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# LCA, s-LCA and LCC & main outcomes from CSS1

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Lead beneficiary:	19 - NTUA
Lead author:	Antonis Peppas, Chrysa Politi, Konstantinos Baldoukas
Contributions:	KFLEX, OPUS, PARZECZEW, UNIBZ, LNEG, NTUA, VELTHA, BKT
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## Executive Summary

Deliverable D3.4 presents an integrated sustainability assessment of Circular Systemic Solution 1 (CSS1), which focuses on the valorisation of wood packaging waste through innovative reuse, recycling, and energy recovery strategies. The aim is to evaluate the environmental, economic, and social impact of the CSS1 technologies in comparison with the current waste management and energy production practices in the Łódzkie region of Poland. Three main scenarios were assessed in this deliverable:

- CSS1\_1.1: Reuse of wood waste in the form of furniture and wooden goods
- CSS1\_1.2: Combined heat and power production with post-combustion CO<sub>2</sub> capture
- CSS1\_1.3: Thermal energy production through combustion, with CO<sub>2</sub> capture

The Life Cycle Assessment is based on the CML 2001 method and EN15804+A2 indicators. Results show that Scenarios 1.2 and 1.3, which involve energy recovery and CO<sub>2</sub> capture, consistently outperform both the Baseline and Scenario 1.1 in several impact categories, achieving net negative values in Abiotic Depletion (fossil), Eutrophication, Freshwater Aquatic Ecotoxicity and Global Warming Potential. This suggests that energy recovery from wood waste, when integrated with carbon capture, not only offsets environmental burdens but can even deliver net environmental benefits. Scenario 1.1, although contributing to waste reduction through reuse, shows higher impacts in resource use and toxicity-related categories, due to additional materials and processing stages required.

In terms of economic performance, the Life Cycle Costing analysis identifies energy input, CO<sub>2</sub> capture costs and material handling as the primary economic drivers. Scenarios involving energy recovery show higher initial capital and operational costs but also offer greater potential for offsetting costs through energy production and CO<sub>2</sub> credits, depending on the future regulatory landscape and carbon pricing mechanisms.

The Social Life Cycle Assessment evaluated stakeholder categories such as workers, local communities, consumers, society, and value chain actors. The results show overall positive performance across the scenarios, especially in terms of worker safety, local employment, and public commitment to sustainability. Scenario 1.1 contributes significantly to job creation and community engagement, while Scenarios 1.2 and 1.3 show stronger performance in technological development and social responsibility, linked to the adoption of advanced CO<sub>2</sub> capture technologies.

Overall, D3.4 confirms that CSS1 offers a scalable, circular approach to managing wood packaging waste, with clear environmental benefits, promising economic pathways and positive social outcomes. The findings provide a solid foundation for further demonstration and upscaling efforts under the FRONTSH1P project.

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# 1 Introduction

## 1.1 Purpose of the deliverable

The purpose of this deliverable is to identify the key measures that had the greatest potential for improving a product from an ecology-oriented perspective. The first step involved identifying the phases of the product life cycle that had the largest environmental impacts. Once these phases were identified, eco-design strategies could be developed and appropriate measures were selected and adapted for implementation. NTUA conducted the LCA, LCC and s-LCA study of the Circular Systemic Solution 1 (CSS1), following ISO 14040/44, 21930 and other relevant standards. This included developing case studies involving industries such as residential heating and chemical recovery plants. The main goal of the study was to estimate the potential reduction in carbon footprint for each scenario. A sensitivity analysis was performed to identify environmental "hotspots" within the CSS1 technology pathway and supply chain configuration. The analysis also considered other significant environmental impacts, such as eutrophication potential, land use and toxicity. This study was carried out using Sphera commercial software.

The data sources for the inventory included both standardized and readily available data and data generated during the course of the project. Particularly, data from software databases compared circular economy processes to traditional linear production processes, which represented the current state-of-the-art. Therefore, Life Cycle Inventory (LCI) data was derived from:

1. Integrated databases in Sphera for raw materials, wastes, products and processes (such as ELCD of the EC Joint Research Centre and others)
2. Real stream analyses through experimental measurements and characterizations
3. Modelling results
4. Actual demo plant performance data, including power consumption, mass and energy balances, among others

Additionally, NTUA collected all cost data for the CSS1 Life Cycle Costing (LCC) analysis. This included equipment and construction costs for each unit of the CSS1 supply chain during the construction, commissioning and operation phases (maintenance, repair, and replacement costs). Fuel costs, particularly those associated with the wood scrap supply chain, as well as cluster distance and transportation requirements, were also defined. All operational costs, including power, heat, raw materials, process water, cooling water, waste liquid disposal or treatment and environmental costs from potential gas emissions (such as sulphur, NO<sub>x</sub> and fly ash), were included in the model.

This analysis was applied to three categories of wood packaging sector products (pallets, industrial packaging and light packaging, including crates, trays, hampers, boxes, etc.) and the energy sector.

## 1.2 Trends in wood waste management: A European and regional perspective

### 1.2.1 Wood waste in Europe

According to Eurostat waste statistics from 2020, the European Union (EU-27) produced a total of 48.28 million tonnes (Mt) of wood waste (WW), with only 1.88 Mt classified as hazardous, accounting for 3.89% of the total wood waste generated. The largest producers of WW in the EU Germany, France and Italy, which generated 13.32 Mt, 7.70 Mt, and 5.10 Mt, respectively <sup>1</sup>.

The manufacturing sector was the largest contributor to WW generation, accounting for 38.77% of the total WW. This includes wood and paper manufacturing, where significant waste is generated during the production of paper products, packaging and furniture. Other major contributors that produce WW include <sup>2</sup>:

- Water supply and waste management (21.71%)
- Construction (17.79%)
- Households (10.58%)
- Services (8.93%)
- Other sectors combined (2.22%)

With the anticipated shortfall of wood supply in Europe by 2030<sup>3</sup>, the treatment and recycling of WW are expected to play a crucial role in the coming years to reduce the reliance on virgin wood resources and mitigate environmental impacts.

In 2020, a significant portion of WW was treated—40.20 Mt or 83.26% of the total. However, 8.08 Mt or 16.74%, of WW was left untreated. Of the WW that was treated, only 0.24 Mt was disposed of representing a mere 0.60% of the total. In contrast, 39.96 Mt or 96.40%, was recovered. A significant portion of the recovered wood waste, 21.45 Mt, was used for energy recovery, while 18.51 Mt was recycled or used for backfilling. This breakdown shows that 53.36% of recovered wood waste was used for energy production, while 46.04% was directed towards recycling and backfilling <sup>4</sup>.

While recovery rates have increased, recycling WW continues to pose challenges due to the variability of materials involved. Factors such as fluctuating levels of cellulose, hemicellulose and lignin; the presence of additives like glues, varnishes and paints; and contaminants such as chlorine, fluorine and heavy metals complicate the recycling process. Moreover, impurities like glass, plastics and metals can also hinder the efficient reuse of wood waste.

In terms of end-use, particleboard production is currently one of the most common methods for WW recovery, with countries such as Italy leading the way in the EU. In Italy, up to 95%

<sup>1</sup> Eurostat, 2023

<sup>2</sup> Eurostat, 2023

<sup>3</sup> Mantau U., Saal U., Prins K.S.F., Lindner M., Verkerk H., Eggers J., Leek N., Oldenburger J., Asikainen A., Anttila P., (2010), EUwood - Real potential for changes in growth and use of EU forests, On line at: <https://ecopedia.s3.eu-central-1.amazonaws.com/pdfs/108.pdf>

<sup>4</sup> Eurostat, 2023

of particleboard can be composed of wood waste <sup>5</sup>. Other countries, such as Belgium and Denmark, have also adopted a similar model, with significant percentages (50%-70%) of WW being utilized for particleboard production. In contrast, countries like Spain, Germany and France use between 15% and 30% of WW for particleboard production, demonstrating variability in how EU nations recover and utilize wood waste. Nevertheless, there are promising methods for utilizing wood waste, such as in pulping and biorefineries. These approaches, though still in early stages of development, hold potential for producing high-value biofuels and biochemicals from wood waste <sup>6,7</sup>. Further research and innovation are required to develop efficient decontamination methods and improve the quality of recovered wood waste to make it suitable for these advanced applications <sup>8</sup>.

The policy framework governing wood waste management in the EU, alongside advancements in technology and decision-making tools, will significantly influence the future of wood waste recycling. As such, there is an urgent need to develop new waste management solutions and technologies that can increase the recovery and recycling rates of wood waste while minimizing environmental impact (see Figure 1).

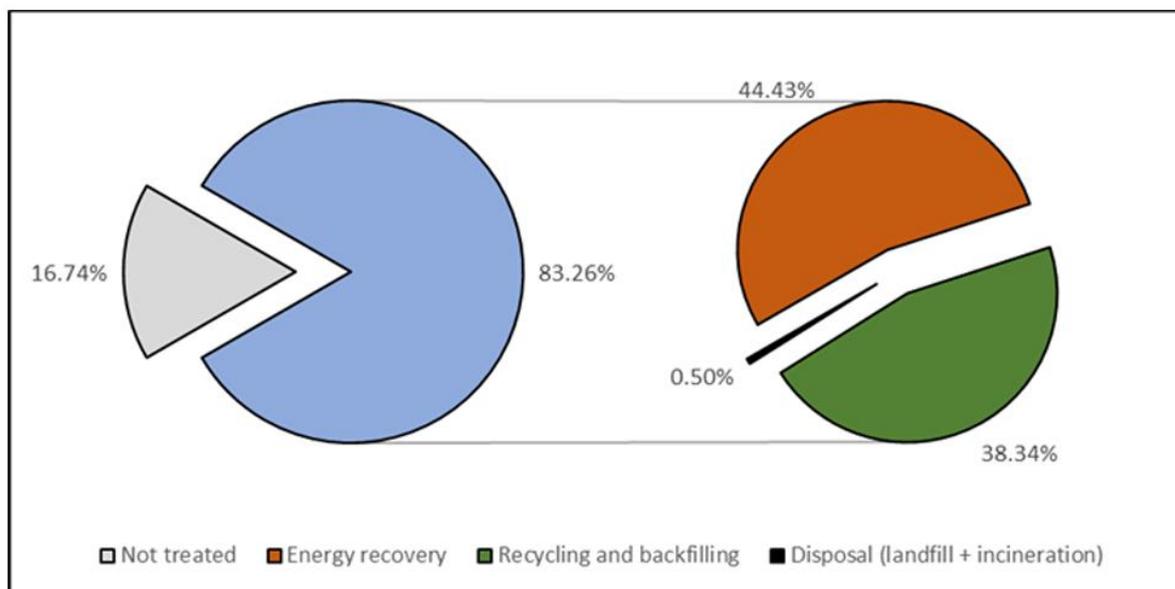


Figure 1 Wood waste produced and treated in EU-27 in 2020 <sup>9</sup>

<sup>5</sup> Vis M., Mantau U., Allen B., (2016), Study on the optimised cascading use of wood. No 394/PP/ENT/RCH/14/7689. Final report, On line at: <https://op.europa.eu/en/publication-detail/-/publication/04c3a181-4e3d-11e6-89bd-01aa75ed71a1>

<sup>6</sup> Ahmed A., Akhtar M., Myers G.C., Scott G.M., (1998), Kraft pulping of industrial wood waste, Pulping Conference, 25-29 October, Queen Elizabeth Hotel, Montreal, Quebec, Canada, Atlanta, GA, TAPPI Press, 993-1000.

<sup>7</sup> Pazzaglia A., Gelosia M., Giannoni T., Fabbri G., Nicolini A., Castellani B., (2023), Wood waste valorization: Ethanol based organosolv as a promising recycling process, Waste Management, 170, 75–81.

<sup>8</sup> Besserer A., Troilo S., Girods P., Rogaume Y., Brosse N., (2021), Cascading Recycling of Wood Waste: A Review, Polymers, 13, 1752, <https://doi.org/10.3390/POLYM13111752>.

<sup>9</sup> Pazzaglia A., Gelosia M., Giannoni T., Fabbri G., Nicolini A., Castellani B., (2023), Wood waste valorization: Ethanol based organosolv as a promising recycling process, Waste Management, 170, 75–81.

### 1.2.2 Wood waste in Lodzkie region

Lodzkie region is a forestry and wood-processing industries region in Poland which produces a noticeable amount of wood waste. Most of them come from the manufacturing sector, including furniture production, sawmills and paper mills where significant amounts of wood by-products are created during production. Additionally, construction and demolition activities contribute to wood waste production. However, much of the wood waste from these industries, particularly from packaging such as pallets, is often discarded due to minor defects or damage. The reuse and recycling of this wood packing waste could create a valuable material stream of up to 4,500 tons per year, presenting opportunities for local job creation, particularly in low-cost furniture manufacturing and other wood-based industries. The potential for recovery and valorisation of wood waste in the Lodzkie region could contribute to a circular economy, helping reduce reliance on virgin wood resources and creating new market opportunities, as outlined in Section 2.1.2 of Grant Agreement.

## 1.3 Description of CSS1 solutions

The CSS1 focuses on the sustainable management of wood packaging waste through end-of-life disposal, reuse and recycling. CSS1 aims to contribute to a circular economy by reducing the environmental impact associated with wood packaging through improved design, manufacturing and end-of-life management strategies.

CSS1 therefore integrates a multitude of new creative solutions for improvement in sustainability and efficiency. Some of the main technologies being considered are those aiming at valorisation of wood packaging waste, from pelletizing up to gasification and combustion in order to extract energy. Additionally, post Carbon Capture and Storage (PCC) can be used to reduce the CO<sub>2</sub> emissions, thus integrating with other systemic circular solutions. These technologies complement each other during the process for a more resource-efficient and sustainable system.

## 2 Methodologies

### 2.1 Life Cycle Assessment

Life Cycle Assessment (LCA) is a systematic method used to evaluate the environmental, social, and economic impacts of a product, process, or service throughout its entire life cycle, from raw material extraction to disposal (Figure 2). Its primary objective is to enhance resource-use efficiency while minimizing environmental liabilities, making it invaluable for environmental decision support.

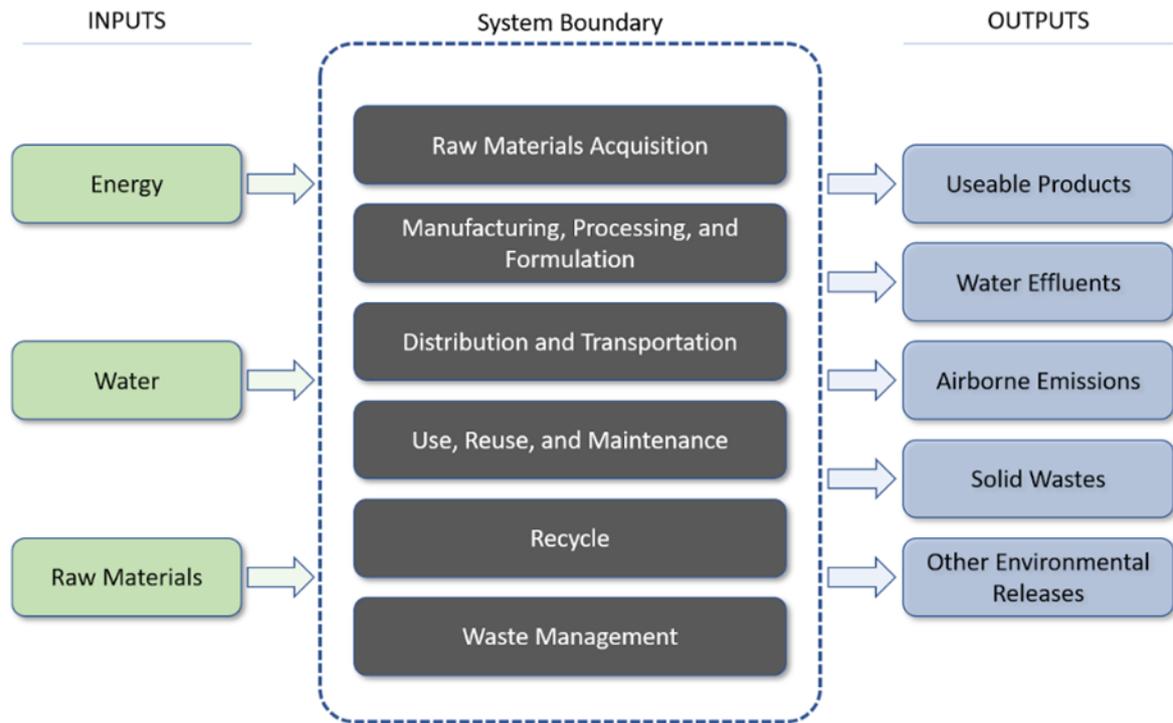


Figure 2 LCA input-output example process.

The several life cycle stages are examined in depth by LCA, which identifies the impact types that are most common and focuses on those that have the greatest environmental consequence. This gives stakeholders the information they need to maximize environmental efforts. This optimization may involve prioritizing certain actions based on their potential effect and putting them in place where they can have the biggest impact. LCA came up as a result of increased business, public, and governmental concerns of how activities and products affect the environment. Its foundations include global modelling and energy audits, which looked at the impact of changes to the environment and natural resources. The two main ISO Standards that are commonly applied are 14040:2006 <sup>10</sup> and 14044:2006/A1:2018 <sup>11</sup>. Adhering to these ISO standards ensures that LCA analyses are conducted in a precise and standardized manner, making their results comparable and internationally accepted.

**ISO 14040 - Environmental Management - Life Cycle Assessment - Principles and Framework:** This standard lays down the fundamental principles and framework for conducting LCA. It provides guidance on the definition of the goal and scope of an LCA, selection of appropriate methodologies, data quality requirements, and reporting. ISO 14040 defines the four main phases of an LCA.

**ISO 14044 - Environmental Management - Life Cycle Assessment - Requirements and Guidelines:** Building upon ISO 14040, ISO 14044 provides detailed requirements and

<sup>10</sup> ISO 14040:2006(en), Environmental management — Life cycle assessment — Principles and framework. Accessed December 4, 2023. <https://www.iso.org/obp/ui/#iso:std:iso:14040:ed-2:v1:en>

<sup>11</sup> ISO 14044:2006 - Environmental management — Life cycle assessment — Requirements and guidelines. Accessed December 4, 2023. <https://www.iso.org/standard/38498.html>

guidelines for implementing the LCA methodology. It offers guidance on data collection, data quality assessment, data normalization, and allocation procedures. ISO 14044 also addresses the importance of sensitivity analysis and uncertainty assessment.

According to ISO 14040:2006, ISO 14044:2006 and the ILCD Handbook, the LCA is carried out in four stages:

1. Goal Definition and Scope definition. In the Goal and Scope phase of an LCA, the goal definition clarifies what, why, how, and for whom the study is relevant, ensuring clear and useful results. The scope outlines the study's detail and limits, ensuring the goal can be achieved within these boundaries.
2. Life cycle inventory. In the inventory analysis phase, data is collected from various sources (industry databases, literature, and direct measurements), quantified (usually by mass or energy), and organized into a detailed inventory of inputs and outputs.
3. Life cycle impact assessment. The LCIA evaluates the potential environmental impacts of the inputs and outputs quantified in the inventory analysis. Using impact assessment methods, it translates data into impacts across categories like climate change, toxicity, ecosystem quality and resource depletion, helping to identify and assess their significance.
4. Interpretation of the results. The interpretation phase analyses data from the inventory and LCIA, assessing environmental impacts, identifying key contributors, and evaluating overall sustainability. It combines quantitative results with qualitative insights to inform decision-making and improvements.

These stages as well as their interaction are presented in the Figure 3.

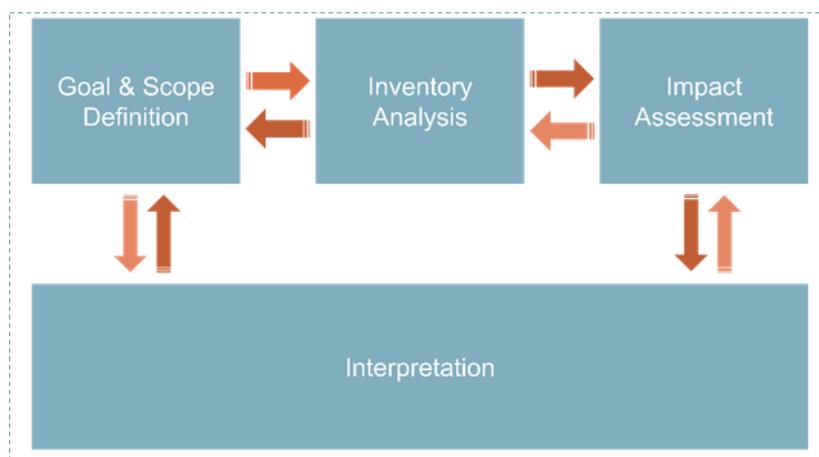


Figure 3 LCA framework

## 2.2 Life Cycle Costing

LCC is one analysis tool based on the principles of economic analysis to evaluate the overall long-term economic feasibility for specific investment options. Through LCC, it is possible to

determine whether a project is economically viable and cost-effective. Besides that, alternative solutions available throughout the project from cradle-to-grave can be identified. The EU Directive 2014/24 in the article 68 gives a precise definition of LCC; Life Cycle Costing shall to the extent relevant cover parts or all the following costs over the life cycle of a product, service or works:

1. Costs, borne by the contracting authority or other users, such as:
  - Costs related to acquisition,
  - Costs of use, such as consumption of energy and other resources,
  - Maintenance costs,
  - End-of-life costs, such as collection and recycling costs.
2. Costs imputed to environmental externalities linked to the product, service or works during its life cycle, provided their monetary value can be determined and verified; such costs may include the cost of emissions of greenhouse gases and of other pollutant emissions and other climate change mitigation costs.

Additionally, ISO 15686-5:2017 - Buildings and constructed assets — Service life planning Part 5: Life-cycle costing is available for LCC of buildings and constructed assets. According to this, LCC is a technique which enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors both in terms of initial capital costs and future operational costs. In particular, it is an economic assessment considering all projected relevant cost flows over a period of analysis expressed in monetary value. LCC analysis follows five simple steps and this general framework is presented below (Figure 4). While the steps are generally sequential, the sequence can be altered as per following the requirements of each project.

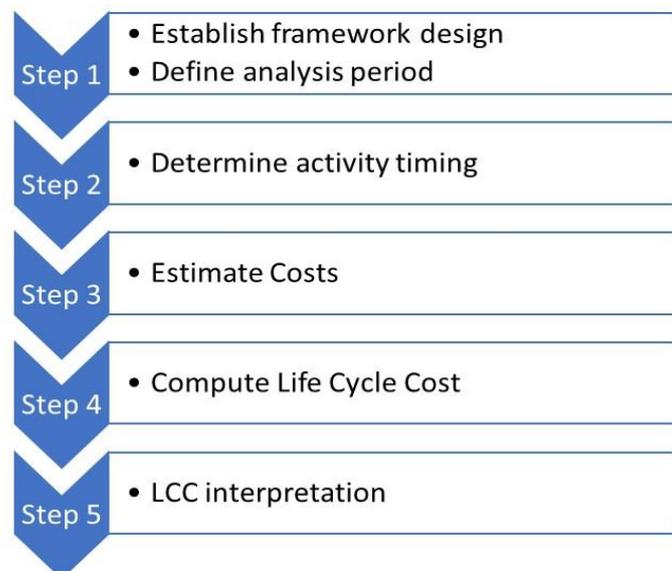


Figure 4 General framework of LCC analysis process.

**Step 1:** Establish framework design and define analysis period. A detailed framework and an analysis period are crucial for the LCC, because it involves the use of time value of money. Setting the duration of the analysis is provided a clear understanding of the overall analysis.

**Step 2:** Determine activity timing. This step is attributed to the determination of timing in respect with all activities that need to be done for running LCC. For instance, collecting financial data, visit a case study site, collect case study data, analyse data as well as data interpretation.

**Step 3:** Estimate costs. The third step in this analysis is to identify and estimate all costs involved in each phase. Among the costs involved will be the cost of materials, equipment, electricity, labor, etc. The cost elements are the cash flows that occur over the life of the system. The cost structure describes the allocation of costs into groups i.e. engineering and development, construction, operation, transportation, disposal.

**Step 4:** Compute life cycle costs. Once, all data is available, the LCC calculation can be done in the fourth step. It is performed by taking into account system lifetime, capital expenditure, operation and maintenance expenditure, labor as well as any additional cost for waste management.

**Step 5:** analyze results and evaluate alternatives. In the last step is to analyze all the results. Through this, where the cause of high-cost contributors can be identified. Based on the status of each case study, alternatives can be identified if it is possible based on the data available.

## 2.3 Social Life Cycle Assessment

A Social and socio-economic Life Cycle Assessment (s-LCA) is a social impact assessment methodology that aims at assessing the social and socio-economic aspects of products and their potential positive and negative impacts along their life cycle encompassing extraction and processing of raw materials, manufacturing, distribution, use, re-use, maintenance, recycling and final disposal<sup>12</sup>. s-LCA methodology follows the UNEP / SETAC guidelines: "Guidelines for Social Life Cycle Assessment of products and organizations 2020" which, in turn, is based on the ISO 14040 and ISO 14044 framework<sup>13,14</sup>. Therefore, this methodology complements the LCA and LCC with social and socio-economic aspects.

Following the 4 steps described by the ISO 14040, the s-LCA can be developed as follows<sup>15</sup>:

**Step 1:** Definition of the objective and application fields, i.e. function, functional unit, system boundaries. In this phase, the "stakeholder categories" are defined, being a cluster of stakeholders that are expected to have shared interests due to their similar relationship to the investigated product systems. For each stakeholder category, particular themes or areas

<sup>12</sup> UNEP – SETAC – Life Cycle Initiative – Guidelines for Social Life Cycle Assessment of products and organizations 2020, United Nations Environment Programme, 2020

<sup>13</sup> ISO 14040:2006(en), Environmental management — Life cycle assessment — Principles and framework. Accessed December 4, 2023. <https://www.iso.org/obp/ui/#iso:std:iso:14040:ed-2:v1:en>

<sup>14</sup> ISO 14044:2006 - Environmental management — Life cycle assessment — Requirements and guidelines. Accessed December 4, 2023. <https://www.iso.org/standard/38498.html>

<sup>15</sup> Sustainability report\_ RESHEALENCE

of interest, which are called "sub-categories", are defined, referring to the categories of impact.

**Step 2:** Inventory analysis, which involves the collection of characteristic and functional data for the development of the s-LCA analysis.

**Step 3:** Evaluation of social impacts.

**Step 4:** Interpretation of results and identification of critical points.

The s-LCA method to be performed in the project is described below:

1. Identification of system(s) to be analysed, including system boundaries; in order to perform a sustainability assessment, this information is the same as for LCA and LCC.
2. For each life cycle phase (EN 15804:2012)<sup>16</sup>, a stakeholders' analysis has to be performed in order to identify the main group of stakeholders related to a specific life cycle phase. The UNEP/SETAC guidelines identify five stakeholders' categories: workers, local community, society, consumers, and value chain actors (Figure 5). For each case study, depending on the phase analyzed and on the type of system considered, the most relevant and significant stakeholders' categories are considered (Figure 6).

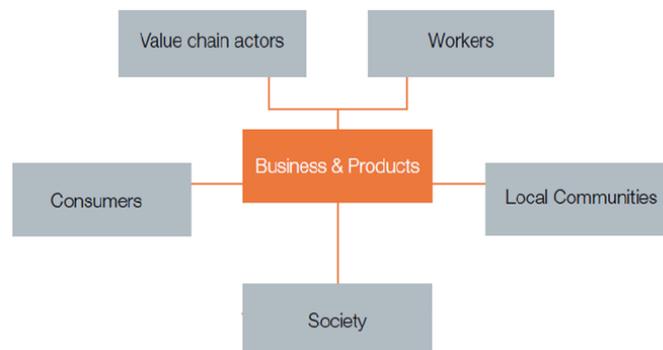


Figure 5 Stakeholders involved in the products lifecycle

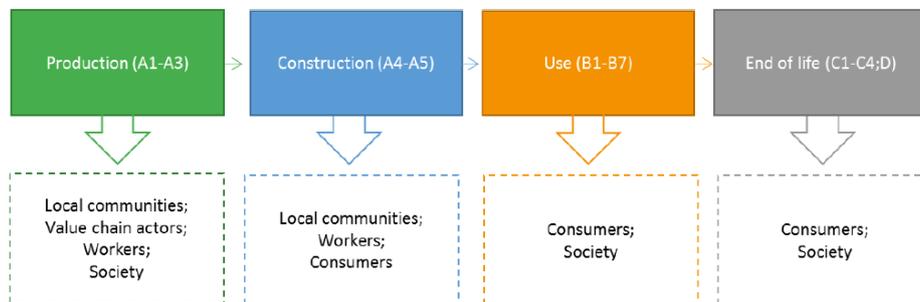


Figure 6 Indicative categories of stakeholders involved in each stage of the product lifecycle

Specifically, the stakeholders (groups) are:

- a) the workers (technicians who maintain and operate the infrastructure, heads and administration)

<sup>16</sup> EN 15804:2012+A1:2013 "Sustainability of construction works — Environmental product declarations Core rules for the product category of construction products"

- b) the value chain actors (actors directly involved in value chain activities such as water agencies, engineers, promoters)
- c) the local community (community living nearby the area)
- d) the consumers (consumers of material/immaterial outputs -natural pigments for food and non-food products and digestate as biofertilizer)
- e) the society (society in general terms)

*Table 1 Stakeholder groups involved in the lifecycle of wood packaging*

<b>Stakeholder</b>	<b>Sub-Categories</b>	<b>End of Life</b>
<b>Local Community</b>	Delocalization and Migration	X
	Community engagement	X
	Cultural Heritage	X
	Respect of indigenous rights	X
	Local employment	-
	Access to immaterial resources	X
	Access to material resources	X
	Safe and Healthy living conditions	X
	Secure living conditions	X
<b>Value chain actors</b>	Fair competition	X
	Respect of intellectual rights	X
	Supplier relationships	X
	Promoting social responsibility	X
<b>Consumers</b>	Health and safety	X
	Feedback mechanism	X
	Consumer privacy	X
	Transparency	X
	End of life responsibility	X
<b>Workers</b>	Freedom of association & collective bargaining	X
	Child labour	X
	Forced labour	X
	Working hours	X
	Fair salary	X
	Equal opportunities/ discrimination	X
	Health and safety	X
	Social benefits/ social security	X
<b>Society</b>	Employment relationships	X
	Public commitments to sustainable issues	-
	Prevention and mitigation of armed conflicts	X
	Contribution to economic development	X
	Corruption	X
	Technology development	X

3. For every stakeholder, special themes of interest are determined; the purpose of the classification of sub-categories according to stakeholder groups is to make sure that the s-LCA matches the goal and scope and is assessing the bulk of the situation. A complete list of sub-categories is reported in agreement with the UNEP/SETAC guidelines <sup>17</sup>.
4. Every sub-category is assessed by different indicators. The list of these indicators and the description of their status for the considered processes is the inventory of the s-LCA. Examples of the indicators are reported in the s-LCA methodological sheets <sup>18</sup>. There are three forms of Social LCA data: quantitative, semi-quantitative (yes/no or rating scale responses) and qualitative (descriptive text) and generally these are collected through questionnaires.
5. Once the inventory is concluded, the social impacts can be evaluated by means of the Social Impact Assessment method. The performance of the sectors/companies are assessed, respectively based on the status of the indicators taking into account the performance of the sector/company in relation to the situation in the country or region.

The Social Life Cycle Impact Assessment is the final stage of a s-LCA. It helps in quantifying the potential social impacts arising from the s-LCA inventory, and it can be performed by firstly doing a performance assessment (PA) and then, by performing an impact assessment (IA). In this study, we will only be doing the performance assessment (PA).

There are many forms of s-LCA data such as rating scales responses, quantitative semi-quantitative (yes/no) or qualitative data (descriptive text) and generally these are collected through s-LCA questionnaires. In order to draw conclusions more efficiently, we have to use one scale for all the indicators, so we rescaled and converted the existing ones to a scale of 1 (least good practice) to 5 (best practice). There are two options for the conversion so we use for every indicator the right equation.

Option 1: the lowest value ( $x_{min}$ ) is the least good and the highest ( $x_{max}$ ) is the best

$$y = \left( \frac{4}{(x_{max} - x_{min})} \right) x - \frac{(5 | x_{min} - x_{max})}{(x_{max} - x_{min})}$$

Option 2: the lowest value ( $x_{min}$ ) is the best and the highest ( $x_{max}$ ) is the least good

$$y = \left( \frac{-4}{(x_{max} - x_{min})} \right) x + \frac{5 | x_{max} - x_{min}}{(x_{max} - x_{min})}$$

<sup>17</sup> UNEP – SETAC – Life Cycle Initiative – Guidelines for Social Life Cycle Assessment of Products, United Nations Environment Programme, 2009

<sup>18</sup> UNEP – SETAC – Life Cycle Initiative – The methodological sheets for sub-categories in Social Life Cycle Assessment (s-LCA), United Nations Environment Programme and SETAC, 2013

## 3 LCA methodology

### 3.1 Goal and Scope

Goal and scope definition is one of the most important steps in any LCA/LCC/s-LCA analysis. This section outlines the purpose of the study, the functional unit (FU), the reference flow, system boundaries and any assumptions and limitations. Clear and precise definitions at this stage ensure the study provides credible results, enabling appropriate comparisons and informed decision-making.

#### 3.1.1 Goal

The primary goal of the LCA for CSS1 is to evaluate the environmental impacts and costs of processing wood packaging waste through the proposed CSS1 in the region of Lodzkie. The study aims to assess the CO<sub>2</sub> footprint reduction, energy preservation and potential for carbon black production. It compares the impacts of this CSS solution with traditional waste management practices, such as landfilling and fossil fuel-based energy production.

##### 1. Intended application:

- To estimate the potential for CO<sub>2</sub> footprint reduction in the CSS1 processes, focusing on waste reduction, energy savings and the valorisation of by-products like char.
- To assess energy resource preservation, specifically through the recovery of thermal energy from wood waste, thereby reducing the reliance on fossil fuels.
- To evaluate the cost of CO<sub>2</sub> savings, specifically the financial implications of CO<sub>2</sub> emissions reductions and the use of recovered energy.

##### 2. Intended audience:

- Waste management companies, municipalities and carbon black producers.
- Policy makers focusing on sustainable waste management and energy solutions.
- Scientific and technical partners involved in environmental and industrial research.

##### 3. Comparative assertions:

The impacts of CSS1 will be compared with current practices such as:

- Landfilling of wood packaging waste.
- Thermal energy production using fossil fuels.
- Carbon black production from fossil fuels.
- Purchase of pigments/fillers and the treatment of char as industrial waste.

#### 3.1.2 Scope

The scope of this study outlines the processes and boundaries considered in the LCA. The product system under evaluation addresses the reduction of wood packaging waste at a

regional scale (Lodzkie). The scope will cover the collection, processing and valorisation of wood waste into thermal energy, CO<sub>2</sub> and char.

### 3.1.3 Functions of product system

The CSS1 system is designed to process wood packaging waste and convert it into valuable by-products such as thermal energy, CO<sub>2</sub> and char, effectively reducing the waste volume sent to landfills.

Functions of the product system include:

- **Waste reduction:** The system reduces the volume of wood waste by converting it into thermal energy and other valuable by-products.
- **CO<sub>2</sub> emissions reduction:** By recovering energy from waste instead of using fossil fuels, the system reduces CO<sub>2</sub> emissions.
- **Energy recovery:** The system produces thermal energy from the wood waste, replacing energy derived from fossil fuels.
- **Valorisation of by-products:** The system generates char, to be used as substitute of carbonaceous materials derived by fossil fuels, such as carbon black, in industrial applications, including in manufacturing processes.

### 3.1.4 Functional Unit

The FU for this study is defined as the treatment of 1 ton of wood packaging waste through the Circular Systematic Solution (CSS1) system. This FU serves as a reference flow to which all input and output data in the LCA are related, ensuring consistency in the analysis. The FU accounts for the mass of the waste untreated.

### 3.1.5 System boundary

LCA is a complex process that involves several stages for assessing the environmental impact of a product/ service / technology referred to the upstream processes, downstream manufacturing, use stage, recycling and end-of-life processes.

The CSS1 approach to wood packing waste is developed into three scenarios. Outputs of these three scenarios could be considered for integration with other Circular Systematic Solutions in the FRONTSHIP project. Each scenario focuses on different methods and processes for reusing wood packaging or producing energy, CO<sub>2</sub> and char.

**Scenario 1.1 (CSS1\_S1.1 Furniture and wooden goods):** The goal of Scenario 1.1 is to repair or reuse wood packaging waste, transforming it into useful objects or furniture, promoting resource efficiency and reducing waste.

**Scenario 1.2 (CSS1\_S1.2 Combined energy production and PCS):** This scenario focuses on producing electricity and thermal energy through Combined Heat & Power (CHP) after pelletizing and gasifying wood packaging waste. Additionally, char is valorised and PCC is

used to capture and store CO<sub>2</sub> for interconnection with other CSSs, minimizing environmental impact.

**Scenario 1.3 (CSS1\_S.1.3 Thermal energy production and PCC):** Similar to Scenario 1.2, Scenario 1.3 also involves energy production through CHP. However, thermal energy is generated through combustion rather than gasification. As with Scenario 1.2, PCC is employed to capture and store CO<sub>2</sub> for interconnection with other CSSs.

### 3.1.6 Impact Assessment Method Description and Impact Categories Description

The CML 2001 standard for LCA is a method for evaluating the environmental consequences of a product or process throughout its entire life cycle. It was developed by the Centre of Environmental Science of Leiden University and was published in a guide to the ISO standards in 2001<sup>19</sup>. The method is divided into baseline and non-baseline, the baseline being the most common impact categories used in LCA. Table 2 shows the categories it contains, according to last update in August-2016<sup>20</sup>. These indicators collectively provide insights into resource use, emissions and impacts on health and the environment across the assessed system's life cycle.

*Table 2 Impact categories included in the method CML*

<b>Method: CML</b>	
<b>Impact category group</b>	<b>Name of the impact category in the method</b>
<b>Acidification</b>	Acidification potential - average Europe
<b>Climate change</b>	Climate change - GWP100
<b>Depletion of abiotic resources</b>	Depletion of abiotic resources - elements, ultimate reserves
	Depletion of abiotic resources - fossil fuels
<b>Ecotoxicity</b>	Freshwater aquatic ecotoxicity - FAETP inf
	Terrestrial ecotoxicity - TETP inf
<b>Eutrophication</b>	Eutrophication - generic
<b>Human toxicity</b>	Human toxicity - HTP inf
<b>Ozone layer depletion</b>	Ozone layer depletion - ODP steady state
<b>Photochemical oxidation</b>	Photochemical oxidation - high Nox

By adding more indicators with the EN 15804 +A2 (based on EF 3.1) method, the modular approach to LCA is strengthened, enhancing transparency and comparability among EPDs. The implementation of EN 15804 +A2 advances the industry toward a more standardized and reliable environmental assessment framework, supporting sustainable decision-making. A more comprehensive evaluation is achieved through the inclusion of impact categories such as 1. Resource use indicators and 2. Human toxicity, along with their subcategories (see Table 3).

<sup>19</sup> R. Frischknecht et al., 'Swiss Centre for Life Cycle Inventories A joint initiative of the ETH domain and Swiss Federal Offices Implementation of Life Cycle Impact Assessment Methods Data v2.0 (2007)', 2007. [Online]. Available: <http://www.ecoinvent.org>

<sup>20</sup> A. P. Acero, C. Rodríguez, and A. C. Changelog, 'LCIA methods Impact assessment methods in Life Cycle Assessment and their impact categories', 2016. [Online]. Available: [http://www.openlca.org/files/openlca/Update\\_info\\_open](http://www.openlca.org/files/openlca/Update_info_open)

Table 3. Impact categories of EN 15804 +A2 (based on EF 3.1) method

Impact category group
<b>1. Resource use indicators</b>
Use of renewable primary energy (PERE) [MJ]
<b>Total use of renewable primary energy resources (PERT) [MJ]</b>
Use of non-renewable primary energy (PENRE) [MJ]
<b>Total use of non-renewable primary energy resources (PENRT) [MJ]</b>
Use of net fresh water (FW) [m <sup>3</sup> ]
<b>2. Human toxicity</b>
<b>Hazardous waste disposed (HWD) [kg]</b>
<b>Non-hazardous waste disposed (NHWD) [kg]</b>

### 3.1.7 Assumptions and limitations

This study specifically excludes the collection and transportation of wood packaging residues to the processing plant from the system boundaries. This decision was made to narrow the focus of the analysis to the processes occurring within the plant, including gasification, combustion and CO<sub>2</sub> capture. The environmental impacts related to logistics (e.g. transportation emissions and fuel consumption) are therefore not accounted for in this analysis. Future assessments could incorporate these factors to provide a more comprehensive view of the system's overall environmental footprint.

### 3.1.8 Data quality

The quality of data used in this study plays a crucial role in ensuring reliable and meaningful results. The data used for the LCI analysis was evaluated based on several key aspects: technological relevance, consistency, completeness, representativeness and location specificity.

#### 1. Technological relevance

The data collected in this study is highly relevant to the specific technologies employed in the CSS1 system, including biomass gasification, producer gas combustion and PCC. These data were derived from the actual operational conditions and experimental setup of the gasifier, combustion chamber and PCC unit. Therefore, the data reflects the technologies in their current form and captures the real-world performance of these systems under the study's scope.

#### 2. Consistency

The data used in this study is consistent with international standards and methodologies, such as ISO 14040/44 guidelines for conducting LCA. Data was collected and processed using industry-standard software tools, including Sphera FE for LCA modelling and ASPEN Plus for thermodynamic simulations. This ensures that the data and results are consistent and comparable with similar studies in the field. Furthermore, the operational data from the

different phases (gasification, combustion and CO<sub>2</sub> capture) were gathered systematically and followed consistent protocols across all stages.

### 3. Completeness

The data collected for the LCI and LCA analysis is comprehensive within the boundaries set by the study. All relevant inputs and outputs for the core processes of the CSS1 system—gasification, combustion, energy recovery and CO<sub>2</sub> capture—are included in the analysis. This includes energy consumption, emissions and material flows (e.g., char production and recovered energy). However, the exclusion of waste collection and transportation means that the environmental impacts from these stages were not considered in this assessment, which could limit the overall completeness of the analysis.

### 4. Representativeness

The data used in this study is representative of the CSS1 system as implemented in the pilot-scale project. The data reflects the actual performance and operational conditions of the system during the study period. However, since the study focuses on a pilot-scale system, it may not fully represent the potential for scaling up to an industrial level. The assumptions made about the stability and efficiency of the system also limit the representativeness of future technological developments or variations that may arise in a full-scale deployment.

### 5. Location specificity

The study acknowledges that the data used in the LCA analysis reflects the operational context of the NTUA (Greece) and UNIBZ (Italy) facilities, where the CSS1 system was designed and operated. The energy mix, infrastructure and waste management practices in these regions are embedded in the data. However, the electricity, water, fuels and other resources used in the model have been applied from Polish (PL) and European (RER) sources in the Sphera model.

## 3.2 Life Cycle Inventory Analysis of the current study

### 3.2.1 CSS1\_S1.1 Furniture and wooden goods

#### Description of Scenario 1

The main goal for Scenario 1 (CSS1\_1.1) is to repair/reuse wood packaging waste as useful pallets or furniture.

#### Main stages included in the scenario

The transformation of wood packaging waste into furniture and wood goods involves five main stages (Figure 7), which are described as follows:

##### Stage 1: Inspection – Sorting

In this stage, pallets made from wood packaging waste are collected and placed on a conveyor belt for inspection and sorting.

Table 4 Inspection – Sorting (Scenario 1) – Input, output and process parameters

	Flow	Quantity	Unit
<b>Inputs</b>	Wood waste	1000	kg
	Diesel	2.7	L
<b>Outputs</b>	Furniture/ wooden goods	400	kg
	Wood waste	600	kg

### Stage 2: Dismantling

A pallet dismantler (specifically the "Specifications Pallet Hawg® PD200 Pallet Dismantler"), is used to disassemble the pallets.

Table 5 Dismantling (Scenario 1) – Input, output and process parameters

	Flow	Quantity	Unit
<b>Inputs</b>	Wood waste	44.75	kg
	Electricity	0.125	kWh
<b>Outputs</b>	Wood waste	44	kg
	Sawdust	0.75	kg

### Stage 3: Board preparation

During this stage, the separated boards from the pallets are prepared for the next step. Some waste, such as sawdust and wood chips, is produced during this process.

Table 6 Board preparation (Scenario 1) – Input, output and process parameters

	Flow	Quantity	Unit
<b>Inputs</b>	Wood waste	44.75	kg
	Lubricant fluid	1.641	g
	Plastic wrapping	0.299	g
	Cardboard packaging	0.225	g
	Natural gas	12.4	L
	Diesel	0.0356	L
	Gasoline	0.000362	L
	LPG	0.00163	L
	Electricity	0.734	kWh
<b>Outputs</b>	Furniture/ wooden goods	37.275	kg
	Sawdust	1.448	kg
	Wood chips	2,306	kg
	Steel scrap	19.661	g
	Plastic wrapping	0.46	g
	Cardboard packaging	5.003	g
	Lubricant fluids	1.069	g

### Stage 4: Furniture assembly

The next step involves assembling the new furniture or pallets. This stage requires more energy compared to the other stages.

Table 7 Furniture assembly (Scenario 1) – Input, output and process parameters

	Flow	Quantity	Unit
<b>Inputs</b>	Furniture/ wooden goods	37.275	kg
	Nails	61.131	g
	Fasteners	558	g
	Lubricant fluids	4.342	g
	Plastic wrapping	0.0146	g
	Cardboard packaging	0.14	g
	Natural gas	1.17	L
	Diesel	0.00582	L
	Gasoline	0.00071	L
	LPG	0.00347	L
	Diesel	0.01585	L
Electricity	0.696	kWh	
<b>Outputs</b>	Furniture/ wooden goods	37.3	kg
	Cardboard packaging	3.549	g
	Lubricant fluids	2.273	g

### Stage 5: Painting, Stamping

The final stage is the painting of the pallets, preparing them for market supply and ensuring they become fully functional products.

Table 8 Painting, Stamping (Scenario 1) – Input, output and process parameters

	Flow	Quantity	Unit
<b>Inputs</b>	Furniture/ wooden goods	37.275	kg
	Fungicide	0.0112	g
	Paint	4.9	g
	Ink	0.00162	g
	Electricity	0.05	kWh
	Natural gas	4.15	L
LPG	0.0556	L	
<b>Outputs</b>	Furniture/ wooden goods	37.275	kg

CSS1\_S1.1 Furniture and Wooden goods  
Process flow (Energy generation)  
The names of the basic process units shown.

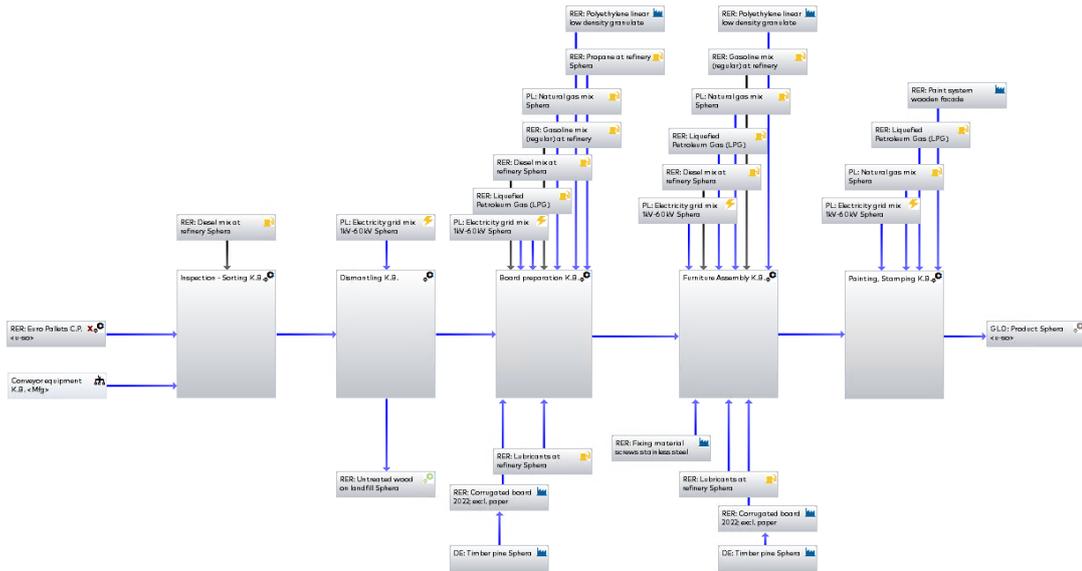


Figure 7 Flowsheet of the Sphera CSS1\_S1.1 Furniture and wooden goods.

### 3.2.2 CSS1\_S1.2 Combined energy production and PCC

#### Description of Scenario 2

The main goal of Scenario 2 (CSS1\_1.2) is to produce electricity and thermal energy using Combined Heat & Power (CHP) from the gasification of pelletized wood packaging waste. Additionally, char is valorised and CO<sub>2</sub> is captured and stored via PCC for interconnection with other CSSs.

#### Main stages included in the scenario

The energy production process from wood packaging waste involves five main stages (Figure 8), which are described as follows:

##### Stage 1: Grinding and metal separation

In this stage, pallets made from wood packaging waste are collected and placed on a conveyor belt for inspection and sorting.

Table 9 Grinding and metal separation (Scenario 2) – Input, output and process parameters

	Flow	Quantity	Unit
<b>Inputs</b>	Wood waste	1000	kg
	Electricity	15.147	kWh
<b>Outputs</b>	Grinded wood waste without metals	972	kg
	Scrap metal (residues of nails, screws)	28	kg

### Stage 2: Pelletizing

Wood packaging waste is pelletized to form small pieces, making it easier to use in the subsequent processes.

Table 10 Pelletizing (Scenario 2) – Input, output and process parameters

	Flow	Quantity	Unit
<b>Inputs</b>	Grinded wood waste without metals	1	kg
	Electricity	0.13	kWh
<b>Outputs</b>	Pellets from pallets	1	kg

### Stage 3: Gasification

During the gasification stage, pellets and air are used to produce thermal energy and char. However, some losses occur due to ventilation and radiation.

Table 11 Gasification (Scenario 2) – Input, output and process parameters

	Flow	Quantity	Unit
<b>Inputs</b>	Pellets from pallets	42.10	kg
	Air	65	kg
	Electricity	0.9	kWh
<b>Outputs</b>	Char	37.275	kg
	Wood gas	1.448	kg
	Thermal energy output	25	kWh
	Loss due to ventilation and radiation	31.65	kWh

### Stage 4: Combined heat & power

At this stage, electrical and thermal energy are combined from the wood gases produced in the previous stage.

Table 12 Combined heat & power (Scenario 2) – Input, output and process parameters

	Flow	Quantity	Unit
<b>Inputs</b>	Wood gas	106.60	kg
	Air	123.40	kg
	Electricity	0,80	kWh
<b>Outputs</b>	Off Gas	230	kg
	CO <sub>2</sub>	23	kg
	H <sub>2</sub> O	27.60	kg
	N <sub>2</sub>	161	kg
	O <sub>2</sub>	18.40	kg
	Electricity	48	kWh
	Thermal power	82	kWh

	Losses due to radiation and ventilation	24	kWh
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### Stage 5: Post Combined Capture - PCC (CO<sub>2</sub> Capture)

Finally, with PCC, CO<sub>2</sub> is captured and stored for interconnection with other CSSs.

Table 13 Post Combined Capture – PCC (Scenario 2) – Input, output and process parameters

	Flow	Quantity	Unit
Inputs	off-gas	4025.24	kg
	O <sub>2</sub>	156.127	kg
	N <sub>2</sub>	2954.0995	kg
	H <sub>2</sub> O	139.657	kg
	CO <sub>2</sub>	774.463	kg
	Active carbon	0.027	kg
	MEA (amines)	1.5	kg
	NaOH	0.047	kg
	Electricity	34	kWh
	Thermal energy	4139647	kJ
Outputs	O <sub>2</sub>	155.873	kg
	N <sub>2</sub>	2954.995	kg
	H <sub>2</sub> O	132.088	kg
	NH <sub>3</sub>	0.232	kg
	CO <sub>2</sub> not captured	38.723	kg
	Water	16.69	kg
	CO <sub>2</sub>	735.74	kg

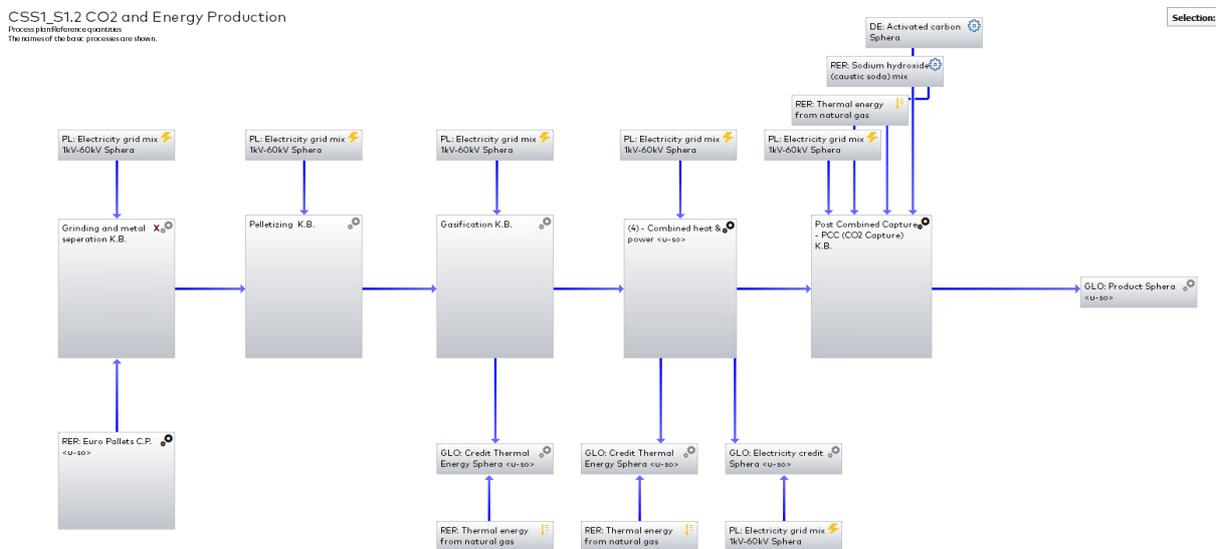


Figure 8 Flowsheet of the Sphera CSS1\_S1.2 Combined energy production and PCC.

### 3.2.3 CSS1\_S1.3 Thermal energy production and PCC

#### Description of Scenario 3

The main goal of Scenario 3 (CSS1\_1.3) is similar to that of Scenario 2 (CSS1\_1.2), but the difference is that only thermal energy is produced through combustion of the gas from the gasification of pellets made with wood packaging waste. Additionally, with PCC, CO<sub>2</sub> is captured and stored for interconnection with other CSSs.

#### Main stages included in the scenario

This scenario involves five main stages (Figure 9), which are described as follows:

##### Stage 1: Grinding and metal separation

In this stage, pallets made from wood packaging waste are collected and placed on a conveyor belt for inspection and sorting.

Table 14 Grinding and metal separation (Scenario 3) – Input, output and process parameters

	Flow	Quantity	Unit
Inputs	Wood waste	1000	kg
	Electricity	15.147	kWh
Outputs	Grinded wood waste without metals	972	kg
	Scrap metal (residues of nails, screws)	28	kg

##### Stage 2: Pelletizing

Wood packaging waste is pelletized, making it suitable for the gasifier.

Table 15 Pelletizing (Scenario 3) – Input, output and process parameters

	Flow	Quantity	Unit
Inputs	Grinded wood waste without metals	1	kg
	Electricity	0.13	kWh
Outputs	Pellets from pallets	1	kg

##### Stage 3: Gasification

During the gasification stage, pellets and air are used to produce gas and char. Some thermal energy is also produced. Losses occur due to ventilation and radiation.

Table 16 Gasification (Scenario 3) – Input, output and process parameters

	Flow	Quantity	Unit
Inputs	Pellets from pallets	42.10	kg
	Air	65	kg
	Electricity	0.9	kWh

<b>Outputs</b>	Char	37.275	kg
	wood gas	1.448	kg
	Thermal energy output	25	kWh
	Loss due to ventilation and radiation	31.65	kWh

#### Stage 4: Combustion

Wood gas from the previous stage is directed into the combustion chamber, where thermal energy is produced.

Table 17 Combustion (Scenario 3) – Input, output and process parameters

	Flow	Quantity	Unit
<b>Inputs</b>	Wood gas	106.60	kg
	Air	187.90	kg
	Electricity	6	kWh
<b>Outputs</b>	Off Gas	294.50	kg
	CO <sub>2</sub>	29,45	kg
	H <sub>2</sub> O	35.34	kg
	N <sub>2</sub>	206,15	kg
	O <sub>2</sub>	23.56	kg
	Thermal energy	154	kWh

#### Stage 5: Post Combined Capture - PCC (CO<sub>2</sub> Capture)

Finally, with PCC, CO<sub>2</sub> is captured and stored for interconnection with other CSSs.

Table 18 Post Combined Capture – PCC (Scenario 3) – Input, output and process parameters

	Flow	Quantity	Unit
<b>Inputs</b>	off-gas	4025.24	kg
	O <sub>2</sub>	156.127	kg
	N <sub>2</sub>	2954.0995	kg
	H <sub>2</sub> O	139.657	kg
	CO <sub>2</sub>	774.463	kg
	Active carbon	0.027	kg
	MEA (amines)	1.5	kg
	NaOH	0.047	kg
	Electricity	34	kWh
	Thermal energy	4139647	kJ
<b>Outputs</b>	O <sub>2</sub>	155.873	kg
	N <sub>2</sub>	2954.995	kg
	H <sub>2</sub> O	132.088	kg
	NH <sub>3</sub>	0.232	kg
	CO <sub>2</sub> not captured	38.723	kg
	Water	16.69	kg

	CO <sub>2</sub>	735.74	kg
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CSS1\_S1.3\_CO2 Production  
 Process plant/thermochemical processes  
 The names of the basic processes are shown.

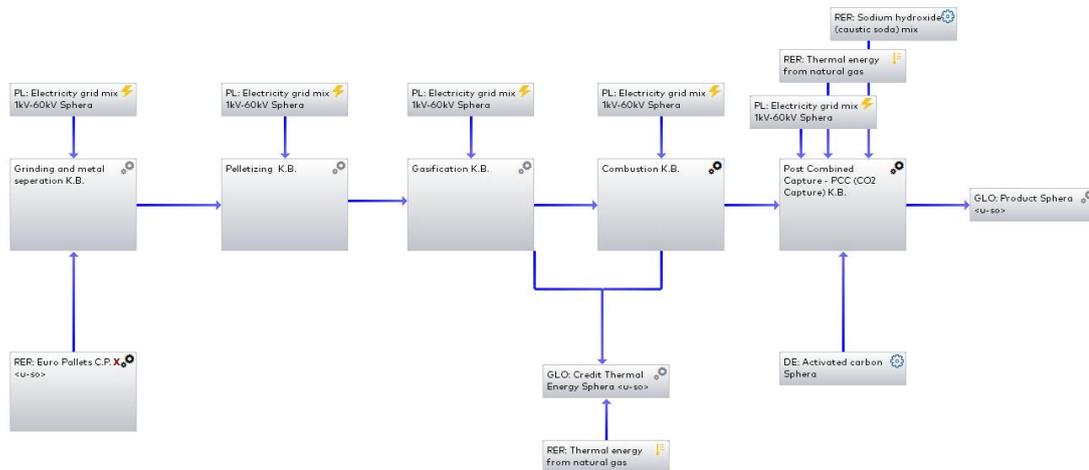


Figure 9 Flowsheet of the Sphera CSS1\_S1.3 Thermal energy production and PCC.

### 3.3 Life Cycle Impact Assessment and Interpretation

#### 3.3.1 Abiotic Depletion

The reduction of abiotic (non-living) resources, such as minerals and metals, important for industrial and societal operations, is estimated by the Abiotic Depletion Potential (ADP). The impact in this category is measured in kilograms of antimony equivalent (kg Sb eq.), with antimony (Sb) being used as the benchmark element to indicate total abiotic resource depletion.

In Figure 10, the ADP impact across the three different wood waste management scenarios and the Baseline scenario (current practices) is compared. The Baseline scenario shows the lowest ADP value of 1.02E-05 kg Sb eq., as it involves no equipment, resulting in minimal abiotic resource depletion. In contrast, Case 1.1 has the highest ADP value of 2.19E-04 kg Sb eq., indicating significant resource depletion due to the added materials in this scenario, as illustrated in Figure 11. Notably, Scenarios 1.2 and 1.3 have negative ADP values (-4.46E-05 and -6.07E-06 kg Sb eq.), indicating that these scenarios provide the most beneficial impact in terms of reducing abiotic resource depletion overall.

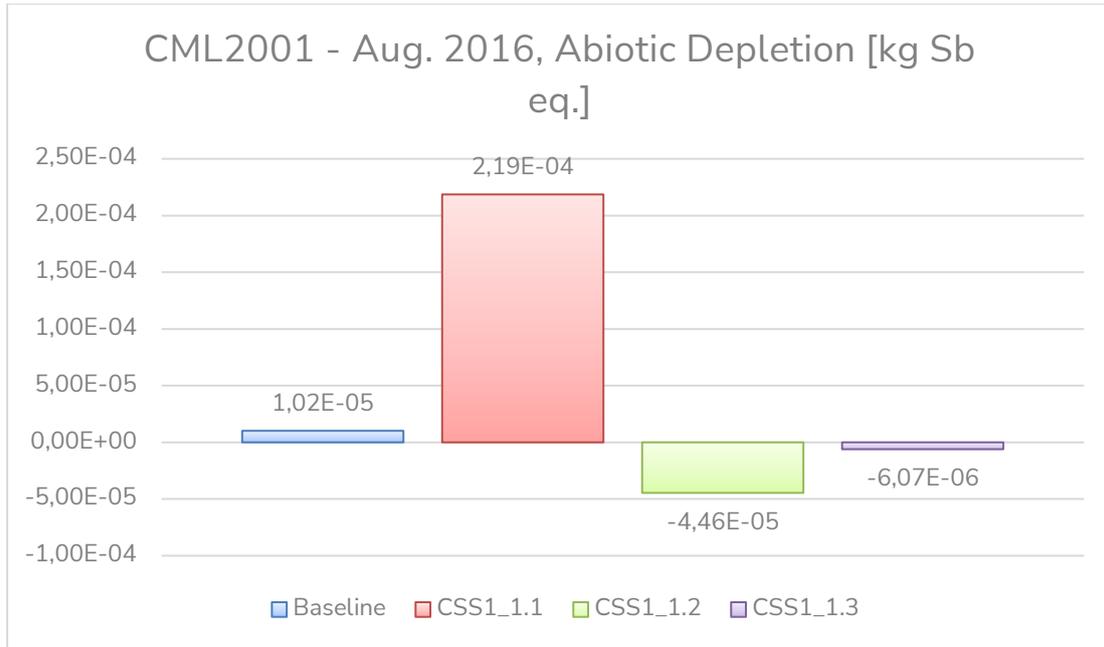


Figure 10 Abiotic Depletion [kg Sb eq.] for each scenario.

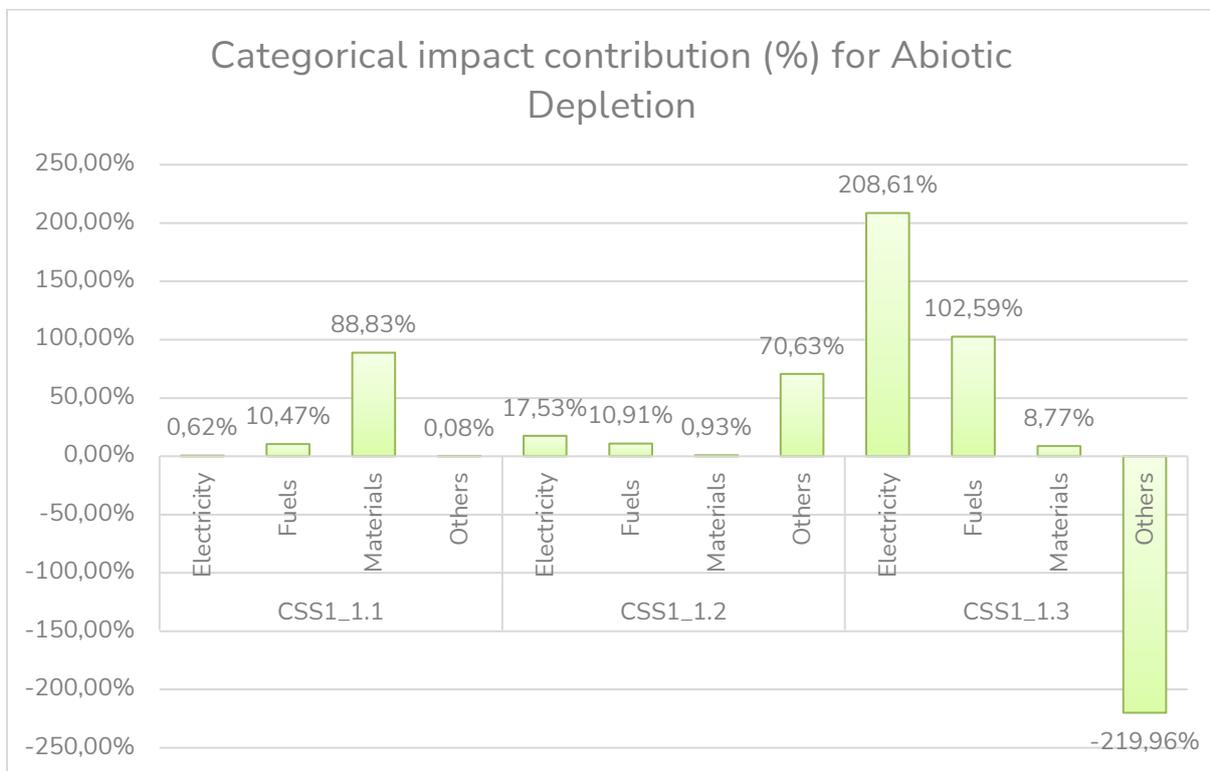


Figure 11 Categorical impact (%) for Abiotic Depletion of each scenario.

### 3.3.2 Abiotic Depletion

The consumption of non-renewable fossil fuels is measured by the Abiotic Depletion Potential for fossil resources (ADP-fossil). The ultimate reserve methodology is used to base this assessment, which estimates total available resources by analysing their average

concentration in the Earth's crust and the mass of the crust itself. ADP-fossil is expressed in megajoules (MJ) and is used to provide a quantifiable indicator of the impact of energy consumption on fossil resource depletion. The need for sustainable resource management and the adoption of alternative energy solutions is highlighted by this, with the aim of reducing dependency on finite fossil fuels.

In Figure 12, the diagram compares the ADP-fossil impact across different wood waste management scenarios. The Baseline scenario, which involves landfill processing, shows a relatively low ADP-fossil impact of  $9.90E+02$  MJ. This is because landfill processing requires minimal energy consumption, resulting in a lower depletion of fossil resources. On the other hand, Scenario 1.1 exhibits the highest ADP-fossil value ( $1,27E+04$  MJ), because of energy-intensive equipment powered by fossil fuels. This is further explained in Figure 11, where the contribution of fuels in Scenario 1.1 is significantly higher. In scenario 1.2 and 1.3, the ADP-fossil impact is reduced. These scenarios show negative ADP-fossil values, indicating that the energy recovery processes contribute positively by reducing the depletion of fossil resources. As shown in Figure 13, in the CSS1\_1.2 and CSS1\_1.3 data, the “Others” category, which refers to the recovery process, has the highest contribution at 65.42% and 34.05%, respectively. Despite the relatively high values for fuels in 1.2 Scenario (23.12%) and 1.3 Scenario (40,54%), the recovery processes play a significant role in reducing the overall ADP-fossil impact.

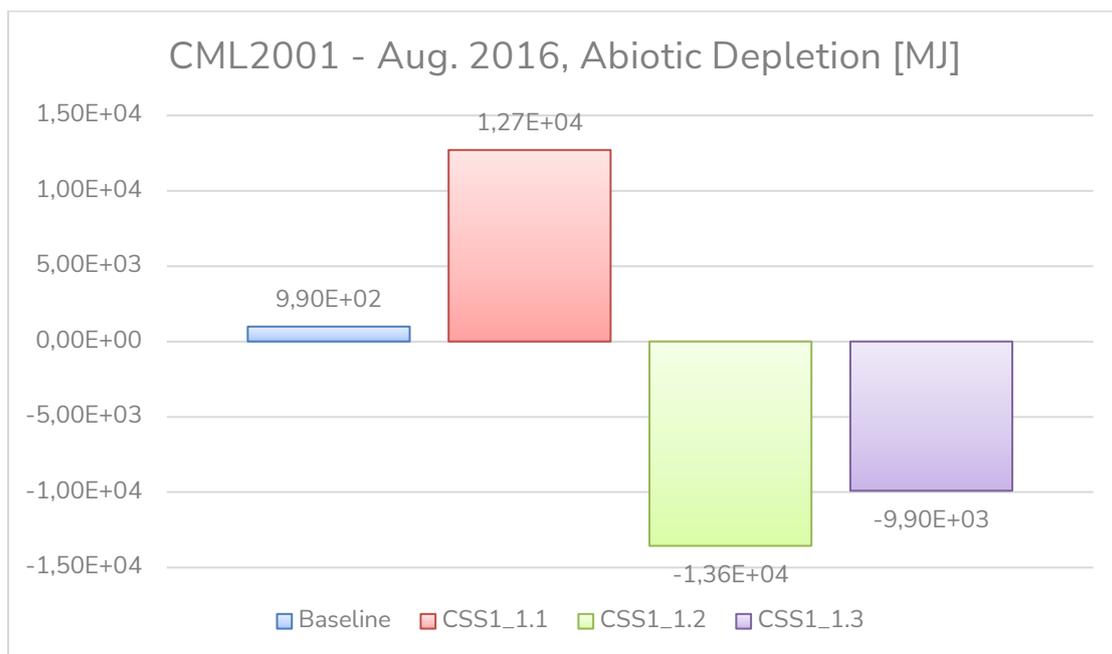


Figure 12 Abiotic Depletion [MJ] impact for each scenario.

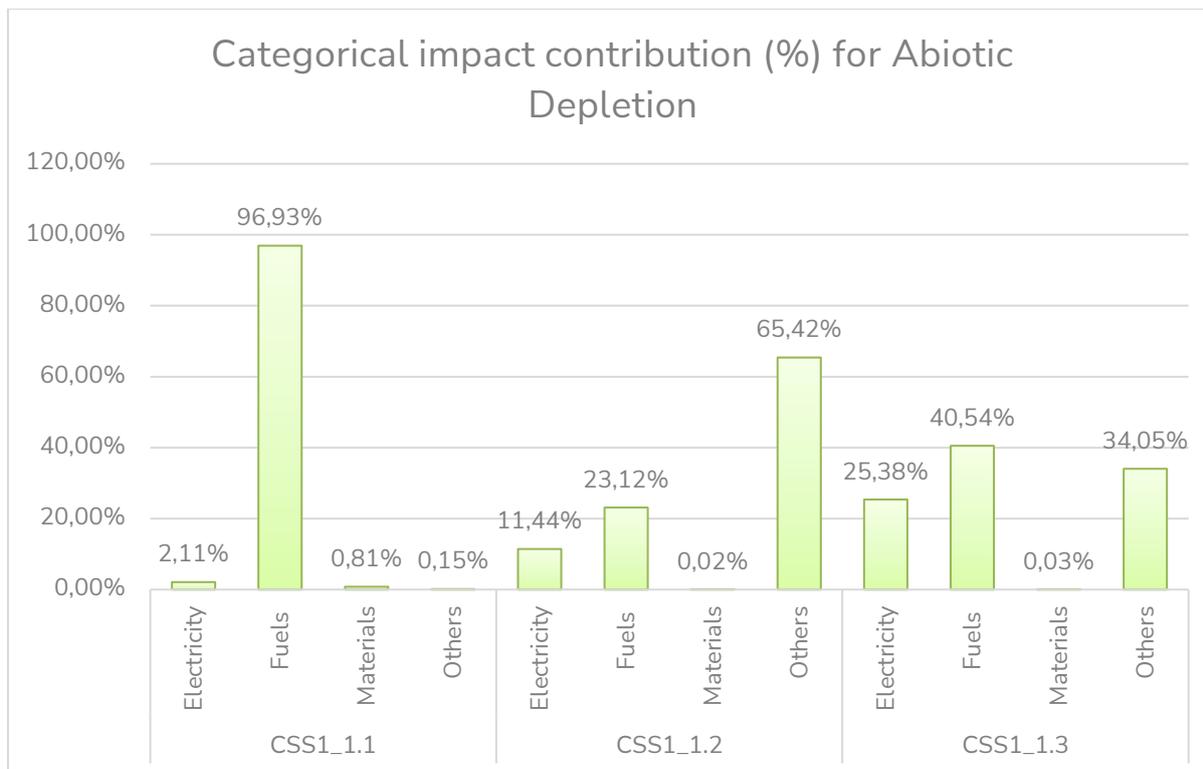


Figure 13 Categorical impact contribution (%) for Abiotic Depletion of each scenario.

### 3.3.3 Acidification Potential

The acidifying effect of substances in water and soil is described by Acidification Potential (AP), highlighting the environmental impact of increased acidity due to substances like carbon dioxide dissolving in water. The reduction of pH levels, leading to acid rain and the consequent degradation of surface waters and forests, is primarily noted on a local scale within the LCA context. Beyond local implications, global concerns are extended by acidification, particularly ocean acidification, which threatens marine biodiversity and by extension, human food sources by jeopardizing the survival of certain species. The acidifying effects of these emissions are quantified by AP, which is expressed in terms of kilograms of SO<sub>2</sub>-equivalents.

In Figure 14, the diagram compares the AP impact across different wood waste management scenarios. The Baseline, scenarios 1.1 and 1.3 show similar AP values (3.32E-01, 2.35E-01 and 4.48E-01 kg SO<sub>2</sub> eq., respectively), indicating similar acidifying effects. In contrast, Scenario 1.2 shows a negative AP value of -9.48E-01 kg SO<sub>2</sub> eq., reflecting a beneficial environmental impact by reducing acidification. This reduction is explained in Figure 15, where the "Others" category, referring to the recovery process, has a very high contribution percentage (67.68%), helping to reduce the acidification effect caused by other emissions.

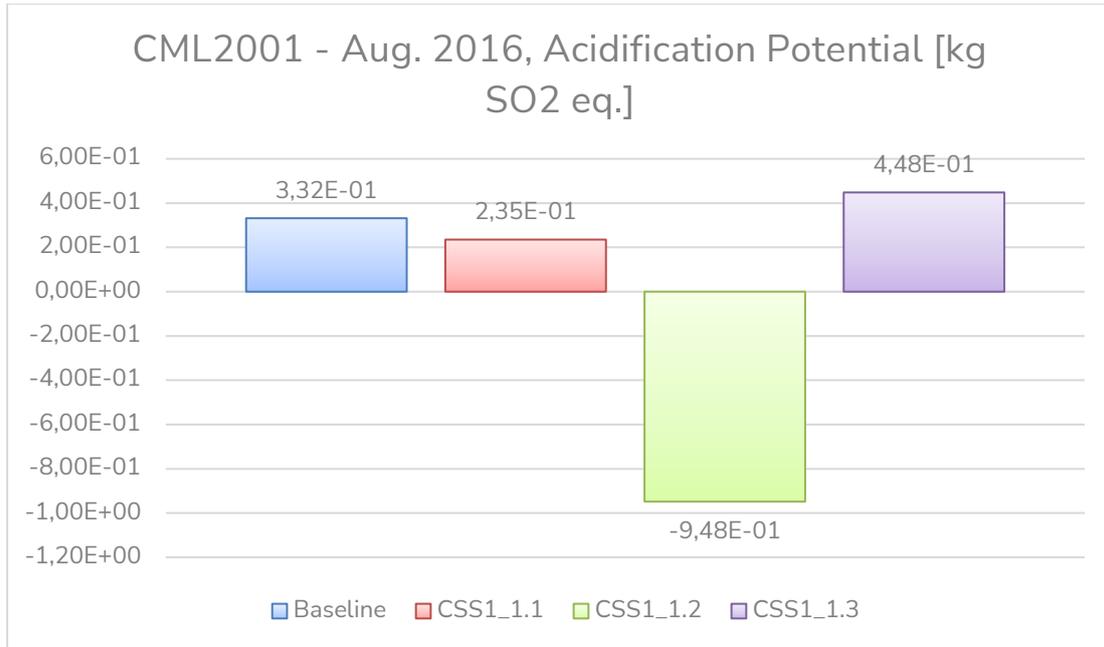


Figure 14 Acidification Potential [kg SO2 eq.] impact for each scenario.

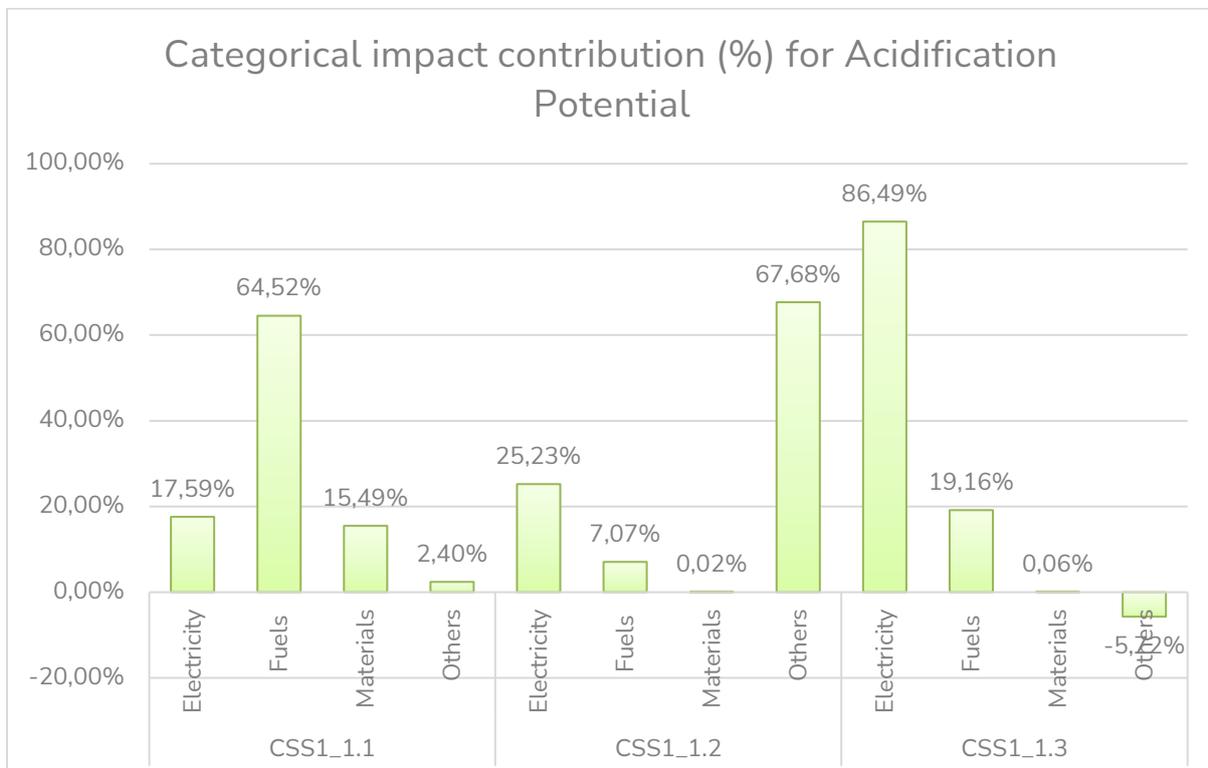


Figure 15 Categorical impact contribution (%) for Acidification Potential of each scenario.

### 3.3.4 Eutrophication Potential

The environmental impact arising from the enrichment of soil and water bodies with nutrients, leading to imbalances in ecosystems, is referred to by Eutrophication Potential (EP). This process, primarily triggered by the addition of nitrogenous and phosphatised

compounds, often through agricultural fertilizers, which promote the unchecked growth of certain species, such as algae. Oxygen levels in aquatic environments are depleted by the resultant algal blooms, which endanger the survival of aquatic flora and fauna by significantly reducing the dissolved oxygen content necessary for their existence. Phosphate ( $\text{PO}_4$ ) equivalents are preferred for characterization and quantification, though nitrogen oxide ( $\text{NO}_3$ ) and oxygen ( $\text{O}_2$ ) equivalents can also serve as interchangeable metrics.

In Figure 16, the diagram compares the EP impact across different wood waste management scenarios. The Baseline scenario has the highest EP value ( $1.72\text{E-}01$  kg  $\text{PO}_4$  eq.), due to the release of organic nutrients during wood waste landfilling, which increases eutrophication potential by promoting excessive algae growth. Scenario 1.1 and Scenario 1.3 show similar EP values ( $4.03\text{E-}02$  and  $5.38\text{E-}02$  kg  $\text{PO}_4$  eq. respectively) indicating moderate eutrophication impacts. In contrast, Scenario 1.2 shows a negative EP value ( $-9.92\text{E-}02$  kg  $\text{PO}_4$  eq.), reflecting a beneficial environmental impact by reducing eutrophication. As shown in Figure 17, the "Others" category (recovery) in CSS1\_1.2 contributes to the reduction of the eutrophication potential impact.

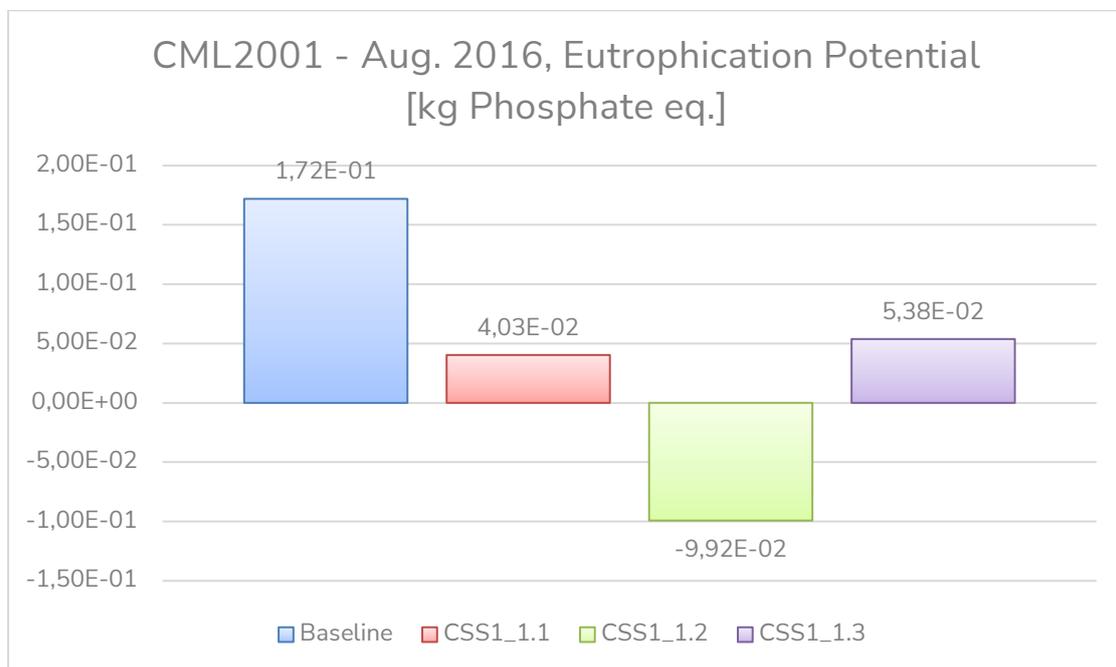


Figure 16 Eutrophication Potential (EP) [kg Phosphate eq.] impact for each scenario.

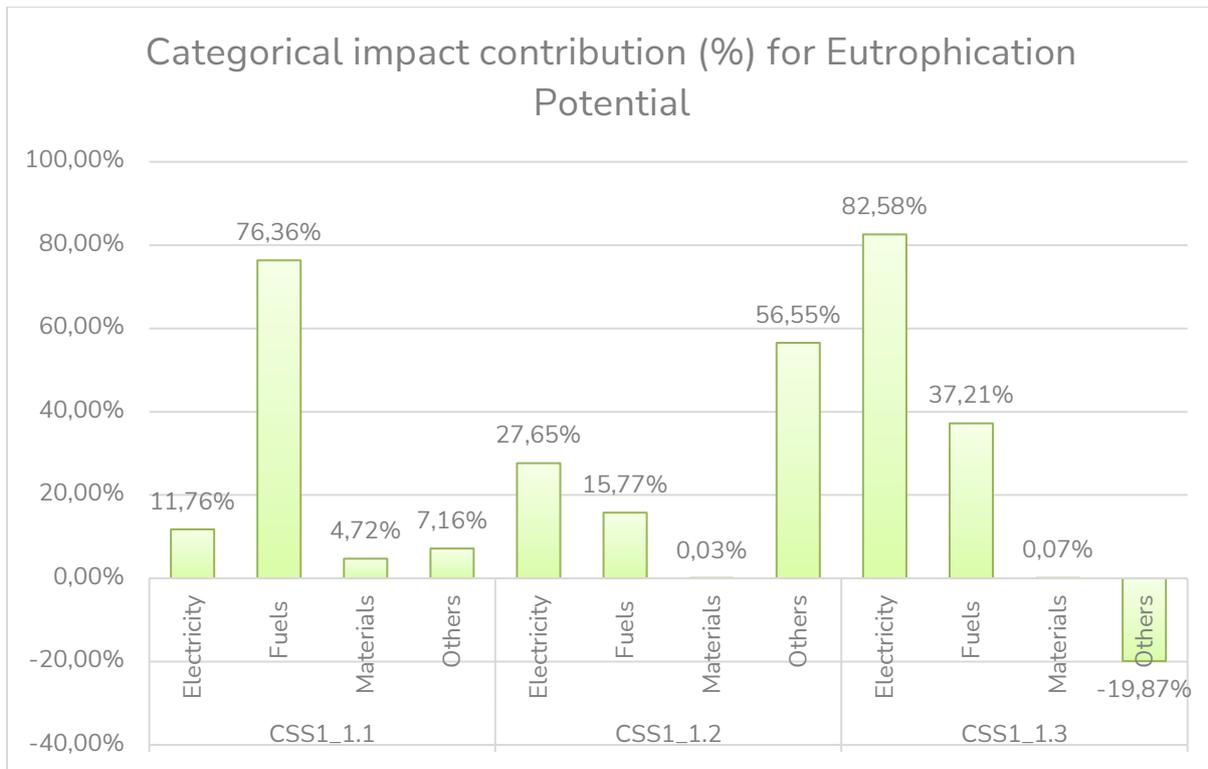


Figure 17 Categorical impact contribution (%) for Eutrophication Potential (EP) of each scenario.

### 3.3.5 Freshwater Aquatic Ecotoxicity Potential

Freshwater Aquatic Ecotoxicity Potential (FAETP) is used as an environmental impact category in LCA and environmental impact assessments. The potential impact of a substance or activity on freshwater aquatic ecosystems is analysed by it. More specifically, the potential toxicity of substances released into freshwater environments and their potential harm to aquatic life is evaluated by FAETP. Kilograms of 1,4-dichlorobenzene (DCB) equivalent (kg DCB eq.) is typically used as the unit of measurement for FAETP. DCB is employed as a reference substance to represent the overall impact on freshwater aquatic ecotoxicity. Various factors, including the toxicity of substances, their environmental fate and their potential to harm aquatic organisms, are taken into account when calculating FAETP.

In Figure 18, the FAETP impact across different wood waste management scenarios is compared. Scenario 1.1 shows the highest FAETP value of 5.58E-01 kg DCB eq., indicating the greatest potential harm to freshwater aquatic ecosystems. The Baseline scenario has a lower FAETP value of 1.67E-01 kg DCB eq., still posing a risk to aquatic life. In contrast, Scenario 1.2 and Scenario 1.3 show negative FAETP values (-6.01E-01 and -7.16E-02 kg DCB eq. respectively), reflecting beneficial impacts on aquatic ecosystems. The negative FAETP value in Scenario 1.3 is explained in Figure 19, where the "Other" category contributes -250.33%, reducing the overall FAETP impact despite the high contribution of electricity (240.11%).

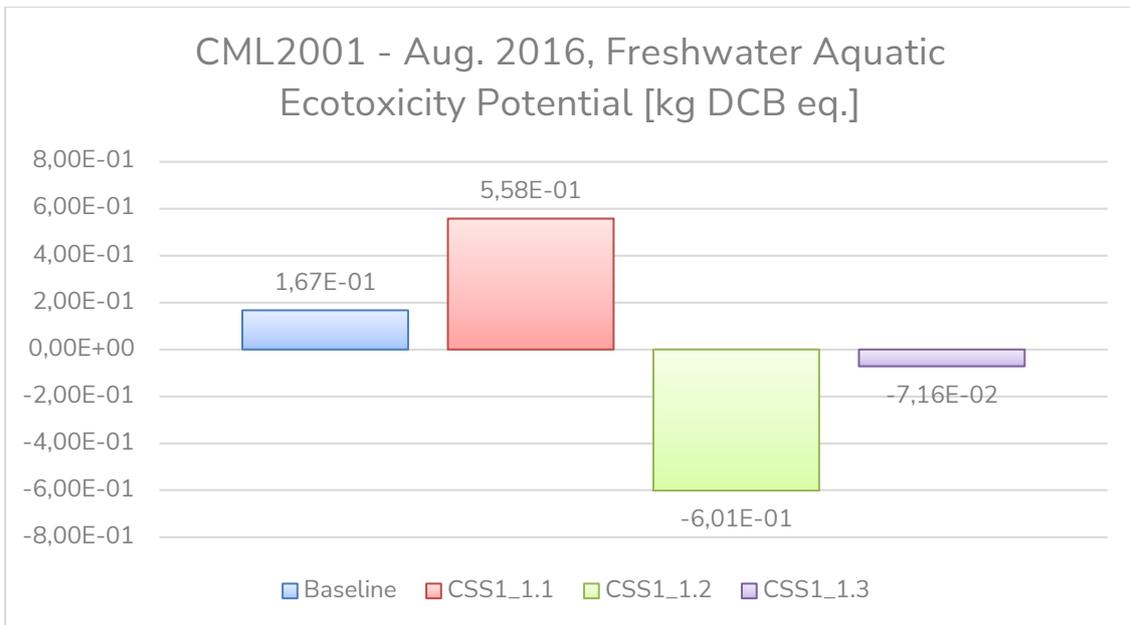


Figure 18 Freshwater Aquatic Ecotoxicity Pot. [kg DCB eq.] impact for each scenario.

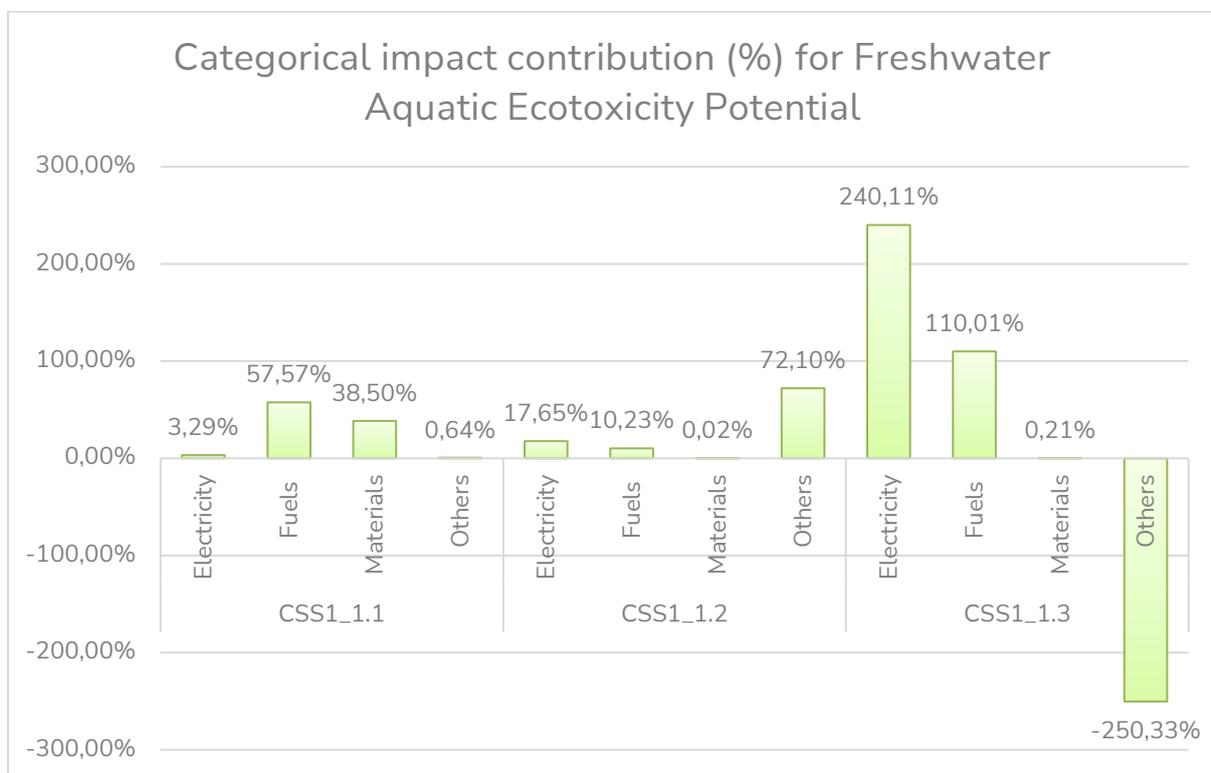


Figure 19 Categorical impact contribution (%) for Freshwater Aquatic Ecotoxicity Pot of each scenario.

### 3.3.6 Global Warming Potential

Global Warming Potential (GWP) is examined as an environmental impact category that looks at the potential for a substance or activity to contribute to global warming or climate change. The total emissions of greenhouse gases, such as carbon dioxide (CO<sub>2</sub>), methane

(CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O), are measured over a specific time frame, typically 100 years. GWP is expressed in units of kilograms of carbon dioxide equivalent (kg CO<sub>2</sub> eq.), which represents the amount of CO<sub>2</sub> emissions that would have the same warming effect as the emissions of the examined greenhouse gases. If a certain activity or substance has a GWP of 10 kg CO<sub>2</sub> eq., it means that its emissions over a 100-year period are equivalent to the warming effect of emitting 10 kilograms of carbon dioxide. Global Warming Potential (GWP 100 years) is used for these purposes.

In Figure 20, the GWP impact across different wood waste management scenarios is compared. The Baseline case shows the highest GWP impact, indicating the greatest contribution to global warming. Scenarios 1.1 and 1.3 have similar, significantly lower GWP values, suggesting a reduced impact compared to the Baseline. Scenario 1.2 shows the lowest GWP value, with the most beneficial impact for global warming potential. This is explained further in Figure 21, where the recovery process in Scenarios 1.2 and 1.3 contributes to the negative GWP impact. Additionally, in Figure 22 are presented the different processes contributing to the overall GWP impact. In CSS1\_1.1, Board preparation process has the highest contribution in GWP impact because of the high energy consumption. On the other hand, Combined heat & energy and CCP processes in CSS1\_1.2 and Combustion and CCP processes in CSS1\_1.3 have significant beneficial contribution in CO<sub>2</sub> reduction in each Scenario respectively.

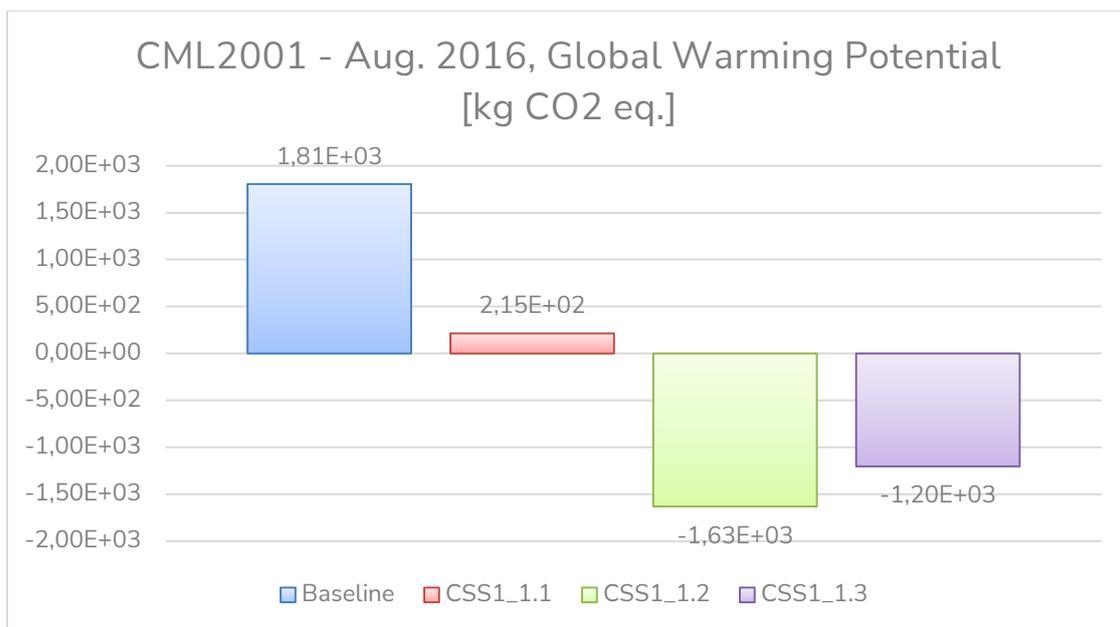


Figure 20 Global Warming Potential [kg CO<sub>2</sub> eq.] impacts.

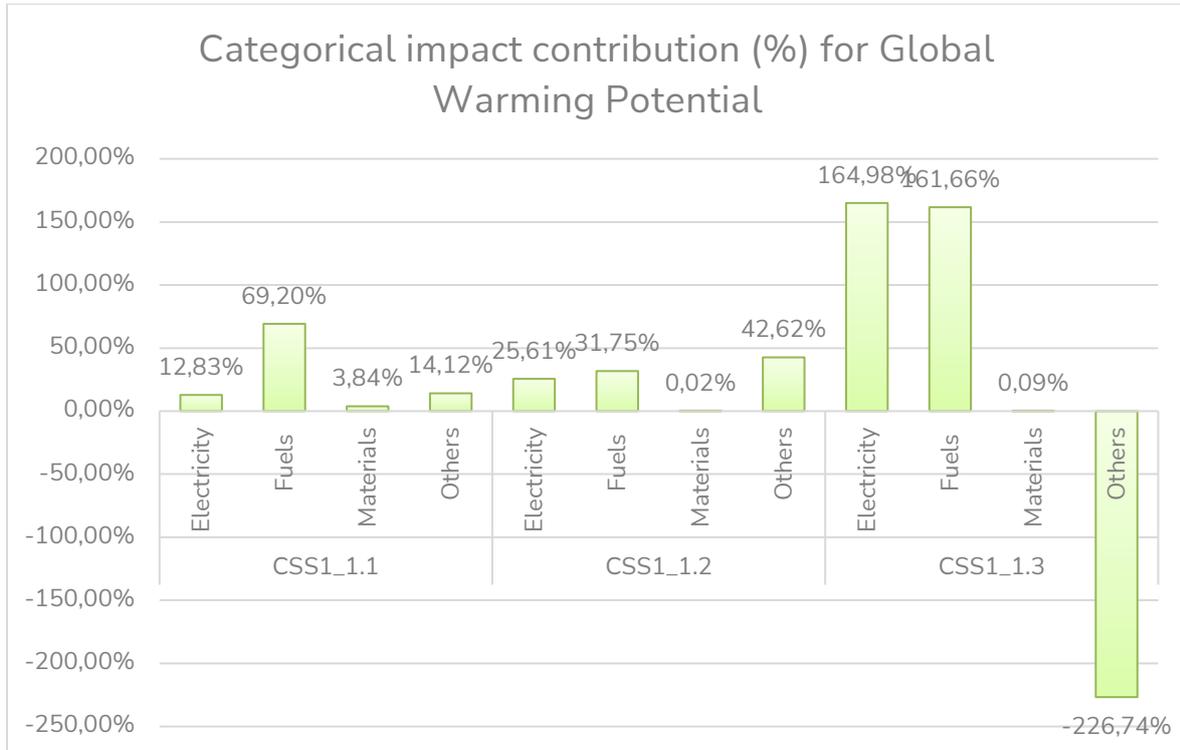


Figure 21 Categorical impact contribution (%) for Global Warming Potential of each scenario.

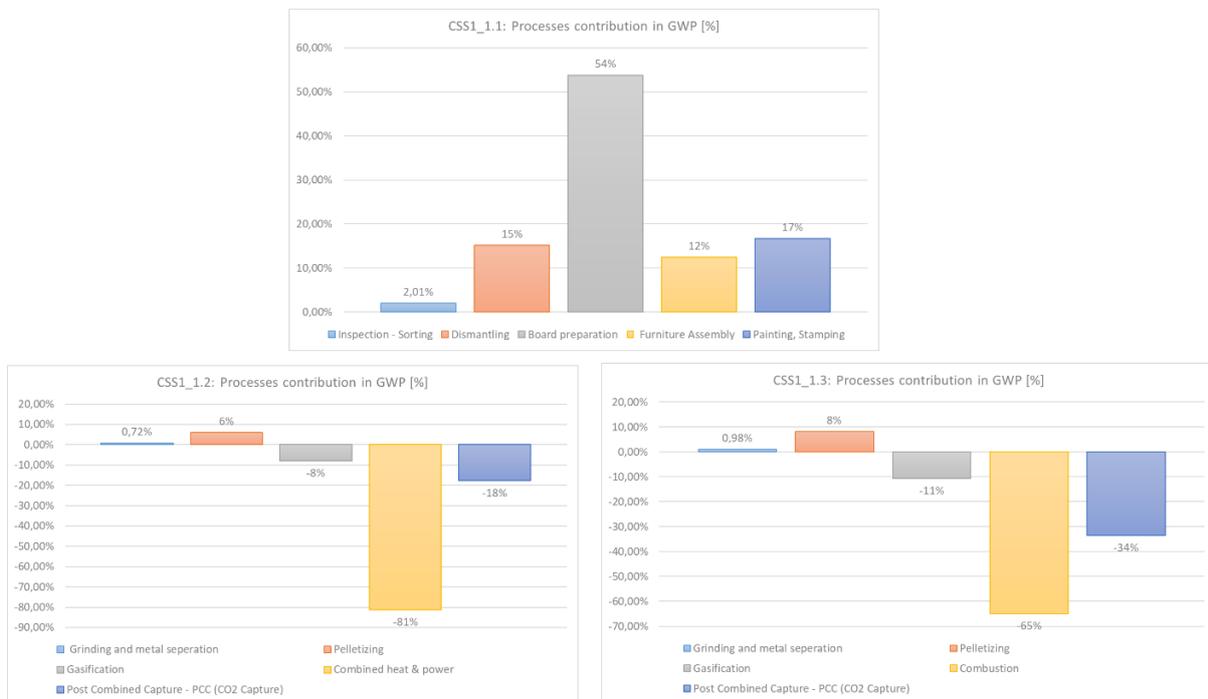


Figure 22 Contribution (%) to GWP impact per process for three different case solution scenarios of wood packaging waste.

### 3.3.7 Human Toxicity Potential

Human Toxicity Potential (HTP) is used to evaluate the potential human health impacts of substances or activities in terms of their toxicity, exposure, and persistence in the environment. The results are expressed in kilograms of DCB equivalent.

In Figure 23, the HTP impact across different wood waste management scenarios is compared. The Baseline scenario has an HTP impact of  $5.41E+00$  kg DCB eq., and Scenario 1.1 has a higher value of  $1.21E+02$  kg DCB eq. Scenario 1.2 shows a negative HTP value of  $-2.50E+01$  kg DCB eq., indicating a more beneficial impact. Scenario 1.3 has the lowest HTP value of all scenarios ( $-4.89E+02$  kg DCB eq.) due to the recovery contribution (-191.72%) (Figure 24), which significantly reduces the human toxicity potential.

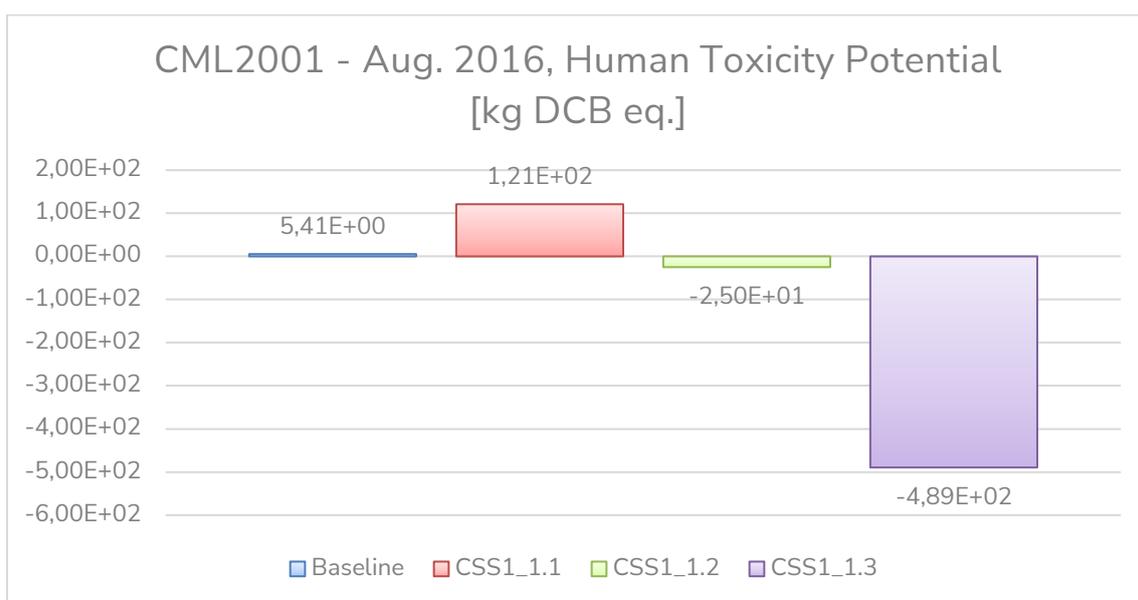


Figure 23 Human Toxicity Potential [kg DCB eq.] impact for each scenario.

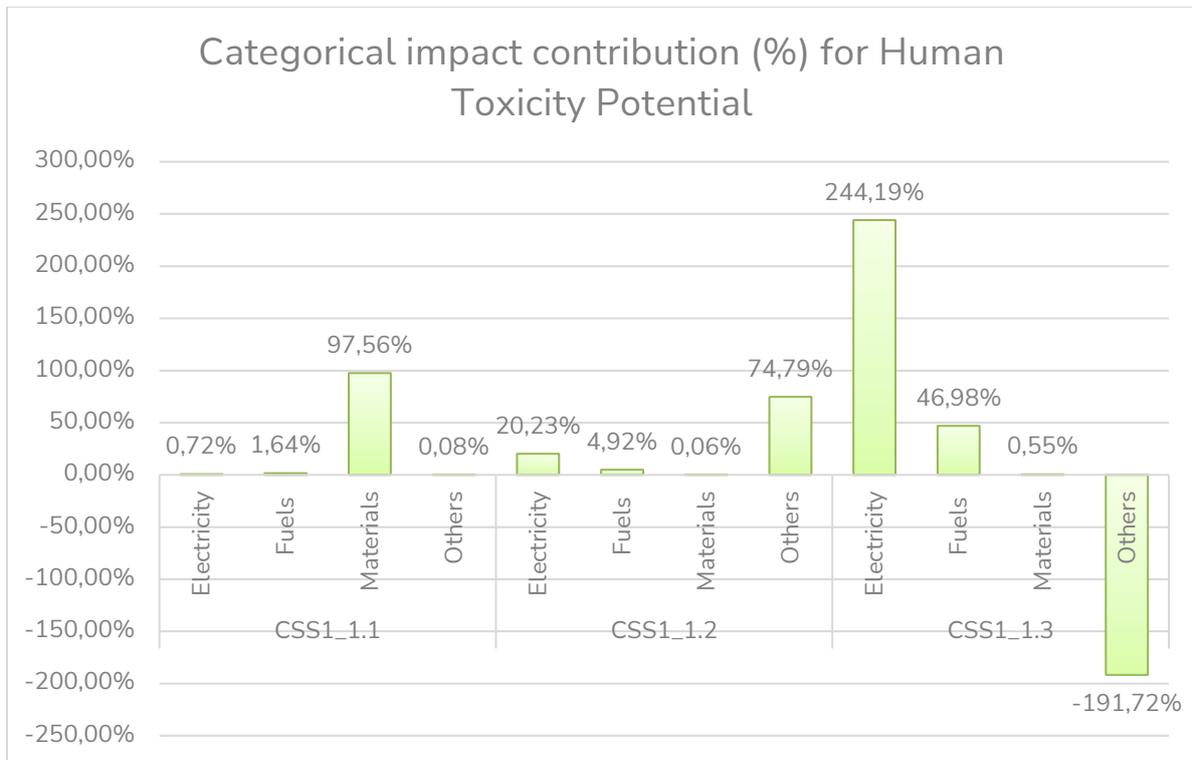


Figure 24 Categorical impact contribution (%) for Human Toxicity Potential of each scenario.

### 3.3.8 Ozone Layer Depletion Potential

Ozone Depletion Potential (ODP) is used as a measure to describe the adverse effects of certain substances on the ozone layer in the stratosphere, particularly their role in diminishing the layer's capacity to block excessive ultraviolet radiation from reaching the Earth's surface. The significance of this issue has been globally recognized, which has led to concerted efforts under the Montreal Protocol to mitigate the impact through international cooperation. Although the impact of building materials on ozone depletion is generally minimal, the use of refrigerants in mechanical systems is a notable concern due to their potential for contributing to ozone layer damage. ODP is quantified in terms of kilograms of R11-equivalents, reflecting the global commitment to reducing the emission of ozone-depleting chemicals and safeguarding the ozone layer.

The ODP impact of various wood waste management scenarios is illustrated in Figure 25. The Baseline scenario (1.59E-10 kg R11 eq.), Scenario 1.1 (2.08E-10 kg R11 eq.), and Scenario 1.3 (9.91E-10 kg R11 eq.) all exhibit positive ODP values, indicating a negative effect on the ozone layer. This impact results from non-renewable sources energy consumption, as shown in Figure 26. In contrast, Scenario 1.2 presents a negative ODP value (-2.80E-09 kg R11 eq.), leading to a beneficial effect in reducing ozone depletion. This

observation is mainly due to contribution from the “Others” category in energy recovery, which helps in minimizing ozone layer depletion (see Figure 26).

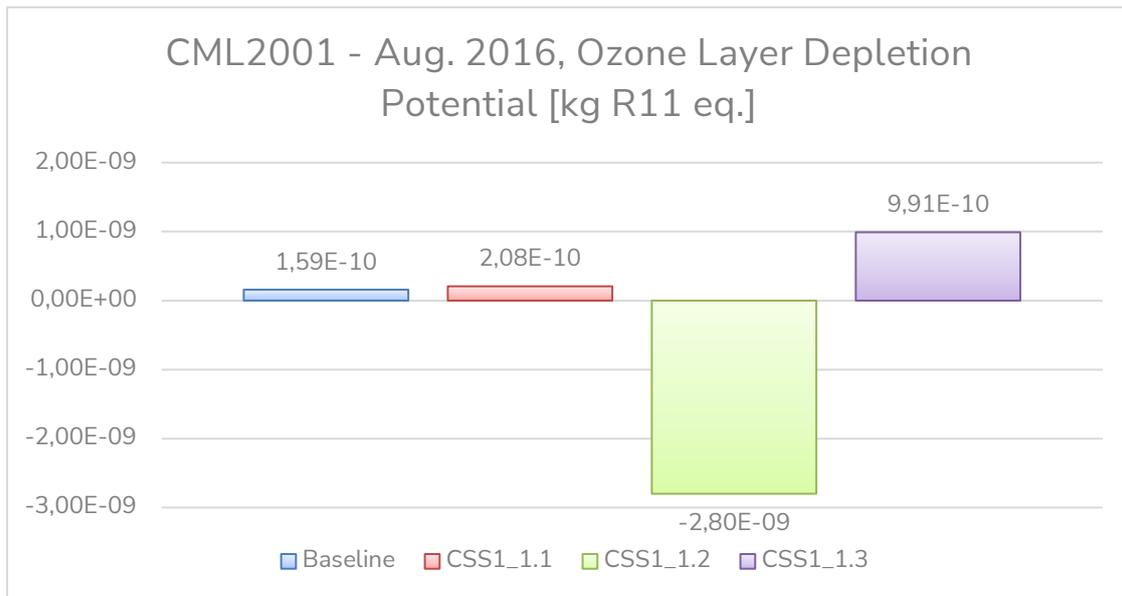


Figure 25 Ozone Layer Depletion Potential [kg R11 eq.] impact for each scenario.

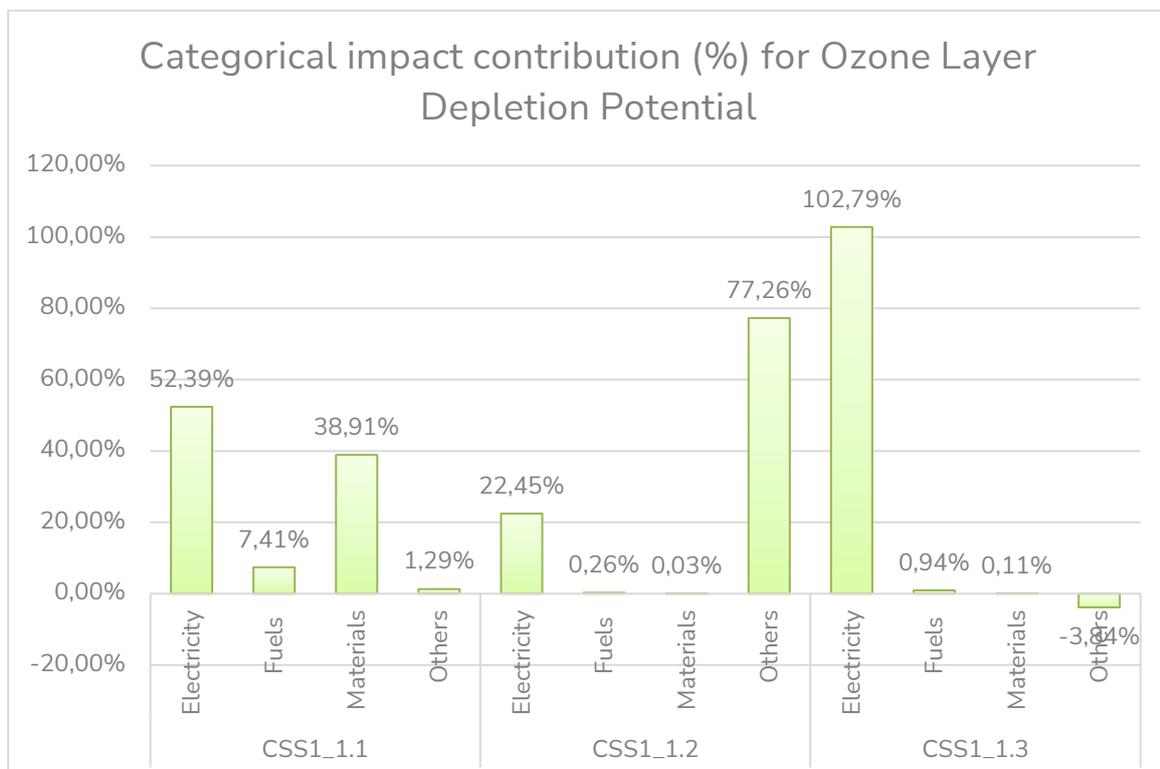


Figure 26 Categorical impact contribution (%) for Ozone Layer Depletion Potential (ODP, steady state) of each scenario.

### 3.3.9 Photochemical Ozone Creation Potential

The majority of tropospheric ozone formation occurs when NO<sub>x</sub>, CO, and VOCs, such as xylene, react in the atmosphere in the presence of sunlight. NO<sub>x</sub> and VOCs are referred to as ozone precursors. A great deal of evidence exists to show that high concentrations (ppm) of ozone, created by high concentrations of pollution and daylight UV rays at the Earth's surface, can harm lung function and irritate the respiratory system. Photochemical Ozone Creation Potential (POCP) is expressed in terms of kg C<sub>2</sub>H<sub>4</sub> equivalent.

According to the Figure 27, POCP impact of Baseline has high value (4,11E-01 kg Ethene eq.) due to the fact that wood packaging waste often contains volatile organic compounds (VOCs) that are released during decomposition of the landfilling. Fuels consumption on 1.1 Scenario has increased the impact value of POCP at 6,00E-02 kg Ethene eq. On the other hand, electrical and thermal energy recovery of 1.2 and 1.3 Scenarios (-1,09E-01 and -3,44E-02 kg Ethene eq. respectively), reduces the potential of Photochemical Ozone Creation, despite the fact that these scenarios have also electrical and fuel consumption.

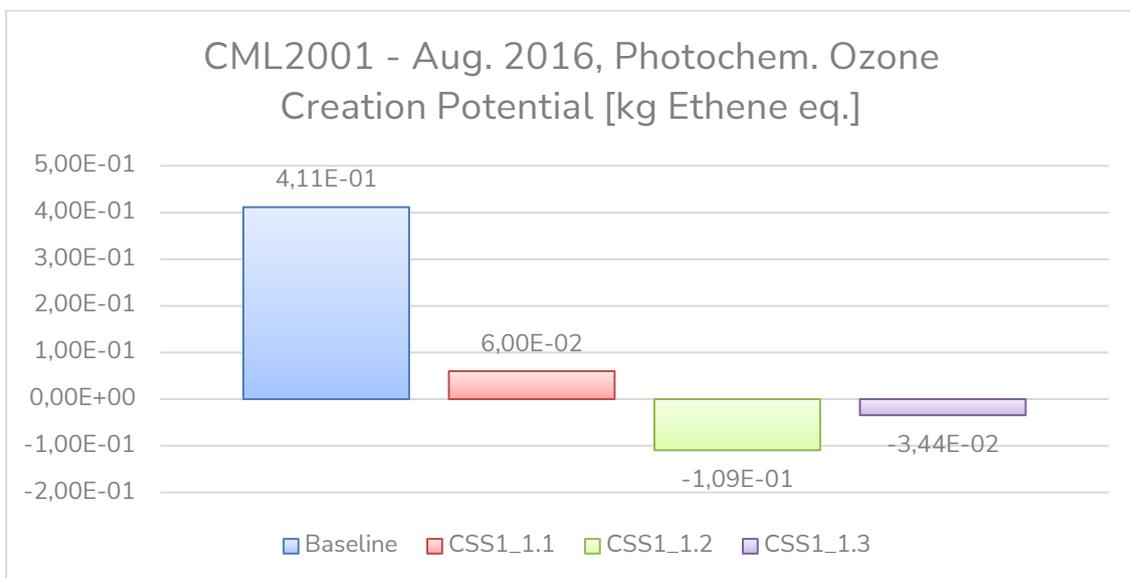


Figure 27 Photochemical Ozone Creation Potential (POCP) [kg Ethene eq.] for each scenario.

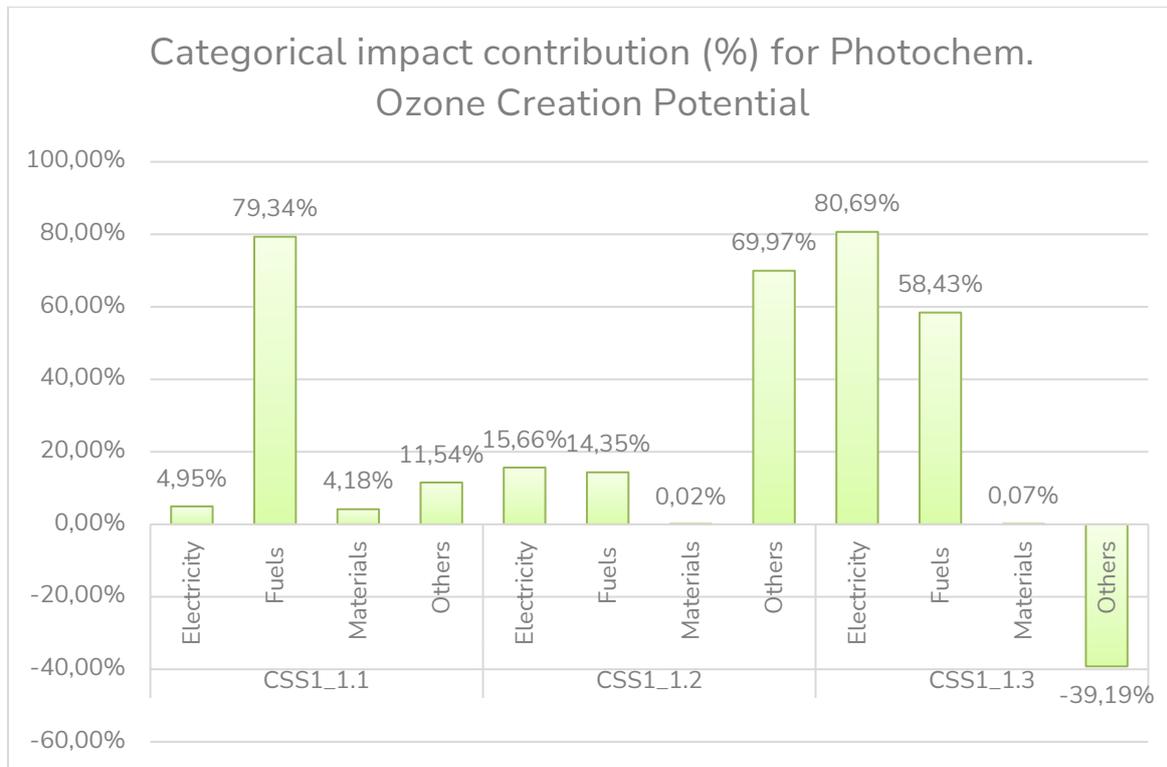


Figure 28 Categorical impact contribution (%) for Photochemical Ozone Creation of each scenario.

### 3.3.10 Terrestrial Ecotoxicity Potential

Terrestrial Ecotoxicity Potential (TETP) is used as an environmental impact category in LCA to evaluate the potential ecological harm to terrestrial ecosystems, including soil and land organisms, as a result of substances or activities. The potential toxicity of substances and their impact on terrestrial ecosystems over the course of their lifetime is measured by TETP. Kilograms of 1,4-dichlorobenzene equivalent (kg DCB eq.) are typically used as the unit of measurement for TETP.

According to Figure 29, Baseline has low TETP inf. impact ( $7,98E-02$  kg DCB eq.) because during landfilling it traps toxic substances rather than dispersing them into the environment through fuel combustion. In contrast, fuel consumption in 1.1 Scenario increases the TETP value to  $8,80E-01$  kg DCB eq., while the 1.2 and 1.3 Scenarios have values  $-9,09E-01$  and  $-5,78E-01$  kg DCB eq. respectively due to the fact that CHP and combustion processes recover the energy and reduce the impact.

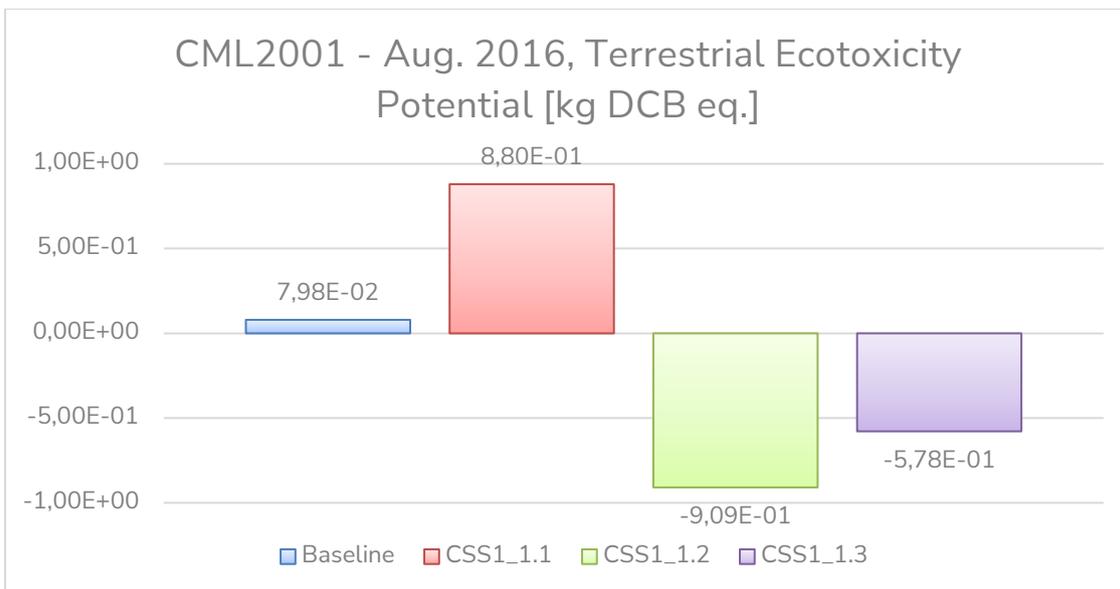


Figure 29 Terrestrial Ecotoxicity Potential [kg DCB eq.]

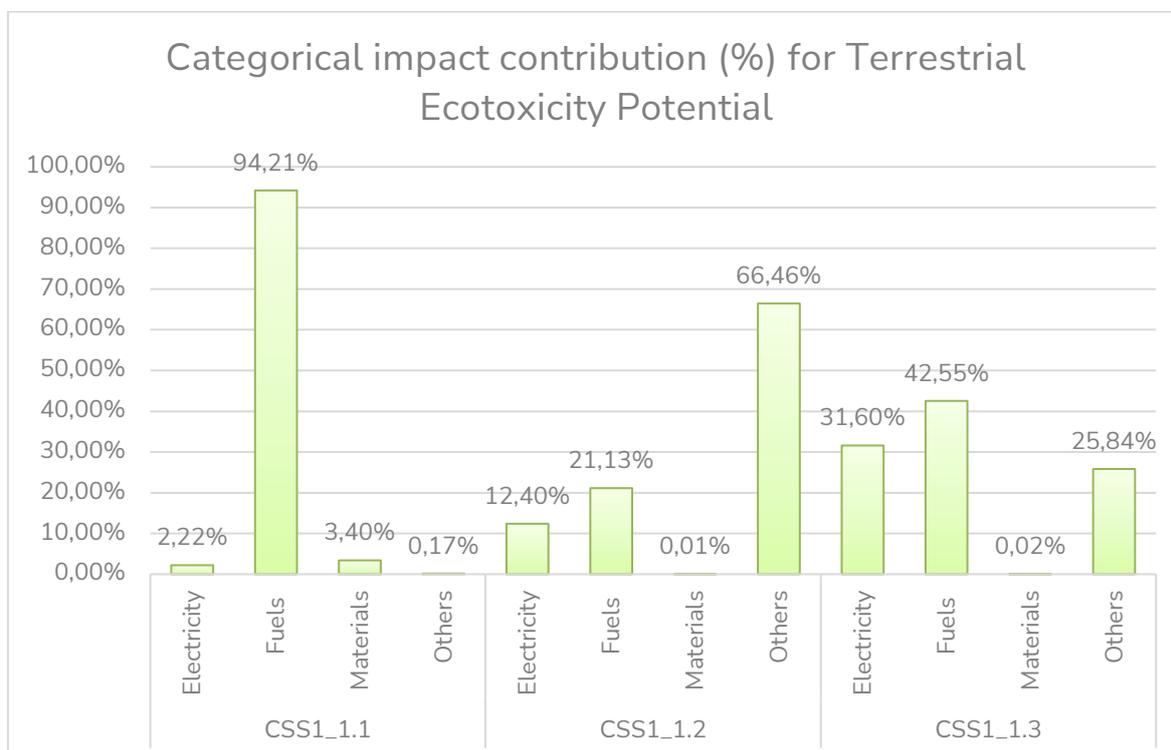


Figure 30 Categorical impact contribution (%) for Terrestrial Ecotoxicity Potential of each scenario.

### 3.4 EN15804+A2

#### 3.4.1 Resource use indicators

Use of renewable primary energy (PERE) and Total use of renewable primary energy resources (PERT) indicators for Baseline is  $1,05E+02$  MJ, for CSS1\_1.1 is  $1,41E+02$  MJ, for CSS1\_1.2 is  $-2,19E+03$  MJ and for CSS1\_1.3 is  $7,74E+02$  MJ.

Use of non-renewable primary energy (PENRE) indicators for Baseline is  $1,03E+03$  MJ, for CSS1\_1.1 is  $1,28E+04$  MJ, for CSS1\_1.2 is  $-1,38E+04$  MJ and for CSS1\_1.3 is  $-9,81E+03$  MJ.

#### 3.4.2 Hazardous Wastes

The hazardous impact category covers various fractions that represent fire, health and environmental hazards posed by substances. These hazards may arise from waste or materials that are dangerous to human, animal and ecosystem. The unit of measurement for hazardous waste disposed (HWD) is typically expressed in kilograms (kg), providing a quantifiable indicator of the potential harmful impact of these materials to health and the environment.

In Figure 31 Hazardous waste disposed [kg], HWD impact of Baseline ( $1,80E-07$  kg), Scenario 1.1 ( $5,13E-07$  kg) and Scenario 1.3 ( $1,78E-06$  kg) have harmful impact, with the latter having the highest value because of the high electric energy consumption which cause the potentials for a hazardous environment. In contrast, HWD impact value Scenario 1.2 indicates the beneficial effect of the electrical energy recovery that takes place in Combined heat & power stage.

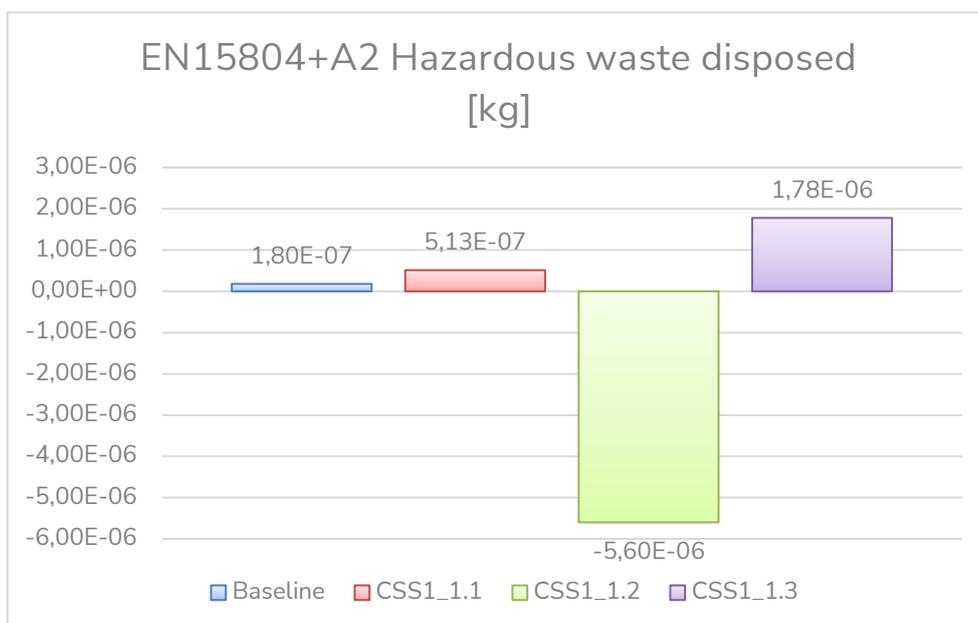


Figure 31 Hazardous waste disposed [kg]

### 3.4.3 Non-hazardous Wastes

The non-hazardous waste disposed (NHWD) impact category encompasses waste materials that are not considered dangerous to human health or the environment. This includes household waste and industrial waste similar to household waste. The unit of measurement for NHWD is typically expressed in kilograms (kg), providing a quantifiable indicator of the amount of waste that requires proper disposal to reduce its environmental impact.

In Figure 32, Baseline with landfilling process has the highest NHWD value (6,06E+02 kg) because wood packaging waste does not significantly affect to human health or the environment during the landfilling. The NHWD values of the other scenarios are close to zero because they do not contain significant non-hazardous waste to increase the impact value.

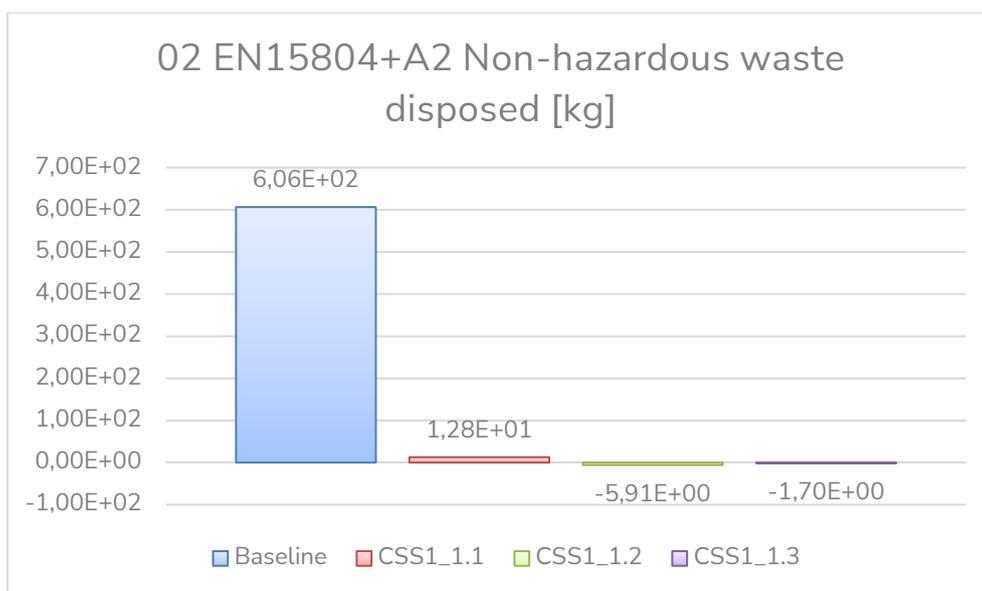


Figure 32 Non-hazardous waste disposed [kg].

### 3.4.4 Use of net fresh water

The use of net fresh water refers to the calculation of the difference between the inflows of water resources and the outflows of water returned to the freshwater environment, as recorded in the LCI. This metric measures the net consumption of freshwater resources during the lifecycle of a product or activity. The unit of measurement is typically expressed in cubic meters (m<sup>3</sup>), providing a quantifiable indicator of freshwater use.

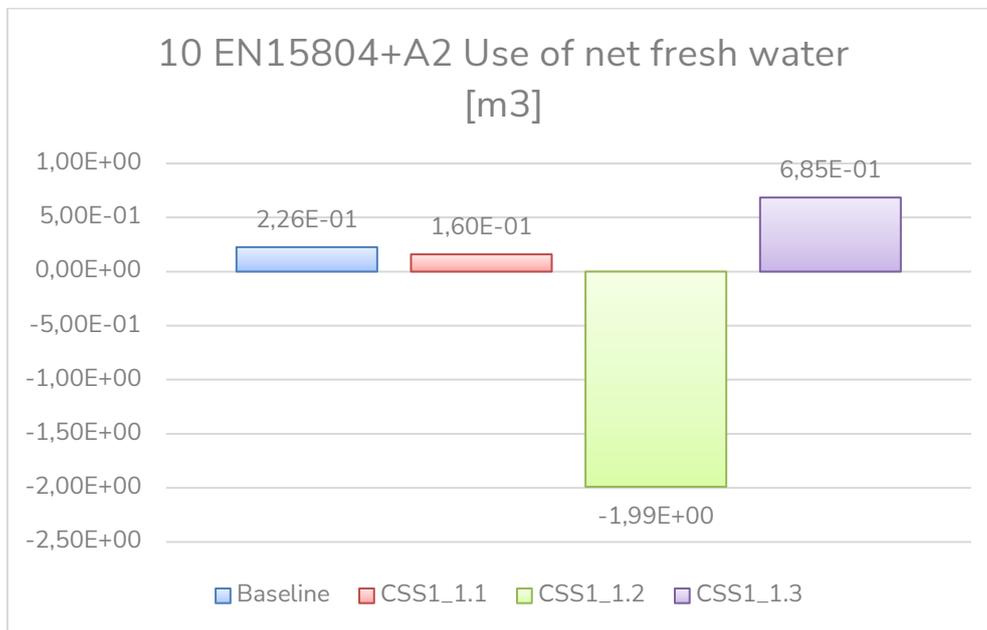


Figure 33 Use of net fresh water [m<sup>3</sup>].

## 4 LCC methodology

### 4.1 Goal and Scope

#### 4.1.1 Goal

The methodology of LCC is more straight forward compared to LCA. The goal and scope definitions are stated as to understand the overall life cycle cost of the proposed CSS1 technology in respect with the sustainable management of wood packing waste. All necessary data to investigate and evaluate the life cycle cost of FRONTSHIP technologies are collected in close collaboration with UNIBZ for understanding the procedures followed during the experimental activity and ensuring the interpretation of valuable data as well as avoiding any data loss. The collected data were properly analysed and interpreted in line with the framework of life cycle cost analysis. Based on this analysis, the most viable and cost-effective part of the cost value chain is identified, and critical review is performed.

The relevant LCC parameters that have to be considered in the current analysis are distributed as shown (in Figure 34) and corresponded to initial capital expenditure (CAPEX) as well as recurring costs i.e. operation and maintenance expenditure (OPEX).

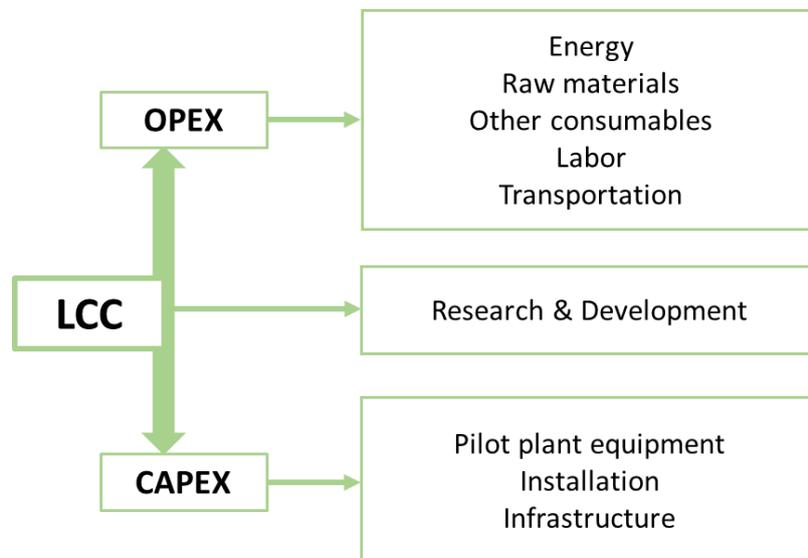


Figure 34 Life Cycle Cost distribution.

More precisely, CAPEX is assumed to be the total cost of the project including the aggregated cost of engineering, civil works, construction, electrical and mechanical components, and contingency percentage. Depending on the project scale, and expected duration, a contractor may choose to include an inflation rate in a tender application. Considering the plant scale range involved in this study it is assumed that a plant can be constructed in one year and that the project cost estimation provided by the contractor does not include an inflationary cost factor. Furthermore, in order to finalize the process flow as well as the design of the stabilization pilot plant, laboratory trials were implemented. For this reason, the cost related to the laboratory instruments as well as laboratory consumables and a bench scale equipment before the final scale-up of the whole technology is taken into account in the current analysis. On the other hand, OPEX refers to the ongoing expenses a company incurs to operate its business daily. The operational costs are divided between labour, energy, chemicals and sludge disposal. Smaller expenses generally fall under the operation and maintenance (O&M) category. OPEX is incurred throughout asset lifespan, but it is not always charged or paid on a uniform basis.

#### 4.1.2 Functions of product system

For all the scenarios under investigation, it is necessary to consider the total cost of labour, maintenance, repairs and any other auxiliary supplies. It is important to note that throughout the entire lifecycle, energy, materials and labour costs should be included, while transportation is not included.

### Calculation of environmental externalities (indirect costs)

The estimation of environmental externalities is based on Climate Change, one of the main externalities mentioned in the EU’s 7th Environment Action Programme as key priorities to be addressed in EU and Member States policies. For the evaluation of the Climate Change externality, it is critical to convert the environmental impact into monetary values. Monetary valuation can be defined as “the practice of converting measures of social and biophysical impacts into monetary units”. The scope of monetary valuation is limited to estimating the value of changes in the availability of non-market goods. Changes in availability concern both changes in the amount and in the quality of a good and the service that the good provides to society. The key point to consider in monetary evaluation is that the main aim is assessing the changes in utility as a result of a given cause and effect relation and this can be done quantifying the marginal utility or damage. From this point of view, monetary value can be used as a measure of utility. The following equation is used for the conversion of potential climate change impact into externality:

$$\text{Climate change externalities [€]} = \text{Total impacts [kg CO}_2 \text{ eq.]} \cdot f \text{ [€/ (kg CO}_2 \text{ eq.)]}$$

where f is equal to 0.004 €/kg CO<sub>2</sub> eq. (or 4 €/ton CO<sub>2</sub> eq.)

#### 4.1.3 System boundary

The boundary system for the LCC of the current study is selected in accordance with that of the LCA analysis. In this way, it is possible to consider the whole procedure in respect to the proposed CSS1 technology. It is noted that the material cost is included in the feed, while the cost of energy is accounted for at different stages of the process. Additionally, maintenance, repair and labour costs are considered. Finally, transportation cost has not been included in Scenarios 1, 2 and 3, as it was not calculated in the LCA analysis.

## 4.2 Data inventory related to LCC analysis

*Table 19 LCC inventory of Baseline.*

Baseline		
Life cycle phase	Target activities	Cost (€)
OPEX	Transportation of resources	176,250
OPEX	Waste disposal	17,625,000

*Table 20 LCC inventory of Scenario 1.*

Scenario 1				
Process	Life cycle phase	Target activities	Cost (€)	
1.1	OPEX	Energy	27,334,796	Diesel
1.2	OPEX	Energy	386,834	Electricity
1.3	OPEX	Labour	27,072	Pallet Dismantler

	OPEX	Energy	794,805	Diesel
	OPEX	Energy	2,232,265	Electricity
	OPEX	Energy	177,540,080	Natural gas
<b>1.4</b>	OPEX	Energy	794,805	Diesel
	OPEX	Energy	2,121,345	Electricity
	OPEX	Energy	16,760,507	Natural gas
<b>1.5</b>	OPEX	Energy	152,320	Electricity
	OPEX	Energy	4,503,318	Natural gas
<b>All</b>	CAPEX	Equipment Acquisition	40,000	Digital tool STAM

Table 21 LCC inventory of Scenario 2.

Scenario 2				
Process	Life cycle phase	Target activities	Cost (€)	
<b>2.1</b>	OPEX	Labour	18,000	Needed workers
	Maintenance_and _Repair	Service Costs	2,000	Cleaning
	OPEX	Energy	2,100,131	Electricity
	OPEX	Equipment Acquisition	446,500,000	Pelletizing
<b>2.2</b>	OPEX	Labour	18,000	Needed workers
	Maintenance_and _Repair	Service Costs	2,000	Cleaning
	OPEX	Energy	17,519,814	Electricity
<b>2.3</b>	OPEX	Labour	18,000	Needed workers
	Maintenance_and _Repair	Labour	500	Cleaning
	OPEX	Energy	2,881,021	Electricity
	CAPEX	Equipment Acquisition	34,000	Gasifier
	CAPEX	Transportation of resources	1,256	Syngas trans
	CAPEX	Equipment Acquisition	700	Gas blower
<b>2.4</b>	OPEX	Labour	36,000	Needed workers
	OPEX	Energy	19,206,812	Electricity
	CAPEX	Equipment Acquisition	20,000	CHP
<b>2.5</b>	CAPEX	Equipment Acquisition	100,000	CCU
	OPEX	Labour	27,000	
	OPEX	Energy	65,775,607	Thermal energy (from natural gas)

	OPEX	Energy	3,232,288	Electricity
All	CAPEX	Equipment Acquisition	650	Cables

Table 22 LCC inventory of Scenario 3.

Scenario 3				
Process	Life cycle phase	Target activities	Cost (€)	
3.1	OPEX	Labour	18,000	Needed workers
	Maintenance_and _Repair	Service Costs	2,000	Cleaning
	OPEX	Energy	2,100,132	Electricity
	OPEX	Equipment Acquisition	446,500,000	Pelletizing
3.2	OPEX	Labour	18,000	Needed workers
	Maintenance_and _Repair	Service Costs	2,000	Cleaning
	OPEX	Energy	17,519,814	Electricity
3.3	OPEX	Labour	18,000	Needed workers
	Maintenance_and _Repair	Labour	500	Cleaning
	OPEX	Energy	2,881,022	Electricity
	CAPEX	Equipment Acquisition	34,000	Gasifier
	CAPEX	Transportation of resources	1,256	Syngas trans
	CAPEX	Equipment Acquisition	700	Gas blower
3.4	OPEX	Labour	36,000	Needed workers
	CAPEX	Transportation of resource	6,200	Pipeline construction & Compressor
	OPEX	Energy	2,560,908	Electricity
	CAPEX	Equipment Acquisition	40,000	Combustion
3.5	CAPEX	Equipment Acquisition	100,000	CCU
	OPEX	Labour	27,000	
	OPEX	Energy	65,775,607	Thermal energy (from natural gas)
	OPEX	Energy	3,232,288	Electricity
All	CAPEX	Equipment Acquisition	650	Cables

### 4.3 Life Cycle Interpretation: Results and discussion

A total of 1,175,000 tonnes of wood waste was subjected to landfilling (Baseline), repairing/reusing (Scenario 1), heat and power recovery (Scenario 2) and electric energy recovery (Scenario 3). The results are presented in the following figure. Based on the costing graph of each scenario, the Baseline exhibits the lowest LCC result (373,081,777 €), followed by Scenario 1 with an increase (2,925,892,232 €). Scenarios 2 (4,336,465,626 €) and 3 (4,273,074,295 €) show similar LCC values.

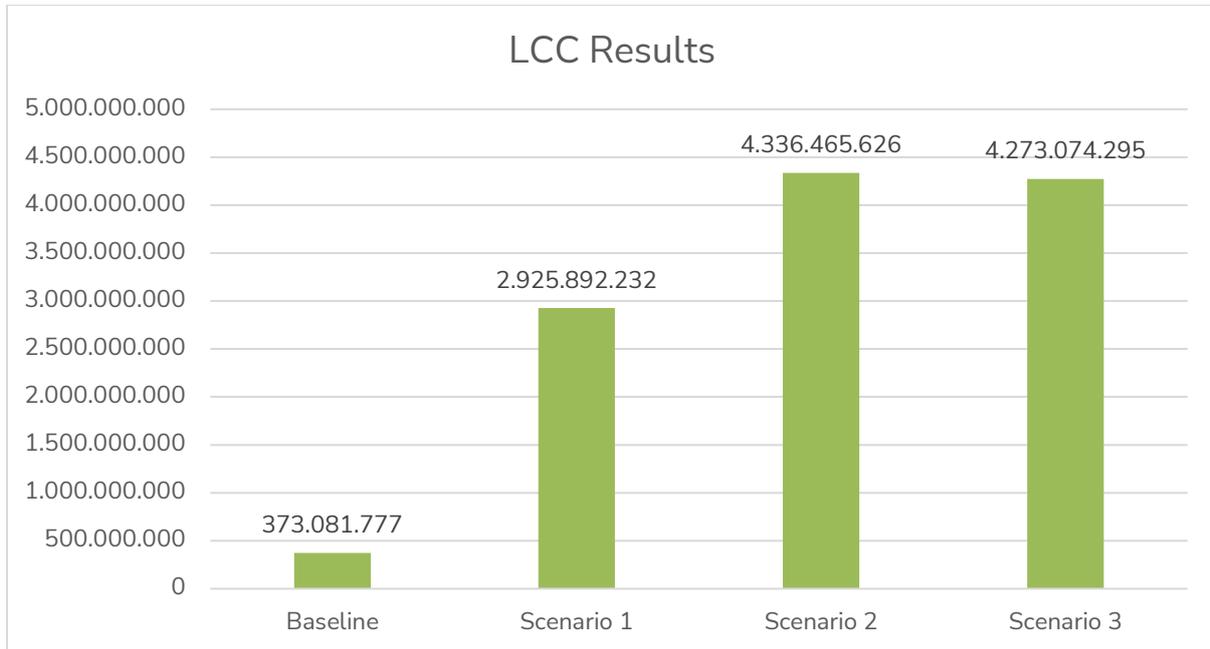


Figure 35 LCC results of each scenario

Results are further supported by the Figure 36, which presents the undiscounted total sensitivity cost for the 1st year. OPEX costs have the highest contribution across all scenarios. In the Baseline, climate change externalities significantly increase the LCC result. Conversely, in Scenario 2, electric and thermal energy recovery and in Scenario 3, thermal energy recovery, contribute to a reduction in the total cost of each scenario. This is due to the fact that energy recovery can lower energy expenses for factories or generate revenue through sales to suppliers.

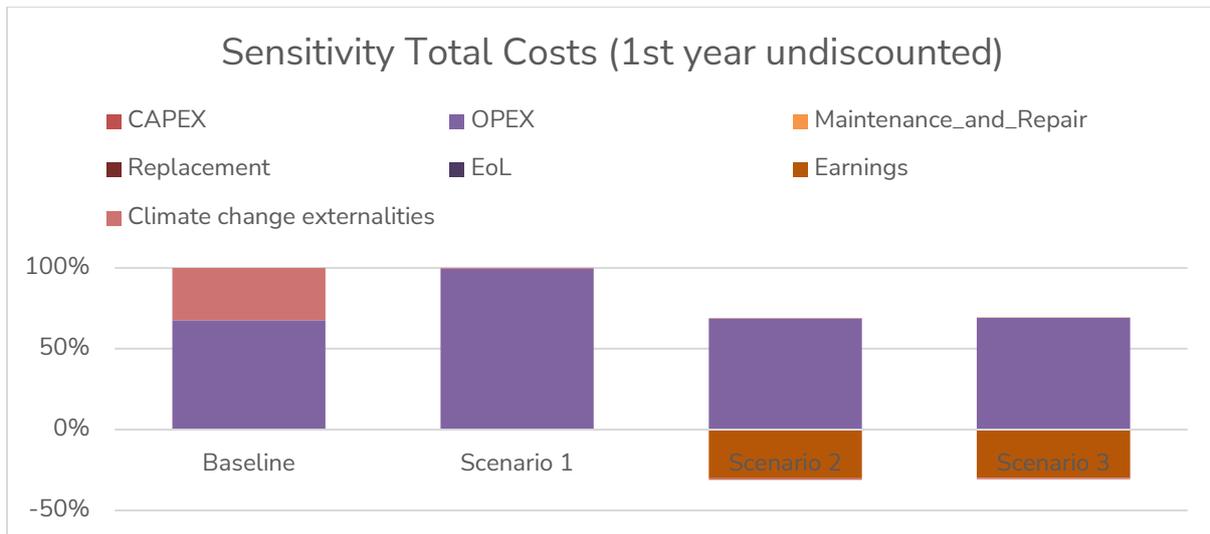


Figure 36 Sensitivity analysis of total costs (1<sup>st</sup> year undiscounted) for each scenario

For a horizon of 20 years, the CAPEX of Scenarios 1, 2, and 3 will remain unchanged due to maintenance. According to the Figure 37, the cost curves of these scenarios exhibit a decreasing trend, while the net present values progressively decline over time based on the annual discount factor CF (T).

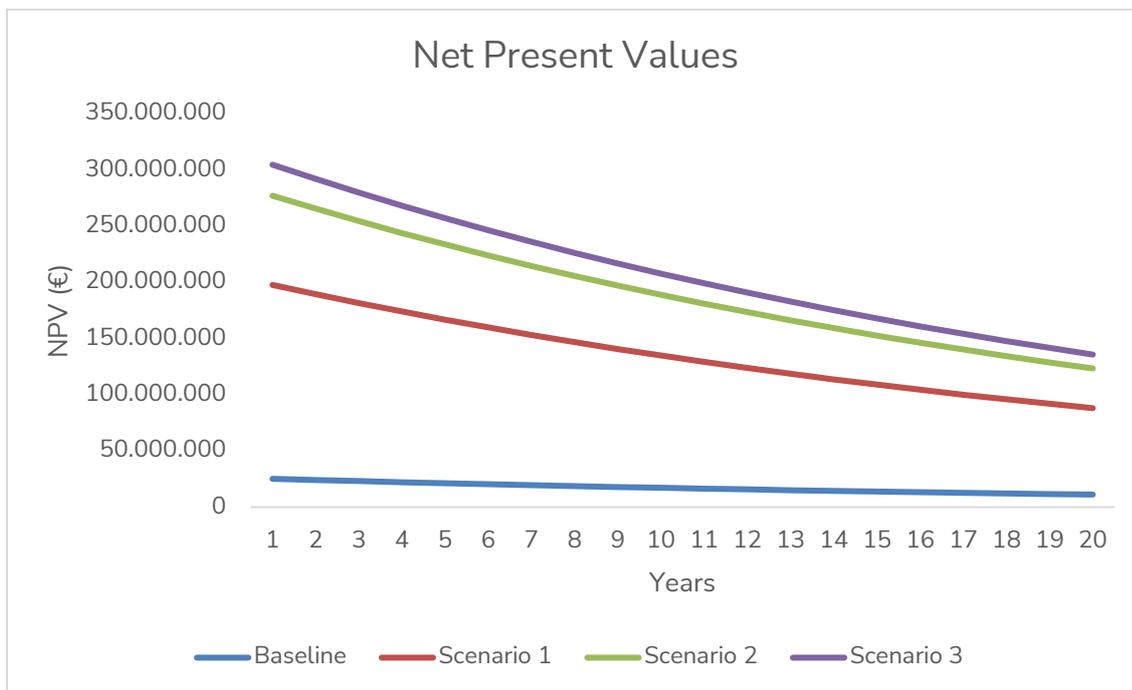


Figure 37 Net present values of each scenario for 20 years horizon

## 5 s-LCA methodology

### 5.1 Goal and Scope

This study focuses on wood waste and wood packaging waste in Europe, specifically in the Lodkie region of Poland, where wood waste production is particularly high. It is anticipated that the wood waste generated by wood-processing industries can lead to various social and sociological impacts throughout their lifecycle.

The goal of the s-LCA is to assess and estimate the social impacts generated the new waste management solutions and technologies within the lifecycle of these industries in order to evaluate whether the results showed an improvement in sustainability and efficiency or not. The social and sociological impacts of the wood packaging waste will be further examined with the use of impact subcategories for each stakeholder group.

In this study, the CSS1 is applied as the new waste management approach, focusing on the sustainable handling of wood packaging waste through end-of-life disposal, reuse, and recycling.

For the analysis, a case study was conducted by an institute in Italy that implements this solution. The results were then compared with the baseline system used in Italy to assess the social risks associated with the newly developed solution.

The scope of the s-LCA is to do a cradle to grave analysis including the system boundaries: Construction-Operation-Maintenance-End of life of wood packaging waste with the use of quantitative-semi quantitative-qualitative data that were collected from the s-LCA questionnaire.

### 5.2 Stakeholders and impact categories

According to the guidelines published by UNEP/SETAC, the stakeholders that can be affected by the life cycle stages of the production of wood packaging waste are the following:

#### 5.2.1 Workers

In this study, the term "workers" refers to the individuals responsible for the operation and maintenance of the systems within the facility, as well as the technicians managing the infrastructure, supervisors and administrative staff. Workers are evaluated across several indicators, but two key categories are really important: i) Health and Safety and ii) Working Conditions.

For the Health and Safety category, the focus was on the availability of safety measures and the rate of fatal accidents in the workplace. Specifically, we assessed the presence of safety protocols, preventive measures, emergency protocols and initiatives aimed at promoting healthy workplace practices. The data for this category was collected both quantitatively

(fatal accident rates) and qualitatively (presence of safety measures), primarily through the s-LCA questionnaire.

In contrast, the Working Conditions category was measured through two subcategories: fair salary and working hours. While we were unable to obtain the exact minimum wage of the employees, we assessed the unequal remuneration between men and women working at the facility, using qualitative data from the questionnaire. For the working hours category, we examined the likelihood of workers having to work overtime, based on their responses in the questionnaire.

Additional indicators for this stakeholder group included: Freedom of Association, Child Labor, Forced Labor, Equal Opportunity/Discrimination, Social Security/Benefits and Employment Relationships. These were also evaluated in a similar manner, relying on both qualitative and quantitative data gathered through the questionnaire.

## 5.2.2 Consumers

Consumers are defined as individuals who "consume" the material or immaterial outputs of the system. The most important impact category for this stakeholder group is Health and Safety, which was evaluated quantitatively through public health spending and the end-of-life responsibility, which refers to the presence of systems within the organization that provide consumers with information on end-of-life options for products and was measured by the recycling rate, indicating the proportion of materials recycled or recovered from waste. Additionally, the feedback mechanism was assessed using the press freedom scale, while consumer privacy was estimated based on the rule of law scale. Lastly, transparency was evaluated using the corruption percentage index.

## 5.2.3 Local community

This group of stakeholders refers to the communities living near the industry region and any other areas where activities directly related to resource recovery take place. Among the various impact categories considered, three were particularly relevant for this stakeholder group: i) Community engagement, ii) Secure, Safe and Healthy living conditions and iii) Local employment.

For community engagement, the contribution of the organization to local development was evaluated, along with the support provided by the organization for community initiatives (such as volunteer hours or financial contributions) and the diversity of community stakeholder groups involved with the organization. Data for these aspects were gathered qualitatively through the questionnaire, answered by members of the local community.

The safety and security of the community are also crucial. In this context, reducing the use of hazardous substances and other materials is essential to improving living conditions in these areas. Additionally, the presence or absence of terrorism in these areas was examined. As with the other indicators, data was collected from the relevant questionnaire responses.

For local employment, the unemployment rates in the local community were considered, as well as the proportion of the local population hired by the organization, to assess how much the organization involves local people in its processes, despite the implementation of the new CSS1 solution. Again, the data for these categories were provided quantitatively. Other indicators for this stakeholder group included access to material and immaterial resources, delocalization and migration and the respect for indigenous rights. These were evaluated in a similar manner, using the same approach as described above.

### 5.2.4 Society

This stakeholder category was analysed using five different impact categories, with two being particularly important: public commitment to sustainability issues and technological development.

For public commitment to sustainability issues, values were assigned based on the percentage of resources allocated to sustainability and social activities that regulate the processes involved, as well as the use of critical raw materials. Another key indicator was the ecological footprint per capita, which was evaluated quantitatively. In terms of technological development, R&D spending was analysed to determine whether the innovative technology systems had a positive impact on the organization.

Other indicators explored for society included economic development, the mitigation of armed conflict, poverty alleviation and corruption.

### 5.2.5 Supply chain

Lastly, for the value chain actors, the main impact categories that were defined included fair competition, promoting social responsibility, supplier relationships and respect of intellectual property rights. Specifically, the fair competition and the supplier relationships were assessed based on regulatory quality, the promotion of social responsibility was evaluated using the Good Country Index and the respect for intellectual property rights was assessed using the Global IP Index.

*Table 23 Summary of stakeholders and their indicators*

Stakeholders	Indicators	Data source
<b>Workers</b>	(1) Freedom of association	ITUC Freedom of association [YES (100) - NO (1)] <a href="#">QL-P</a>
	(2) Child labour	Child labour [% of children ages 7-14] <a href="#">QN-N</a>
	(3) Forced labour	Forced labour and slavery [% of population] <a href="#">QN-N</a>
	(4) Fair salary	Minimum wage [EUR/month] <a href="#">QN-P</a>
	(4) Fair salary	Unequal remuneration [YES-100, NO-0] <a href="#">QL-N</a>
	(5) Working hours	Hours worked per week [hours] <a href="#">QN-N</a>
	(6) Equal opportunity/Discrimination	Women's share of work force [%] <a href="#">QN-P</a>

	(6) Equal opportunity/Discrimination	Establishment of a committee/person for matters of discrimination [YES-100, NO-0] <a href="#">QL-P</a>
	(7) Health and safety	Fatal accidents at work [-] <a href="#">QN-N</a>
	(7) Health and safety	Presence of preventive measures and emergency protocols (YES-100, NO-0) <a href="#">QL-P</a>
	(7) Health and safety	Measures to improve wellbeing and healthy practices in the facilities (YES-100, NO-0) <a href="#">QL-P</a>
	(8) Social Security/Benefits	Social protection expenditure [% of GDP] <a href="#">QN-P</a>
	(9) Employment relationships	Social or training activities planned [YES-100, NO-0] <a href="#">QL-P</a>
	(9) Employment relationships	Anonymous procedure for employees to state issues related with working conditions [YES-100, NO-0] <a href="#">QL-P</a>
<b>Consumers</b>	(10) Health & Safety	Public health spent per capita [%] <a href="#">QN-P</a>
	(11) Feedback Mechanism	Press freedom [0, constrained - 100, free] <a href="#">QN-P</a>
	(12) Consumer Privacy	Rule of law [0-100] <a href="#">QN-P</a>
	(13) Transparency	Corruption percentage index [0, highly corrupt - 100, very clean] <a href="#">QN-P</a>
	(14) End of life responsibility	Safe and harmless to handle the end of life [YES-100, NO-0] <a href="#">QL-P</a>
	(14) End of life responsibility	Recycle rate (proportion of materials recycled or recovered from waste) <a href="#">QN-P</a>
<b>Local community</b>	(15) Access to material resources	GDP per capita [EUR per capita] <a href="#">QN-P</a>
	(16) Access to immaterial resources	Total literacy above 15 years [%] <a href="#">QN-P</a>
	(16) Access to immaterial resources	Public expenditure In Education [percent of GDP] <a href="#">QN-P</a>
	(17) Delocalization and Migration	Wellbeing [0-100] <a href="#">QN-P</a>
	(17) Delocalization and Migration	Satisfaction with Life Scale (SWLS) [0-100] <a href="#">QN-P</a>
	(18) Safe & healthy living conditions	Public health expenditure per capita [percent of GDP] <a href="#">QN-P</a>
	(18)1 Safe & healthy living conditions	Management effort to minimize use of hazardous substances [YES 100, NO 0] <a href="#">QL-P</a>
	(18) Safe & healthy living conditions	Certified environmental management system [YES-100, NO-0] <a href="#">QL-P</a>
	(19) Respect of indigenous rights	Political freedom and Civil rights [1 (complete freedom) to 7 (no freedom)] <a href="#">QN-N</a>
	(20) Community engagement	Voice and accountability [0-100] <a href="#">QN-P</a>
	(20)1 Community engagement	Contribution of the organization to the local development (YES - 100, NO - 0) <a href="#">QL-P</a>

	(20)2 Community engagement	Organizational support (volunteer hours or financial) for community initiatives (YES - 100, NO - 0) <b>QL-P</b>
	(20)3 Community engagement	Diversity of community stakeholder groups that engage with the organization (YES - 100, NO - 0) <b>QL-P</b>
	(20)4 Community engagement	Presence of organizational reports disclosed to local community (YES-100, NO-0) <b>QL-P</b>
	(20) Community engagement	Indigenous communities in the local community [YES-100, NO-0] <b>QL-P</b>
	(21) Local employment	Unemployment rates [% of population] <b>QN-N</b>
	(21)1 Local employment	Employees originally from the local community (%) <b>QN-P</b>
	(21)2 Local employment	Percentage on spending on locally based suppliers [% of GDP] <b>QN-P</b>
	(22) Secure living conditions	Political Stability and Absence of Violence and Terrorism [0, very bad - 100, very good] <b>QN-P</b>
	(22) Secure living conditions	Presence of risks in the facility [YES-100, NO-0] <b>QL-N</b>
<b>Society</b>	(23) Commitment to sustainability	Ecological Footprint per capita [global hectares - GHA per capita] <b>QN-N</b>
	(23) Commitment to sustainability	Percentage of the resources spend in sustainability and social activities (%) <b>QN-P</b>
	(23) Commitment to sustainability	Use of critical raw materials [YES 100, NO 0] <b>QL-N</b>
	(24) Economic development	UN Human Development Index [0-100] <b>QN-P</b>
	(25) Technology development	R&D spend [percent of GDP] <b>QN-P</b>
	(25) Technology development	Involvement in technology transfer projects [High-100, Medium -50, Low-0] <b>QL-P</b>
	(26) Mitigation of armed conflict	Global Peace Index [1(very peaceful) to 5 (maximum unrest)] <b>QN-N</b>
	(27) Poverty alleviation	Formalized commitment to reduce poverty [YES-100, NO-0]
	(28) Corruption	Control of corruption index (WB) [0, very bad - 100, very good] <b>QN-P</b>
<b>Value chain actors</b>	(29) Fair competition	Regulatory quality [0 (lowest) to 100 (highest)] <b>QN-P</b>
	(30) Promoting social responsibility	Good Country Index <b>QN-P</b>
	(31) Supplier relationships	Regulatory quality [0 (lowest) to 100 (highest)] <b>QN-P</b>
	(32) Respect of intellectual property rights	Global IP Index [0 (no IP protection)- 35 (best IP protection)] <b>QN-P</b>

\*Note: QL: qualitative indicator. QT: quantitative indicator. P: the higher, the more positive. N: the higher, the more negative

## 5.3 Performance assessment - Impact assessment

Following the methodology of the performance and impact assessment, we did the performance assessment as shows in Table 24.

*Table 24 s-LCA performance assessment of WP3*

Stakeholders	Indicators	Data source	Reference Study	Case Study
<b>Workers</b>	(1) Freedom of association	ITUC Freedom of association	5,00	5,00
	(2) Child labour	Child labour	4,73	5,00
	(3) Forced labour	Forced labour and slavery	4,99	5,00
	(4) Fair salary	Minimum wage	-	-
	(4) Fair salary	Unequal remuneration	4,48	4,48
	(5) Working hours	Hours worked per week	1,00	5,00
	(6) Equal opportunity/Discrimination	Women's share of work force	2,80	3,00
	(6) Equal opportunity/Discrimination	Establishment of a committee/person for matters of discrimination	5,00	5,00
	(7) Health and safety	Fatal accidents at work	4,99	5,00
	(7) Health and safety	Presence of preventive measures and emergency protocols	5,00	5,00
	(7) Health and safety	Measures to improve wellbeing and healthy practices in the facilities	5,00	5,00
	(8) Social Security/Benefits	Social protection expenditure	2,2	2,2
	(9) Employment relationships	Social or training activities planned	5,00	5,00
	(9) Employment relationships	Anonymous procedure for employees to state issues related with working conditions	5,00	5,00
<b>Consumers</b>	(10) Health & Safety	Public health spent per capita	1,38	1,38
	(11) Feedback Mechanism	Press freedom	3,79	3,79
	(12) Consumer Privacy	Rule of law	3,64	3,64
	(13) Transparency	Corruption percentage index	3,16	3,16
	(14) End of life responsibility	Safe and harmless to handle the end of life [YES-100, NO-0]	3,13	5,00

	(14) End of life responsibility	Recycle rate (proportion of materials recycled or recovered from waste)	1,00	5,00
<b>Local community</b>	(15) Access to material resources	GDP per capita	2,11	2,11
	(16) Access to immaterial resources	Total literacy above 15 years	4,96	4,96
	(16) Access to immaterial resources	Public expenditure In Education	1,17	1,17
	(17) Delocalization and Migration	Wellbeing	3,58	3,58
	(17) Delocalization and Migration	Satisfaction with Life Scale (SWLS)	3,60	3,60
	(18) Safe & healthy living conditions	Public health expenditure per capita	1,35	1,35
	(18)1 Safe & healthy living conditions	Management effort to minimize use of hazardous substances	5,00	5,00
	(18)2 Safe & healthy living conditions	Certified environmental management system	5,00	1,00
	(19) Respect of indigenous rights	Political freedom and Civil rights	5,00	5,00
	(20) Community engagement	Voice and accountability	4,43	4,43
	(20)1 Community engagement	Contribution of the organization to the local development	1,00	5,00
	(20)2 Community engagement	Organizational support (volunteer hours or financial) for community initiatives	5,00	5,00
	(20)3 Community engagement	Diversity of community stakeholder groups that engage with the organization	5,00	5,00
	(20)4 Community engagement	Presence of organisational reports disclosed to local community	5,00	5,00
	(20)5 Community engagement	Indigenous communities in the local community [YES-100, NO-0]	5,00	1,00
	(21) Local employment	Unemployment rates	4,75	4,75
	(21)1 Local employment	Percentage of workforce hired locally	2,84	3,39
	(21)2 Local employment	Percentage on spending on locally based suppliers	3,70	5,00

	(22) Secure living conditions	Presence of risks in the facility [YES-100, NO-0]	1,00	5,00
	(22) Secure living conditions	Political Stability and Absence of Violence and Terrorism	3,596	3,596
<b>Society</b>	(23) Commitment to sustainability	Ecological Footprint per capita	4,00	4,00
	(23) Commitment to sustainability	Percentage of the resources spend in sustainability and social activities	-	-
	(23) Commitment to sustainability	Use of critical raw materials	1	5
	(24) Economic development	UN Human Development Index	4,58	4,58
	(25) Technology development	R&D spend	1,06	1,06
	(25) Technology development	Involvement in technology transfer projects [High-100, Medium -50, Low-0]	3,00	5,00
	(26) Mitigation of armed conflict	Global Peace Index	4,31	4,31
	(27) Poverty alleviation	Formalised commitment to reduce poverty [YES-100, NO-0]	5,00	1,00
	(27) Corruption	Control of corruption index (WB)	3,72	3,72
<b>Value chain actors</b>	(28) Fair competition	Regulatory quality	3,91	3,91
	(29) Promoting social responsibility	Good Country Index	4,04	4,04
	(30) Supplier relationships	Regulatory quality	3,91	3,91
	(31) Respect of intellectual property rights	Global IP Index	4,36	4,36

## 5.4 Social LCA results and discussion

In this subsection, the results for each stakeholder group and impact category, as described earlier, are presented. The aim of this section is to identify which indicators contributed to the improvements observed in the CSS1 solution, thereby enhancing the lifecycle sustainability in the region. Additionally, a final comparison between the two cases is provided to highlight the differences and evaluate the overall impact of the new solution.

*Table 25: Average results for the five stakeholder groups*

	<b>Reference Study Aver</b>	<b>Case Study Aver</b>
Workers	4,25	4,59

Consumer	2,68	3,66
Local Community	3,65	3,75
Society	3,33	3,58
Supply chain	4,05	4,05



Figure 38 Average results for each stakeholder group in the two cases.

As shown in Figure 38, all stakeholder groups, except for the supply chain (which remains unchanged), were positively impacted by the new waste management solution of the case study. Therefore, the overall results can be considered satisfactory.

In Figure 39, we can compare the overall results between the reference and the case study of this analysis. Figure 39-44 provide a more detailed examination of each stakeholder group.

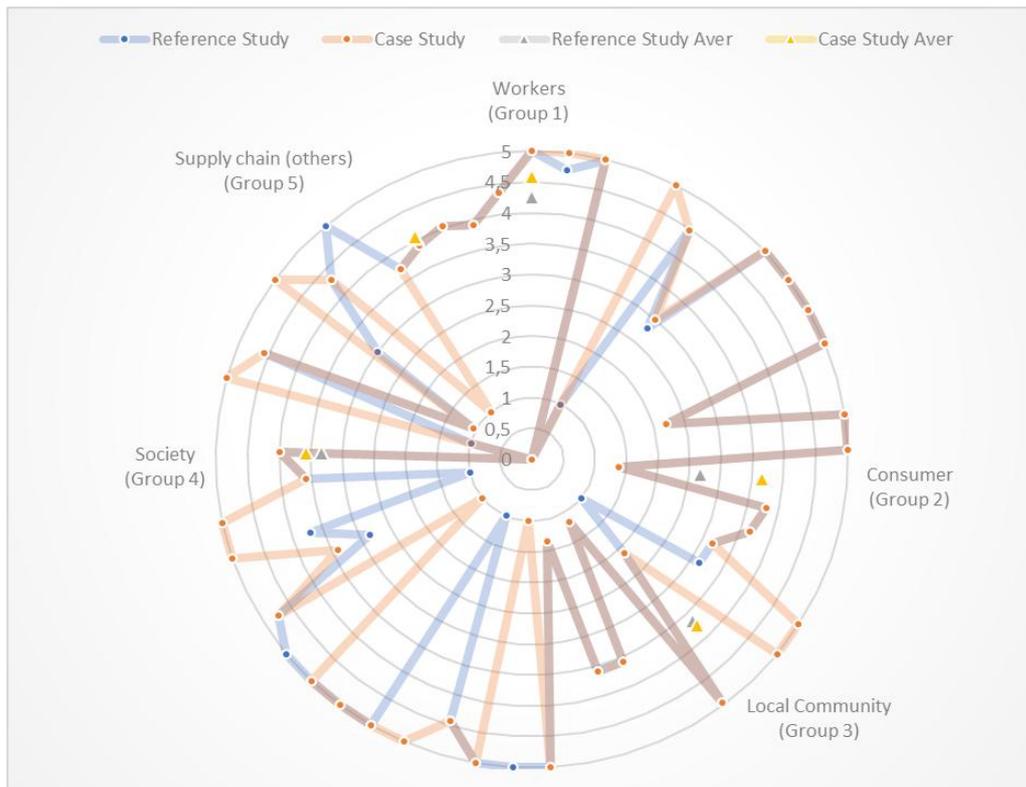


Figure 39 Results for each stakeholder group in the two cases.

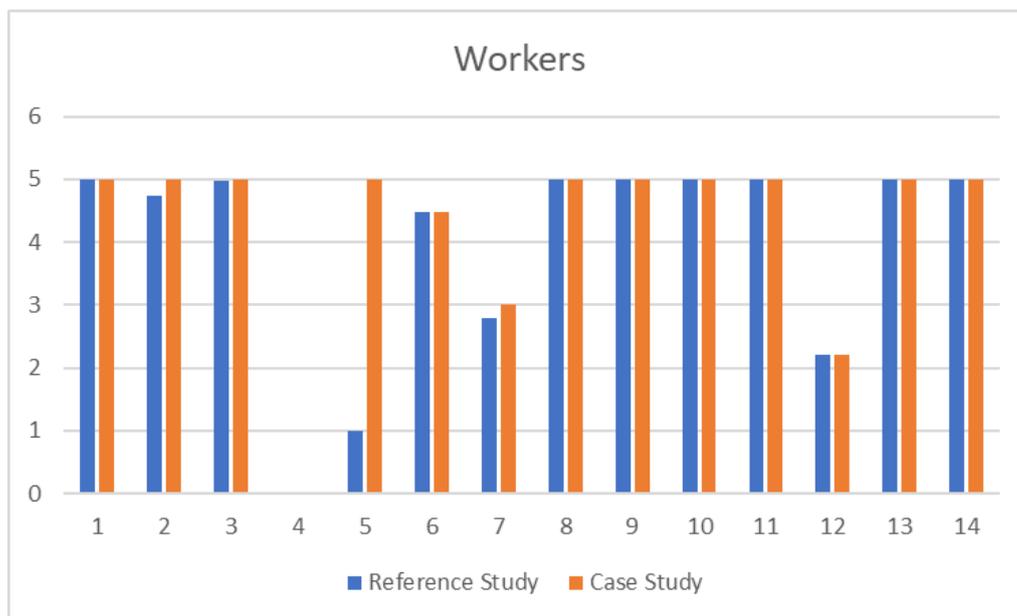


Figure 40 Worker's results for the two cases.

As seen in Figure 40, the categories that differ between the two cases and show an improvement in the case study are mainly the unequal remuneration and to a lesser extent the women's participation in workforce as well as the child and forced labour. This outcome is really important for the working environment of the industrial site.

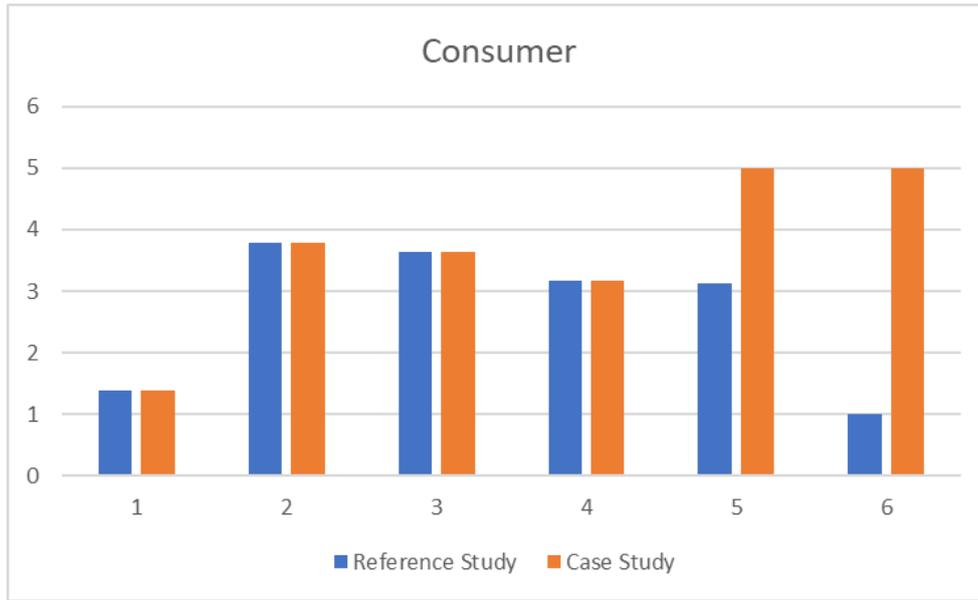


Figure 41 Consumer's results for the two cases.

In Figure 41, it can be observed that both the recycling rate and the safety of handling the end of life are improved in the case study, which indicates that the new management solution is highly efficient.

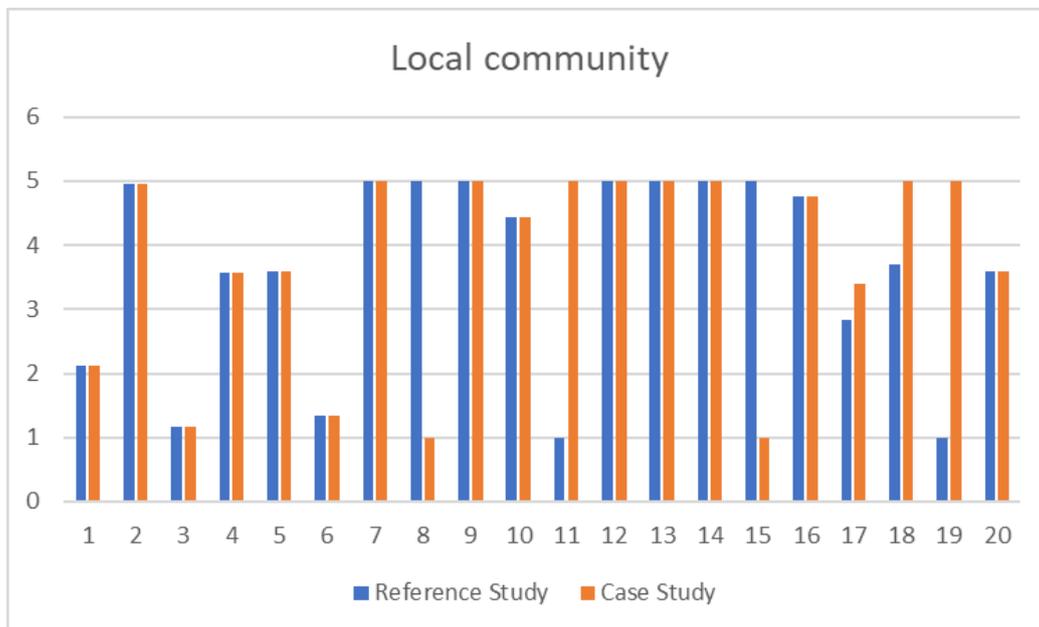


Figure 42 Local community's results for the two cases.

In Figure 42, there are several differences between the two studies. Firstly, we identify a significant improvement in the organization's contribution to the local development and in the reduction of risks at the facility. Additionally, there is an increase in the percentage of spending on locally based suppliers and the percentage of employees originally from the local community, demonstrating that the local community benefits very much from this wood packaging waste management solution. On the other hand, the only two negative outcomes

are the lack of a certified environmental management system and the absence of indigenous communities in the local area. Overall, the results for the local community are positive in the case study.

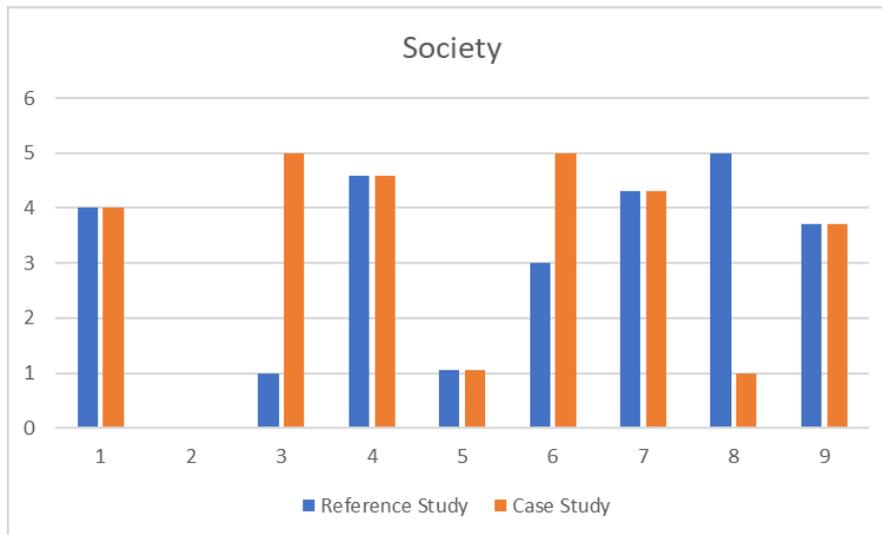


Figure 43 Society's results for the two cases.

For society, as seen in Figure 43, there is an improvement in the case study due to the non-use of critical raw materials and the high involvement in technology transfer projects. The only negative outcome is the lack of a formalized commitment to reduce poverty, which can be explained by the fact that the institute's purpose is not focused on this area.

Based on the results, it is clear that the two scenarios analysed show differences in the social impacts across most stakeholder groups. The only stakeholder group that remained unaffected was the supply chain.

As previously mentioned, the s-LCA focuses on the social aspects of the study, specifically examining the significant improvements brought about by the use of the new wood packaging waste solution. The results revealed that the scenario utilizing the CSS1 solution alternative (case study) achieved the best outcomes across several stakeholder and impact categories considered. Across most groups, particularly workers, consumers, the local community and society there were positive changes, indicating that the new solution contributes to enhancing lifecycle sustainability in the region. The case study showed notable progress in areas like workplace safety, environmental management (recycling rate and end-of-life handling), local development, and technological involvement. Despite some negative parts that do not affect the outcome much, the overall impact of the new solution is largely positive, showcasing its potential for long-term sustainability improvements across multiple sectors.

## 6 Conclusions

This deliverable presented an integrated sustainability assessment of the CSS1 for the management of wood packaging waste in the Lodzkie region, employing LCA, LCC and s-LCA methodologies. The outcomes of the analysis offer valuable insights into the environmental, economic and social dimensions of implementing circular economy principles at a territorial level.

From an environmental perspective, the comparative LCA analysis of three alternative CSS1 scenarios against the Baseline (landfilling) demonstrated significant potential for impact reduction across key categories. Scenarios involving energy recovery and carbon capture (CSS1\_1.2 and CSS1\_1.3) exhibited the most beneficial environmental profiles, including negative values in categories such as Global Warming Potential ( $-7.35E+02$  and  $-5.10E+02$  kg CO<sub>2</sub> eq.), Abiotic Depletion (fossil:  $-1.38E+04$  and  $-9.81E+03$  MJ), Acidification ( $-9.48E-01$  and  $-3.12E-01$  kg SO<sub>2</sub> eq.) and Human Toxicity ( $-2.50E+01$  and  $-4.89E+02$  kg DCB eq.), respectively. These scenarios effectively valorized waste into useful outputs (82–154 kWh of thermal energy, up to 48 kWh of electricity and over 735 kg of captured CO<sub>2</sub> per functional unit), while also mitigating CO<sub>2</sub> emissions through integration with CCS technologies.

In economic terms, the LCC analysis revealed that, while the baseline scenario incurred the lowest immediate costs (€373 million), it failed to account for environmental externalities and offered limited long-term sustainability. In contrast, Scenario 1 (reuse and furniture manufacturing) incurred €2.93 billion and energy recovery Scenarios 2 and 3 involved total costs of €4.34 billion and €4.27 billion, respectively. However, Scenario 2 demonstrated promising potential for long-term viability due to the opportunity to recover over 130 kWh per ton of waste, helping reduce energy expenses or generate revenue. Additionally, energy valorization scenarios significantly reduced dependency on fossil fuels, PENRE dropped from  $1.03E+03$  MJ in the baseline to  $-1.38E+04$  MJ in Scenario 2, suggesting substantial savings when externalities are internalized.

The s-LCA further confirmed the positive social implications of CSS1 implementation. Compared to the baseline, the case study scenarios improved scores across most stakeholder groups—including workers, consumers, local communities and society, particularly in areas such as workplace safety, community engagement and end-of-life responsibility. Notably, the CSS1 solution facilitated higher rates of recycling (up to 95% of wood waste repurposed in some streams), increased local employment and enhanced technological development without introducing new social risks. The only stakeholder group with no notable change was the supply chain, indicating a stable performance in this area.

In summary, the combined results of the LCA, LCC and s-LCA assessments underline the multifaceted value of the CSS1 solution in transitioning toward a circular and sustainable regional economy. The environmental gains, while subject to system boundary limitations (e.g., exclusion of logistics), are substantial; the economic analysis supports further

investment in such technologies and the social outcomes highlight improved inclusivity and community integration. These findings support the scalability and replicability of CSS1, aligning with the broader objectives of the FRONTSH1P project and EU policy goals on circularity and climate neutrality.