection of sustainability performance improvement solutions

The main solution identified for further study within the Task 5.3 for the biochemicals case study will include:

- 1) Investigating the environmental and socioeconomic performance of producing an ester at BIM Kemi, using a bio-based PEG. As pointed out previously, when shifting from fossil-based to bio-based PEG the net CO₂ emissions can be significantly lower, or even negative, when accounting for biogenic carbon.
- 2) Alternatives for using a larger share of renewable energy sources in the production processes for bio-based PEG as well as making the processes more energy-efficient
- 3) Adopting carbon capture and utilization from CO₂ released during ethylene-oxide production, reusing it the captured CO₂ in other chemical processes.
- 4) Integrate waste heat recovery: Capture and reuse waste heat from esterification or upstream processes (e.g., ethylene oxide production) to reduce additional heating requirements.

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5 PULP AND PAPER

5.1 Contextualization

5.1.1 Case Study Description

Two case studies were employed within the pulp and paper sector in Task 2.1: One focusing on tissue production and one focusing on forestry production. Both studies were conducted together by IVL Swedish Environmental Research Institute and Essity Hygiene and Health AB⁷.

Tissue Case Study

Tissue was chosen as an interesting product as this is one of the main pulp and paper products produced in Europe and can be generated from primary wood fibres as well as wood fibres recovered from recycled paper (Joint Research Centre, 2015). During the development of the Product Environmental Footprint (PEF) methodology and the Product Environmental Footprint Category Rules PEFCR for the product group, “intermediate paper products” (Ringman et al., 2018), several gaps and challenges related both to inventory data and impact assessment and interpretation were identified. Examples include assessment of biodiversity and other land use related impacts such as using the LANCA land use indicators or carbon flows on forest level.

The aim of the tissue case study was to assess the sustainability impacts of the production of average tissue paper to identify areas of improvement for the PEF methodology as well as for economic and social LCA. The overall goal of the case study was to create a base line and to test the current impact assessment methodology. The purpose of this goal was to identify any data gaps for further assessment and the development of methodologies for including biodiversity, ecosystem services, and climate change impacts in the PEF method.

The study was carried out on an average intermediate tissue paper, put together based on statistics to be representative for a European average tissue paper. The tissue is assumed to be wet strong, i.e., it can potentially be used to produce handtowels, household towels, napkins or handkerchiefs, but not toilet paper. The functional unit of the study was the production of 1 tonne of intermediate tissue paper grade at the tissue machine gate and with an average moisture content of 5%. Since we assessed a theoretical average intermediate tissue paper, the actual grammage was assumed to vary between 15-35 g·m⁻² and the code for the products by activity in the PEFCR document is 17.12.2: *Toilet or facial tissue stock, towel or napkin stock, cellulose wadding and webs of cellulose fibres.*

The outline of the life cycle is shown in **Figure 12** with the sustainability impacts of the tissue studied from cradle-to-factory gate (where the production of the mother reel, i.e., the end of the tissue machine, is the point of cut-off). The cradle-to-gate system starts when resources are extracted from nature and ends when the product components enter the gate of the studied product’s production facility, either for further processing or further distribution.

The production starts with the inflow of fibre raw materials, either from collected paper for recycling or from wood. For the production of the tissue, pulp production is a core process which is studied further within the project (see below in Sections describing optimisation of selected variables within the pulping process). In addition, other materials like chemicals or packaging, energy wares and water needed for the manufacture of the product have been taken into consideration. The system ends with the intermediate product before further processing such as converting, and before it is distributed to and used by a customer.

In the base scenario, it is assumed that the raw material extraction and production processes takes place in

Sweden. As an alternative scenario to illustrate a European average setting, the background energy data for externally supplied electricity, steam, and thermal energy are changed to a European average mix. In the Swedish case, the output of sludge from the tissue production process is used to generate internal electricity and steam. In the case of the European average case, it is considered that all electricity and steam are purchased, and that the sludge is sent to incineration.

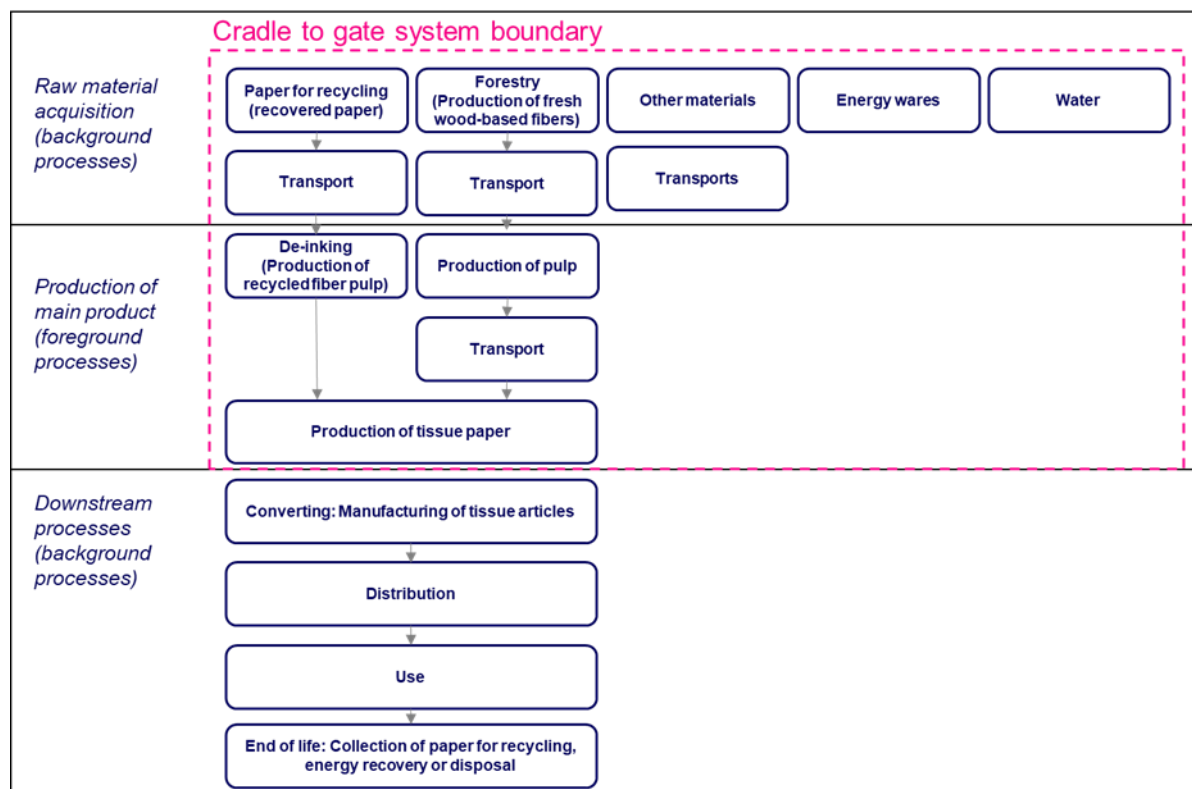


Figure 12 System boundary diagram of the actual intermediate tissue product assessed

Forestry Case Study

With regards to forestry, this was considered as an interesting case study as the forest industry delivers raw material to several of the CALIMERO project bio-based sectors (i.e., pulp and paper, construction, and woodworking).

Moreover, the focus in the methodological development within this project is on developing the methods used for assessing for example biodiversity, ecosystem services and the climate change impact, which all are highly relevant for the forestry activity. It was also mentioned in D1.1 for pulp and paper, that data is missing, especially for forestry, where there currently are difficulties in obtaining data regarding land use and related to soil quality and biodiversity. Additionally, background data for forestry in LCA databases is not counted (e.g. Ecoinvent) or currently missing (e.g. LCA for experts by Sphera). Consequently, a proper application of the LANCA method in the EF Land use impact category, regionalized at country level or macro-areas, is challenging.

The overall aim of the forestry case study was to create a base line methodology for including biodiversity, ecosystem services and other relevant environmental impact indicators. This would be done by assessing and gaining knowledge about currently available data for forestry and identifying gaps in terms of inventory data according to the current methodology (PEF).

The studied system was forestry in Sweden from production of seedlings to harvesting of softwood, suitable for use in the pulp and paper industry. The functional unit of the study is the production of 1 m³ pulp wood solid under bark (m³sub). As an intermediate product the functional unit can be seen as a declared unit and is at the same time the reference flow, i.e., 1 m³ pulp wood solid under bark (m³sub).

A flowchart of the included activities is shown in **Figure 13**. In the case study, the sustainability impacts of forestry are studied from cradle-to-forest operations gate (where seedling production is the starting point and the transportation from the cutting site to a landing point of pick up, i.e., before transportation to sawmills or pulp mills, is the point of cut-off). The cradle-to-gate system starts when resources are extracted from nature and ends when pulpwood enter the gate of the studied forest system, either for further processing or for further distribution. In addition, materials like lubrication oil, energy wares and water needed for the manufacture of the product, as well as land use in terms of land occupation, are included. It was assumed that the raw material extraction and production processes takes place in Sweden. Capital goods and infrastructure (e.g., construction of greenhouses for seedling production) are excluded from the system boundaries. However, road maintenance and its occupation are included in the system boundaries.

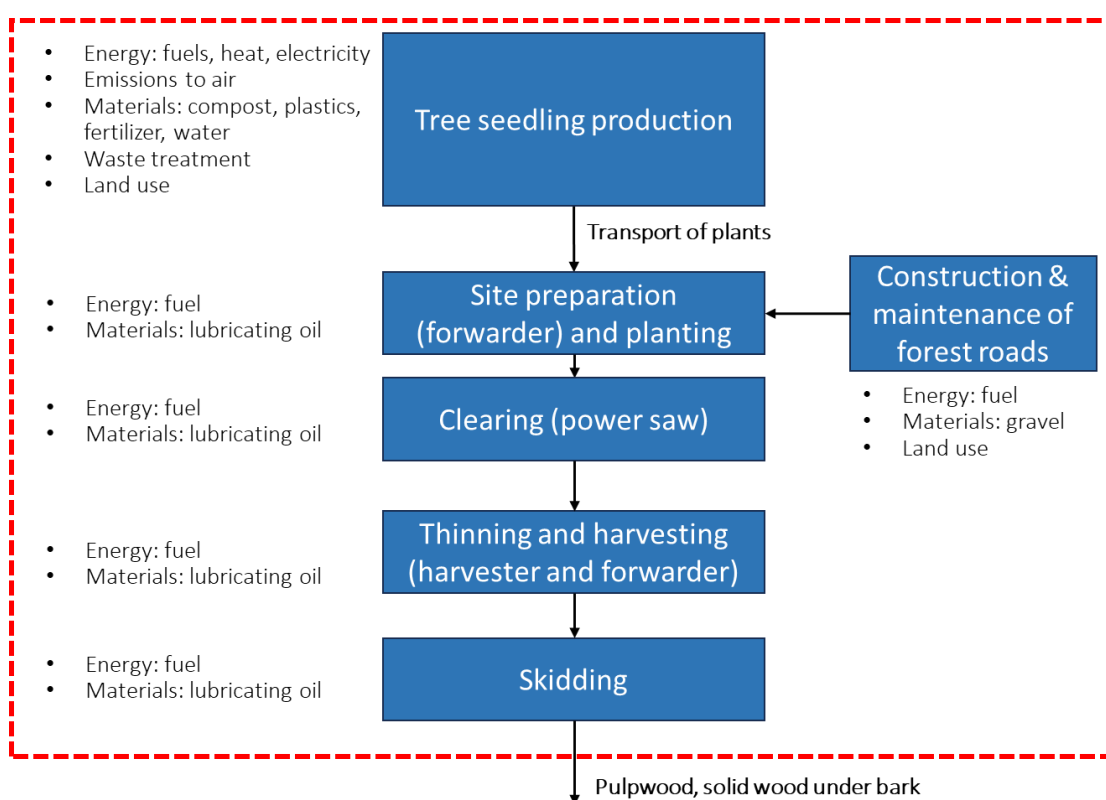


Figure 13 Flowchart of the included activities. The dashed line illustrates system boundaries

5.1.2 Case Study Lifecycle Aspects, Impacts and Hotspots

The pulp and paper industry is among the top five most energy-intensive industries globally, accounting for approximately 6% of global industrial energy use and 2% of direct industrial CO₂ emissions (Del Río et al., 2022). Much of the energy use comes from burning biomass, but fossil resources are also used, especially during papermaking. The use of energy from fossil resources in pulp and paper production has environmental implications and is an important issue for the sector. Since 1990s, the industry has conducted significant environmental improvements, such as use of environmental and energy management systems. Ecolabelling has also been used widely by the industry for many years. Today, the challenge is to continue improving the

production processes from an environmental perspective. In the past, emissions to air have been a significant problem, where sulphur emissions from pulp production have contributed to acidification. However, sulphur emissions have been reduced due to process technology improvements and efforts to not exceed critical air pollution levels for mills in Europe (Suhr et al., 2015).

A major challenge within the pulp and paper industry is the demand for wood, which makes it one of the main drivers of forest loss and deforestation of both natural and plantation forests. From 1700 to 2020, the world has lost 1.5 billion hectares of forest with deforestation rates peaking in the 1980s. However, although deforestation rates have declined since then, the net loss remains significant at an average rate of 4.7 million hectares per year between 2010 and 2020. Approximately 95% of global deforestation occurs in tropical regions, with Latin America and Southeast Asia being the most affected regions (Our World in Data, 2023). Deforestation contributes significantly to global CO₂ emissions, with contributions estimated to be around 10% of global anthropogenic GHG emissions (IPCC, 2019; FAO, 2024). Apart from generating GHG emissions, environmental concerns also include loss of natural habitat leading to biodiversity loss and species extinction and soil erosion.

With regards to the use of chemicals, pulp and paper/paperboard production is an important hotspot from an environmental perspective, both in terms of production of the chemicals themselves and the release of chemicals to the water recipient. Water emissions have been improved over time, but high water-flow rates mean that water emissions remain a central environmental issue. Examples of contaminants in emission to water are chemical additives like EDTA, nutrients (nitrogen and phosphorus) contributing to eutrophication and discharge of suspended solids (Suhr et al., 2015).

Another significant environmental aspect is the water used by the pulp and paper mills. Water recirculation techniques have been developed to decrease net use of freshwater. Further reduction of water use is essential for regions with scarce water resources or a dry climate (Suhr et al., 2015).

With regards to the tissue production case study in Task 2.1, results showed that the most relevant processes to a large extent depend on the type of energy used in the tissue process. In the case study performed, this is represented by different energy supply set ups in the two included locations of the deinking and tissue production processes. In general, the energy input (thermal and electricity) has a large influence on the environmental impact. In situations where the energy supplier is decarbonized and/or internal energy from decarbonized sources is used, the production of chemicals used in the processes contribute significantly to the total environmental impact. In addition, applying the circular footprint formula has the effect of changing the contribution shares from the manufacturing of fresh fibre pulp and recycled fibre pulp (de-inked pulp) 74% and 25%, respectively, when based in the actual content, to 87% fresh fibre and 13% from recycled fibre. Considering this, it is not surprising that the manufacturing of fresh fibre pulp contributes more to the total environmental impact than the recycled fibre production.

A major sustainability challenge within the pulp and paper sector entails life-cycle waste generation, where estimations suggest the industry is responsible for up to 40% of the annual municipal solid waste worldwide. Recycling of paper waste has therefore been highlighted as a top priority within the sector (Del Río et al., 2022). Globally, around 50% of waste-paper is recycled, with numbers being higher in Europe with around 72% of all paper waste and over 80% of paper boards being recycled (Del Río et al., 2022).

For the update of the case study of tissue in Task 5.3, it is of importance to consider the full life-cycle for tissue, i.e., including use and end of life. For tissue, which in most cases is a single-use disposable product, this means including collection of tissue paper for recycling and also considering a higher share of recycled material input or use of alternative fibre sources such as wheat straw. However, the tissue industry is already a high user of recycled fibre and the decreased availability of paper for recycling, due to an overall lower use in the society of newspaper and graphic paper, is currently a barrier.

In the case study, the guidelines stipulated by the PEFCR for paper products were followed, which included the environmental categories of acidification, climate change, abiotic resource depletion (fossil fuels) and particulate matter. Another relevant impact category for products based on forestry raw materials is land use. The PEF and the PEFCR requires that land use is modelled using the LANCA method (European Commission, 2021) and including the following 5 sub-indicators:

- Soil quality index
- Biotic production
- Erosion resistance
- Mechanical filtration
- Groundwater replenishment

A more detailed dataset should be created for forest operations, taking into account local characterization factors to use for LANCA. This would also enable to make one of the largest flows in the case study compliant with the PEF standards (regarding carbon flows in the forest and how outputs of energy are handled) as well as using the dataset generated in the forestry case study as an input.

5.1.3 Industrial Processes Simulated

In D2.2, one case study was performed within the pulp and paper sector. The case study focused on the environmental effect of alternative process routes in the chemical recovery of a pulp plant to reduce the environmental impact of produced tissue paper.

The alternative routes investigated included:

- Lignin recovery (1-4) to reduce recovery boiler load and thus increase production capacity.
- Electric plasma lime calcination (5, 6) to reduce bio- and fossil-fuel consumption.
- CO₂ capture (7, 8) from recovery boiler and calcination.

The chemical recovery section of the pulp plant was the focus of the simulation model as that is where the alternative process routes take place. A simplified flowchart of the pulp plant is presented in **Figure 14**.

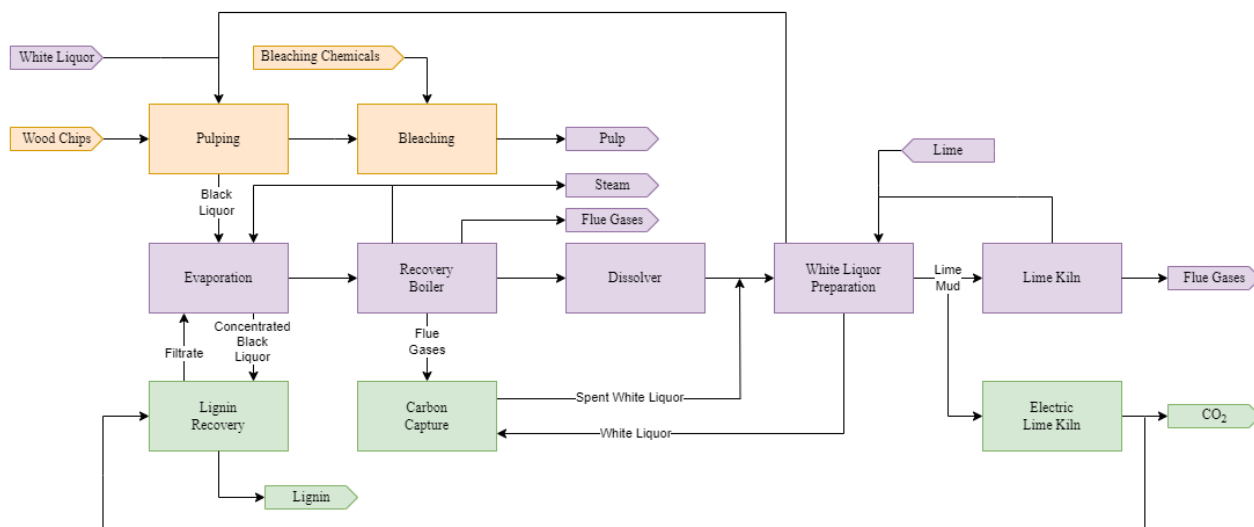


Figure 14 Flowchart of chemical recovery with alternative process routes. The alternative process routes are represented in green, the existing chemical recovery section is represented in purple, and the steps not part of the simulation are represented in orange

5.1.4 MOO Framework Analysis

In WP4 of the CALIMERO project, one case study was performed related to the pulp and paper industry, taking further the simulation from WP2. In the case study, an assessment was made of alternative chemical recovery routes in a pulp plant, aiming to reduce the environmental impacts of pulp while maintaining sodium/sulphur balance. The focus in the case study was on lignin recovery, electric plasma lime calcination, and CO₂ capture from recovery boiler and calcination. The calcination section was prioritized for optimization due to its significant influence on plant efficiency and environmental impact.

In the analysis, five different solutions were examined based on the proportion of material fed into an electricity oven and their corresponding environmental and operational impacts. As the reliance on the electricity oven decreases from Solution 1 (100%) to Solution 5 (73%), noticeable shifts were observed in climate change impact, human toxicity, ecotoxicity, and overall environmental performance (**Table 8**).

Objectives	Solution 1	Solution 2	Solution 3	Solution 4	Solution 5
Climate Change (kg CO ₂ eq.)	4.89·10 ⁻¹	4.96·10 ⁻¹	5.14·10 ⁻¹	5.16·10 ⁻¹	5.17·10 ⁻¹
Human Toxicity: Non-Carcinogenic (CTUh)	4.08·10 ⁻⁹	3.88·10 ⁻⁹	3.42·10 ⁻⁹	3.36·10 ⁻⁹	3.33·10 ⁻⁹
Human Toxicity: Carcinogenic (CTUh)	2.16·10 ⁻¹⁰	2.09·10 ⁻¹⁰	1.92·10 ⁻¹⁰	1.90·10 ⁻¹⁰	1.89·10 ⁻¹⁰
Ecotoxicity: Freshwater (CTUe)	1.38	1.31	1.15	1.13	1.12
Single score sum of the remaining not relevant impact categories (Pt)	3.03·10 ⁻⁵	2.92·10 ⁻⁵	2.67·10 ⁻⁵	2.64·10 ⁻⁵	2.63·10 ⁻⁵
OPEX (€)	1.17·10 ⁺²	1.17·10 ⁺²	1.17·10 ⁺²	1.17·10 ⁺²	1.17·10 ⁺²

Table 8 Solutions identified for the Pulp and Paper case study

In summary, Solution 5 was found to be the most environmentally sustainable option due to its lower toxicity, whereas Solution 1 was found to be the better choice for reducing GHG emissions and human toxicity. The optimal solution depends on whether the primary focus is on minimizing climate change impact or achieving broader environmental benefits.

Moreover, the case study findings indicated that the use of an electric mesa oven could reduce the emissions to zero given that the released CO₂ is captured for other purposes, e.g. lignin precipitation or electro-fuel. The CO₂ emissions were found to be very dependent on type of electricity. Electricity from coal power plants were observed to make the emissions worse, while Swedish mix or wind/water electricity essentially was found to reduce all emissions. The influence on CO₂ emissions of different fuel mixtures was low, in the order of 5%.

LCSA Methodological Improvements Considered

For the update of the case studies in Task 5.3, the pulp and paper sector study will focus on including the socioeconomic indicators of Job creation potential (JCP) as well as Life Cycle Costing (LCC) indicators. A specific objective for the pulp and paper sector in the CALIMERO project is to reduce waste generation by 20%, and toxic substances by 25%. For reducing waste generation, the tissue case study will extend the system boundaries to also include EoL, as well as looking at a scenario of recycling of tissue. This includes measuring the circularity performance. With regards to reductions of toxic substances, the novel methodology based on UseTox, developed in WP3, will be applied. Additionally, the case studies will consider applying the methodologies developed for biodiversity impacts and ecosystem services which were highlighted as relevant for the pulp and paper industries already in Task 2.1.

5.2 Search on sustainability performance improvement solutions

5.2.1 Solutions from Contextualization Review

Based on the work with the baseline case studies in WP2, the following processes were identified as crucial for improved sustainability performance for the tissue production:

- Energy type used in the tissue process: in the case study this is represented by different energy supply set ups in the two included locations of the deinking and tissue production processes. In general, the energy input (thermal and electricity) has a large influence on the environmental impact of the deinking and tissue production process.
- In situations where the energy supplier is decarbonized and/or internal energy from decarbonized sources is used, the production of chemicals used in the processes contribute significantly to the total environmental impact.
- Assess the impact of the full life cycle for tissue, i.e., including use and end of life. For tissue being a single-use disposable production, collection of tissue for recycling of tissue paper, but also to consider a higher share of recycled material input or use of alternative fibre sources such as wheat straw.

With regards to the forestry case study, the aim was to identify data gaps and aspects for improved sustainability assessment methodology, rather than assessing and improving the sustainability performance within the sector. As such, no sustainability improvement options will be presented for this case study. Instead, the solutions brought forward in CALIMERO Task 5.3 will be based on applying the improved impact assessment methodology.

An important impact category relevant for products based on forestry products is land use. The PEF and the PEFCR requires that land use is modelled using the LANCA method (European Commission, 2021) and including the following 5 sub-indicators soil quality index; biotic production, erosion resistance; mechanical filtration; and groundwater replenishment. A more detailed dataset should be created for forest operations, taking into account local characterization factors to use for LANCA. This would also enable to make one of the largest flows in the case study compliant with the PEF standards (regarding for example carbon flows in the forest and how outputs of energy are handled) as well as using the dataset generated in the forestry case study as input.

5.2.2 Solutions from Literature and BREF Documents Review

Within the BAT reference document for the Production of Pulp, Paper and Board (Suhr et al., 2015), the following solutions relevant for the CALIMERO project were identified:

- An important measure to tackle deforestation issues is to ensure using wood from responsibly managed forests, taking into consideration both environmental as well as economic and social impacts. Several certification schemes exist such as the Forest Stewardship Council (FSC), as well as the Programme for the Endorsement of Forest Certification (PEFC) (Suhr et al., 2015).
- Reduction of water use through water recirculation techniques, which have been developed to decrease the net freshwater usage by the pulp and paper mills, for regions with scarce water resources or a dry climate (Suhr et al., 2015).
- Applying energy saving opportunities, e.g. having productive mills focus on reducing energy consumption, conserving environmental resources and replacing old, low-efficiency and legacy products with efficient upgrades. Moreover, use of sustainable energy sources in the pulp and paper mills, like using of energy from bio-based sources, instead of fossil resources (Suhr et al., 2015).
- Improving the process technology for boilers, due to their significant impact of the industry's GHG emissions, as well as causing the majority of sectorial SO₂ and NO_x emissions and a large part of particulate matter emissions. In Sweden, where the case studies in Task 2.1 were located, many mills employ bio-based energy source alternatives instead of fossil-based. (Del Río et al., 2022).
- Improving energy efficiency and employing renewable energy sources is also of importance in the drying process of paper production (Del Río et al., 2022).
- Employing increased recycling of pulp and paper products, such as pointed out by Del Río et al. (2022). In this sense, there are potentials of industrial symbiosis between the pulp and paper industry and other sectors where waste streams from the pulp and paper sector could become valuable feedstocks for the biochemicals and metallurgical industries (le Roux et al., 2024). For example, one waste stream that could be used is the pulp ash that is generated in the combustion processes of the pulp and paper making. This waste stream needs to be prepared for disposal, where it is usually sent to landfills. However, Ahmad et al. (2023) suggest an innovate approach with potential of industrial symbiosis between the paper and pulp industry and the construction industry. Using waste ashes generated in the pulping process could have the potential to substitute up to 10% of the material input components that go into concrete production, which could reduce the amount of ash waste stream from landfills and instead contribute to decarbonizing the construction sector by material substitution of concrete (Ahmad et al., 2023).

5.3 Selection of sustainability performance improvement solutions

The solutions to go forward with in the CALIMERO project were chosen based on internal discussions between academic (IVL) and industrial (ESSITY) partners (Cederstrand, P., pers. comm., 2025). The chosen solutions are part of the tissue manufacturing as this has been highlighted as a hotspot for various environmental categories. As such, these solutions were considered as having largest potential for decreasing the environmental impacts within the life cycle of the tissue. On the other hand, pulp production solutions were considered less relevant to study further as these generally stand for a minor part of the life cycle impacts of the tissue. However, modelling recycling of the tissue will also indirectly lead to decreased demand for pulp which will thus, naturally, reduce the environmental impacts from this process. The solutions to go forward with in the project are the ones stated as follows:

- 1) Include calculations with the +1/-1 approach for the biogenic part of the climate impact assessment.
- 2) Tissue product end-of-life waste collection for recycling.
- 3) Changed energy supply for tissue manufacturing by employing paper machines, which use green hydrogen for steam production and heat generation for drying step.

The reason for adding calculations with the +1/-1 approach is that this is seen as very important for bio-based disposable systems, the balance between removal and emission is different for different types of waste handling and Essity (along with other similar companies) need to be able to compare composting and incineration, for example. It is also expected that the next update of the PEF guidelines will include such an approach for biogenic carbon which is why it makes sense to analyse the applicability and usefulness of such an approach. In order to include calculations with this approach, a changed life cycle scope from cradle to tissue mill gate to cradle to grave will be required and a new reference case will therefore be calculated.

Essity is already offering a service for recycling used tissue at end of life for big customers. The reason for including it in the calculation is to show the potential of increasing those volumes. Recycling tissue at end of life is also a way to increase the pool of recycled materials where competition is currently very high regarding the supply of high-quality secondary paper materials which has been decreasing for many years.

As energy consumption in the papermaking is the main hotspot for many of the impact categories it is important to show the potential of changed energy sources.

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Personal communication

Cederstrand, P., 2025. Senior Sustainability Specialist, Essity.

Conclusions

This deliverable presents a comprehensive overview of potential solutions to improve the sustainability performance of case study industrial processes in the construction, textiles, woodworking, bio-chemicals, and pulp and paper sectors. Rather than quantitatively assess the improvement potential of these solutions against project-defined sustainability KPIs, this report evaluates them based on applicability, feasibility, and qualitative potential for sustainability gains. This approach enabled the systematic identification and preliminary prioritization of sector-specific solutions that are now positioned for further assessment.

Expert and stakeholder consultation played a role in shaping the direction and depth of this work to varying degrees depending on the case study at hand. These dialogues enabled iterative refinement of the proposed solutions, ensuring their technical feasibility, operational relevance, and alignment with current regulatory and industrial realities. Importantly, in several case studies, including construction, textiles (T.I.L.), biochemicals, and tissue recycling, consultation processes led to a broadened scope of analysis. Sustainability improvement opportunities were identified not only within the originally targeted production processes but also upstream or downstream in the value chain, where significant influence on the overall sustainability performance was observed. Adopting an iterative and systemic perspective to home in on sustainability optimization opportunities enhanced the quality and relevance of the solutions identified.

Where feasible, insights from BREF documents and ecolabel criteria were used to guide solution assessment. However, the availability and applicability of these reference documents varied by sector, with more consistent resources identified for construction and textiles. In the case of the textiles sector, the corresponding BREF document was assessed in a systematic manner to assess which techniques were already adopted/not adopted in the case study sector. Viewing the textile case studies' search results of sustainability solutions from academic literature and expert dialogue, against those identified from the textiles BREF document provides a basis for potential updates to the textiles BREF document in the future. Similar results for the other four bio-based sectors in CALIMERO, that are presented in this deliverable may be used as a basis to inform future updates to corresponding sectoral BREFs and Ecolabel criteria.

Table 9 provides a consolidated summary of the selected sustainability improvement solutions across all sectors. These findings lay the groundwork for the demonstration activities of Task 5.3, where selected solutions will be tested, with outcomes feeding into subsequent deliverables aimed at supporting the broader sustainability transition of Europe's bio-based industries.

Bio-based sector	Sustainability improvement solution	Description of the solution	Source(s)
<i>Construction</i>	Biobased additive	Replacement or reduction of mineral additives with biobased alternatives.	DTU case study
	Biochar	EOI treatment of insulation fibers using pyrolysis and producing Biochar.	Refer to 2.1.3
	Using cardboard	Partial substitution of waste newspaper with cardboard	Internal sector investigation
<i>Textiles</i>	Enzymes for the bleaching (laccase)	The use of laccase leads to a lower hydrogen peroxide dosage, a reduced bleaching temperature about 30 °C lower than in the conventional process and a bleaching duration reduced by 33%.	(Liqiang et al.,2011)
	Enzymes for the desizing (amylase)	The use of enzymes like α-amylase or pectinase (for water-insoluble sizes) allows the process to operate at lower temperatures compared to oxidative desizing.	(BAT 10)
	Ozone or plasma bleaching pre-treatment	Improves textile processing by modifying fiber surfaces, enhancing bleaching efficiency. It reduces the need for harsh bleaching agents, lowers environmental impact, and improves wettability	(C.-W. Kan, 2015)
	Simultaneous processes	solutions of combined desizing, bleaching, and scouring, and ultrasound-assisted bio-scouring optimize the washing process after desizing by enhancing the removal of impurities before the actual washing step. This reduces the need for excessive rinsing and chemical use while improving process efficiency.	(Ahmed et al., 2019).
	Heat exchanger	Installing heat recovery equipment would decrease the heat demand provided by the boiler, consequently reducing natural gas combustion and boosting resources circularity.	(BAT 11)
	Counterflow washing	This technique is relatively straightforward and inexpensive and can be applied for washing after continuous desizing.	(BAT 10)
	Membrane filtration of the wastewater	Water streams can be filtrated through membranes to reuse it in processes such as cleaning, rinsing or cooling avoiding or postponing the treatment in the wastewater treatment plant.	(BREF)
	Reusable synthetic stone	Use of a plastic based reusable stone to replace commonly used pumice stone for the abrasion step in the denim garment washing	Ereks case study
	e-flow nanobubbles	Use of e-flow nanobubbles instead of pumice stone or synthetic stone for the abrasion step, allowing to avoid the impacts associated with the supply and consumption of pumice stone, chemicals and water consumption	(Garcia 2015; Periyasamy and Periyasamy 2023)
	Ozone washing	Use of ozone dissolved in water for the fabric bleaching, eliminates the need for the chemicals generally used in this step	(Garcia 2015; Sarker et al. 2021)
CO ₂ laser	A CO ₂ laser fading represents a valid alternative to the conventional wet treatment with stone washing and bleaching	(Tarhan and Sariisik 2009; Chi-Wai Kan 2014; Venkatraman and Liauw 2019)	

<i>Woodworking</i>	Application of a bio-based adhesive in replacement of the already used	Use of bio-based resources for the adhesive in substitution for the already used (i.e., pMDI) for reducing impacts on both production of the adhesive itself and pressing process during its application	(Jeswani et al., 2019)
	Simulation of the emissions and optimization of the pressing process	Simulation of the emissions generated by means of mathematical models and optimization of the pressing process using the MOO framework of the WP4	Tabsal case study
	Replacement of the equipment related to the drying process	Updating the drying process to improve its energy consumption	BREFs documents
<i>Bio-chemicals</i>	Bio-based PEG in ester production	Shifting from fossil-based to bio-based PEG in ester production	Case study WP2
	Larger share of renewable energy sources	Using a larger share of renewable energy sources in the production processes for bio-based PEG as well as making the processes more energy-efficient	Kiss & Smith (2020)
	Carbon capture and utilization	Adopting carbon capture and utilization from during ethylene oxide production for the reuse of captured CO ₂ in other chemical processes.	de Faria et al. (2019)
	Waste heat recovery	Capture and reuse waste heat from esterification or upstream processes (e.g., ethylene oxide production) to reduce additional heating requirements.	Nyhlen, F., pers. comm. (2024)
<i>Pulp and paper</i>	Include biogenic emissions	Adding calculations with the +1/-1 approach to include biogenic emissions.	Case study WP2
	Recycling of tissue	Collection for recycling at end of life for tissue products	Case study WP2
	Changed energy supply for tissue manufacturing	Changed energy supply for tissue manufacturing, i.e. paper machines, e.g. use of green hydrogen for steam production and gas used in drying step.	Cederstrand, P., pers. comm. (2025)

Table 9 Sectoral solutions identified for the 5-target bio-based sectors of the CALIMERO project

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