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LCA, s-LCA and LCC & main outcomes from CSS4

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Lead beneficiary:	**19 - NTUA**
Lead author:	**Antonis Peppas, Chrysa Politi, Konstantinos Baldoukas**
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Partners

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HISTORY OF CHANGES			
Version	Date	Author/Contributor	Changes
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V0.2	10/04/2025	K-Flex	Updates on LCI section
V1.0	08/04/2025	NTUA	Final Version

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Executive Summary

Deliverable D6.5 presents the sustainability assessment of Scenario 4.1 and Scenario 4.2 within Circular Systemic Solution 4 (CSS4), focused on the valorisation of plastic waste through advanced material recovery. The evaluation integrates Life Cycle Assessment, Life Cycle Costing and Social Life Cycle Assessment, comparing the two circular scenarios against a Baseline representing conventional plastic waste disposal (landfilling).

The Life Cycle Assessment results demonstrate that both CSS4 scenarios offer considerable environmental advantages over the Baseline. In Scenario 4.1, the transformation of char and carbon black into insulation material leads to a reduction in Global Warming Potential (–11.6 kg CO_2 eq.), fossil resource use (–420 MJ) and other categories, thanks to energy substitution and material reuse. Scenario 4.2, which focuses on converting recycled polyethylene into foam material, achieves an even stronger environmental performance, including net-negative GWP (–99.1 kg CO_2 eq.) and near-zero values in human toxicity, eutrophication and acidification. In contrast, the Baseline shows significantly higher impacts across all categories.

The Life Cycle Costing analysis reveals that both scenarios currently incur notable costs due to energy input, processing equipment, and operational expenses, especially at pilot scale. However, the potential for cost recovery through the sale of recovered materials, combined with avoided landfill costs, indicates clear pathways toward economic viability as the processes are scaled and optimised. Scenario 4.2 shows particular promise in this respect.

The Social Life Cycle Assessment indicates a positive social performance for both CSS4 scenarios, especially regarding worker safety, local employment and social responsibility. Scenario 4.2, in particular, performs well across most stakeholder categories. Some challenges persist in the value chain, especially concerning supplier certification and environmental transparency, but the overall social outlook is favourable.

In conclusion, CSS4 demonstrates strong potential to transform plastic waste into useful, circular products with measurable environmental, economic and social benefits. With further optimisation and market alignment, both scenarios support regional circular economy goals and align with broader EU sustainability targets.

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1 Introduction

1.1 Purpose of the deliverable

The purpose of this deliverable is to determine the actions that can most effectively drive ecological improvements in a product. The first step involves identifying the stages in the product's life cycle with the highest environmental impact. After that, eco-design strategies can be explored, and appropriate measures for the specific product can be selected and tailored for implementation.

1.2 Trends in plastic waste management: A European and regional perspective

1.2.1 Plastics waste in Europe

In 2022, the EU generated an estimated 186.5 kg of packaging waste per inhabitant. This quantity varied between 78.8 kg per inhabitant in Bulgaria and 233.8 kg per inhabitant in Ireland. Figure 1 shows that in 2022, paper and cardboard (40.8%), plastic (19.4%), glass (18.8%), wood (16.0%) and metal (4.9%) are the most common materials of packaging waste in the EU. Other materials represented only 0.2% of the total volume of packaging waste generated in 2022.

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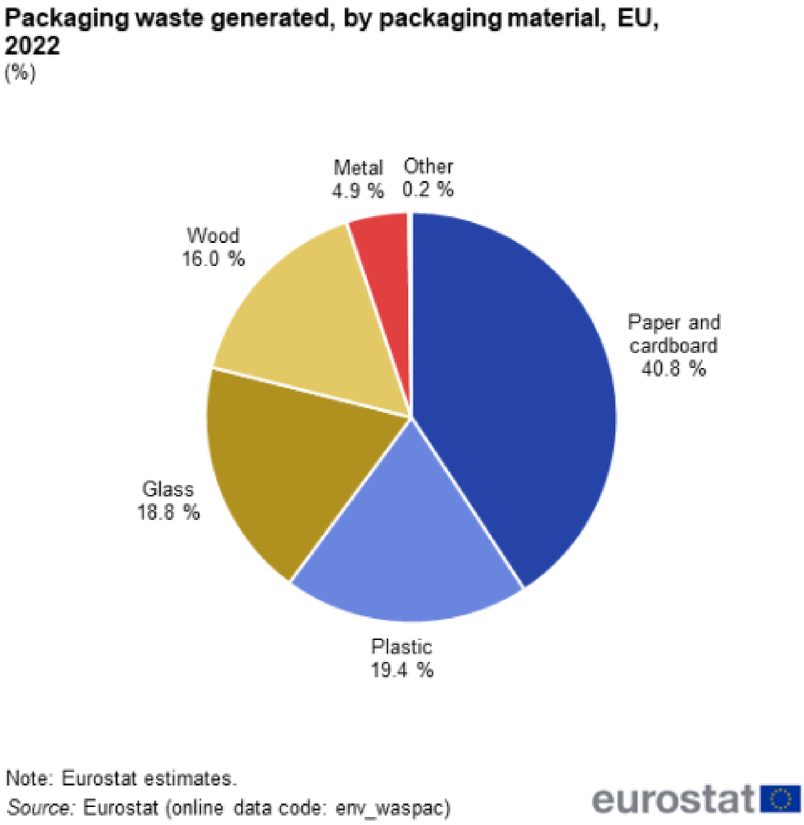

Figure 1 Packaging waste generated, by packaging material, EU, 2022 (%)[1].

Figure 2 shows the recycling rate of plastic packaging waste for the EU countries and the EEA/EFTA countries in 2022. The recycling rate includes only material recycling and no other forms of recycling, i.e. exclusively material that is recycled back into plastics. The target of 22.5% recycled plastic packaging waste was met by all EU countries except Malta (16.4%) in 2022.

[1] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Packaging_waste_statistics.

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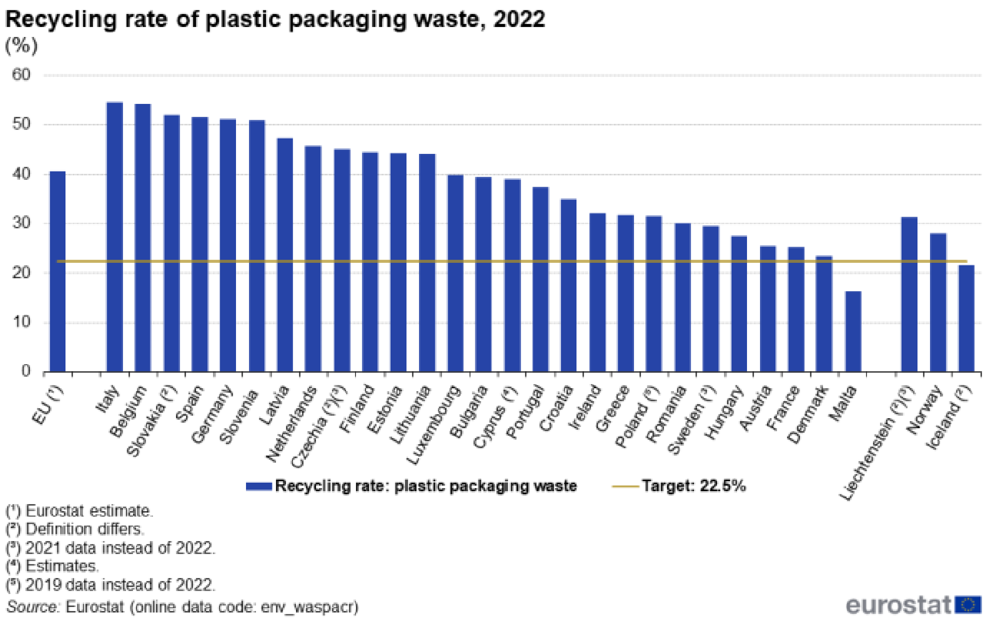

Figure 2 Recycling rate of plastic packaging waste, 2022 (%)[1]

The amount of packaging waste generated in the EU increased overall during the period 2011-2022. In 2022, the amount of packaging waste generated fell slightly, breaking with the overall upward trend observed since 2012 with only a slight exception in 2018.

Over the period 2011–2022, the generation of all types of packaging waste material increased, although to a different extent. The highest relative increases were observed for plastic packaging waste, followed by paper and cardboard and wood. In absolute amounts, paper and cardboard packaging waste increased the most. The recycling rate for packaging waste rose continuously from 2011 to 2016, fell back to slightly below the 2011 level in 2020 and 2021, but recovered in 2022.

1.2.2 Plastics waste in Lodzkie region

In 2018 Poland generates 128 million tons of waste, of which 10% was municipal waste[2]. Compared to the EU average (486 kg) and other EU countries (e.g. Denmark – 781 kg, Germany – 633 kg or Luxembourg – 607 kg), Poland has one of the lowest rates of municipal waste generation per capita (325 kg) (Eurostat, 2020). The problem, however, is the low level of recycling. In 2018 only 57% of the municipal waste collected was intended for recovery, of which 26% was subjected to mechanical and chemical recycling and 23% to energy recycling. The structure of municipal waste is dominated by biodegradable waste (26 kg per inhabitant), mixed packaging waste (15 kg), bulky waste (14 kg), glass (13 kg), plastics (9 kg), paper and cardboard (7 kg). Plastics are the third largest stream of mixed municipal waste (14%), immediately after bio-waste (which accounts for nearly 20%) and the segment of paper and cardboard (14.5%). Plastics constitute about 10% by weight and 40% by volume of household waste. Although the amount of municipal waste collected selectively

[2] Plastic recycling in Poland – a transformation towards a circular economy? http://dx.doi.org/10.15611/pn.2021.1.01.

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has increased (in 2005 it constituted 5% of municipal waste collected while in 2018 it was 29%), but the recycling of plastic waste is largely based on easily collected waste from commercial networks and transport.

This state of affairs is due to legal and organizational conditions. The most important are:

- the imprecise definition of organizational roles in the waste management system (stakeholders and their competencies);
- the imprecise definition of the issue of waste ownership, its transfer and disposal (which hinders the possibility of optimizing the costs of functioning of the municipal waste management system; the revenues from trading in secondary raw materials do not constitute municipalities' income);
- institutional solutions that result in the consolidation of the municipal waste collection market and the creation of local monopolies (which results from the scope and manner of conducting public tenders);
- institutional solutions that favour activities contrary to the hierarchy of waste management (the privileged position of municipal waste incineration plants in the municipal waste management system and the functioning of the Regional Municipal Waste Processing Installations as part of regulated rather than free market activities);
- barriers preventing the development of technological, business, social and organizational innovation and achieving synergies between the waste management industry and other sectors of the economy;
- the lack of extensive social campaigns, which maintains low ecological awareness of the inhabitants.

The low level of selective collection certainly also results from technological barriers. Recycling of plastic waste generates higher costs than recycling of glass, cardboard or metal packaging waste. Therefore, the prices obtained for secondary plastics are not competitive with the prices of primary raw materials. The recycling sector in Poland is still under-developed. This problem is also visible in other EU countries. As a result, the demand for recycled plastics accounts for only 6% of demand for plastics (EPRO). The recycling sector faces the need for technological change to make it more profitable. It is estimated that the economic losses resulting only from the single-use plastic packaging amount to 95% of their material value, which is between EUR 70 and 105 billion per year (EPRO; Eurostat). The scale of the problem associated with the improper management of plastic waste is therefore enormous, which entails economic costs and, above all, irreversible damage to the environment.

Plastics are valuable materials covering a wide range of applications in everyday life and have the potential to be recycled many times while retaining their value and functional properties. The efficiency of plastic waste management in the EU is improving between 2006 and 2016 the amount of plastic waste recycled increased by 79%, for energy recovery by 61% and the amount of landfilled waste decreased by 43%. However, the problem is that

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the energy recovery rate (41.6%) is still higher than the recycling rate (31.1%), and the recycling rate only slightly exceeds the landfill rate.

Poland produces less plastic waste than the EU15, but the level of recycling is lower than the EU average. The recycling of plastic waste is largely based on easy-to-collect waste from commercial networks and transport. A further increase in the recycling rate will be possible when the selective collection and recycling of household waste is intensified. However, this requires legal and organizational changes as well as extensive social campaigns increasing the ecological awareness of the inhabitants. The Polish sector of plastics producers and the recycling industry will have to increase their investments in technology and cooperate more closely with R&D centres.

A circular economy has become a strategic goal at EU level both in the context of environmental restrictions and because of its economic potential. Legal regulations will enforce specific behaviour among stakeholders, whose responsibility will no longer be only their good will, but an obligation imposed by law. Add to this the growing consumer awareness, then real changes can be expected. EU regulations will have the greatest impact on the process of changes in the Polish recycling sector. Poland will have to meet the indicators, yet currently it is far from achieving them.

1.3 Description of CSS4 solutions

CSS4 (Circular Systematic Solutions 4) for plastics waste focuses on creating a sustainable, circular economy model that effectively manages and reduces plastic waste. Through innovative processes and advanced technologies, CSS4 aims to minimize the environmental impact of plastic products and promote their recycling, reuse and eventual replacement with biobased alternatives. The core idea is to close the loop of plastic production and consumption by recovering valuable materials from plastic waste, converting waste into new products and designing for recyclability.

1. **Key Features of CSS4 solutions for plastic waste:**
    - **Mechanical recycling**: CSS4 incorporates advanced mechanical recycling technologies to process post-consumer and post-industrial plastics waste, turning it back into raw materials suitable for new products. This includes sorting, cleaning and shredding plastic waste to be reused in manufacturing new plastic products, reducing the need for plastic.
    - **Chemical recycling:** In addition to mechanical recycling, CSS4 explores chemical recycling technologies, such as pyrolysis, depolymerization and gasification, which break down plastics into their monomers or other useful chemicals. This enables the recycling of plastics that are not suitable for traditional mechanical recycling, including mixed and contaminated plastic wastes.

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- **Energetical recycling:** Due to their calorific value, hydrocarbon petroleum-based plastics can be burned in special installations, generating heat and inorganic residues that can be used in civil engineering and road construction.

2. **Biodegradable plastics and biopolymers:**
    - CSS4 emphasizes the development and use of biodegradable plastics and biopolymers derived from renewable resources such as plant-based materials or microorganisms. These materials decompose naturally over time, reducing the long-lasting environmental impacts of conventional plastics.
    - This solution promotes the transition from petroleum-based plastics to bio-based alternatives, such as polylactic acid (PLA), polyhydroxyalkanoates (PHA) or other bioplastics, which can be used for packaging, agricultural films, etc.
3. **Design for recycling:**
    - CSS4 incorporates eco-design principles, ensuring that products are designed with the end of their life cycle in mind. This involves creating products that are easier to disassemble, contain fewer hazardous substances and use materials that can be efficiently recycled or repurposed.
    - In particular, CSS4 encourages mono-material packaging, which reduces the complexity of recycling processes and ensures that plastics can be recycled more easily, thereby improving recycling rates and reducing contamination.
4. **Circular economy business models:**
    - CSS4 integrates innovative business models that incentivize the recycling and reuse of plastics waste. For example, deposit-return schemes, plastic recycling credits or take-back programs can encourage consumers to return used plastic products for recycling.
    - Companies are encouraged to adopt product-as-a-service models, where consumers rent or lease products made from recyclable plastics rather than owning them. This model supports the reuse of materials and prevents the need for additional plastic production.
5. **Plastics waste-to-value technologies:**
    - CSS4 includes advanced waste-to-value technologies that transform plastic waste into valuable by-products, such as biofuels, chemicals, or new plastics. Pyrolysis and gasification are two such processes that can convert mixed plastics into valuable liquid fuels or other chemicals, reducing landfill waste while creating a new stream of usable resources.
    - Upcycling of plastic waste into higher-value products, like composite materials or construction materials, is another avenue pursued by CSS4. This process adds value to plastics waste by turning it into durable, long-lasting products that can serve different industries.
6. **Plastic waste collection and sorting systems:**

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- Efficient collection and sorting of plastic waste are key components of CSS4 solutions. Improved infrastructure for waste collection, sorting and pre-treatment ensures that different types of plastic are correctly processed for recycling or upcycling.
- Advanced technologies, such as artificial intelligence (AI) and robotics, are integrated into waste sorting systems to improve efficiency and accuracy, ensuring that the right plastic waste is directed to the appropriate recycling or processing stream.

7. **Integration of microalgae for bioplastic production:**
   - As part of the CSS4 solutions, microalgae can be used as a sustainable feedstock for the production of biodegradable plastics. Microalgae-based bioplastics can be produced with fewer land and water resources compared to traditional crops used for bioplastic production (e.g. corn).
   - These algae-based plastics are designed to degrade in the environment, offering an eco-friendly alternative to conventional plastics while reducing the need for petroleum-based materials.

2 Methodologies

2.1 Life Cycle Assessment

Life Cycle Assessment 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 3). Its primary objective is to enhance resource-use efficiency while minimizing environmental liabilities, making it invaluable for environmental decision support.

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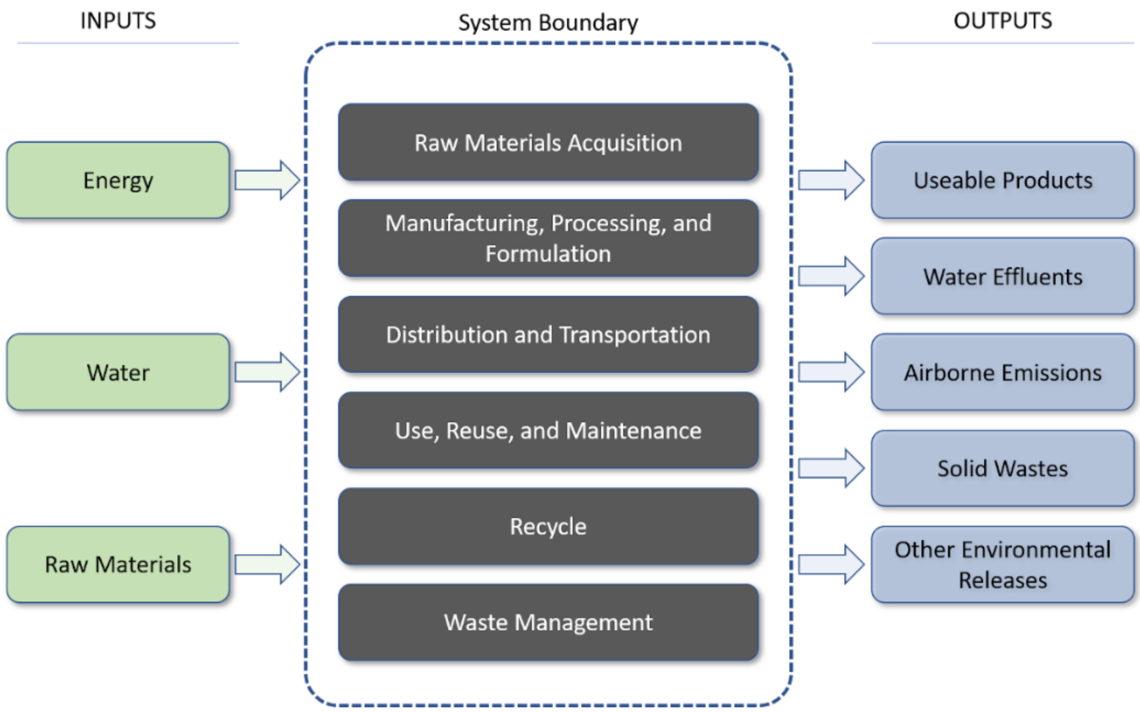

Figure 3 LCA input-output example process

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 [3] and 14044:2006/A1:2018 [4]. 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: These 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 guidelines for implementing the LCA methodology. It offers guidance on data collection, data

[3] 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

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

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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 4.

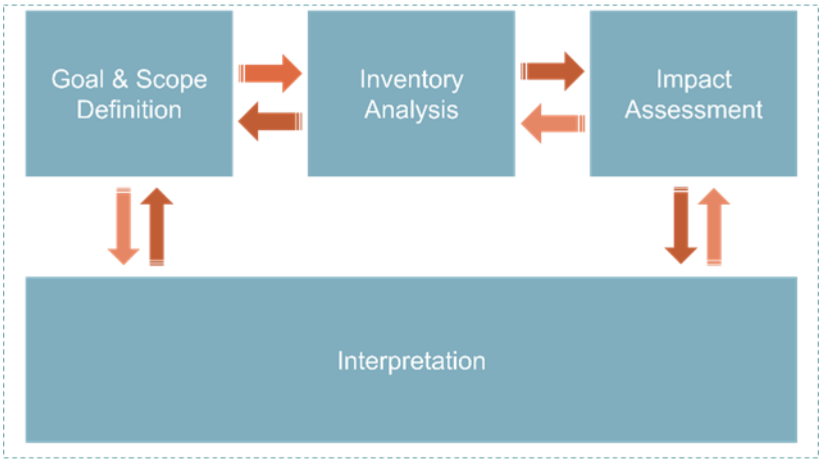

Figure 4 LCA framework

2.2 Life Cycle Costing

Life cycle costing 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

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that, alternative solution that is 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 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 5). While the steps are generally sequential, the sequence can be altered as per following the requirements of each project.

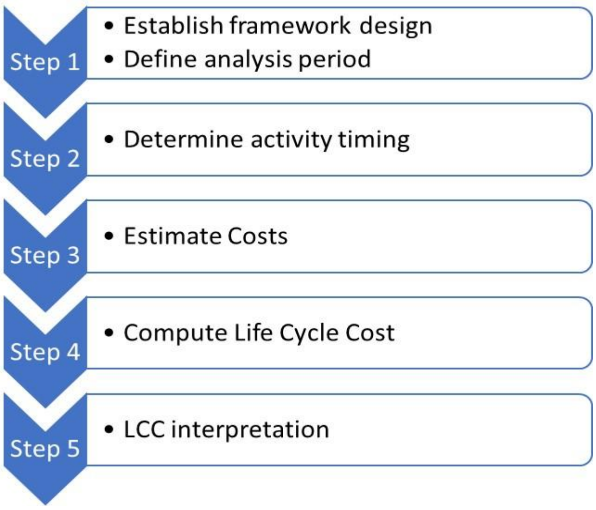

Figure 5 General framework of Life Cycle Cost (LCC) analysis process.

Step 1: Establish framework design & 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.

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Therefore, 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, labour, 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, labour as well as any additional cost for waste management.

Step 5: Analyse results and evaluate alternatives. In the last step is to analyse 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 [5].

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 [6, 7]. 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:

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

[5] UNEP – SETAC – Life Cycle Initiative – Guidelines for Social Life Cycle Assessment of products and organizations 2020, United Nations Environment Programme, 2020

[6] 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

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

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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 element(s), 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)[8], 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 6). For each case study, depending on the phase analysed and on the type of system considered, the most relevant and significant stakeholders' categories are considered (Figure 7).

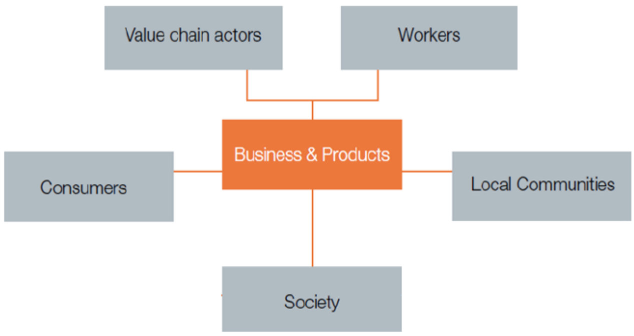

Figure 6 Stakeholders involved in the products life cycle.

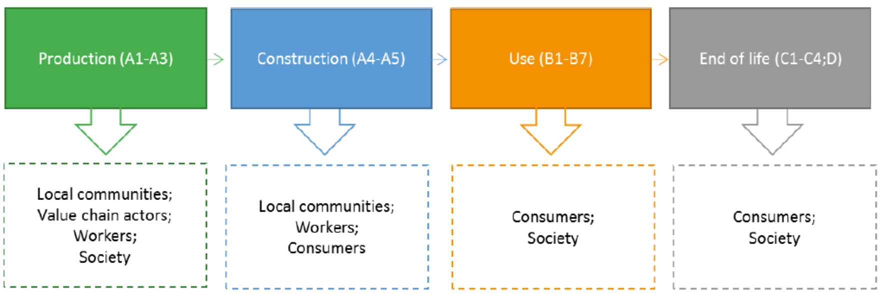

Figure 7 Indicative categories of stakeholders involved in each stage of the product life cycle.

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

[8] EN 15804:2012+A1:2013 "Sustainability of construction works — Environmental product declarations Core rules for the product category of construction products"

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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 [9].

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 [10]. 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.

3 LCA methodology

3.1 Goal and Scope

Goal and scope definition is one of the most important steps in any LCA/LCC 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 CSS4 is to evaluate the environmental impacts and costs of processing plastics waste through the proposed CSS4 in the region of Lodzkie. The study aims to assess the CO_2 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 (Baseline), incineration, mechanical recycling, disposal via open dumping, source reduction, plastic-to-fuel (pyrolysis).

1. **Intended application:**
    - To estimate the potential for CO_2 footprint reduction in the CSS4 process, focusing on waste reduction, energy savings and the valorisation of by-products like carbon black and char.
    - To assess energy resource preservation, specifically through the recovery of thermal energy from plastics waste, thereby reducing the reliance on fossil fuels.

[9] UNEP – SETAC – Life Cycle Initiative – Guidelines for Social Life Cycle Assessment of Products, United Nations Environment Programme, 2009
[10] 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

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- To evaluate the cost of CO_2 savings, specifically the financial implications of CO_2 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 CSS4 will be compared with current practices such as:

- Landfilling of plastics 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 plastics waste at a regional scale (Lodzkie). The scope will cover the collection, processing and valorisation of plastics waste into Biodegradable Plastics (Polylactic acid (PLA) and polyhydroxyalkanoates (PHA)) and Bio-Based Plastics (bio-based PET, bio-based PUR, starch-based plastics and plant-based polyamides).

3.1.3 Functions of product system

The CSS4 system is designed to process plastic waste and convert it into valuable by-products such as insulation foam material, reducing the waste volume sent to landfills.
Functions of the product system include:

- **End-of-life treatment of expanded rubber:** The system processes expanded rubber waste, converting it into valuable by-products such as insulation foam.
- **End-of-life treatment of collected plastic:** The system treats collected plastic waste and transforms it into insulation foam material, contributing to waste reduction and sustainability.

3.1.4 Functional Unit

The functional unit (FU) for this study is defined as the treatment of 1 ton of plastics waste through the CSS4 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.

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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 Circular Systematic Solution (CSS4) approach to plastics waste is developed into two scenarios. Outputs of these two scenarios are final products or intermediate resources for integration with other Circular Systematic Solutions in the FRONTSH1P project. Each scenario focuses on different methods and processes for reusing plastics waste or producing insulation materials.

3.1.6 Scenarios

1. **Scenario 4.1 (CSS4-S24.1 Insulation material)**:

This scenario focuses on producing insulation material from char or carbon black through a series of processes including mixing, extrusion, heating, and cooling. By utilizing these materials, the process aims to create energy-efficient insulation products that can be used in various construction applications. The combination of these production methods enhances the material's thermal properties, contributing to improved energy efficiency in buildings and reducing overall energy consumption.

2. **Scenario 4.2** (**CSS4-S4.2 Foam material recycled)**

This scenario focuses on producing foam material from recycled plastic waste (PE) through a process of segregation, extrusion and cooling. By repurposing polyethylene (PE) waste, the process creates an eco-friendly foam material that can be used in insulation. The use of recycled plastic helps reduce waste and the demand for new plastic production, contributing to more sustainable material production and waste management.

3.1.7 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 [11]. The method is divided into baseline and non-baseline, the baseline being the most common impact categories used in LCA. The following table shows the categories it contains, according to last update in August-2016[12]. These indicators collectively provide insights into resource use, emissions and impacts on health and the environment across the assessed system's life cycle.

[11] 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: www.ecoinvent.org

[12] 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

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Table 1 Impact categories included in the method CML

Method: CML	
Impact category group	**Name of the impact category in the method**
Acidification	Acidification potential - average Europe
Climate change	Climate change - GWP100
Depletion of abiotic resources	Depletion of abiotic resources - elements, ultimate reserves
	Depletion of abiotic resources - fossil fuels
Ecotoxicity	Freshwater aquatic ecotoxicity - FAETP inf
	Terrestrial ecotoxicity - TETP inf
Eutrophication	Eutrophication - generic
Human toxicity	Human toxicity - HTP inf
Ozone layer depletion	Ozone layer depletion - ODP steady state
Photochemical oxidation	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 2).

Table 2 Impact categories of EN 15804 +A2 (based on EF 3.1) method

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

3.1.8 Assumptions and limitations

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 CSS4 system for plastic waste management, including mixing, extrusion, and cooling processes. These data were derived from the actual operational conditions and experimental setup of the mixing, extrusion and cooling units at the K-FLEX facility in Poland. Therefore,

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the data reflects the technologies in their current form and captures the real-world performance of these systems under the study's scope. The use of these processes in plastic waste recycling directly aligns with industry practices and the operational conditions at the pilot-scale plant at K-FLEX.

2. Consistency

The data used in this study is consistent with international standards and methodologies, such as ISO 14040/44 guidelines for conducting Life Cycle Assessment (LCA). Data was collected and processed using industry-standard software tools, including Sphera FE for LCA modelling. These methodologies ensure that the data and results are consistent and comparable with similar studies in the field of plastic waste management. Furthermore, the operational data from the different phases of mixing, extrusion, and cooling were gathered systematically and followed consistent protocols across all stages of the processes.

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 CSS4 system—mixing, extrusion, cooling, and plastic waste processing—are included in the analysis. This includes energy consumption, emissions, and material flows (e.g., plastic raw material input and extruded product output). However, the exclusion of waste collection, transportation and post-processing stages 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 CSS4 plastic waste management system as implemented at the K-FLEX facility in Poland. The data reflects the actual performance and operational conditions of the system during the study period, providing a realistic snapshot of plastic waste recycling through mixing, extrusion and cooling. However, since the study focuses on pilot-scale operations, it may not fully represent the potential for scaling up to industrial levels. 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 full-scale deployments.

5. Location specificness

The study acknowledges that the data used in the LCA analysis reflects the operational context of the K-FLEX (Poland) facility, where the CSS4 system was designed and operated. The energy mix, infrastructure and waste management practices in this region are embedded in the data. 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, with adjustments made to account for regional variations. This ensures that the data remains specific to the location where the system is implemented while still reflecting broader European contexts.

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3.2 Life Cycle Inventory Analysis

CSS4_4.1 Insulation material

Description of Scenario 1

The main goal of Scenario 4.1 is to transform char into insulation material. This process occurs through stages such as mixing, extrusion, heating and cooling. Due to confidentiality constraints, specific quantities for input and output flows cannot be disclosed. As such, these values are represented using the "*" symbol throughout the inventory tables.

Main stages included in the scenario

The system of converting insulation material involves five main stages (Figure 8), which are described as follows:

Stage 1: Mixing 1 - production of masterbatch

At this stage, the main input (char) is being mixed with other components to form the initial production of the masterbatch.

	Flow	Quantity	Unit
Inputs	1,3-dihydro-4(or 5)-methyl-2H-benzimidazole-2-thione, zinc salt	*	kg
	Poly(oxy-1,2-ethanediyl), α-hydro-ω-hydroxy- Ethane-1,2-diol, ethoxylated	*	kg
	2,6-di-tert-butyl-p-cresol	*	kg
	Soybean oil, epoxidized	*	kg
	Carbon black	*	kg
	ACRYLONITRILE-BUTADIENE POLYMER	*	kg
	Calcium carbonate	*	kg
	Aluminium hydroxide	*	kg
	Paraffin waxes and Hydrocarbon waxe	*	kg
	WAX M50	*	kg
	Ethene, chloro-, homopolymer	*	kg
	1,2-Benzenedicarboxylic acid, di-C8-10-branched alkylesters, C9-rich; di- "isononyl" phthalate	*	kg
	Fatty acids, C16-18	*	kg
	1-Chlorethylen and Vinyl acetate	*	kg
Outputs	Char processed	*	kg

Stage 2: Mixing 2 - production of final batch

The second mixing takes place with the addition of the foaming agent (azodicarbonamide) to complete the final batch of the mixing process.

	Flow	Quantity	Unit
Inputs	Bis(piperidinothiocarbonyl) tetrasulphide	*	kg

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	Ziram	*	kg
	Zinc oxide	*	kg
	Sulphur	*	kg
	N-(cyclohexylthio)phthalimide	*	kg
	Zinc bis(benzenesulphinate)	*	kg
	C,C'-azodi(formamide)-AZODECARBONAMIDE	*	kg
	Paraffin and Hydrocarbon waxes	*	kg
Outputs	Char processed	*	kg

Stage 3: Extruder

After mixing, the processed char, along with the rest of the inputs, is fed into an extruder to form a rigid shape.

	Flow	Quantity	Unit
Inputs	Char processed	*	kg
	Electricity	*	MJ
Outputs	Char processed	*	kg

Stage 4: Oven

At this stage, the mass of the processed char is placed in the oven, where the temperature increases until it reaches 170°C.

	Flow	Quantity	Unit
Inputs	Char processed	*	kg
	Natural gas	*	MJ
Outputs	Char processed	*	kg

Stage 4: Cooling pawn

After heating, the mass is placed into a cooling pawn at 40°C, marking the final stage of the process, where the final product of rubber insulation is produced.

	Flow	Quantity	Unit
Inputs	Char processed	*	kg
	Fresh water	*	m^3
Outputs	PE foam	*	kg

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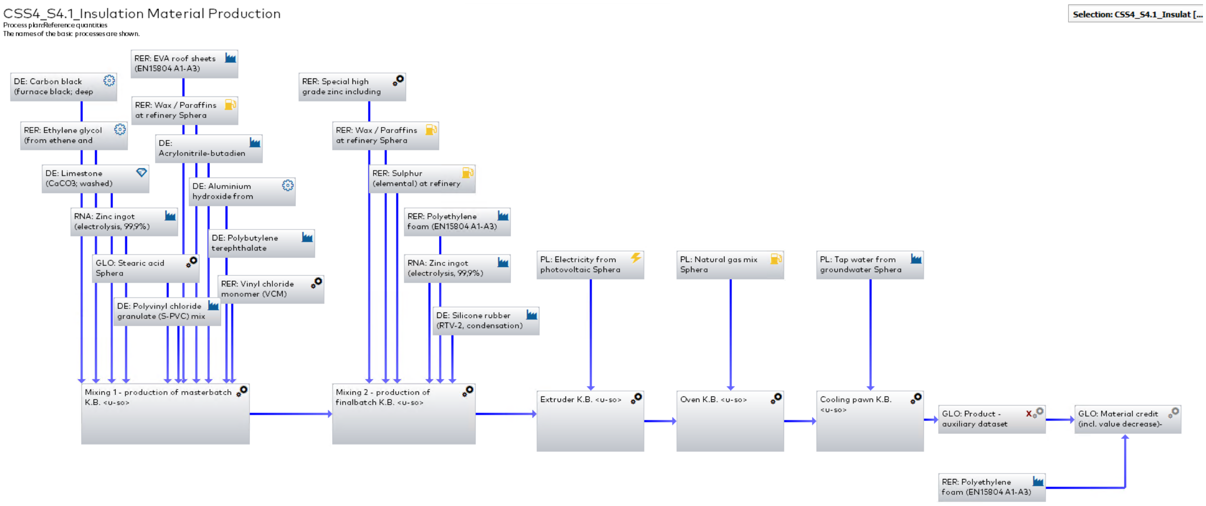

Figure 8 Flowsheet of the Sphera CSS4_S4.1 Insulation material production.

CSS4_4.2 Foam material recycled

Description of Scenario 2

The main goal of Scenario 4.2 is to transform plastic waste into thermoplastic material. This process occurs through stages such as segregation, extrusion and cooling. Due to confidentiality constraints, specific quantities for input and output flows cannot be disclosed. As such, these values are represented using the "*" symbol throughout the inventory tables.

Main stages included in the scenario

The system of converting thermoplastic material involves three main stages (Figure 9), which are described as follows:

Stage 1: Preliminary analysis and segregation

In the first stage, the main input (plastic waste) is segregated and mixed with other components to form a rigid mass.

	Flow	Quantity	Unit
Inputs	plastic waste	*	kg
	GMS 50%	*	kg
	Talc	*	kg
	Aluminium	*	kg
	Colour	*	kg
	ISOBUTAN	*	kg
	C02	*	kg
	Natural gas	*	MJ
Outputs	Processed plastic waste	*	kg

Stage 2: Extruder

The output of the segregation process, along with the rest of the inputs and a heating temperature of 100°C, is fed into an extruder to take shape.

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	Flow	Quantity	Unit
Inputs	Processed plastic waste	*	kg
	Electricity	*	MJ
Outputs	Processed plastic waste	*	kg

Stage 3: Cooling pawn

After heating, the mass is placed into a cooling pan at 40°C, marking the final stage of the process, where the final product (polyethylene foam) is produced.

	Flow	Quantity	Unit
Inputs	Processed plastic waste	*	kg
	Fresh water	*	m^3
Outputs	Thermoplastic material	*	kg

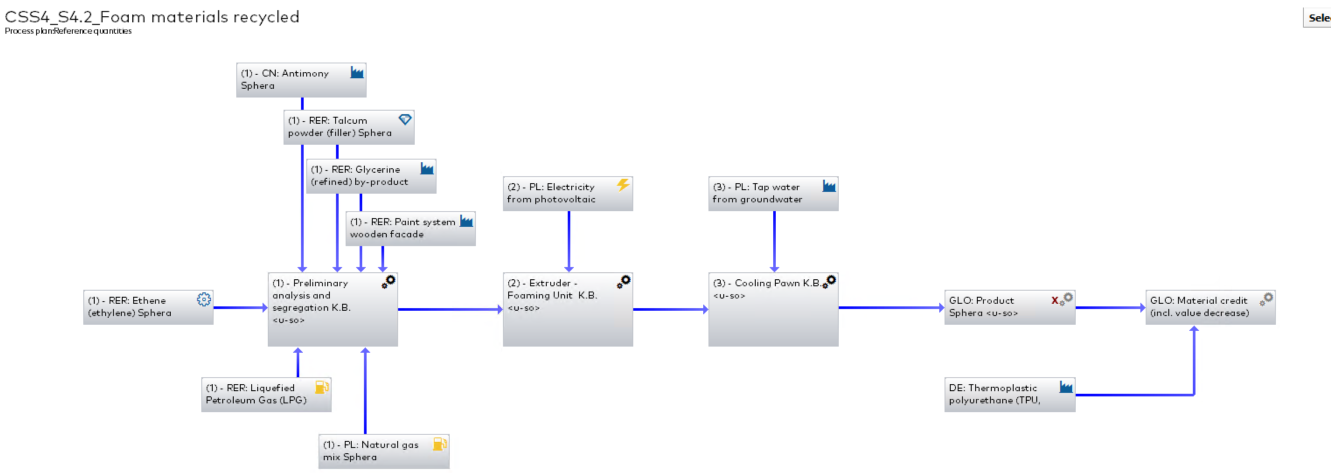

Figure 9 Flowsheet of the Sphera CSS4_S4.2 Foam materials recycled.

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 represented 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 CSS4 scenarios and the Baseline scenario (current practices) is compared. The Baseline scenario shows the lowest ADP value of 2.34E-4 kg Sb eq., as it involves minimal processing and no additional resource-intensive steps, leading to relatively low abiotic resource depletion. In contrast, Scenario 4.1 (Insulation

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Material Production) has the highest ADP value of 5.29E-4 kg Sb eq., indicating significant resource depletion due to the added materials and energy requirements throughout the production process. Notably, Scenario 4.2 (Foam Material Recycled) has a lower ADP value of 1.75E-4 kg Sb eq., suggesting that this recycling process provides a more efficient use of abiotic resources overall, reducing the depletion compared to Scenario 4.1, as illustrated in Figure 11.

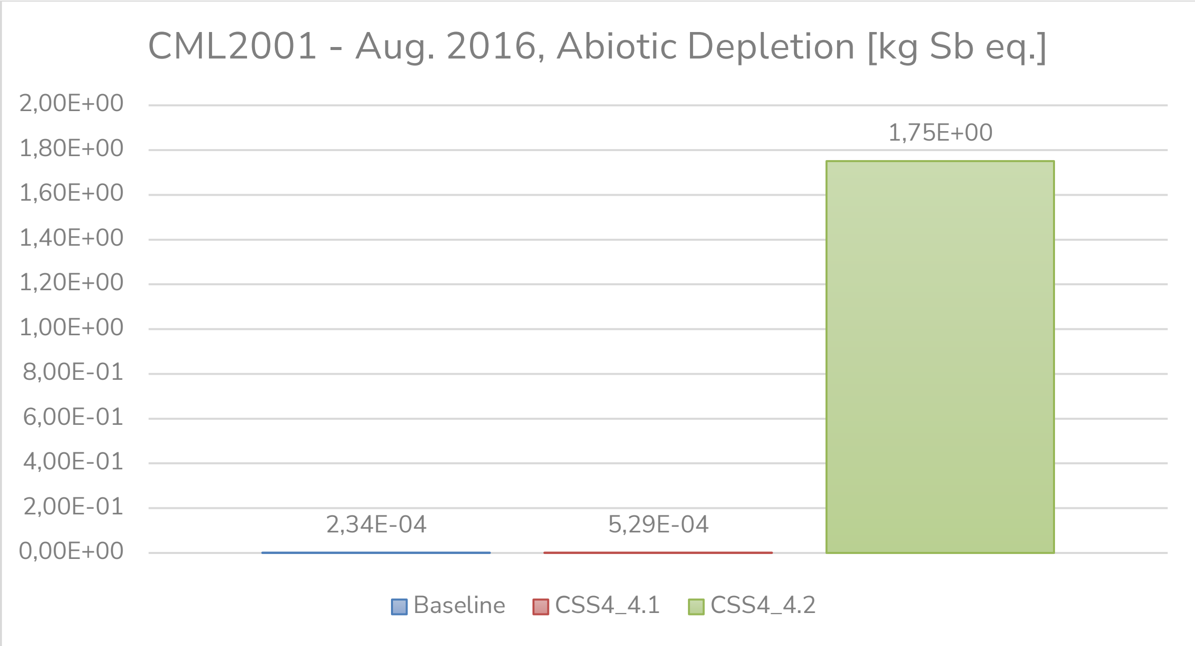

Figure 10 Abiotic Depletion [kg Sb eq.] for each scenario.

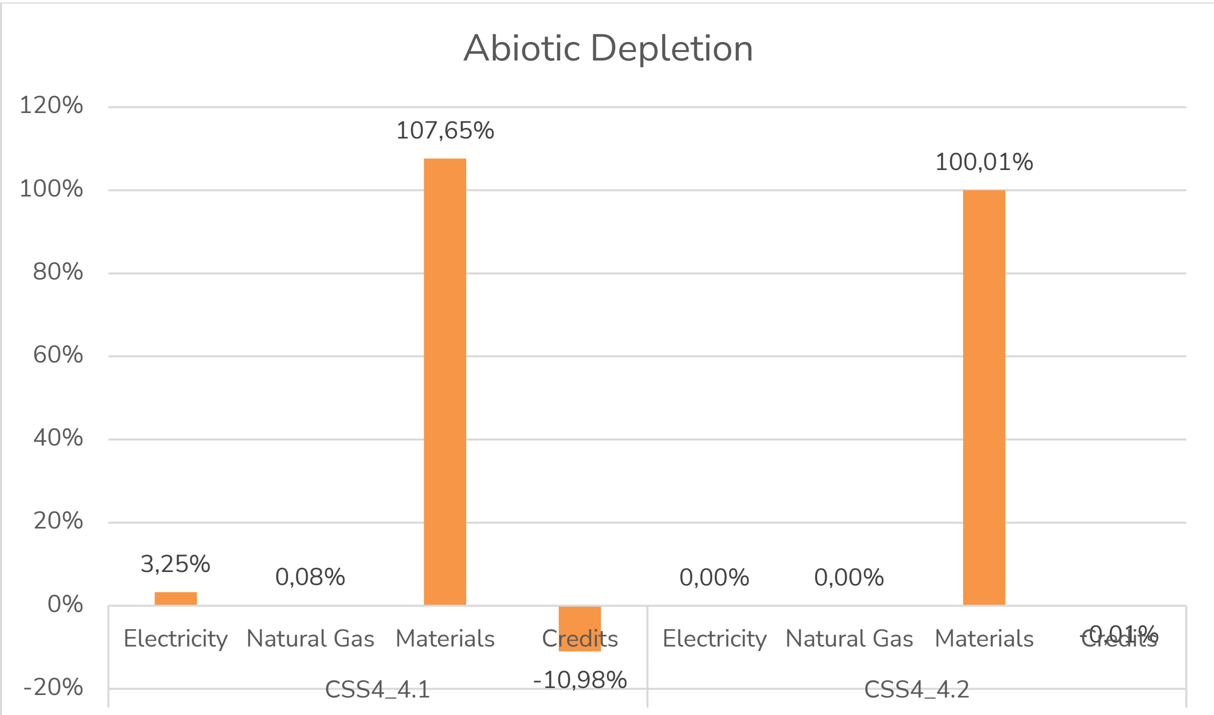

Figure 11 Categorical impact for Abiotic Depletion of each scenario.

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3.3.2 Abiotic Depletion - Fossil

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 the different CSS4 scenarios. The Baseline scenario, which involves conventional processing methods, shows a relatively high ADP-fossil impact of 6.80E+04 MJ, indicating the significant fossil energy consumption associated with these practices. In contrast, Scenario 4.1 (Insulation Material Production) exhibits a reduced ADP-fossil value of -4.20E+02 MJ, suggesting that the energy recovery processes in this scenario contribute positively by reducing the depletion of fossil resources. As shown in Figure 13, the contribution of recovery processes in Scenario 4.1 has a significant impact, counteracting the energy demand from the production steps. Scenario 4.2 (Foam Material Recycled) shows a moderate ADP-fossil value of 6.06E+02 MJ, reflecting a more balanced approach where energy consumption is lower than in the Baseline but still requires some fossil fuel input for the recycling process. This shows that while Scenario 4.2 provides some fossil resource depletion reduction, it is not as effective as Scenario 4.1 in reducing the overall ADP-fossil impact.

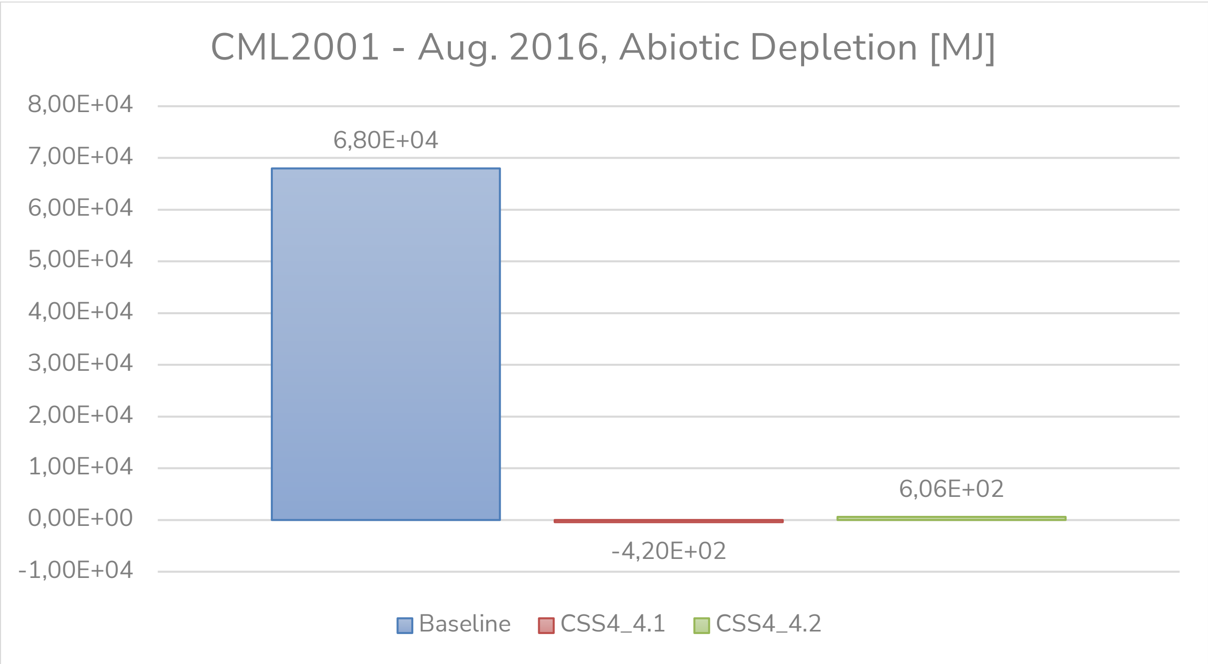

Figure 12 Abiotic Depletion [MJ] impact for each scenario.

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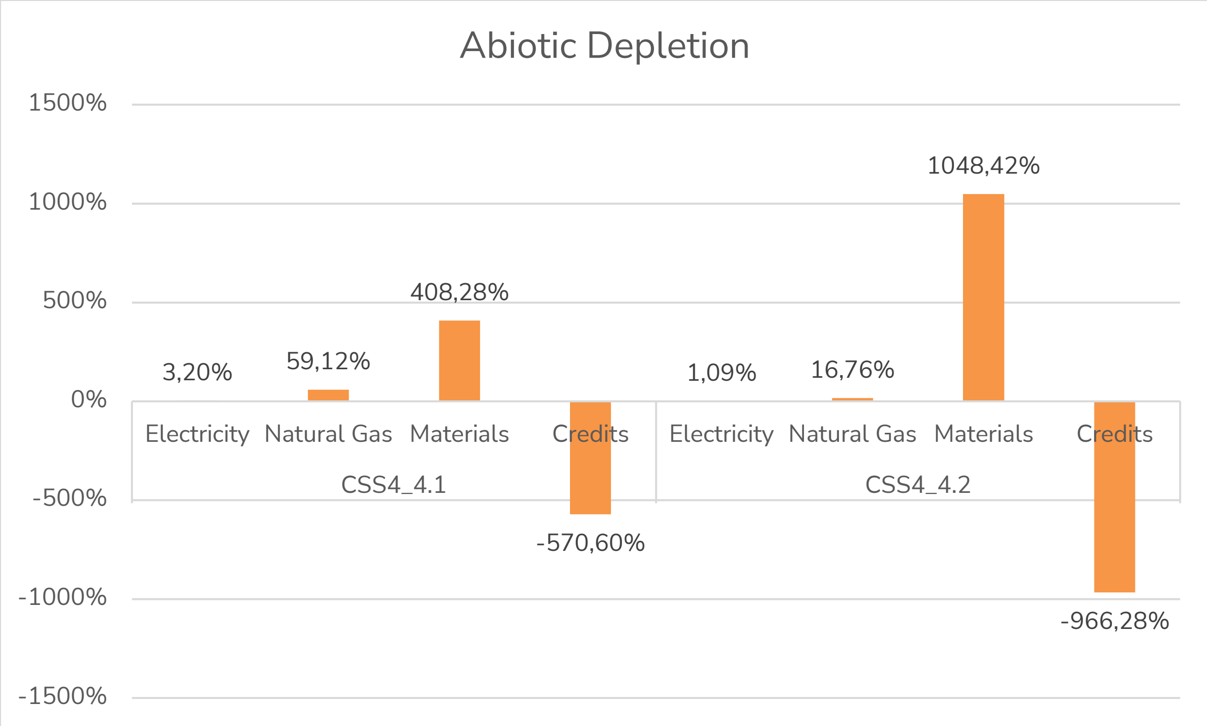

Figure 13 Categorical impact contribution (%) for Abiotic Depletion of each scenario.

3.3.3 Acidification Potential

The acidifying effect of substances in water and soil is described by acidification potential, 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_2-equivalents.

In Figure 14, the diagram compares the Acidification Potential (AP) impact across the different CSS4 scenarios. The Baseline scenario, which involves conventional practices, shows a significantly high AP value of 3.12 kg SO_2 eq., indicating substantial acidifying effects due to emissions during processing. In contrast, Scenario 4.1 (Insulation Material Production) exhibits a much lower AP value of 2.04E-02 kg SO_2 eq., reflecting a significant reduction in acidifying emissions. This reduction is attributed to the energy recovery processes and efficient management practices in Scenario 4.1, as shown in Figure 15. On the other hand, Scenario 4.2 (Foam Material Recycled) shows a relatively high AP value of 9.77E-01 kg SO_2 eq., indicating that while the recycling process reduces some acidification potential, it still results in notable emissions contributing to acidification. This highlights the need for further optimization of processes to minimize the acidification impact in recycling operations.

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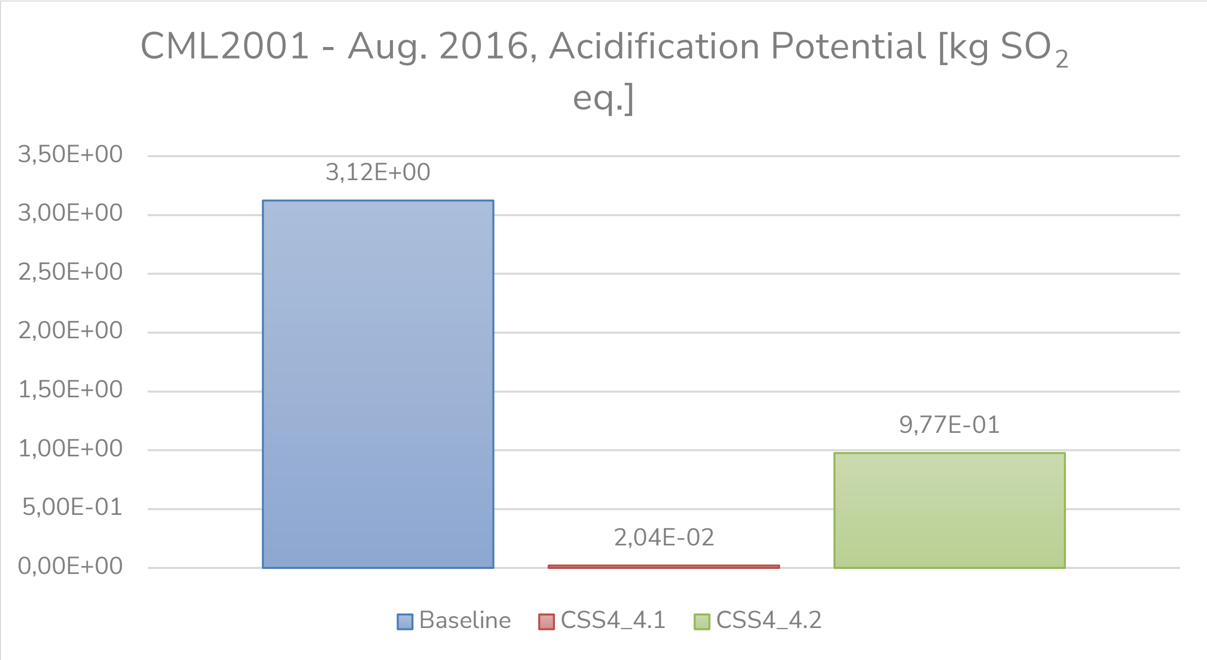

Figure 14 Acidification Potential [kg SO_2 eq.] impact for each scenario.

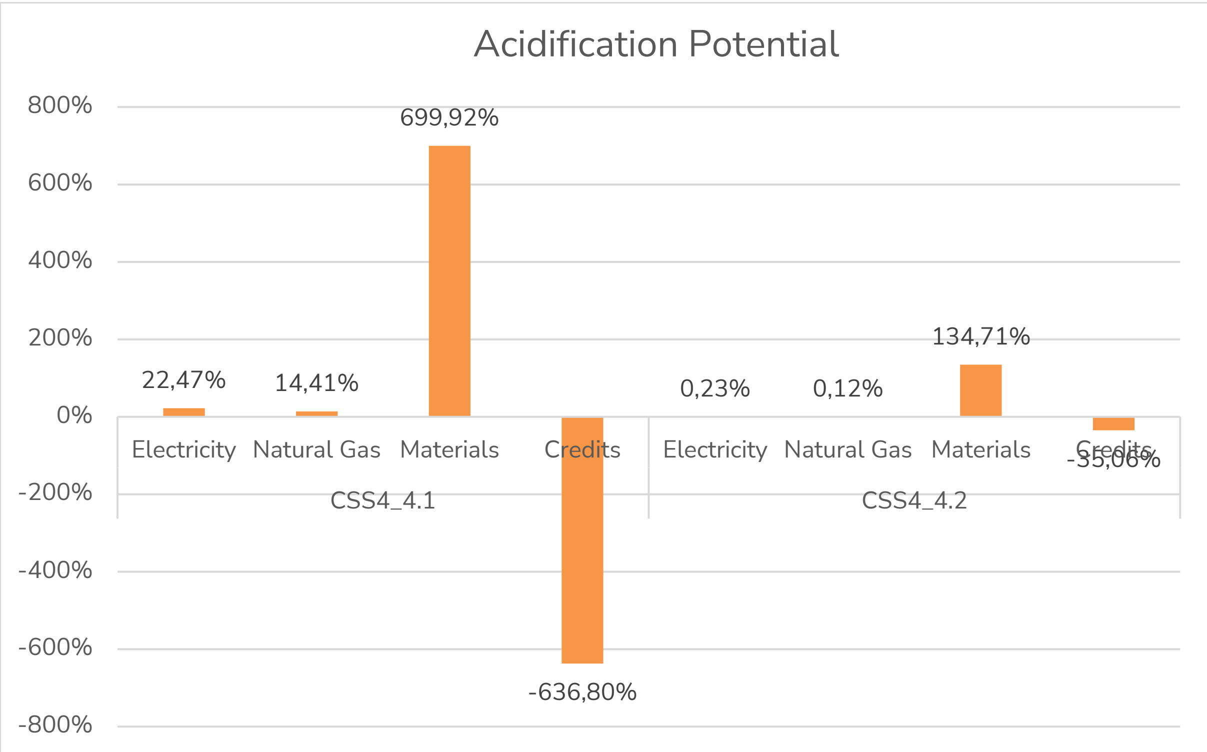

Figure 15 Categorical impact contribution (%) for Acidification Potential of each scenario.

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).

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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 (PO_4) equivalents are preferred for characterization and quantification, though nitrogen oxide (NO_3) and oxygen (O_2) equivalents can also serve as interchangeable metrics.

In Figure 16, the diagram compares the EP impact across the different CSS4 scenarios. The Baseline scenario shows the highest EP value of 6.53E-01 kg PO_4 eq., which is primarily due to the organic nutrients released during conventional waste management processes, contributing to the eutrophication of water bodies and ecosystems. In contrast, Scenario 4.1 (Insulation Material Production) demonstrates a significantly lower EP value of 3.26E-03 kg PO_4 eq., reflecting a substantial reduction in eutrophication potential. This is attributed to the efficient resource management practices employed during the production process, as illustrated in Figure Y. Furthermore, Scenario 4.2 (Foam Material Recycled) exhibits a negative EP value of -8.40E-04 kg PO_4 eq., indicating a beneficial environmental impact by reducing eutrophication. The negative value highlights that the recycling processes in Scenario 4.2 contribute positively by lowering the release of nutrients that could otherwise lead to eutrophication, as shown in Figure 17.

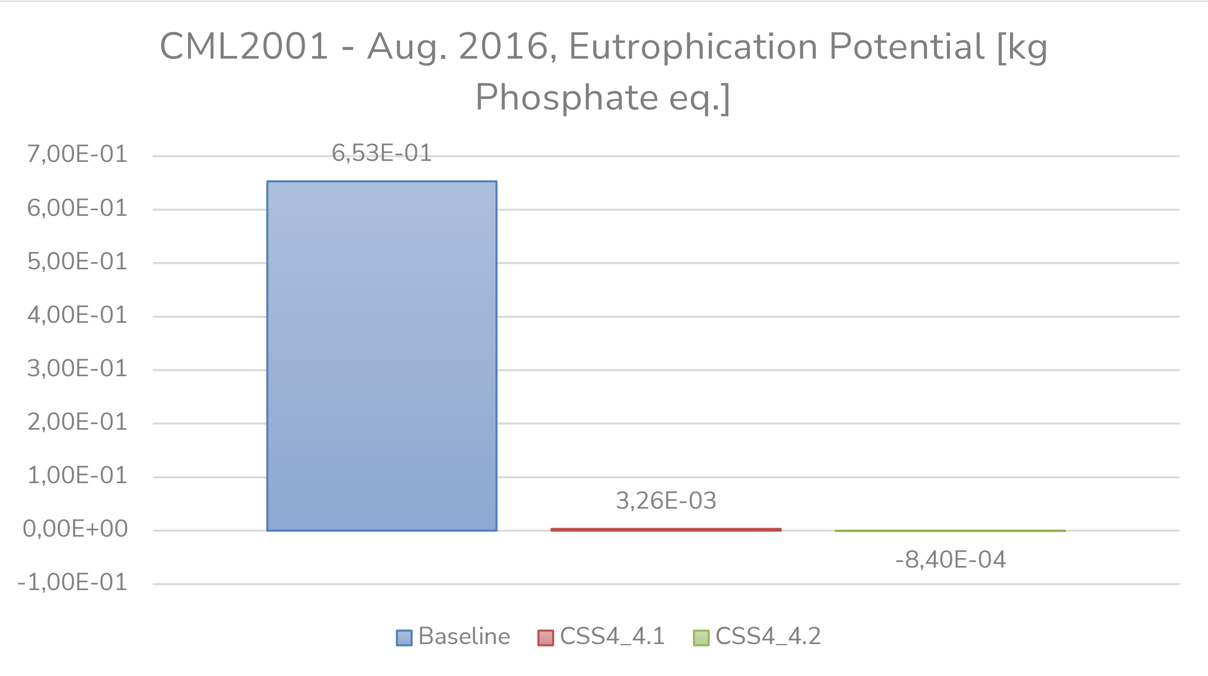

Figure 16 Eutrophication Potential (EP) [kg Phosphate eq.] impact for each scenario.

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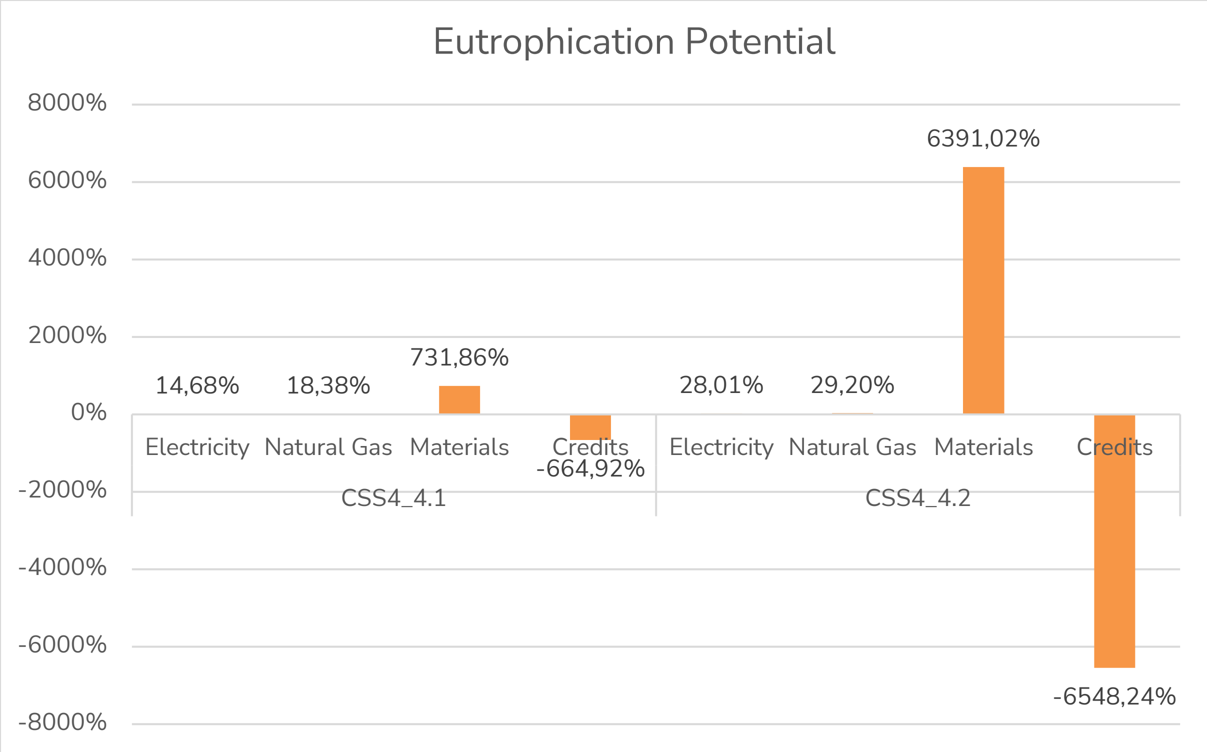

Figure 17 Categorical impact contribution (%) for Eutrophication Potential.

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 CSS4 scenarios is compared. The Baseline scenario shows the highest FAETP value of 2.24E+01 kg DCB eq., indicating significant potential harm to freshwater aquatic ecosystems due to the substances involved in the standard processing of waste. In contrast, Scenario 4.1 (Insulation Material Production) demonstrates a dramatic reduction in FAETP, showing a value of -8.70E+03 kg DCB eq. This negative value suggests a highly beneficial impact on freshwater ecosystems, largely due to the resource and material management processes that minimize harmful substances. The "Materials" category in CSS4_4.1 contributes a large negative value (-99.99%), indicating the reduced ecotoxicity of the materials used in the production process. On the other hand, Scenario 4.2 (Foam Material Recycled) shows a positive FAETP value of 1.03E+00 kg DCB eq., indicating a potential lower impact on freshwater aquatic ecosystems. The contribution

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of materials in this scenario (205.43%) plays a significant role in the overall impact, as detailed in Figure 19. Despite this, the "Credits" category contributes a negative impact of -105.90%, suggesting that while some materials may contribute to ecotoxicity, the processes involved in recycling help to mitigate the overall impact on aquatic ecosystems. Additionally, the contributions from electricity (0.28%) and natural gas (0.19%) are minimal, which is consistent with the relatively low contribution of these inputs to the overall FAETP in Scenario 4.2.

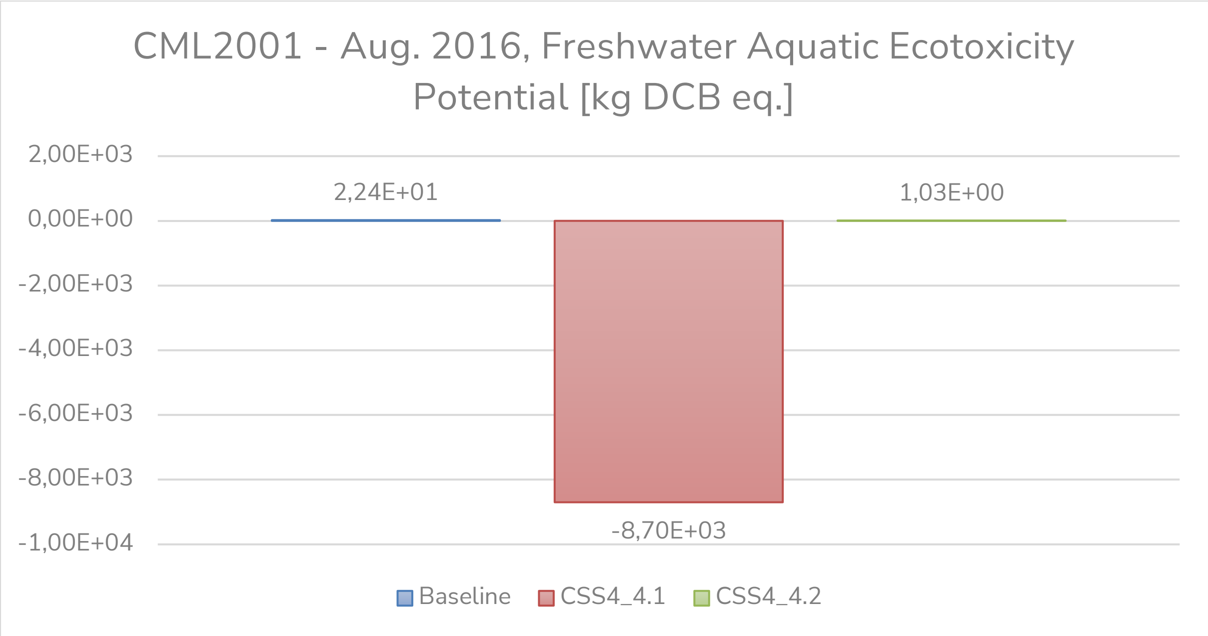

Figure 18 Freshwater Aquatic Ecotoxicity Pot. [kg DCB eq.] impact for each scenario.

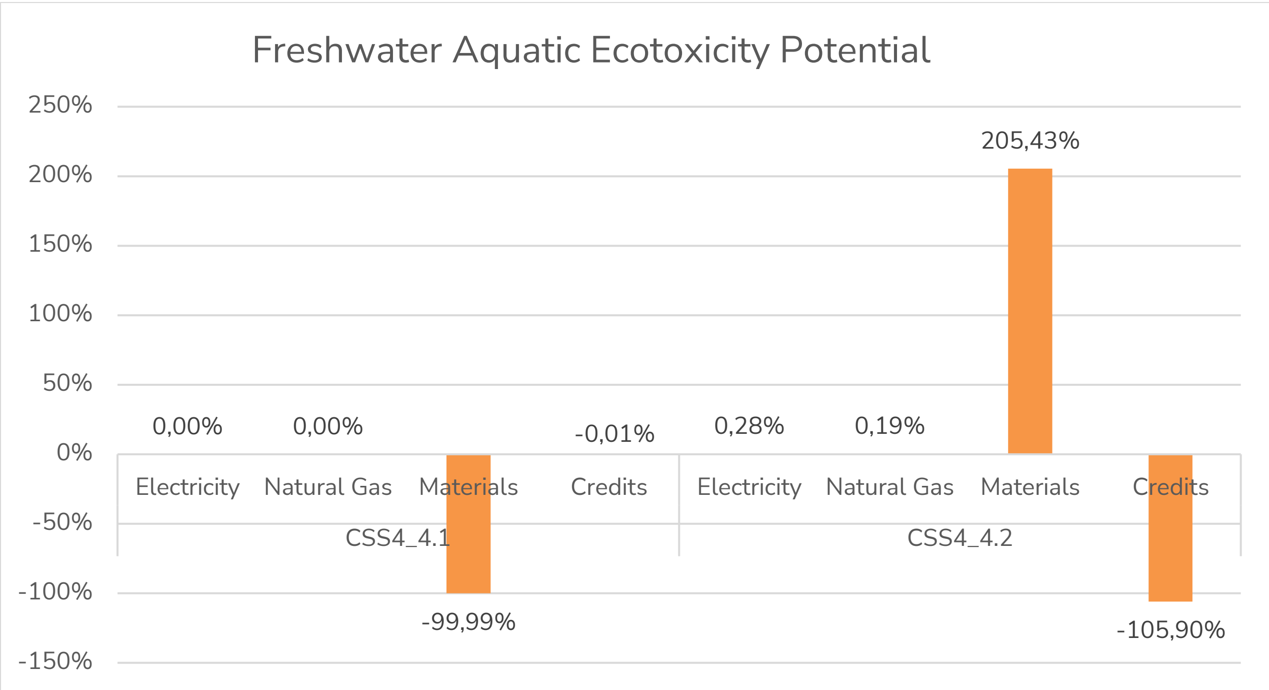

Figure 19 Categorical impact contribution (%) for Freshwater Aquatic Ecotoxicity Pot.

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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_2), methane (CH_4), and nitrous oxide (N_2O), are measured over a specific time frame, typically 100 years. GWP is expressed in units of kilograms of carbon dioxide equivalent (kg CO_2 eq.), which represents the amount of CO_2 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_2 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 CSS4 scenarios is compared. The Baseline scenario shows the highest GWP value of 1.76E+03 kg CO_2 eq., indicating the greatest contribution to global warming due to standard waste processing practices. In contrast, Scenario 4.1 (Insulation Material Production) demonstrates a significant reduction in GWP, with a value of -1.16E+01 kg CO_2 eq., largely due to the material and energy management processes, with the "Credits" category playing a major role in reducing the impact (-689.12%). Additionally, contributions from electricity (10.79%) and natural gas (25.86%) are moderate in this scenario. Scenario 4.2 (Foam Material Recycled) shows an even greater reduction in GWP, with a value of -9.91E+01 kg CO_2 eq., reflecting the beneficial impact of material recovery and recycling processes, where the "Credits" category also significantly reduces GWP (-267.31%). While electricity (0.62%) and natural gas (1.24%) have minimal contributions, the recycling processes in this scenario result in a strongly positive overall impact on global warming (Figure 21).

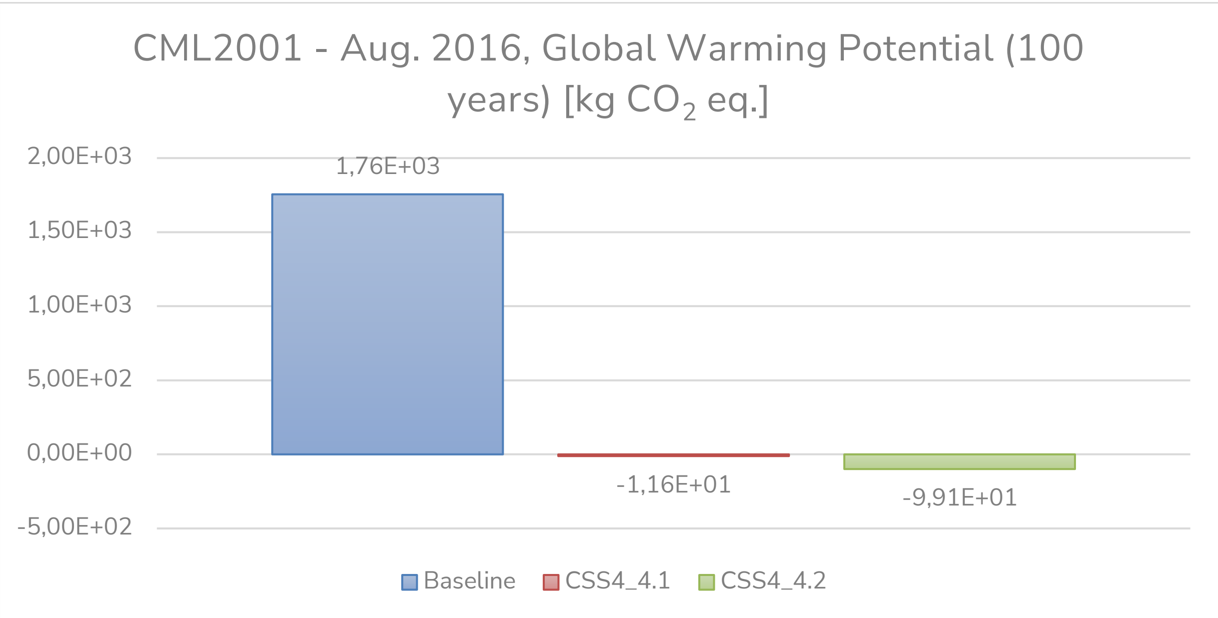

Figure 20 Global Warming Potential [kg CO_2 eq.] impacts.

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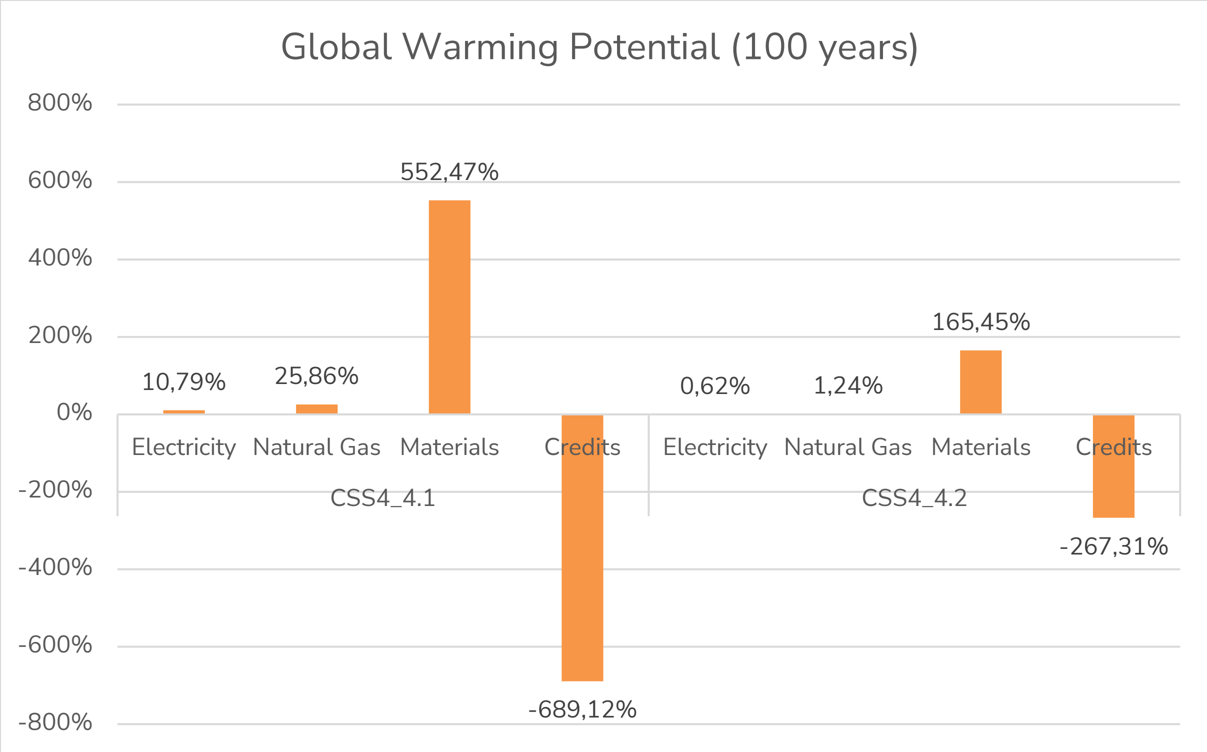

Figure 21 Categorical impact contribution (%) for Global Warming Potential.

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 22, the HTP impact across different CSS4 scenarios is compared. The Baseline scenario shows the highest HTP value of 7.98E+01 kg DCB eq., indicating significant potential harm to human health due to substances involved in standard waste processing. In contrast, Scenario 4.1 (Insulation Material Production) demonstrates a reduced HTP value of 1.81E+01 kg DCB eq., reflecting a lower impact on human health due to the materials and processes involved. Notably, Scenario 4.2 (Foam Material Recycled) shows a near-zero HTP value of 1.01E-09 kg DCB eq., indicating a negligible impact on human health, largely due to the recycling processes that minimize exposure to toxic substances. This reduction in HTP highlights the significant benefits of the recovery and recycling approach in Scenario 4.2, which substantially decreases the human toxicity potential.

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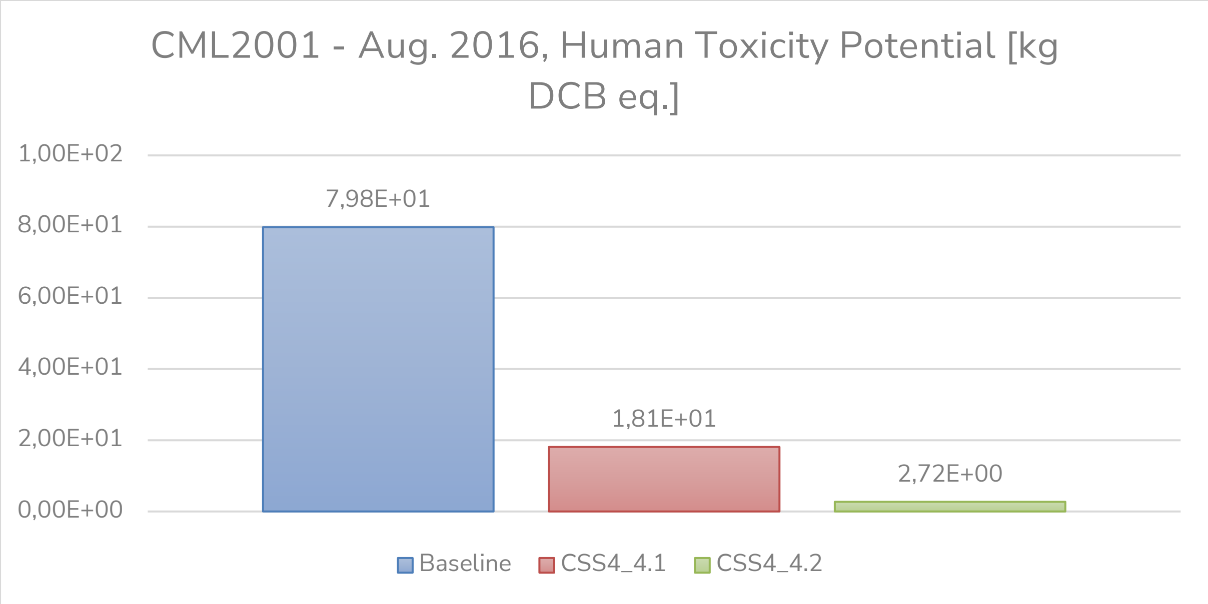

Figure 22 Human Toxicity Potential [kg DCB eq.] impact for each scenario.

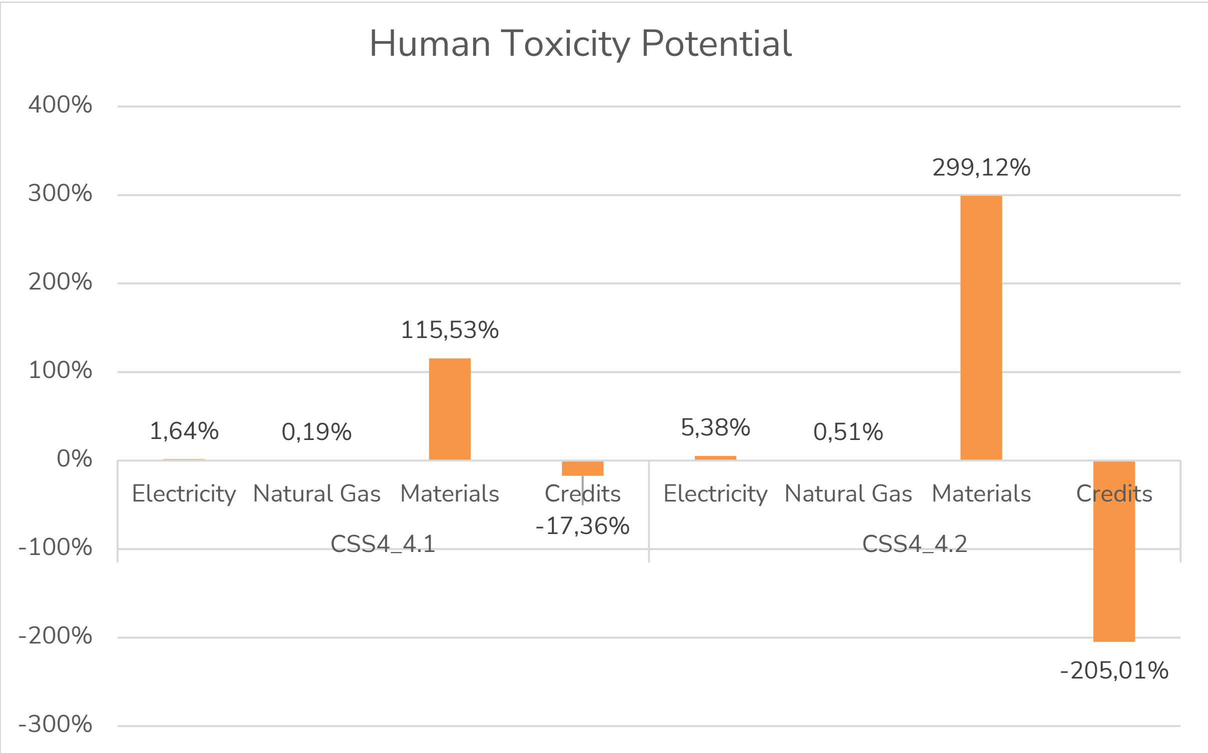

Figure 23 Categorical impact contribution (%) for Human Toxicity Potential

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

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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.

In Figure 24, the ODP impact across different CSS4 scenarios is compared. The Baseline scenario shows a relatively low ODP value of 1.16E-09 kg R11 eq., indicating a minimal impact on the ozone layer. However, Scenario 4.1 (Insulation Material Production) exhibits a significantly higher ODP value of 4.91E-06 kg R11 eq., reflecting a more substantial adverse effect on the ozone layer. This is largely due to the energy and material processes involved in insulation production. The categorical contributions in Scenario 4.1 show that the "Materials" category plays a dominant role, contributing 99.89% to the ODP impact, followed by electricity (10.12%) and a small contribution from credits (0.01%). On the other hand, Scenario 4.2 (Foam Material Recycled) shows a value of 1.01E-09 kg R11 eq., which is similar to the Baseline scenario, indicating that the recycling processes in this scenario have a minimal impact on ozone depletion. The contributions in Scenario 4.2 show that electricity (285.47%) and materials (12.46%) are significant, while the credits category contributes negatively (-197.94%), indicating that the recycling process helps mitigate the overall ODP impact. This comparison highlights that while the insulation material production in Scenario 4.1 contributes more to ozone depletion, the recycling process in Scenario 4.2 demonstrates a more sustainable outcome in terms of ozone layer protection (Figure 25).

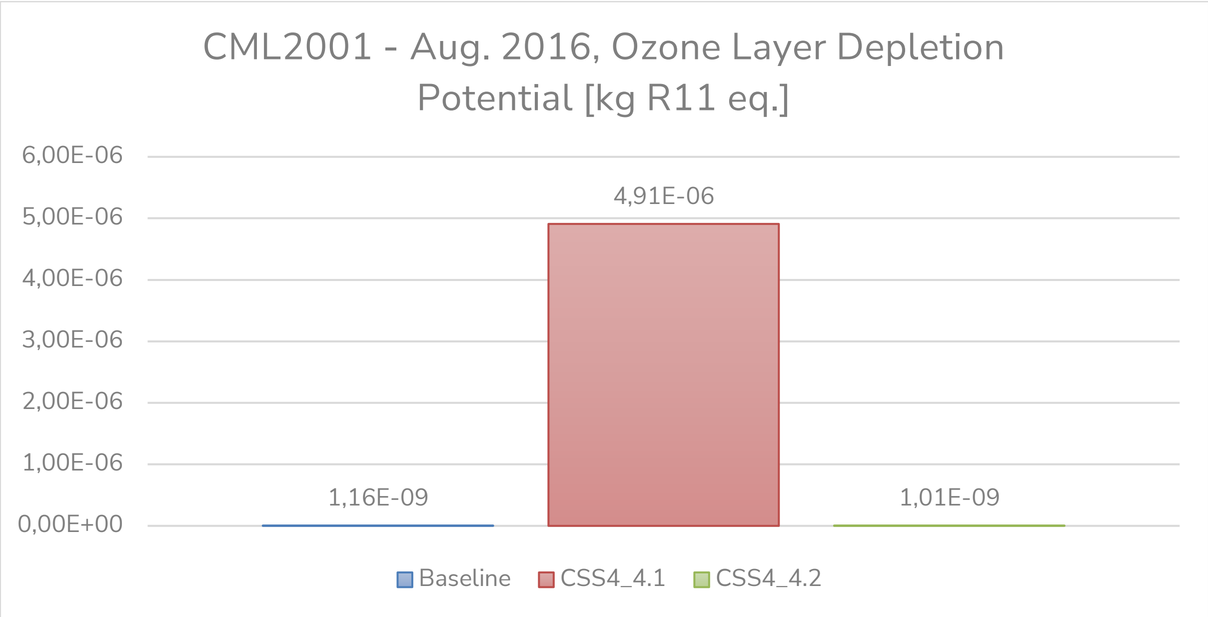

Figure 24 Ozone Layer Depletion Potential [kg R11 eq.] impact for each scenario.

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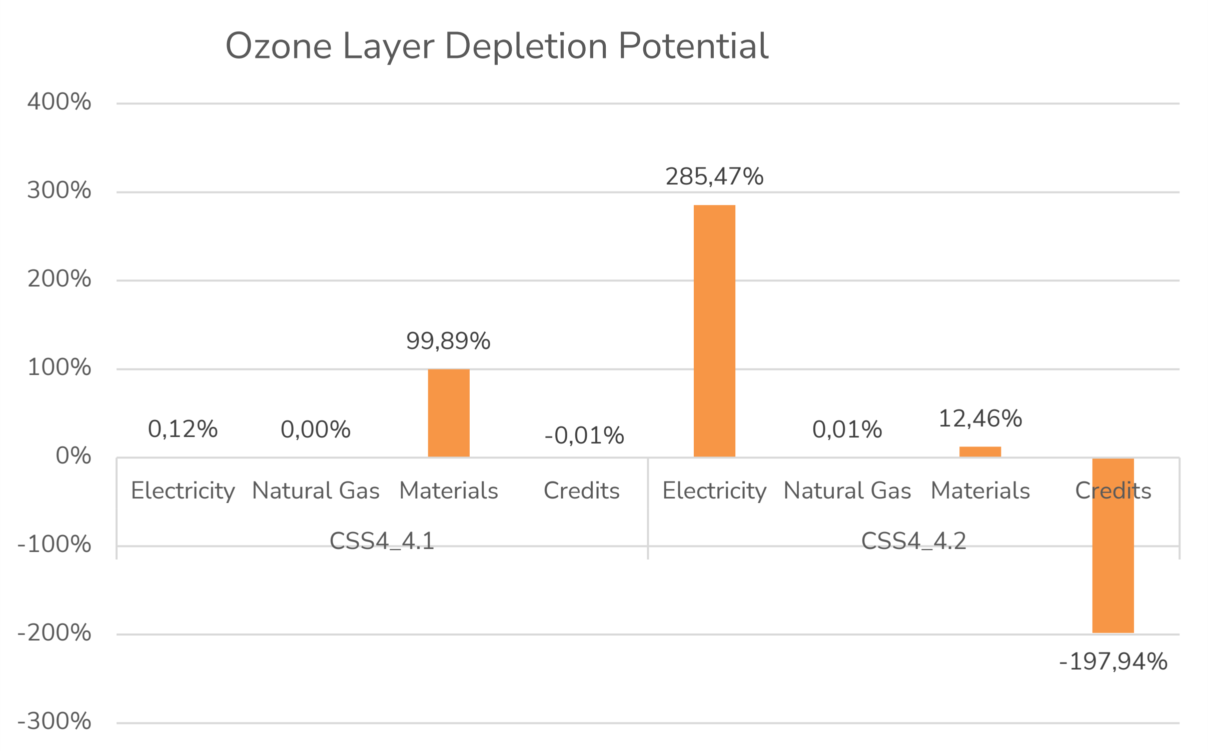

Figure 25 Categorical impact contribution (%) for Ozone Layer Depletion Potential

3.3.9 Photochemical Ozone Creation Potential

The majority of tropospheric ozone formation occurs when NO_x, CO, and VOCs, such as xylene, react in the atmosphere in the presence of sunlight. NO_x 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_2H_4 equivalent.

In Figure 26, POCP impact across different CSS4 scenarios is compared. The Baseline scenario has a high POCP value of 7.80E-01 kg C_2H_4 eq., reflecting the significant impact of volatile organic compounds (VOCs) released from wood packaging waste during landfilling. Scenario 4.1 (Insulation Material Production) shows a dramatic reduction in POCP, with a value of -7.75E-03 kg C_2H_4 eq. This negative value suggests a positive environmental impact, largely due to the material and energy management processes that minimize the creation of photochemical ozone. The categorical contributions for Scenario 4.1 reveal that the "Materials" category plays the most significant role, contributing 294.72%, while electricity (5.87%) and natural gas (11.95%) have a smaller influence. On the other hand, Scenario 4.2 (Foam Material Recycled) has a POCP value of 4.12E-02 kg C_2H_4 eq., indicating a moderate potential for photochemical ozone creation. In this scenario, the contributions from electricity (0.54%), natural gas (0.92%), and materials (275.79%) contribute to the overall POCP impact, while the credits category significantly mitigates the impact with a contribution of -177.25%. This comparison illustrates that while the insulation material production in

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Scenario 4.1 results in a lower POCP value, the recycling process in Scenario 4.2 leads to a more moderate but still beneficial outcome in reducing photochemical ozone formation (Figure 27).

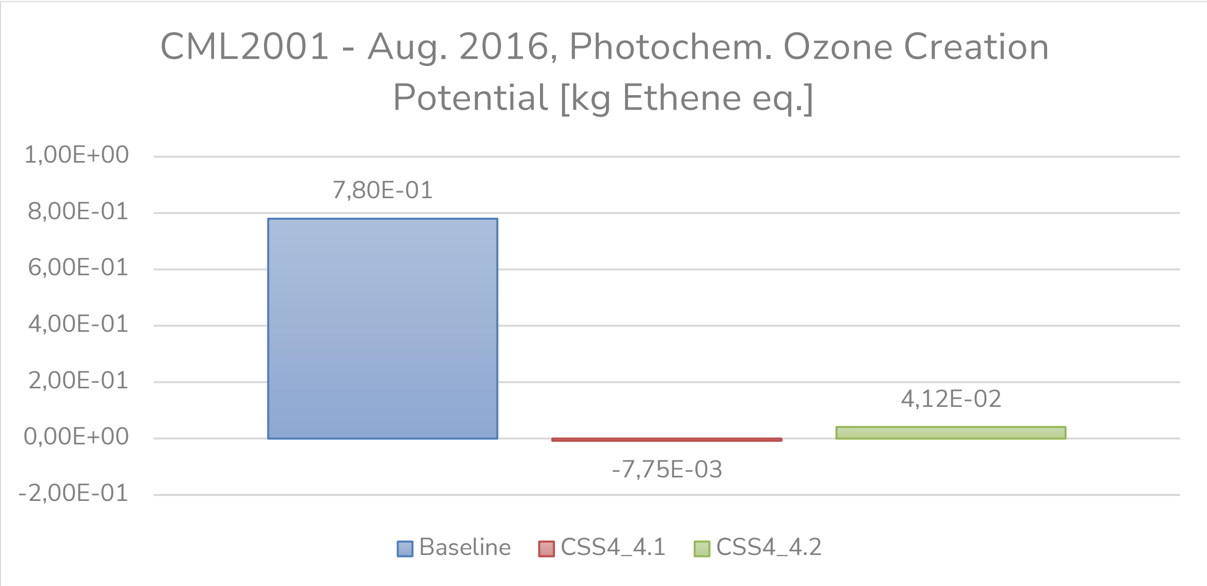

Figure 26 Photochemical. Ozone Creation Potential (POCP) [kg Ethene eq.] for each scenario.

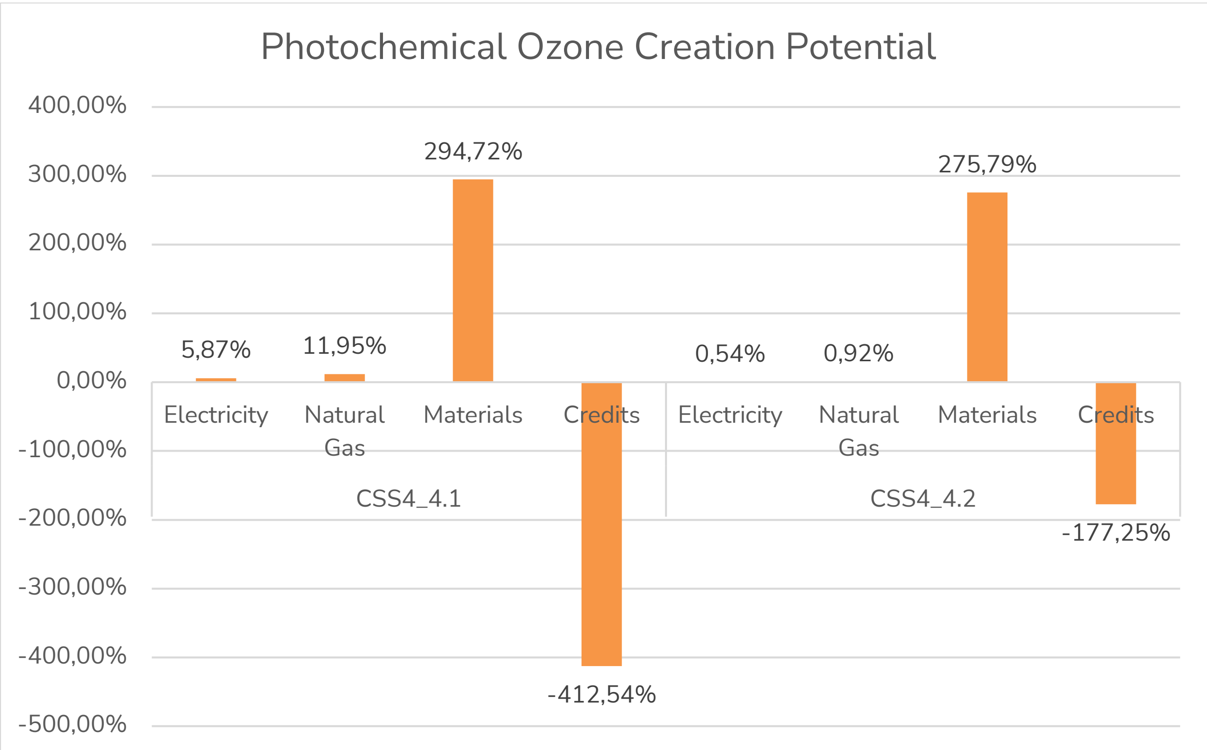

Figure 27 Categorical impact contribution (%) for Photochemical Ozone Creation

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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-DCB equivalent (kg DCB eq.) are typically used as the unit of measurement for TETP.

In Figure 28, the TETP impact across different CSS4 scenarios is compared. The Baseline scenario has a TETP value of 5.01E+00 kg DCB eq., indicating a relatively high potential ecological harm to terrestrial ecosystems due to the release of toxic substances during landfilling. In contrast, Scenario 4.1 (Insulation Material Production) shows a significantly lower TETP value of 3.42E-02 kg DCB eq., reflecting the reduced ecological impact from the materials and energy processes involved. The categorical contributions for Scenario 4.1 reveal that materials play the most significant role, contributing 501.23%, while electricity (21.14%) and natural gas (47.68%) have a more moderate influence. On the other hand, Scenario 4.2 (Foam Material Recycled) demonstrates a negative TETP value of -3.96E-02 kg DCB eq., indicating a beneficial reduction in terrestrial ecotoxicity. This is largely due to the significant contribution from the "Credits" category (-1488.38%), which offsets the impacts from electricity (8.97%), natural gas (16.84%), and materials (1362.57%). Overall, Scenario 4.2 presents the most beneficial impact in terms of reducing terrestrial ecotoxicity, while Scenario 4.1 shows a more moderate but still positive effect.

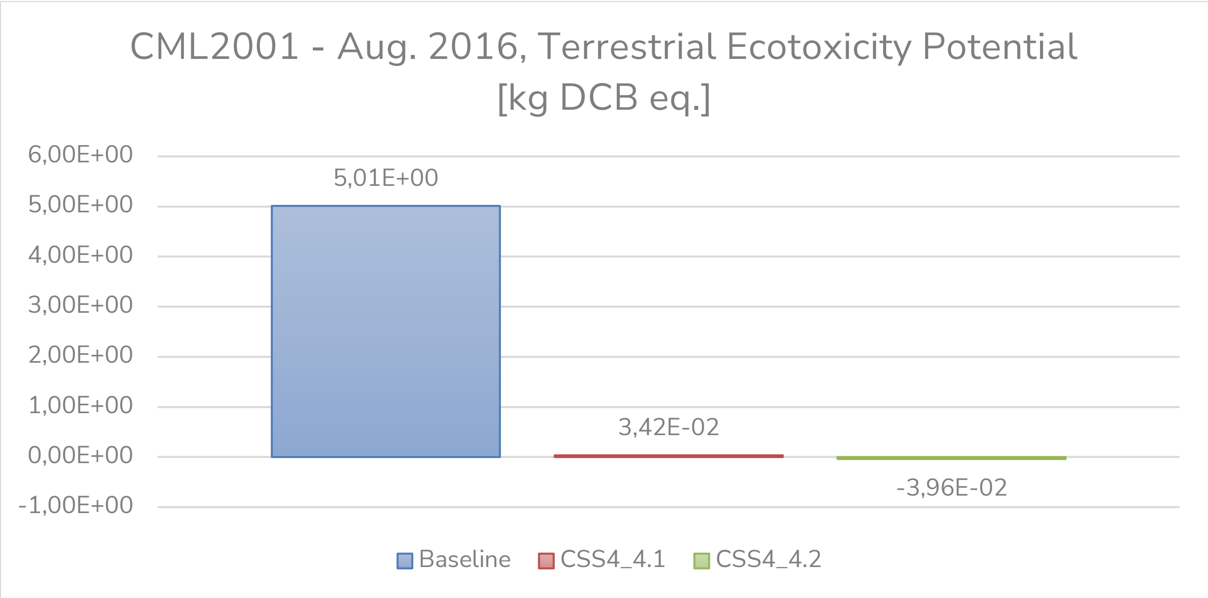

Figure 28 Terrestrial Ecotoxicity Potential [kg DCB eq.].

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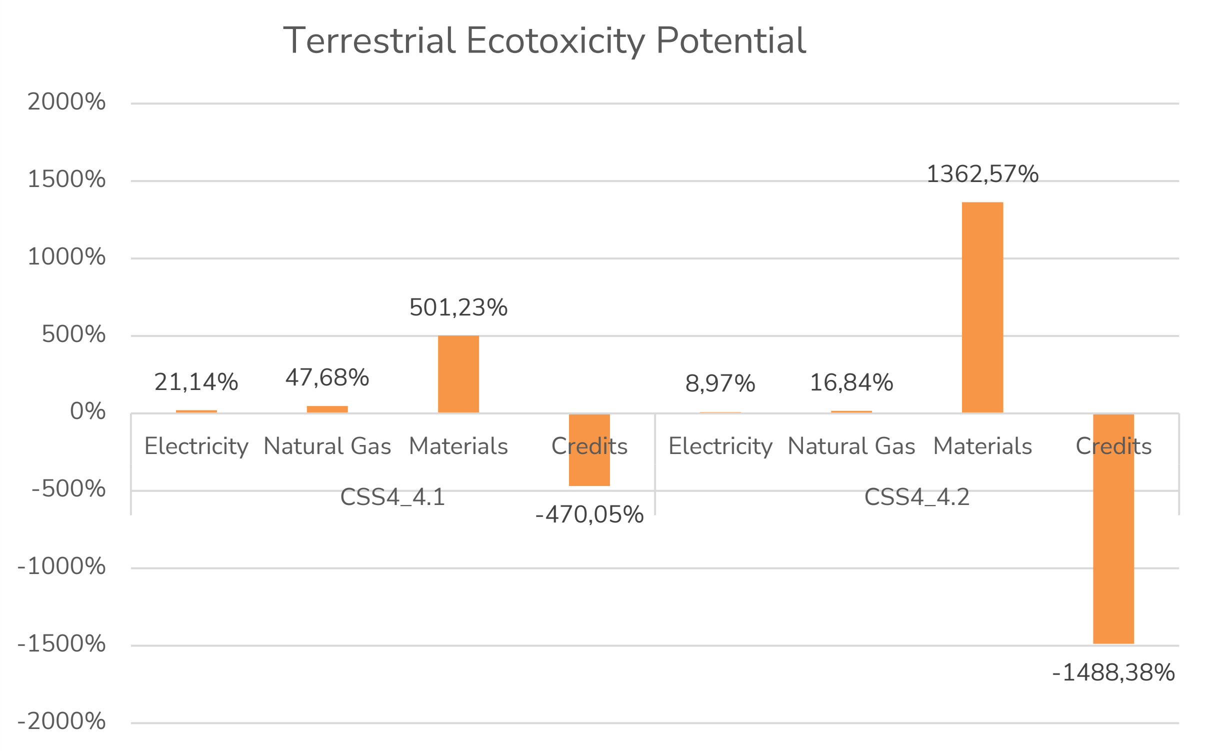

Figure 29 Categorical impact contribution (%) for Terrestrial Ecotoxicity Potential.

3.4 EN15804+A2

3.4.1 Resource use indicators

The resource use indicators for different CSS4 scenarios are compared in terms of renewable and non-renewable primary energy use. The Baseline scenario has the highest use of renewable primary energy, with values of 6.97E+02 MJ for both PERE and PERT. Scenario 4.1 (Insulation Material Production) shows a slight reduction in renewable energy use, with PERE and PERT values of 6.48E+02 MJ. Scenario 4.2 (Foam Material Recycled) demonstrates a negative value for both PERE and PERT at -3.66E+02 MJ, indicating a significant reduction in renewable energy use due to the recycling process.

Regarding non-renewable primary energy use, the Baseline scenario shows the highest value at 6.84E+04 MJ. Scenario 4.1 shows a large reduction in non-renewable energy use with a value of -4.97E+02 MJ, reflecting a positive impact from the material and energy management processes. Scenario 4.2 shows a small increase in non-renewable energy use with a value of 4.35E+02 MJ, due to energy consumption in the recycling process.

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

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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 30, the HWD impacts across different scenarios are compared. The Baseline scenario shows an HWD impact of 2.69E-06 kg, indicating the potential hazardous effects associated with standard wood waste processing. Scenario 4.1 (Insulation Material Production) has a significantly higher impact at 7.84E-05 kg, reflecting the increased energy consumption and potentially hazardous waste generation during the production process. In contrast, Scenario 4.2 (Foam Material Recycled) demonstrates a positive outcome with a reduced HWD value of -1.54E-06 kg, reflecting the beneficial effects of recycling and energy recovery processes in reducing hazardous waste generation.

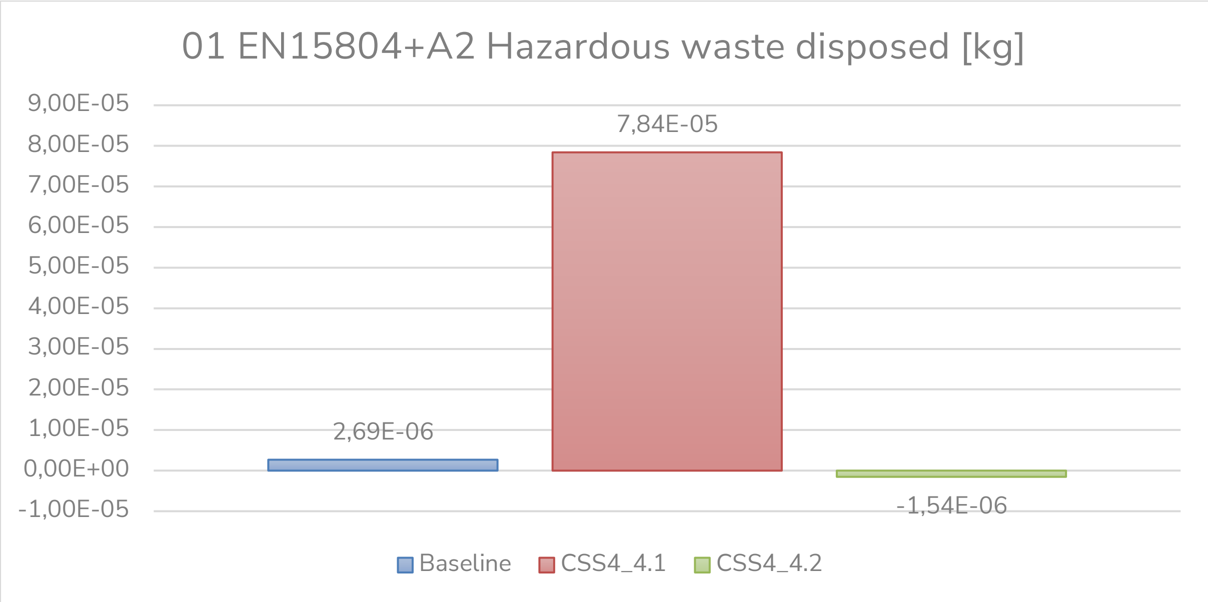

Figure 30 Hazardous waste disposed [kg].

3.4.3 Non-hazardous Wastes

The non-hazardous 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 non-hazardous waste (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 31, the NHWD impacts across different scenarios are compared. The Baseline scenario, which involves landfilling, shows the highest NHWD value of 1.01E+03 kg, indicating the significant amount of non-hazardous waste generated during the standard disposal process. In contrast, Scenario 4.1 (Insulation Material Production) and Scenario 4.2 (Foam Material Recycled) exhibit much lower NHWD values of 4.65E+00 kg and 4.36E+00 kg, respectively. These lower values suggest that these scenarios generate significantly less

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non-hazardous waste compared to the Baseline, with the waste from production processes being reduced or better managed in these cases.

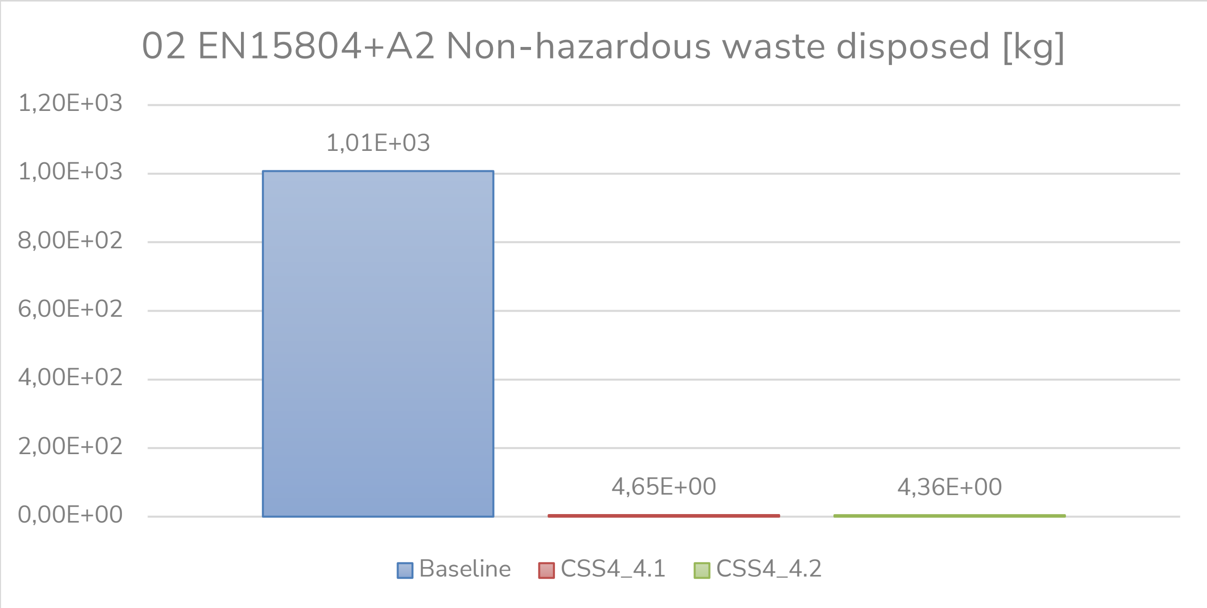

Figure 31 Non-hazardous waste disposed [kg].

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^3), providing a quantifiable indicator of freshwater use.

In Figure 32, the use of net freshwater is compared across different scenarios. The Baseline scenario shows a value of 7.24E+00 m^3, indicating the net consumption of freshwater resources during the standard waste management process. Scenario 4.1 (Insulation Material Production) exhibits a lower value of 4.78E+00 m^3, suggesting a reduced use of freshwater compared to the Baseline. On the other hand, Scenario 4.2 (Foam Material Recycled) shows a higher value of 8.89E+00 m^3, indicating an increased use of freshwater resources in the recycling process. These differences highlight the varying levels of freshwater consumption depending on the materials and processes involved in each scenario.

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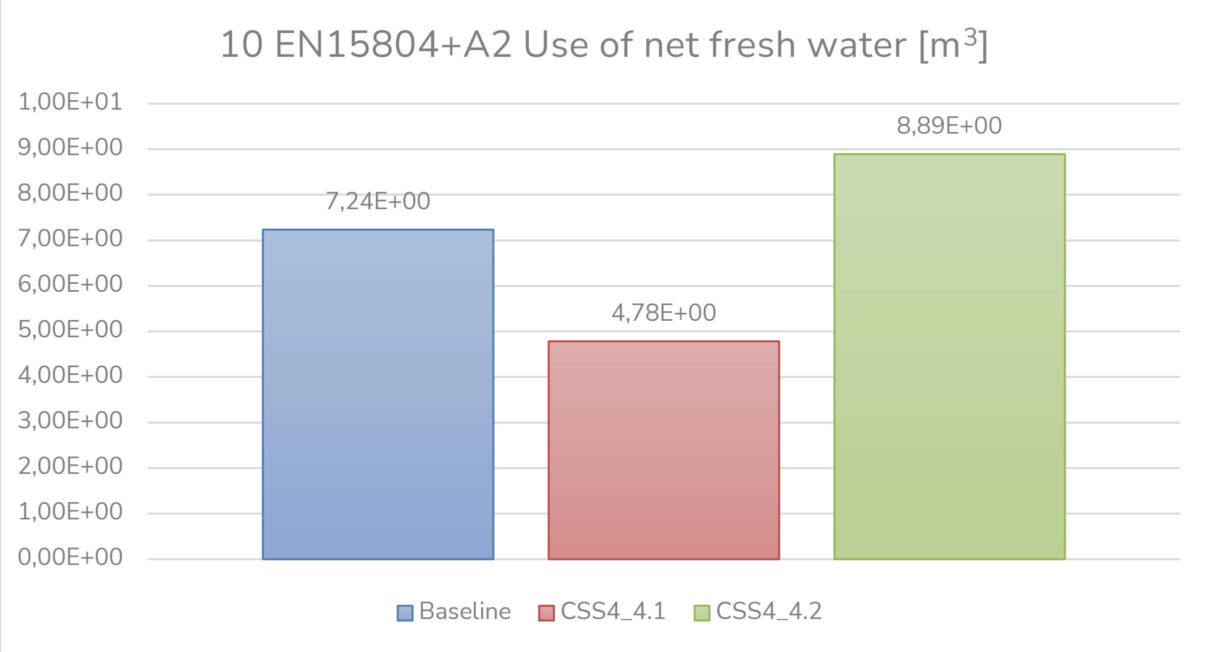

Figure 32 Use of net fresh water [m^3].

4 LCC methodology

4.1 Goal and Scope

4.1.1 Goal

The methodology of LCC is more straightforward compared to LCA. The goal and scope definitions are stated to understand the overall life cycle cost of the proposed CSS3 technology in respect with the sustainable management of wood packing waste. All necessary data to investigate and evaluate the life cycle cost of FRONTSH1P technologies are collected in close collaboration with K-FLEX 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 proper 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 33 and corresponded to initial capital expenditure (CAPEX) as well as recurring costs i.e. operation and maintenance expenditure (OPEX).

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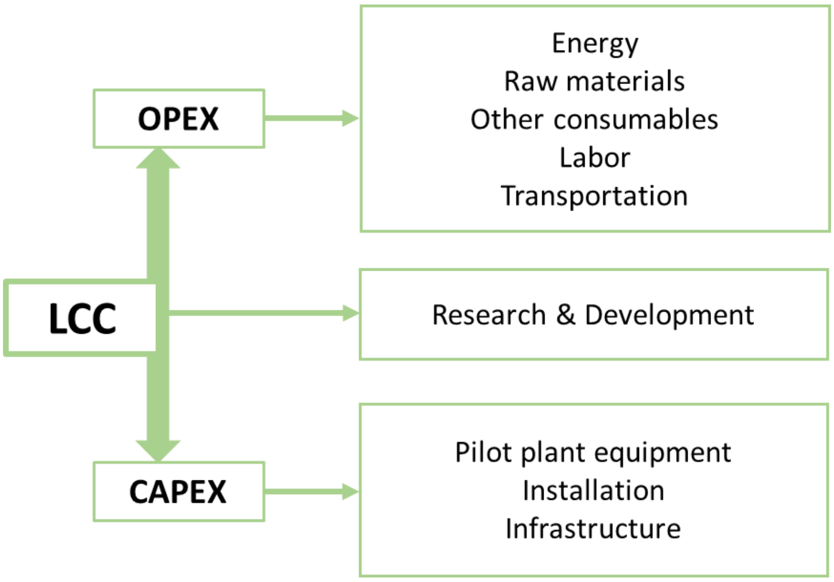

Figure 33 Life Cycle Cost distribution.

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 include labour, energy, chemicals and sludge disposal. Smaller expenses generally fall under the operation and maintenance (O&M) category. OPEX is incurred throughout the asset's 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

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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:

Climate change externalities [€] = Total impacts [kg CO_2 eq.] · f [€/ (kg CO_2 eq.)]

where f is equal to 0.004 €/ kg CO_2 eq. (or 4 €/ ton CO_2 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 CSS4 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 Baseline, Scenarios 1 and 2, as it was not calculated in the LCA analysis

4.2 Data inventory related to LCC analysis

Table 3 LCC inventory of Baseline.

Baseline		
Life cycle phase	**Target activities**	**Cost (€)**
OPEX	Waste disposal	315,006

Table 4 LCC inventory of Scenario 1.

Scenario 1				
	Life cycle phase	**Target activities**	**Cost (€)**	**Comment**
	OPEX	Energy	221,596,558	8%*60
	OPEX	Labour	332,394,838	12%*60
	OPEX	Service Costs	553,991,396	20%*60
	OPEX	Materials	1,661,974,188	60%*60
	CAPEX	Equipment Acquisition	20,000,000	rubber line production
	Earnings	Products	-2,771,341,959	12%

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Table 5 LCC inventory of Scenario 2.

Scenario 1				
	Life cycle phase	Target activities	Cost (€)	Comment
	OPEX	Energy	5,952,033	8%*60
	OPEX	Labour	8,928,049	12%*60
	OPEX	Service Costs	14,880,082	20%*60
	OPEX	Materials	44,640,247	60%*60
	CAPEX	Equipment Acquisition	8,000,000	PE line production
	Earnings	Products	-74,772,414	12%

4.3 Life Cycle Interpretation: Results and discussion

A total of 5,250 tonnes of plastic waste were subjected to landfilling (Baseline), and to the production of rubber (Scenario 1) and polyethylene (Scenario 2) insulation materials. The results are presented in the following figure. Based on the cost graph for each scenario (Figure 34), the Baseline exhibits the highest LCC result (4,989,771 €), followed by Scenario 1, which shows a significant reduction (355,930 €) and Scenario 2, with a higher value (2,695,066 €).

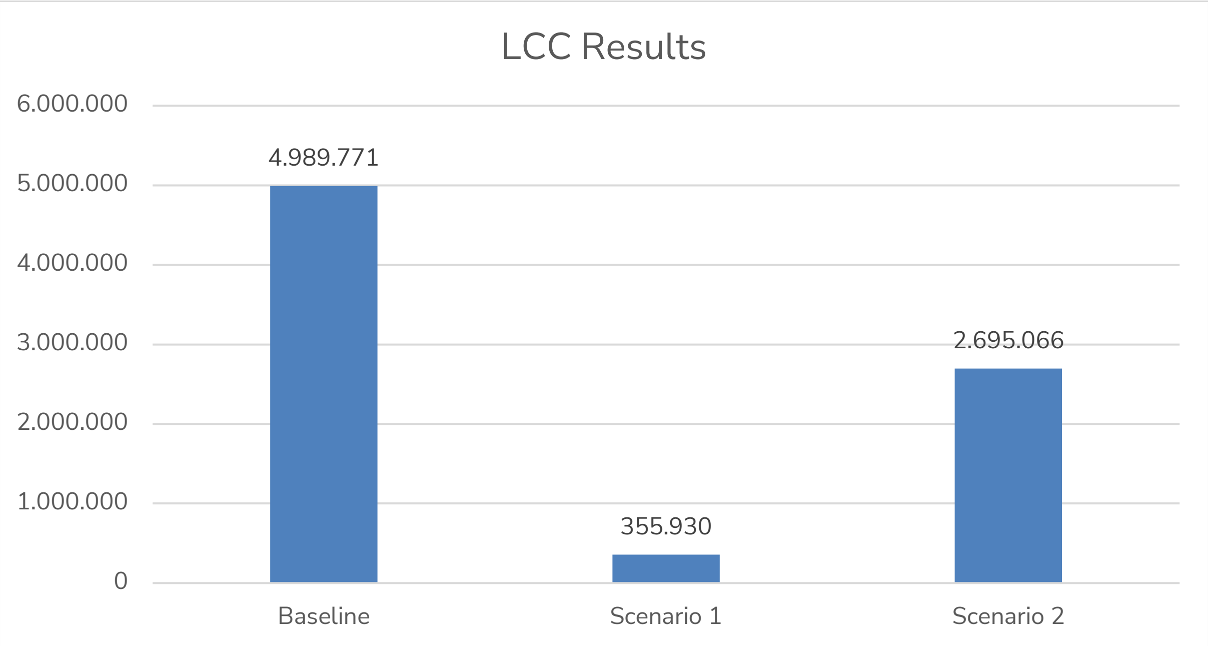

Figure 34 LCC results of each scenario.

The results are further supported by Figure 35, which presents the undiscounted total sensitivity cost for the first year. OPEX costs have the highest contribution across all scenarios. In the Baseline, climate change externalities significantly increase the LCC result. Conversely, in Scenarios 1 and 2, earnings from the insulation material products contribute

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to a reduction in the total cost of each scenario. This is because foam and polyethylene insulation material products from these Scenarios generate revenue through sales to supplier factories.

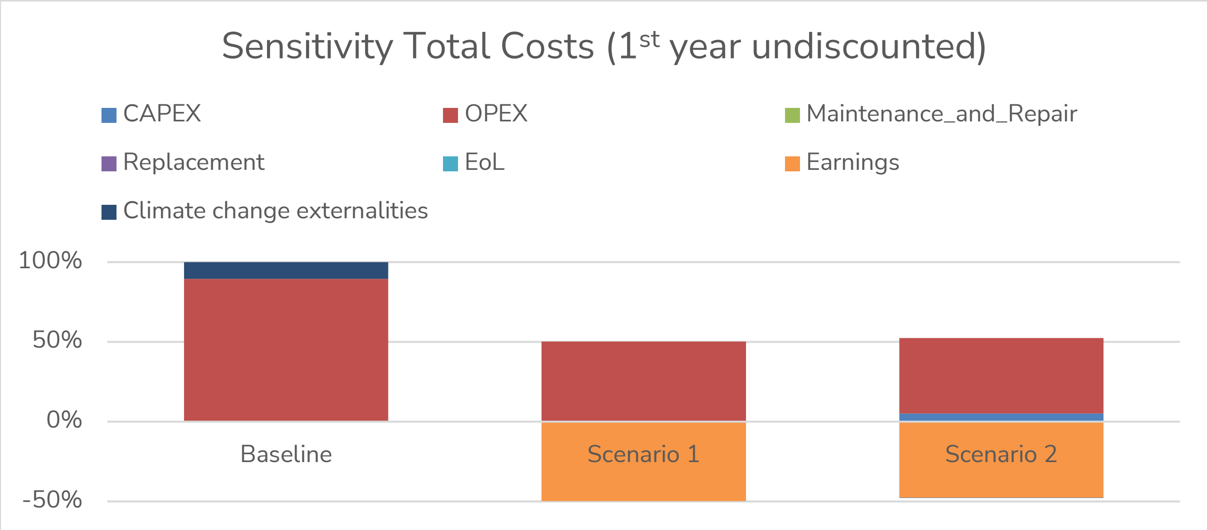

Figure 35 Sensitivity analysis of total costs (1st year undiscounted) for each scenario

For a 20-year horizon, the CAPEX of Scenarios 1 and 2 will remain unchanged due to maintenance. According to Figure 36, the cost curves of these Scenarios exhibit a decreasing trend, while the net present values progressively decline over time as earnings increase.

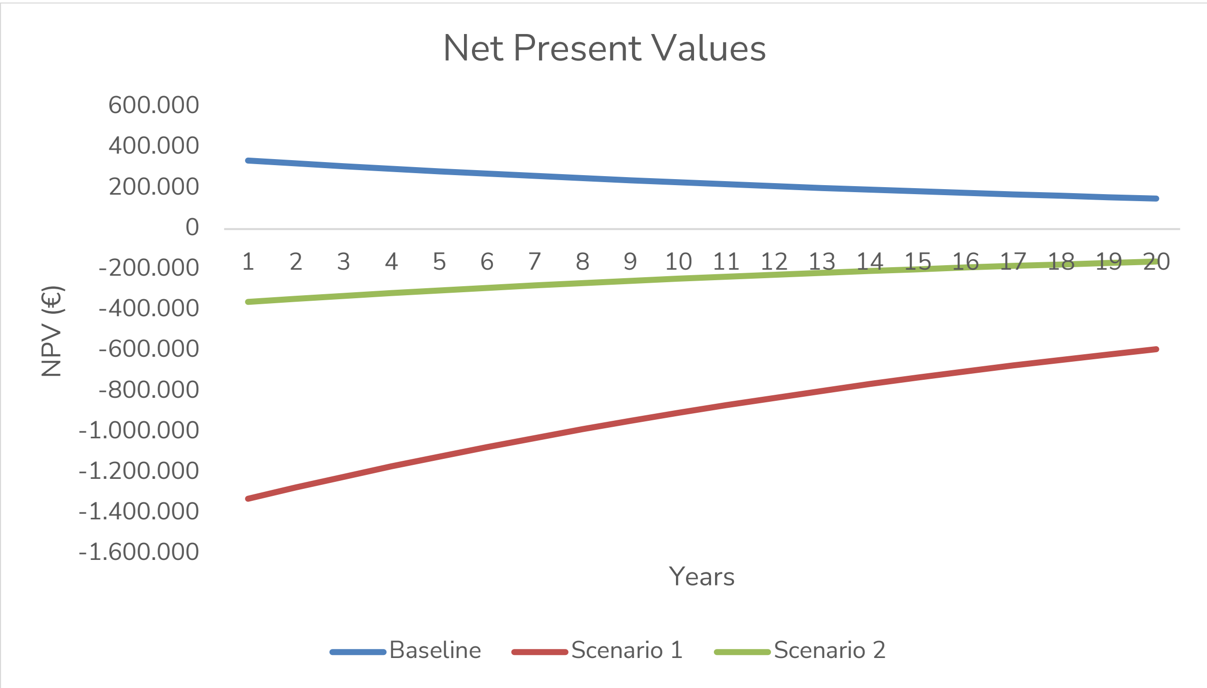

Figure 36 Net present values of each scenario for 20 years horizon

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5 s-LCA methodology

5.1 Goal and Scope

This study focuses on the management of plastic waste, which is one of the most significant municipal waste types in Europe, particularly in the Lodzkie region of Poland. It is anticipated that an inadequate system for managing the big amounts of plastic used daily in various circumstances, could result in a range of social and sociological impacts throughout the lifecycle.

The aim of this Social Life Cycle Assessment (S-LCA) is to evaluate and quantify the social impacts of new waste management solutions and technologies across the lifecycle of these industries. The assessment will help determine whether these innovations lead to improvements in sustainability and efficiency. Additionally, the social and sociological effects of plastic waste will be analysed using impact subcategories for each relevant stakeholder group.

In this study, the Circular Systemic Solution 4 (CSS4) is applied as the new sustainable plastic waste management approach, focusing on plastic reduction through recycling, reuse and converting it into biobased alternatives.

For the analysis, a case study was conducted by a company that implements this solution. The results were then compared with the baseline system used in Europe to assess the social risks associated with the newly developed scenarios of CSS4. The social life cycle assessment of all the scenarios of the CSS4 is performed together given the same organization is involved into the analysis.

The scope of the S-LCA is to do a cradle to grave analysis including the system boundaries of End of life of plastic 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 stage of the production of plastic waste are the following:

5.2.1 Workers

In this study, workers are the individuals responsible for operating and maintaining the systems within the facility, including technicians, supervisors, and administrative personnel. Workers are assessed across multiple indicators, with two key categories being particularly significant: i) Health and Safety, and ii) Working Conditions.

For the Health and Safety category, the primary focus was on the availability of safety measures and the rate of fatal accidents in the workplace. Specifically, we evaluated the

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presence of safety protocols, preventive actions, emergency procedures, and initiatives promoting healthy work practices. Data for this category was collected both quantitatively (fatal accident rates) and qualitatively (presence of safety measures), mainly through the S-LCA questionnaire.

Furthermore, the Working Conditions category was assessed through two subcategories: fair salary and working hours. Although we were unable to obtain exact figures on the minimum wage for employees, we looked at the wage disparity between male and female workers at the facility, based on qualitative data from the questionnaire. For the working hours aspect, we analysed the likelihood of workers being required to work overtime, as reported in their questionnaire responses.

Other indicators for this stakeholder group included: Freedom of Association, Collective Bargaining, Child Labour, Forced Labour, Equal Opportunity/Discrimination, Social Security/Benefits, and Employment Relationships. These factors were also evaluated similarly, using both qualitative and quantitative data collected from the questionnaire.

5.2.2 Consumers

Consumers are individuals who "use" the material or immaterial outputs of a system. Two key impact categories for this stakeholder group are Health and Safety, which was assessed quantitatively through public health expenditure, and end-of-life responsibility, which refers to the existence of systems within the organization that provide consumers with information on disposal options for products. This was measured by the internal management and the safety measures involved in handling products at the end of their life cycle. Furthermore, the feedback mechanism was evaluated using the press freedom scale, while consumer privacy was gauged based on the rule of law scale. Finally, transparency was assessed through the corruption percentage index.

5.2.3 Local community

This group of stakeholders consists of the communities residing near the industrial area and other locations where resource recovery activities occur. Among the various impact categories, three were particularly relevant for this group: i) Community engagement, ii) Safe, Secure, and Healthy living conditions, and iii) Local employment.

For community engagement, the organization's contribution to local development was evaluated, including its support for community-driven initiatives (such as volunteer work or financial contributions) and partnerships with local higher education institutions. Data on these aspects was gathered qualitatively through a questionnaire completed by local community members.

The safety and well-being of the community are also vital concerns. In this context, reducing the use of hazardous substances and materials plays a significant role in improving living conditions in these areas. Additionally, the presence or absence of terrorism in these regions

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was taken into account. As with other indicators, relevant data was collected through questionnaire responses.
Regarding local employment, the local unemployment rate and the proportion of local residents employed by the organization were assessed to understand how much the organization engages local workers in its operations, even with the introduction of the new CSS4 solution. This data was collected quantitatively.
Other indicators for this stakeholder group included access to material and immaterial resources, migration and relocation patterns, and the protection of indigenous rights. These were evaluated using a similar approach, as described above.

5.2.4 Society

This stakeholder group was assessed across five different impact categories, with two major ones standing out: public commitment to sustainability and technological development.
For public commitment to sustainability, values were determined based on the proportion of resources allocated to sustainability and social initiatives that impact existing processes, as well as the use of critical raw materials. Another key indicator was the per capita ecological footprint, which was measured quantitatively.
As of the technological development, R&D investment was analysed to assess whether the innovative technological systems had a positive impact on the organization, alongside the level of involvement in technology transfer projects.
Additional factors considered for this stakeholder group included economic growth, efforts to reduce armed conflict, poverty alleviation, and corruption.

5.2.5 Supply chain

Finally, for the value chain actors, the key impact categories identified included fair competition, promotion of social responsibility, supplier relationships, suppliers of raw materials and technology, downstream actors and respect for intellectual property rights. Supplier relationships and suppliers of raw materials and technology were two categories evaluated using various indicators.
For the supplier relationships category, factors such as the identification of significant actual and potential negative social impacts were considered, along with the nature of the relationship between the organization and its suppliers on specific issues. In the suppliers of raw materials and technology category, the assessment focused on the traceability of raw materials, the protection of human rights among supplier employees, and the integration of ethical, social, environmental, and gender equality criteria.
As for the promotion of social responsibility, only the Good Country Index was evaluated, as we were unable to obtain data on the percentage of suppliers assessed for social impacts.
Additionally, fair competition was assessed based on regulatory quality and respect for intellectual property rights was evaluated through the Global IP Index.

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Table 6 Summary of stakeholders and their indicators.

Stakeholders	Indicators	Data source
Workers	(1) Freedom of association	ITUC Freedom of association [YES (100) - NO (1)] QL-P
	(1) Collective bargaining	Subject to collective bargaining [YES-100, NO-0] QL-P
	(2) Child labour	Child labour [% of children ages 7-14] QN-N
	(3) Forced labour	Forced labour and slavery [% of population] QN-N
	(4) Fair salary	Minimum wage [EUR/month] QN-P
	(4)1 Fair salary	Unequal remuneration [YES-100, NO-0] QL-N
	(5) Working hours	Hours worked per week [hours] QN-N
	(6) Equal opportunity/Discrimination	Women's share of work force [%] QN-P
	(6)1 Equal opportunity/Discrimination	Establishment of a committee/person for matters of discrimination [YES-100, NO-0] QL-P
	(6) Equal opportunity/Discrimination	Percentage of employees with a disability per employment level QN-P
	(7) Health and safety	Fatal accidents at work [-] QN-N
	(7)1 Health and safety	Presence of preventive measures and emergency protocols (YES-100, NO-0) QL-P
	(7)2 Health and safety	Measures to improve wellbeing and healthy practices in the facilities (YES-100, NO-0) QL-P
	(7)3 Health and safety	Hours of the health and safety training sessions that are usually attended per employee per year? (per level of employment) QN-P
	(8) Social Security/Benefits	Social protection expenditure [% of GDP] QN-P
	(8)1 Social Security/Benefits	Violations of obligations to employees under labour or social security laws [YES-100, NO-0] QL-N
	(9) Employment relationships	Social or training activities planned [YES-100, NO-0] QL-P
	(9)1 Employment relationships	Anonymous procedure for employees to state issues related with working conditions [YES-100, NO-0] QL-P
Consumers	(10) Health & Safety	Public health spend per capita [%] QN-P
	(11) Feedback Mechanism	Press freedom [0, constrained - 100, free] QN-P
	(12) Consumer Privacy	Rule of law [0-100] QN-P
	(13) Transparency	Corruption percentage index [0, highly corrupt - 100, very clean] QN-P
	(14) End of life responsibility	Internal management of organization on the product's end-of-life [YES-100, NO-0] QL-P
	(14)1 End of life responsibility	Safe and harmless to handle the end of life [YES-100, NO-0] QL-P

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	Description of final product	Certification/label of organisation/facility [YES-100, NO-0] QL-P
Local community	(15) Access to material resources	GDP per capita [EUR per capita] QN-P
	(16) Access to immaterial resources	Total literacy above 15 years [%] QN-P
	(16)1 Access to immaterial resources	Public expenditure In Education [percent of GDP] QN-P
	(17) Delocalization and Migration	Wellbeing [0-100] QN-P
	(17)1 Delocalization and Migration	Satisfaction with Life Scale (SWLS) [0-100] QN-P
	(18) Safe & healthy living conditions	Public health expenditure per capita [percent of GDP] QN-P
	(18)1 Safe & healthy living conditions	Management effort to minimize use of hazardous substances [YES 100, NO 0] QL-P
	(18)2 Safe & healthy living conditions	Certified environmental management system [YES-100, NO-0] QL-P
	(19) Respect of indigenous rights	Political freedom and Civil rights [1 (complete freedom) to 7 (no freedom)] QN-N
	(20) Community engagement	Voice and accountability [0-100] QN-P
	(20)1 Community engagement	Contribution of the organization to the local development (YES - 100, NO - 0) QL-P
	(20)2 Community engagement	Collaboration with local centres of higher education (YES - 100, NO - 0) QL-P
	(20)3 Community engagement	Presence of organizational reports disclosed to local community (YES-100, NO-0) QL-P
	(20)4 Community engagement	Protection of Indigenous communities in the local community [YES-100, NO-0] QL-P
	(21) Local employment	Unemployment rates [% of population] QN-N
	(21)1 Local employment	Employees originally from the local community (%) QN-P
	(21)2 Local employment	Percentage on spending on locally based suppliers [% of GDP] QN-P
	(21)3 Local employment	Support resettled employees [Yes-100, NO-0] QL-P
	(22) Secure living conditions	Political Stability and Absence of Violence and Terrorism [0, very bad - 100, very good] QN-P
	(22)1 Secure living conditions	Presence of risks in the facility [YES-100, NO-0] QL-N
Society	(23) Commitment to sustainability	Ecological Footprint per capita [global hectares -GHA per capita] QN-N
	(23)1 Commitment to sustainability	Percentage of the resources spend in sustainability and social activities (%) QN-P
	(23)2 Commitment to sustainability	Use of critical raw materials [YES 100, NO 0] QL-N
	(24) Economic development	UN Human Development Index [0-100] QN-P
	(25) Technology development	R&D spend [percent of GDP] QN-P

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	(25)1 Technology development	Involvement in technology transfer projects [High-100, Medium -50, Low-0] QL-P
	(26) Mitigation of armed conflict	Global Peace Index [1(very peaceful) to 5 (maximum unrest)] QN-N
	(27) Poverty alleviation	Formalized commitment to reduce poverty [YES-100, NO-0] QN-P
	(28) Corruption	Control of corruption index (WB) [0, very bad - 100, very good] QN-P
Value chain actors	(29) Fair competition	Regulatory quality [0 (lowest) to 100 (highest)] QN-P
	(30) Promoting social responsibility	Good Country Index QN-P
	(30)1 Promoting social responsibility	Percentage of suppliers assessed for social impacts (%) QN-P
	(31) Supplier relationships	Regulatory quality [0 (lowest) to 100 (highest)] QN-P
	(31)1 Supplier relationships	Suppliers identified as having significant actual and potential negative social impacts [YES-100, NO-0] QL-N
	(31)2 Supplier relationships	Organisation provides guidance / instructions to customers on how to handle your materials to avoid health and safety issues [YES-100, NO-0] QL-P
	(31)3 Supplier relationships	Organisation provides support to suppliers in terms of consciousness-raising and counselling concerning social responsibility issues [YES-100, NO-0] QL-P
	(32) Suppliers of raw materials and technology	Integration on ethical, social, environmental, and gender equality criterions in purchasing policy, distribution policy, and contract signatures [YES-100, NO-0] QL-P
	(32)1 Suppliers of raw materials and technology	Presence of a specific explicit code of conduct that protect human rights of employees among suppliers [YES-100, NO-0] QL-P
	(32)2 Suppliers of raw materials and technology	Raw material traceability [YES-100, NO-0] QL-P
	(33) Respect of intellectual property rights	Global IP Index [0 (no IP protection)- 35 (best IP protection)] QN-P
	(34) Downstream actors	Health and safety problems reported by your customers when handling your materials [YES-100, NO-0] QL- N

*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 above, we performed the performance assessment of this analysis:

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Table 7 S-LCA performance assessment of WP6.

Stakeholders	Indicators	Data source	Performance assessment in Reference Study	Performance assessment in the Average Case Study
Workers	(1) Freedom of association	ITUC Freedom of association	5,00	5,00
	(1) Collective bargaining	Subject to collective bargaining	5,00	5,00
	(2) Child labour	Child labour	4,77	5,00
	(3) Forced labour	Forced labour and slavery	4,98	5,00
	(4) Fair salary	Minimum wage	-	-
	(4)1 Fair salary	Unequal remuneration	1,00	5,00
	(5) Working hours	Hours worked per week	2,78	2,78
	(6) Equal opportunity/Discrimination	Women's share of work force	2,80	2,98
	(6)1 Equal opportunity/Discrimination	Establishment of a committee/person for matters of discrimination	5,00	5,00
	(6) Equal opportunity/Discrimination	Percentage of employees with a disability per employment level	3,12	1,08
	(7) Health and safety	Fatal accidents at work	4,99	5,00
	(7)1 Health and safety	Presence of preventive measures and emergency protocols	5,00	5,00
	(7)2 Health and safety	Measures to improve wellbeing and healthy practices in the facilities	5,00	5,00
	(7)3 Health and safety	Hours of the health and safety training sessions that are usually attended per employee per year?	1,01	1,00

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		(per level of employment)		
	(8) Social Security/Benefits	Social protection expenditure	2,08	2,08
	(8)1 Social Security/Benefits	Violations of obligations to employees under labour or social security laws	1,00	5,00
	(9) Employment relationships	Social or training activities planned	5,00	5,00
	(9)1 Employment relationships	Anonymous procedure for employees to state issues related with working conditions	5,00	5,00
Consumers	(10) Health & Safety	Public health spend per capita	1,42	1,42
	(11) Feedback Mechanism	Press freedom	4,03	4,03
	(12) Consumer Privacy	Rule of law	3,80	3,80
	(13) Transparency	Corruption percentage index	3,44	3,44
	(14) End of life responsibility	Safe and harmless to handle the end of life [YES-100, NO-0]	5,00	5,00
	(14)1 End of life responsibility	Recycle rate (proportion of materials recycled or recovered from waste)	1,00	5,00
	Description of final product	Certification/label of organisation/facility	5,00	5,00
Local community	(15) Access to material resources	GDP per capita	2,34	2,34
	(16) Access to immaterial resources	Total literacy above 15 years	4,95	4,95
	(16)1 Access to immaterial resources	Public expenditure In Education	1,19	1,19
	(17) Delocalization and Migration	Wellbeing	3,60	3,60
	(17)1 Delocalization and Migration	Satisfaction with Life Scale (SWLS)	3,92	3,92

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	(18) Safe & healthy living conditions	Public health expenditure per capita	1,39	1,40
	(18)1 Safe & healthy living conditions	Management effort to minimize use of hazardous substances	5,00	1,00
	(18)2 Safe & healthy living conditions	Certified environmental management system	5,00	5,00
	(19) Respect of indigenous rights	Political freedom and Civil rights	4,33	4,33
	(20) Community engagement	Voice and accountability	3,92	3,92
	(20)1 Community engagement	Contribution of the organization to the local development	1,00	5,00
	(20)2 Community engagement	Collaboration with local centres of higher education	5,00	5,00
	(20)3 Community engagement	Presence of organisational reports disclosed to local community	5,00	1,00
	(20)4 Community engagement	Protection of Indigenous communities in the local community	5,00	1,00
	(21) Local employment	Unemployment rates	4,75	4,75
	(21)1 Local employment	Employees originally from the local community	3,30	3,00
	(21)2 Local employment	Percentage on spending on locally based suppliers	4,10	2,20
	(21)3 Local employment	Support resettled employees	5,00	5,00
	(22) Secure living conditions	Presence of risks in the facility	1,00	5,00

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	(22)1 Secure living conditions	Political Stability and Absence of Violence and Terrorism	3,32	3,32
Society	(23) Commitment to sustainability	Ecological Footprint per capita	3,90	3,90
	(23)1 Commitment to sustainability	Percentage of the resources spend in sustainability and social activities	-	1,60
	(23)2 Commitment to sustainability	Use of critical raw materials	1,00	5,00
	(24) Economic development	UN Human Development Index	4,49	4,49
	(25) Technology development	R&D spend	1,09	1,08
	(25)1 Technology development	Involvement in technology transfer projects	3,00	5,00
	(26) Mitigation of armed conflict	Global Peace Index	4,34	4,34
	(27) Poverty alleviation	Formalised commitment to reduce poverty	5,00	1,00
	(28) Corruption	Control of corruption index (WB)	3,82	3,82
Value chain actors	(29) Fair competition	Regulatory quality	3,97	3,97
	(30) Promoting social responsibility	Good Country Index	4,41	4,41
	(30)1 Promoting social responsibility	Percentage of suppliers assessed for social impacts	-	-
	(31) Supplier relationships	Regulatory quality	3,97	3,97
	(31)1 Supplier relationships	Suppliers identified as having significant actual and potential negative social impacts	1,00	5,00
	(31)2 Supplier relationships	Organisation provides guidance / instructions to	5,00	5,00

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		customers on how to handle your materials to avoid health and safety issues		
	(31)3 Supplier relationships	Organisation provides support to suppliers in terms of consciousness-raising and counselling concerning social responsibility issues	5,00	1,00
	(32) Suppliers of raw materials and technology	Integration on ethical, social, environmental, and gender equality criterions in purchasing policy, distribution policy, and contract signatures	5,00	1,00
	(32)1 Suppliers of raw materials and technology	Presence of a specific explicit code of conduct that protect human rights of employees among suppliers	5,00	1,00
	(32)2 Suppliers of raw materials and technology	Raw material traceability	1,00	5,00
	(33) Downstream actors	Health and safety problems reported by your customers when handling your materials	1,00	5,00
	(34) Respect of intellectual property rights	Global IP Index	3,49	3,49

5.4 S-LCA results and discussion

This subsection presents the results for each stakeholder group and impact category outlined previously. The purpose of this section is to determine which indicators played a role in the improvements seen with the CSS4 solution, thus contributing to enhanced lifecycle

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sustainability in the region. Furthermore, a final comparison between the two cases is included to emphasize the differences and assess the overall impact of the new solution.

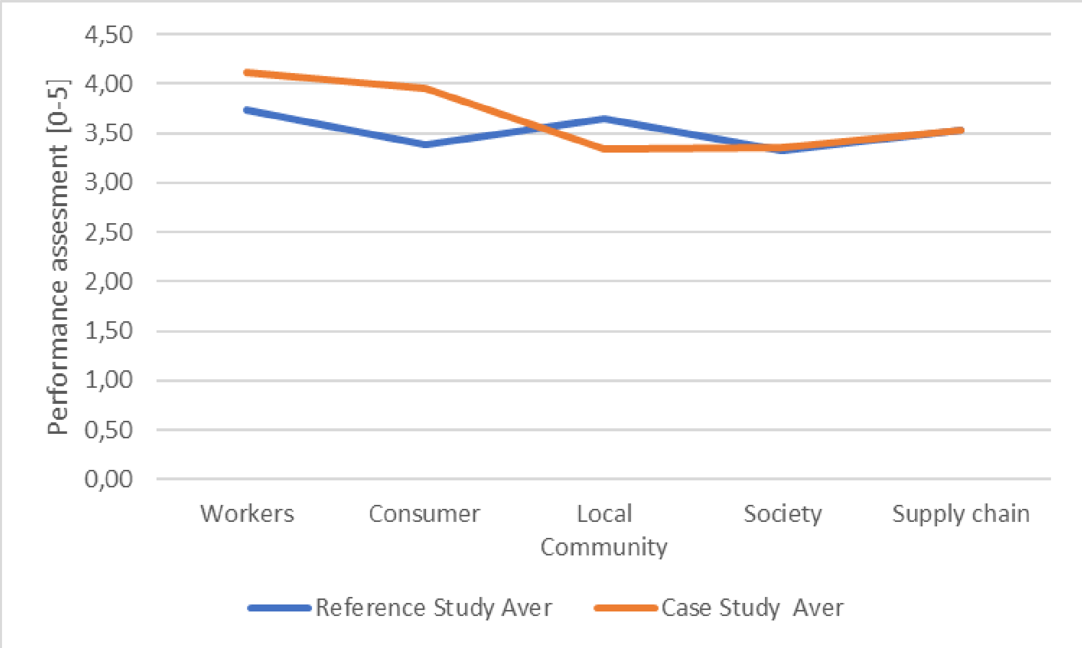

Figure 37 Average results for each stakeholder group in the two cases.

Based on the data from Figure 37, it is evident that the workers and consumers showed improvement in the case study, while society and the supply chain remained unchanged. Although the local community did not benefit in the case study compared to the reference study, the overall, the results are positive. In Figure 38, we compare the overall results between the reference case and the case study of this analysis. Below, the individual graphs offer a more detailed examination of each stakeholder group (Figure 39-43).

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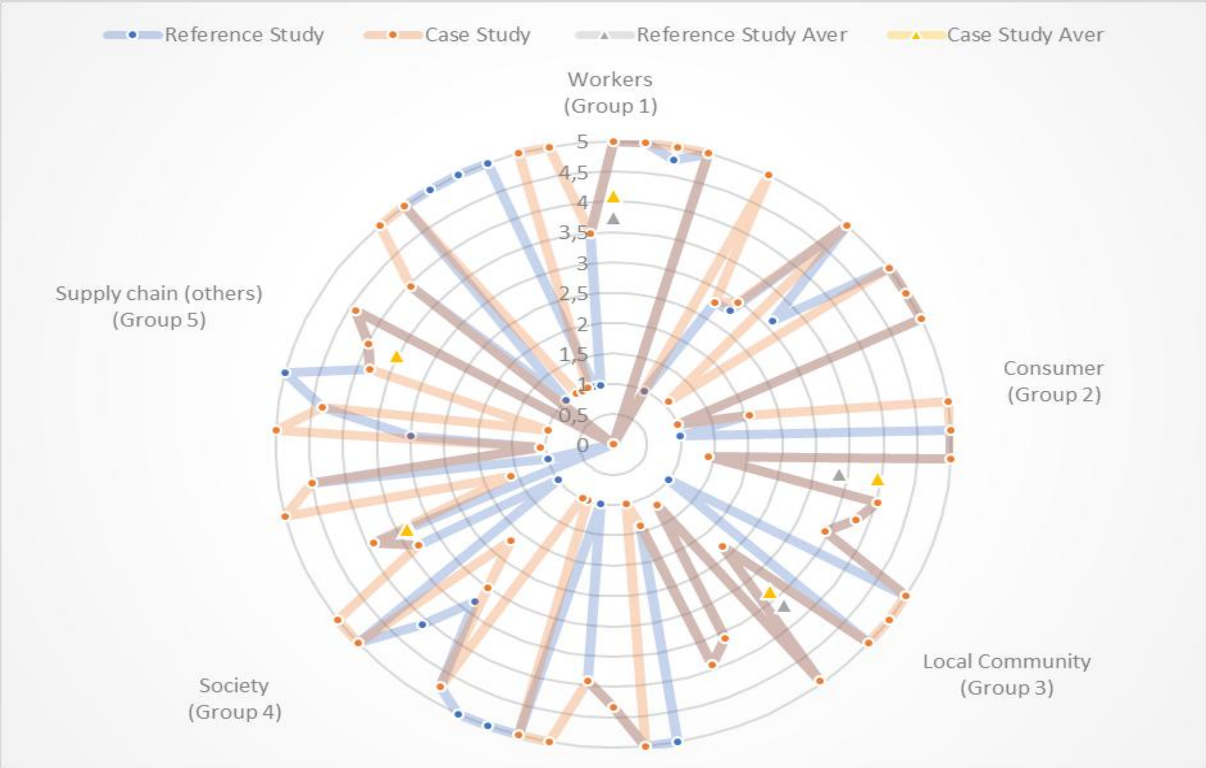

Figure 38 Results for each stakeholder group in the two cases.

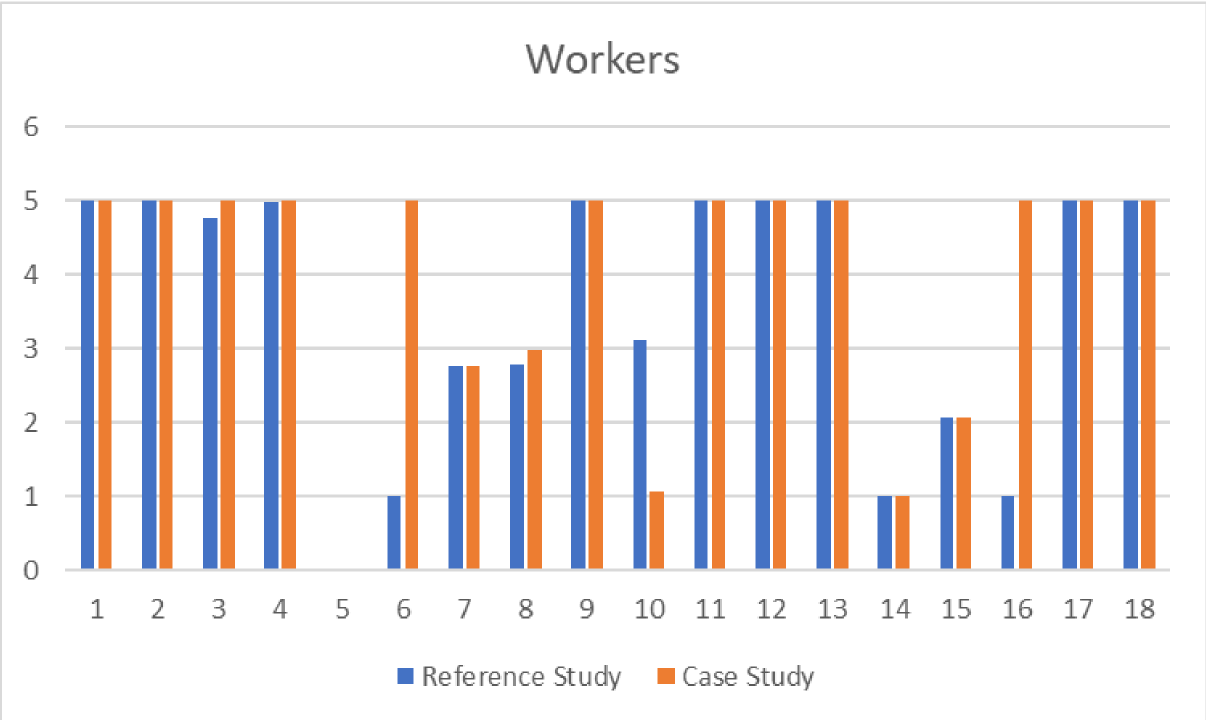

Figure 39 Workers' results for the two cases.

As shown in Figure 39, huge improvement was made in the case study since there was not unequal remuneration and no violations of obligations to employees under labour. In addition, positive impacts were seen in the impact categories of women's share of work force

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and there were no incidents of forced or child labour and no fatal accidents at work. The only negative outcome was that weren't as many employees with a disability as in the reference study.

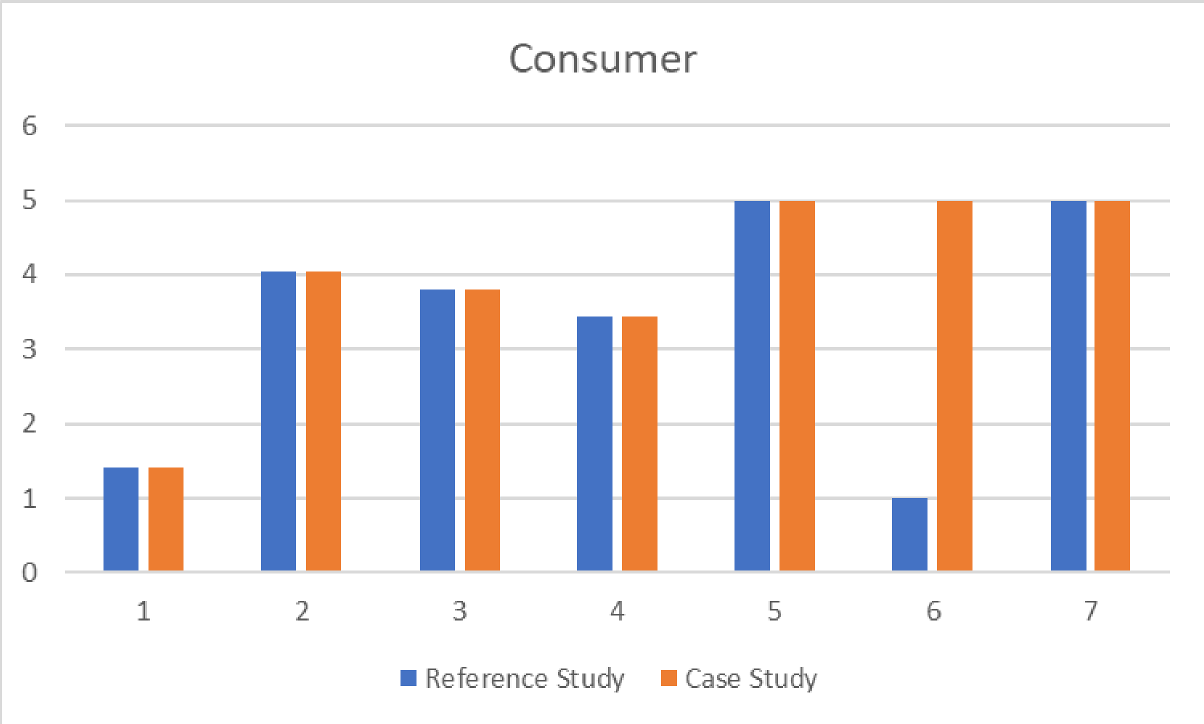

Figure 40 Consumer's results for the two cases.

In Figure 40, we observe that the only difference between the reference and the case study is the positive development of the safe and harmless handling of the end of life. So, the new management of plastic waste is really effective.

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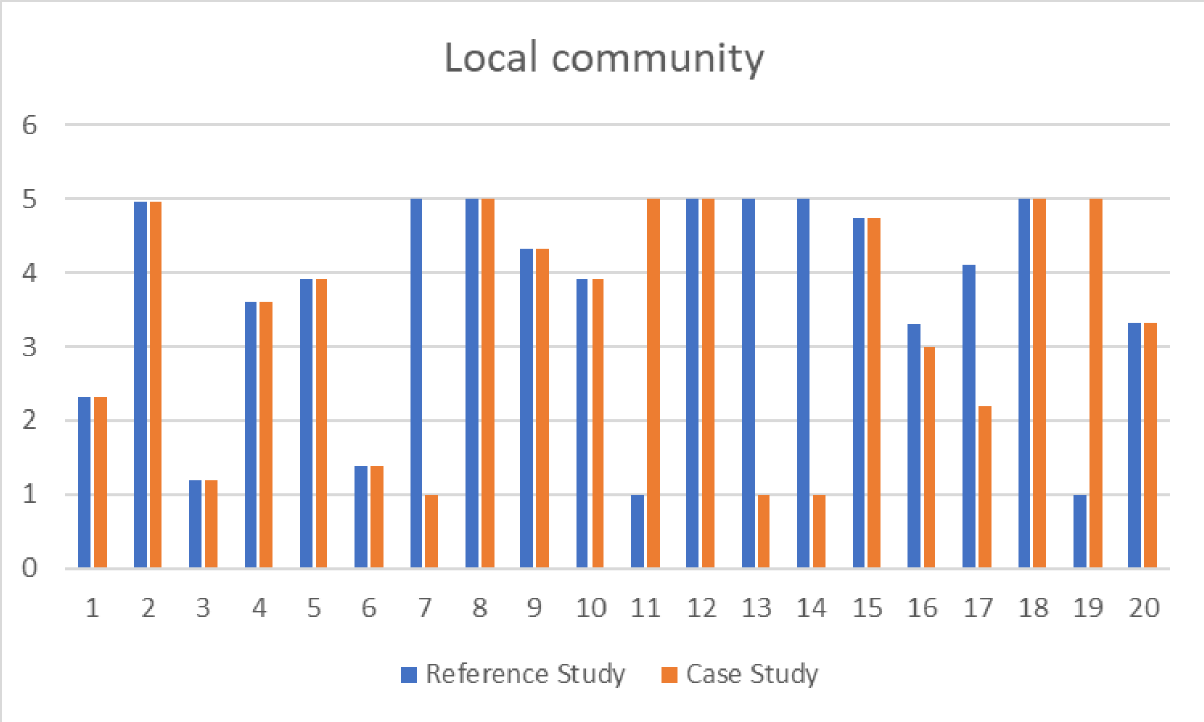

Figure 41 Local community's results for the two cases.

According to Figure 41, we observe both positive and negative outcomes in the case study. Firstly, we identify a significant improvement in the organization's contribution to the local development and in the reduction of risks at the facility. However, there are certain drawbacks that arise with this alternative approach. For example, there are no organizational reports disclosed to the local community and no management efforts to minimize the use of hazardous substances. Another primary concern includes the failure to protect indigenous groups within the local community, while a secondary concern is the small percentage on spending on locally based suppliers. Furthermore, a slight, though not significant, difference is observed in the number of employees originally from the local community. While the overall outcome for the local community has not improved with the adjustments made in the case study, these negative impacts—except for the lack of effort to minimize hazardous substances—do not undermine the objective of the management solution.

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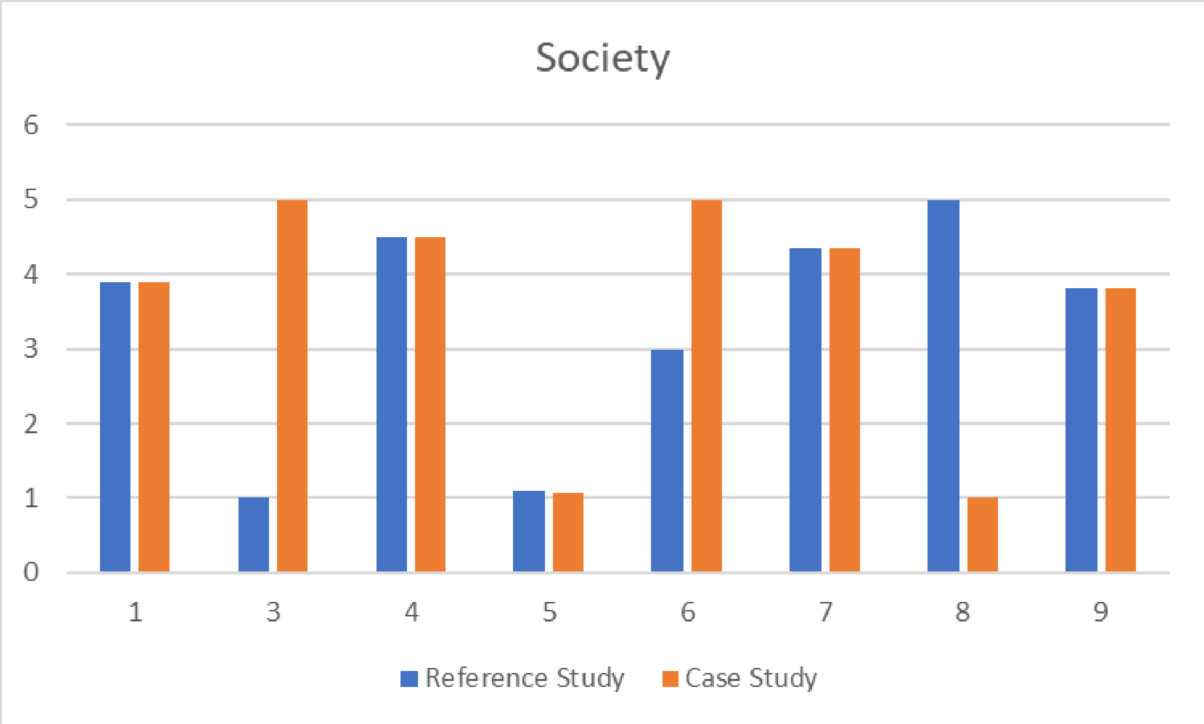

Figure 42 Society's results for the two cases.

For society, as shown in Figure 42, the case study demonstrates an improvement due to the non-use of critical raw materials and the significant involvement in technology transfer projects. The only negative aspect is the absence of a formalized commitment to poverty reduction, which can be attributed to the fact that the company's primary focus does not include this area.

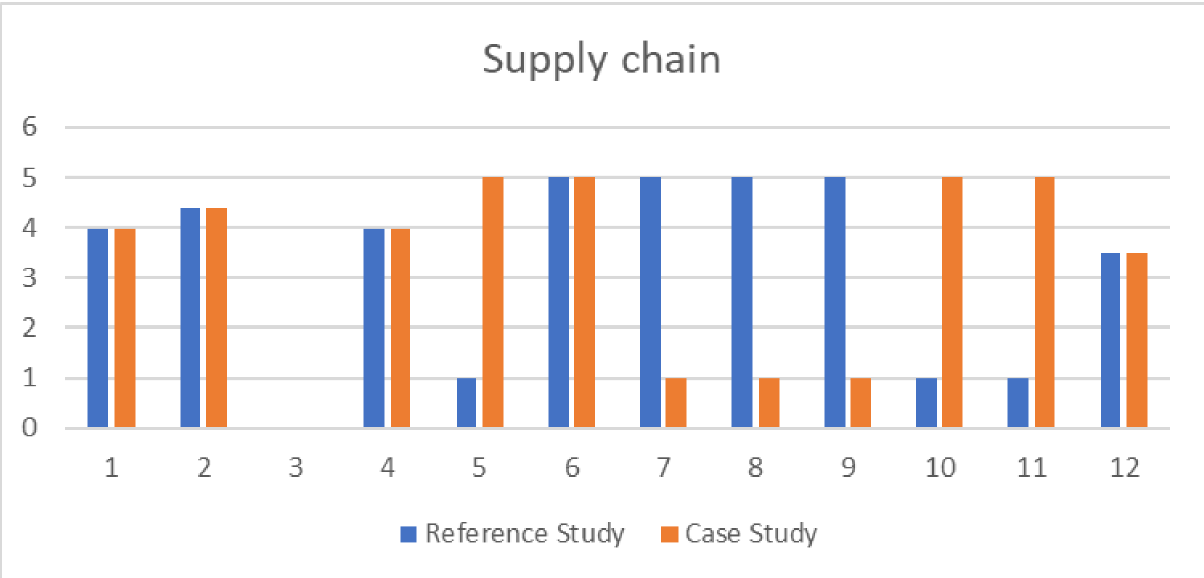

Figure 43 Supply chains for the two cases.

Finally, in Figure 43, although the overall result for the supply chain did not change, some differences were observed. Significant improvements were made, including the absence of

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suppliers identified with actual or potential negative social impacts, no health and safety issues reported by customers when handling materials, and improved traceability of raw materials. On the other hand, some negative outcomes were found, such as the lack of a specific code of conduct to protect the human rights of employees among suppliers and the failure to integrate ethical, social, environmental, and gender equality criteria. Additionally, another negative outcome was that the organization did not provide support to suppliers in raising awareness and offering counselling on social responsibility issues.

In conclusion, the s-LCA primarily focuses on the social aspects of the study, specifically evaluating the significant improvements resulting from the implementation of the new plastic waste treatment solution. The results indicate that the scenario utilizing the alternative CSS4 solution (case study) had the most positive outcomes across various stakeholder groups (with the exception of the local community) and impact categories. The case study demonstrated substantial progress in areas such as workplace safety, working conditions, environmental management (end-of-life handling), safe and healthy conditions, local development, commitment to sustainability, and technological engagement. While there was no improvement in the local community stakeholder group, the overall results emphasize the positive advancements of the new management solution in promoting sustainable practices across multiple sectors.

6 Conclusions

This deliverable presented an integrated sustainability assessment of the CSS4 for the management and valorisation of plastic 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 two alternative CSS4 scenarios against the Baseline (conventional plastic waste management) demonstrated substantial potential for impact reduction across key categories. Scenario 4.2 (foam production from recycled polyethylene) exhibited the most beneficial environmental profile, with sharp reductions in Global Warming Potential (-99.1 vs 1,760 kg CO_2 eq.), Abiotic Depletion – Fossil (606 vs 68,000 MJ) and Human Toxicity Potential (2.72 vs 79.8 kg DCB eq.). Scenario 4.1 (insulation material from char) also achieved negative or near-zero values in categories such as Freshwater Aquatic Ecotoxicity Potential, Acidification and Eutrophication. These results reflect the effectiveness of both scenarios in transforming waste into valuable outputs, such as foam and insulation materials, while substantially lowering environmental burdens and reducing dependence on virgin fossil-based resources.

In economic terms, the LCC analysis revealed that, while Baseline practices offer the lowest short-term costs, they neglect environmental externalities and do not support long-term

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value recovery. Scenario 4.2 demonstrated favourable cost dynamics due to the relatively lower energy and operational inputs required for mechanical recycling. Scenario 4.1 also offered economic promise by valorising char into insulation materials and recovering energy from waste. Both scenarios contribute to avoided disposal costs and open potential revenue streams from secondary material markets. Notably, Scenario 4.2 reduced PENRE from over 68,000 MJ in the Baseline to just 606 MJ, suggesting significant long-term savings when environmental costs are internalized.

The s-LCA further confirmed the positive social implications of CSS4 implementation. Compared to the baseline, both scenarios improved performance across key stakeholder groups —workers, local communities, consumers, and society— particularly in areas such as occupational health and safety, fair labour practices, community engagement and public investment in sustainability. Scenario 4.1 supported regional innovation and skill development through advanced processing systems, while Scenario 4.2 enabled scalable circularity through accessible recycling models. Supply chain impacts remained stable, with opportunities for enhanced traceability as the system scales up.

In summary, the combined results of the LCA, LCC and s-LCA assessments underline the multifaceted value of the CSS4 solution in transitioning toward a circular and sustainable regional economy. The environmental gains, although subject to limitations such as data availability and system scaling assumptions, are robust; the economic analysis supports long-term investments in plastic valorisation technologies and the social outcomes highlight strengthened inclusivity, regional development and public awareness. These findings support the replicability and scalability of CSS4, aligning with the overarching objectives of the FRONTSH1P project and EU policies on circular economy and sustainable resource use.

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