Deliverable report

Deliverable no./title: D6.8 Report on Life Cycle Assessment and Life Cycle Cost Assessment for the CREAToR technology

Lead beneficiary: ITB

Nature of deliverable: Report

Dissemination level: PU – Public (including the Commission Services)

Due date: 07.06.2023

Grant Agreement number: 820477

Project acronym: CREAToR

Project title: Collection of raw materials, Removal of flAme reTardants and Reuse of secondary raw materials

Funding scheme: H2020-SC5-2018-2019-2020

Coordinator: FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V.

Project Website: www.creatorproject.eu

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ABBREVIATION	DESCRIPTION
ABS	Acrylonitrile butadiene styrene
AOP	Areas of protection
CAPEX	Capital expenditures
CFC	Chloro-fluoro-carbons
GHG	Greenhouse gas
GWP	Global warming potential
LCA	Life cycle analysis
LCCA	Life cycle cost analysis
LCCI	Life cycle cost inventory
LCI	Life cycle inventory
LCIA	Life cycle inventory analysis
ODP	Ozone depletion potential
OPEX	Operative expenditures
PS	Polystyrene
PSO	Particle swarm optimisation
SA	Sensitivity analysis
TRL	Technology readiness level
WEEE	Waste of electrical and electronic equipment
WMO	World Meteorological Organization

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1 INTRODUCTION

This document aims to publicise the most relevant results of the life cycle assessment (LCA) and life cycle cost assessment (LCCA) analysis of the CREAToR project. The project uses continuous purification technologies, including supercritical CO_2 and cost-effective solvent-based processes using natural deep eutectic solvents (NADES) in twin-screw extruders. The entire value chain is covered, starting from the collection of thermoplastic waste streams from building and construction (B&C) and waste of electrical and electronic equipment (WEEE). The goal is to collect secondary raw materials, identify the presence of hazardous flame retardants, remove these contaminants, and enable the reuse of the materials.

The LCA involved defining the goal, scope, and boundaries of the analysis, as well as identifying relevant stakeholders. Additionally, the functional unit, which is a critical aspect of the analysis, was defined to establish the standard for evaluating the environmental impact and cost performance of the system. The technical, temporal, and geographical boundaries of the system were also specified to clearly define the scope of the analysis. Next, we examined the relationship between the sub-processes involved and the CREAToR process flow. Understanding these interconnections between different parts of the system was important to ensure that all relevant elements were considered during the analysis. Having a clear understanding of the process flow was essential for conducting a comprehensive and accurate assessment of the environmental impact and cost performance of the system.

The LCA analysis proceeded with the creation of an approximate model that incorporated all interactions among the individual processes. This model was then evaluated for energy consumption, resource utilisation, emissions, and waste outputs. The result of this evaluation was the life cycle inventory (LCI), which listed the resources required, including materials and energy inputs, as well as the emissions released into the air and water, and solid waste. OpenLCA, a specialised LCA software, was used to assist with this process. In the LCA analysis, low-TRL parameters obtained from laboratory test results were utilised. These parameters provided important information on the performance and feasibility of the system at its current stage of development. By incorporating results from laboratory tests into the analysis, the data used remained up-to-date and relevant to the current state of the system. This approach established a solid foundation for further development and optimisation of the system, guiding progress towards higher TRL levels in the future.

The section of the report dedicated to the LCCA details the methodology for conducting the LCCA. It begins by defining the purpose of the study, followed by a description of the analysis boundaries, including the functional unit and system boundaries.

The LCCA methodology was performed using MATLAB software, which is described in detail. The data sources considered were also identified, and the sub-processes with the greatest impact on the economic performance of the overall process were highlighted.

The approach of both the LCA and LCCA analysis is based on a comprehensive view of the CREAToR technology, and the modelling of a plant that will achieve the goal of the developed technologies for sorting and purifying plastic with and without brominated flame retardants.

The approach is therefore gate-to-gate, which means it examines the entire production process from raw material inputs to the output of the CREAToR process. This allows for a comprehensive evaluation of the environmental impact and cost performance of the CREAToR process in comparison to traditional methods. However, it is important to note that logistical considerations, such as transportation and collection of waste materials, were not included in this particular analysis. These aspects were thoroughly addressed and optimised in WP5, which specifically focused on logistics within the CREAToR project. For this analysis, we agreed to focus on a scenario where the whole process takes place at one site.

By adopting the gate-to-gate approach, this analysis provides a detailed understanding of the potential environmental benefits and cost advantages of the CREAToR process for ABS and PS polymer production from WEEE waste. The results and insights generated from this analysis will serve as valuable inputs for decision-makers, industrial stakeholders, and policymakers, enabling them to make informed choices regarding sustainable waste management practices and the adoption of innovative technologies in the polymer industry. Furthermore, this analysis serves as a foundation for further optimisation and scale-up of the CREAToR process, aiming to achieve higher TRLs and drive the transition towards a more circular and sustainable economy.

2 LCA METHODOLOGY

2.1 Introduction

The LCA analysis involved assessing the environmental benefits, sensitive points, and economic performance in comparison to traditional methods of producing virgin polymers. The methodology followed adhered to internationally recognised guidelines, such as ISO 14040 (2006) and ISO 14044 (2006). Primary data obtained from the upscale study and pilot-scale experiments were combined with validated secondary data sources to enable a comprehensive evaluation of the entire life cycle, from gate-to-gate.

An approximate model and specialised LCA software were utilised to examine the interactions among individual processes, allowing for the assessment of energy consumption, resource utilisation, emissions, and waste outputs. Low-TRL parameters derived from laboratory test results were integrated to ensure that the analysis accurately reflected the system's current developmental stage.

The LCA methodology adheres to the ISO 14040 series standard, which involves four steps:

1) Goal and scope definition,

2) Inventory analysis,

3) Impact assessment,

4) Results interpretation.

The LCA aimed to evaluate the potential environmental impact of plastic recycling processes using CREAToR's innovative technologies, comparing two different scenarios. The LCA method was applied to analyse and verify the environmental performance of CREAToR's innovative technologies and to compare the innovative scenario, represented by an industrial plant, with the traditional scenario involving the production and disposal of virgin plastics.

2.2 LCA impact assessment methods

According to the ISO 14044 standard for LCA, the selection of impact categories to be covered by an LCA “shall reflect a comprehensive set of environmental issues to the product system being studied, taking the goal and scope into consideration”. This means that all environmental impacts to which the product system contributes must be included in the impact assessment.

When selecting an LCIA method, the requirements, recommendations, external and internal factors and constraints need to be considered. This leads to some questions and criteria that should be answered to identify the most suitable method, including:

- What impact categories or environmental problems need to be covered?
- Is there a specific region where the analysed life cycle takes place?
- Is there the need for a midpoint or endpoint assessment, or both?
- Publication date of the method.

The main selected method is **ReCiPe**, first developed in 2008 through cooperation between RIVM, Radboud University Nijmegen, Leiden University and PRé Sustainability.

The primary objective of the ReCiPe method is to transform the long list of LCI results into a limited number of indicator scores. These indicator scores express the relative severity of an environmental impact category. In ReCiPe indicators are determined at two levels:

- 18 midpoint indicators
- 3 endpoint indicators

Midpoint indicators focus on single environmental problems, for example, climate change or acidification. Endpoint indicators show the environmental impact on three higher aggregation levels, which are 1) effect on human health, 2) biodiversity and 3) resource scarcity. Converting midpoints to endpoints simplifies the interpretation of the LCIA results. However, with each aggregation step, uncertainty in the results increases. Figure 1 provides an overview of the structure of ReCiPe.

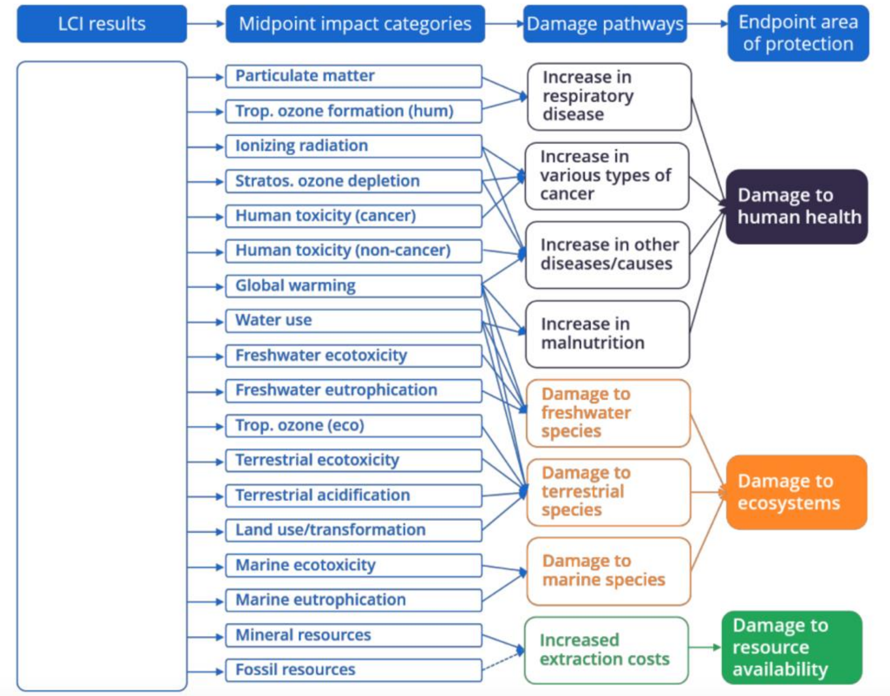


Figure 1 Overview of the impact categories that are covered in the ReCiPe 2016 method and their relation to the areas of protection.

Each method (midpoint, endpoint) contains factors according to three cultural perspectives. These perspectives represent a set of choices on issues like time, or expectations that proper management or future technology development can avoid future damages.

- Individualist: short term, optimism that technology can avoid many problems in future.
- Hierarchist: consensus model, as often encountered in scientific models - this is often considered to be the default model.
  - This perspective will be the selected one for the CREAToR assessment.
- Egalitarian: long term, based on precautionary principle thinking.

ReCiPe 2016 is an improvement on ReCiPe 2008, and its predecessors CML 2000 and Eco-indicator 99. The method is updated regularly, to incorporate new data and new research.

2.3.1 Sustainability indicators - definition and calculation

As shown in Figure 1, there are several impact categories in the ReCiPe method. The standard ISO 14040 specifies two mandatory steps to follow for a correct assessment:

I. Classification: after selecting the method, the elementary flows of the LCI are assigned to the impact categories to which they contribute; for example, the emission of CO_2 into the air is assigned to climate change, or the consumption of water to the water use impact category. This step requires considerable understanding and expert knowledge of environmental impacts and is therefore typically handled automatically by LCA software.

II. Characterisation: In this step, all elementary flows in the LCI are assessed according to the degree to which they contribute to an impact. To this end, all elementary flows E, classified within a specific impact category c (representing an environmental issue of concern), are multiplied by their respective characterisation factor CF and summed up over all relevant interventions i (emissions or resource extractions) resulting in an impact score IS for the environmental impact category:

$$IS_c = \sum_i (CF_i \cdot E_i)$$

For each impact category, the indicator results are summed up to determine the overall results for the category.

When the impact assessment is based on *midpoint impact indicators*, the classification gathers the inventory results into groups of substance flows that can contribute to the same environmental effect, in preparation for a more detailed assessment of potential impacts of the environmental interventions, applying the characterisation factors that have been developed for the impact category concerned.

Additional modelling elements are used to expand or link midpoint indicators to one or more endpoint indicators (sometimes also referred to as damage or severity). These endpoint indicators are representative of different topics or “Areas of Protection” (AoP) that “defend” our interests as a society concerning human health, ecosystems or planetary life support functions including ecosystem services and resources. The numerous different midpoint indicators therefore all contribute to a relatively small set of endpoint indicators: human health, ecosystem quality, natural resources and ecosystem services. All endpoint indicators for the same AoP have a common unit and can be summed up to an aggregated impact score per AoP (assuming equal or different weighting of each endpoint indicator).

For the CREAToR assessment, all ReCiPe midpoint indicators will be considered, giving particular importance to the following indicators:

I. **Global warming potential (GWP)**, is an emission metric first introduced in the IPCC First Assessment Report (IPCC 1990) and continuously updated by IPCC since then with the latest version in the Fifth Assessment Report (IPCC 2013).

Global warming potentials are calculated for each GHG according to:

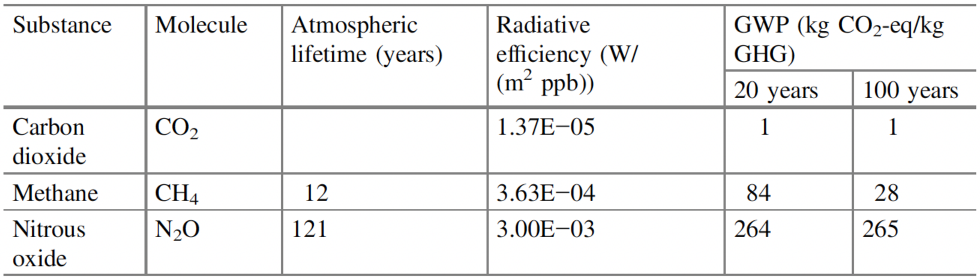
$$GWP_i = \frac{\int_0^T a_i \cdot C_i(t)dt}{\int_0^T a_{CO2} \cdot C_{CO2}(t)dt}$$

Where:

- a_i: thermal radiation absorption (instant radiative forcing) following an increase of one unit in the concentration of gas i
- $C_i(t)$: concentration of gas i remaining at time t after emission
- T: number of years for which the integration is carried out (e.g. 20 or 100 years)

GWP100-year is directly used in LCIA as the characterisation factor. As shown above, it is the ratio of the cumulated radiative forcing over 100 years of a given GHG and that of CO_2, with the unit of kg CO_2-eq/kg GHG.

The GWP for CO_2 is therefore always 1, and a GWP100 for methane of 28 kg CO_2-eq/kg methane (see Figure 2) means that methane has 28 times the cumulated radiative forcing of CO_2 when integrating over 100 years.



Substance	Molecule	Atmospheric lifetime (years)	Radiative efficiency (W/(m^2 ppb))	GWP (kg CO_2-eq/kg GHG)	
				20 years	100 years
Carbon dioxide	CO_2		1.37E−05	1	1
Methane	CH_4	12	3.63E−04	84	28
Nitrous oxide	N_2O	121	3.00E−03	264	265

Figure 2 - Excerpt from the list of GWP (IPCC 2014a)

II. Ozone layer depletion (ODP)

The midpoint indicator used without exception in all LCIA methods to calculate characterisation factors is the ozone depletion potential (ODP). Similar to the global warming potential (GWP), it evaluates the potential of a chemical to destroy the ozone layer based on a model from the World Meteorological Organization (WMO 2014).

$$ODP_i = \frac{\Delta C_{0_3}(i)}{\Delta C_{0_3}(CFC-11)}$$

The ODP essentially expresses the global reduction in stratospheric O_3 concentration CO_3 due to an ozone depleting substance i relative to the global reduction of stratospheric O_3 concentration CO_3 due to 1 kg of CFC-11 ($CFCl_3$) and is hence expressed in CFC-11 equivalents.

The definition and calculation of these indicators: energy consumption, resource use, and waste generation will be reported in deliverable D6.5 since a more complex calculation needs to be performed.

III. Human toxicity (HTP)

The human toxicity potential (HTP), a calculated index that reflects the potential harm of a unit of chemical released into the environment, is based on both the inherent toxicity of a compound and its potential dose. It is used to weigh emissions inventoried as part of a life-cycle assessment (LCA) or in the toxics release inventory (TRI) and to aggregate emissions in terms of a reference compound. Total emissions can be evaluated in terms of benzene equivalence (carcinogens) and toluene equivalents (noncarcinogens).

The potential dose is calculated using a generic fate and exposure model, CalTOX, which determines the distribution of a chemical in a model environment and accounts for several exposure routes, including inhalation, ingestion of produce, fish, and meat, and dermal contact with water and soil. Toxicity is represented by the cancer potency q1* for carcinogens and the safe dose (RfD, RfC) for noncarcinogens. This article presents cancer and noncancer HTP values for air and surface-water emissions of 330 compounds. This list covers 258 chemicals listed in the U.S. Environmental Protection Agency TRI or 79 weight-% of the TRI releases to air reported in 1997.

2.2.1 Data quality

For correct data collection, a specific data quality definition was needed. The foreground data are represented by the primary data collected from CREAToR partners, while the background data have been selected from the existing literature and database.

The three important dimensions to consider for a consistent choice of secondary data are the following:

I. The **geographical** representativeness reflects how well the inventory data represents the actual processes regarding location-specific parameters. Since a single plant is not present yet, the European area was chosen for the selection of processes from the Ecoinvent database (e.g. energy mix).

II. The **time-related** representativeness reflects how well the inventory data represents the actual processes regarding the time (e.g., year) they occur.

III. The **technological** representativeness reflects how well the inventory data represents the actual technologies involved in the studied product system. Technological representativeness is interlinked with geographical and temporal representativeness.

During LCIA the collection of data and the modelling of the flows to, from and within the product system is carried out. This must be in line with the goal definition and meet the requirements derived from the scope definition.

The input-output data for sorting and purification processes were collected through specific direct interviews with CREAToR partners. Information about the technical composition of the materials and process was sourced from Ecoinvent database v.3.9.1 deployed on OpenLCA v.1.11 software.

In more specific terms, each phase can be subdivided into several processes, which require specific inputs. For the sorting phase, the unique input to consider is the energy consumption for the different machines. For the purification process, several inputs and outputs needed to be considered.

There are two main sources for the two phases: data collected by partners and background data from the Ecoinvent database.

3 LCCA METHODOLOGY

3.1 Introduction

The LCCA aims to evaluate the economic efficiency of the CREAToR technology, in comparison to the state-of-the-art, based on results from the CREAToR project. To address the challenges of limited references and uncertain parameters due to the innovation of the processes being studied, ITB developed a MATLAB-based modelling tool to simulate the process behaviour.

The boundaries of the life cycle cost inventory (LCCI) were defined according to the LCA, and the MATLAB model was implemented using a gate-to-gate representation. The technological data used in the modelling was aligned with the LCA data collection and was based on expert opinions, information from CREAToR partners, experimental findings from CREATOR WPs, and literature data. The data collection process identified key variable parameters that will be used to optimise economic performance.

The proposed analysis is composed of three main steps: LCCI calculation, economic performance optimisation, and decision-making support. This step will be completed by implementing the model of the CREAToR plant using the SIMULINK graphical environment integrated with MATLAB.

3.2 Methodology definition for the LCCA

The cost evaluation was performed using the LCCA methodology, which considers all expenses throughout the entire life cycle of a process or service, not just the initial acquisition of raw materials. This methodology, as defined, considers not only the costs of procuring materials, but also the costs associated with operation, maintenance, and final disposal[1]. This information provides decision makers with a comprehensive picture of the economic indicators of the system's life cycle and helps them to identify opportunities for improvement.

The present study conducts an environmental LCCA analysis to evaluate the costs of the industrial processes within the CREAToR technology. This method combines a LCA with an economic analysis of the same system, considering all internal costs including end-of-life expenses. However, external costs, which are financial impacts on third parties not directly involved in the system, are not considered unless they are internalised in the short term. The purpose of conducting an environmental LCCA is to broaden the system boundaries of a conventional LCCA to align with the LCA and to provide a more comprehensive understanding of the economic and environmental impacts of the system from multiple stakeholder perspectives. It's important to note that the LCCA and LCA should have the same functional unit to ensure that the results of the LCA can also be interpreted in terms of economics.

This research is broken down into the following key steps:

I. Modelling process and collecting data

The initial phase of this work involves creating a model of the process. The boundaries for the CREAToR technology were established based on the LCA boundaries outlined in Chapter 2.2. The information incorporated into the model flows was aligned with the data utilised in the LCA analysis and collected from various WPs within the CREAToR project. Additionally, costs were estimated by taking into consideration the interviews with the partners and publicly available data.

This approach ensures that the model is built on a solid foundation of accurate and relevant information, leading to more reliable and meaningful results.

For the analysis, only two of the cases provided by the CREAToR technology were selected as the most promising and feasible, as determined by the results of the various WPs. These scenarios specifically relate to the recycling of ABS and PS.

II. LCCA inventory

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[1] Hunkeler, D., Lichtenvort, K., & Rebitzer, G. (2008). *Environmental Life Cycle Costing*. Crc press. https://doi.org/https://doi.org/10.1201/9781420054736

The initial simulation campaign aims to establish a LCCI, which involves evaluating all resources used, products produced, waste generated, and emissions released.

The method used to evaluate inventory is block modelling, which considers the gate-to-gate boundaries of the process. Each block represents a step in the process and is connected to other steps through links that describe the flow of materials. Further details can be added to each block to include the relationships between inputs and outputs, ensuring consistency with the LCA.

Various software options exist for block modelling processes; however, the CREAToR project has implemented a unique method using the SIMULINK environment to perform a flexible and dynamic analysis. The inventories developed through the simulations are based on various reference units, such as quantity-based (e.g., tons of polymer produced, tons of waste recycled etc.) and time-based (e.g., days of plant operation). Table 1 provides a comprehensive list of the inputs required to run the simulation and the outputs generated. This approach allows for a comprehensive and detailed analysis of the various factors that impact the LCCA and enables the identification of potential areas for improvement and optimisation.

Table 1 - List of input and output for the LCC inventory

INPUT	**OUTPUT**
• Mathematical relations which describe reactions and technological process	• Resource consumption for each process and subprocess
• Number and type of machines	• Total resource consumption
• Machine performance	• Product and sub-product volumes
• Presence of auxiliary systems (pumps, coolers, filters etc.)	• Wastes and emissions for each process and sub-process
• Time required for each reaction/process	• Total wastes and emissions
• Storage capacity	• Comparison charts
• Resource stock size	
• Temporal window for the simulation	
• Limits on resources	
• Limits on emissions	
• Limits on wastes	

III. Model validation

To ensure the accuracy and credibility of the analysis results, it is essential to conduct model validation. This activity involves comparing the data forecasted by the model with the actual performance of the process. The validation process will be partially carried out by comparing the results of the lab-scale experiments with the model predictions. However, a comprehensive validation can only be completed after the pilot plant becomes operational. Overall, the model validation process is crucial in ensuring the validity and accuracy of the analysis results and helps to identify any potential issues or discrepancies that may affect the overall accuracy of the analysis.

IV. Assessing and optimising costs

The simulation results for each scenario are used to evaluate the operational costs. In addition to costs associated with the technological processes, such as resources, energy, and consumables, other costs are also considered, including waste disposal, transportation, labour, and taxes. Following the cost assessment, the next step is to optimise these costs. To achieve this, an optimisation algorithm is employed to determine the optimal values for the key variable parameters that were previously defined.

Table 2 provides an overview of the inputs required to perform the cost analysis and the outputs that are generated. Cost optimisation is essential to identify the most cost-effective solutions and to reduce operational expenses, as it allows the evaluation of different sets of parameters to find the best one that minimises the total costs and maximises the performance of the process.

Table 2 List of input and output for the cost assessment

INPUT	OUTPUT
• All the input required for the inventory • Resources prices • Fixed and management costs • Maintenance costs • Wastes disposal costs • Labour cost • Carbon taxes • Taxes (related to production volumes) • Selling price of the final products • By-product valorisation prices	• Resource consumption for each process and subprocess • Total resource consumption • Products and sub-product volumes • Wastes and emissions for each process and sub-process • Total wastes and emissions • Comparison charts • Partial and total OPEX • Matrix of costs and flows

V. Decision making

The work described in the previous steps is designed to be an iterative process, aimed at improving and optimising the recycling technology of polymers. The simulation results will be used to aid in the process of adjusting key parameters and making decisions. These adjustments will be experimentally verified and used as input for new simulations, leading to a convergent, iterative process towards optimal performance. Additionally, the analysis will take into account not only the costs associated with the technological process, but also those associated with waste disposal, transportation, labour, and taxes. The aim is to find the most cost-effective and efficient solution for the CREAToR technology, achieving optimal performance.

VI. Comparing CREAToR technology and standard processes to produce granulated polymers from recycled polymer waste.

The ultimate goal of this LCCA is to evaluate and compare the cost efficiency of the recycling technology developed by the innovative CREAToR technologies with other currently used technologies for producing virgin polymers. This comparison will be conducted on multiple levels to ensure a thorough and fair assessment. The study will consider various factors such as the cost of resources, energy, labour, and waste disposal, as well as any other relevant costs. Additionally, the analysis will take account of the performance of the technology in terms of efficiency and effectiveness, to provide a comprehensive evaluation of the CREAToR technology against its competitors.

3.3 Multifunctionalities

Multifunctionality refers to when a system serves additional functions, known as co-functions, in addition to its primary purpose. In this analysis, the main function is the production of a purified granulated polymer, and the co-function is represented for example by the recycling of WEEE wastes.

According to ISO 14044 and the ILCD handbook (EC-JRC, 2010), it is best to avoid multifunctionality as much as possible, such as by breaking down the system into subsystems, each one producing a single product. However, in cases where this is not feasible, as in the current analysis, two methods can be applied to handle multifunctionality. The first is allocation, where inflows and outflows of the system are distributed among different products based on their physical relationships, such as mass or energy content, or based on other factors, such as economic value. Using different allocation methods can lead to significant differences in results. For this reason, it is recommended to use the second method, expanding the system boundaries. This involves including the avoided impacts for the production of the co-function in the analysis. For example, if product A also produces co-function B during its lifecycle, it is possible to expand the boundaries of the system by including, with the opposite sign, an alternative process for the production of B. Figure 3 illustrates this approach.

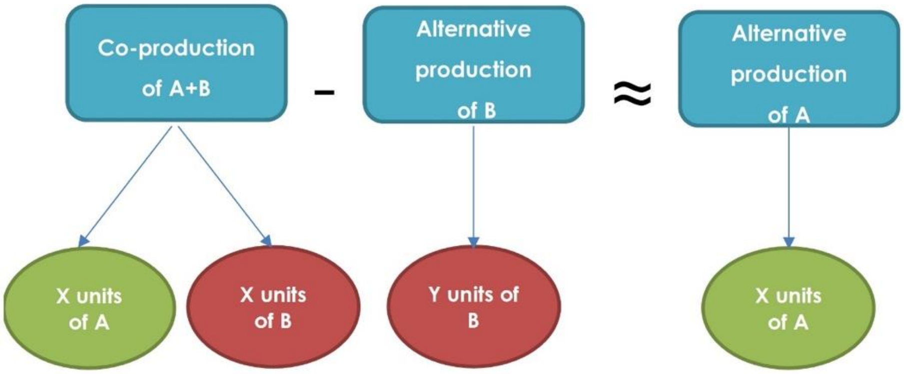

Figure 3 Solving the multifunctionality problem by substitution of the non-required cofunctions (Figure 9 in the EC-JRC ILCD Handbook[2]).

In this analysis, multi-functional cases have been solved by applying the system boundaries expansion method with the inclusion of the avoided impacts.

3.4 Tool employed for the LCCA

In the context of the CREAToR project, a novel approach for LCCA was implemented. The necessity to employ a novel tool for this analysis is closely linked to the level of innovation of the project itself. The CREAToR technology involves a variety of technological steps and the data is not readily available in existing databases. A flexible and detailed LCCA can therefore serve as a powerful tool to guide the project in the right direction.

The tool developed aims to:

- Model complex processes
- Evaluate the flow of materials, energy, waste, emissions, etc. in a flexible manner
- Provide data that can be used for further analysis
- Model different scenarios and compare them quickly
- Present results in an easy-to-interpret format

Existing software tools are commonly used for well-established processes, but for the CREAToR technology, it was worthwhile to adopt a novel approach due to certain limitations such as reliance on databases, poor parametrisation, lack of interactivity, inability to export data in a format that is compatible with other software, inability to simulate discrete events, and inability to customise the calculation of performance indicators.

The software used in this work is MATLAB, with its graphical environment SIMULINK, which allows the simulation of systems composed of interconnected blocks describing complex interactions and dynamics (Figure 4).

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[2] ILCD Handbook, International Reference Life Cycle Data System, General Guide for Life Cycle Assessment - https://eplca.jrc.ec.europa.eu/uploads/ILCD-Handbook-General-guide-for-LCA-DETAILED-GUIDANCE-12March2010-ISBN-fin-v1.0-EN.pdf

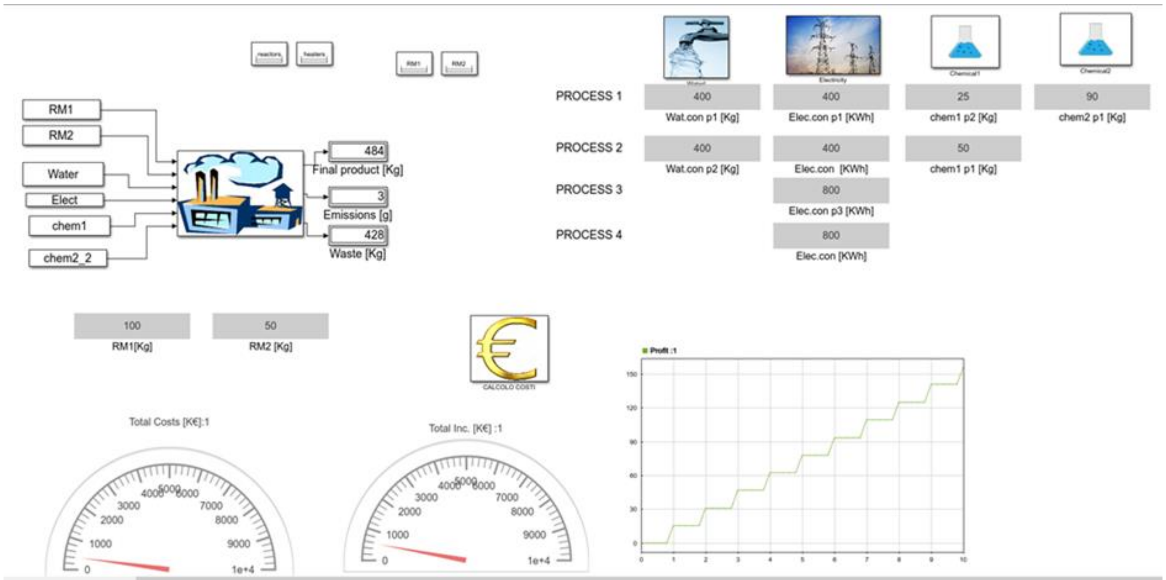

Figure 4 Example of the outer interface of a process modelled with SIMULINK

4 GOAL, SCOPE AND BOUNDARIES DEFINITION

4.1 Goal and scope

On the one hand, the goal and scope of the LCA analysis are to assess the potential environmental impact of plastic recycling processes using CREAToR's innovative technologies and compare them to traditional methods. This analysis aims to determine the viability and environmental benefits of CREAToR's technology as a sustainable solution for plastics recycling.

On the other hand, the goal and scope of the LCCA study are to assess the operational expenditures (OPEX) associated with producing purified granulated polymer using CREAToR's technology, contrasting it with the costs associated with traditional polymer production methods that do not incorporate recycling. The LCCA analysis also includes the consideration of capital expenditures (CAPEX), which involve the expenses related to creating or obtaining non-consumable components for the system. The LCCA study aims to provide valuable insights into the economic viability and cost performance of CREAToR's technology.

Both the LCA and LCCA studies were conducted with both industrial plant and experimental results, with information flowing in both directions. The LCA analysis collects parameters from experimental work packages and calculates the inventory using simplified simulation tools, considering upscaling parameters and the current applied technology. The LCCA analysis focuses on evaluating the operational expenditures and includes considerations of the running plant cost and sub-process partial results as key indicators for performance improvement.

The target audience for these studies includes policy and industrial decision-makers, investors, stakeholders in polymer production and those involved in WEEE waste recycling. The research serves as a strategic decision-making tool, providing comprehensive insights into the environmental and economic aspects of CREAToR's innovative technologies. However, it is important to note that as the processes are still being optimised in a laboratory setting, the results should be interpreted with caution, and long-term implementation will help clarify parameters and reduce uncertainties.

4.2 System boundaries

The system boundary establishes which components of the product's life cycle, as well as the associated life cycle stages and processes, are included in the analysed system. To facilitate a more practical and comparable assessment, a gate-to-gate approach was chosen. This approach focuses on the main stages of sorting and purification, with the final output being the purified plastic granules (Figure 5).

The gate-to-gate approach in life cycle assessment (LCA) offers several advantages. It simplifies the analysis by narrowing the scope to specific stages, allowing for a more detailed examination and targeted improvements. It enables a direct comparison between different scenarios or alternatives within these stages, providing valuable insights for decision-making. Additionally, it is often more cost-effective and less time-consuming than a cradle-to-grave analysis.

Thus, the omitted steps from the scope are:

- Collection and transportation of waste streams before the sorting phase;
- Transformation processes for the purified plastics.

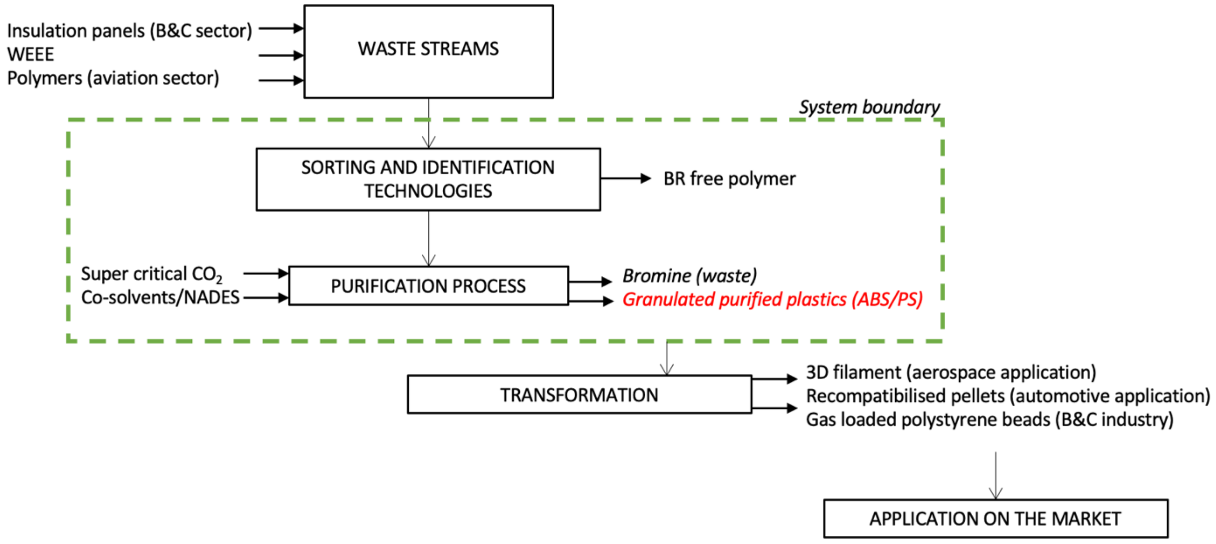

Figure 5 - Flow chart and definition of system boundaries

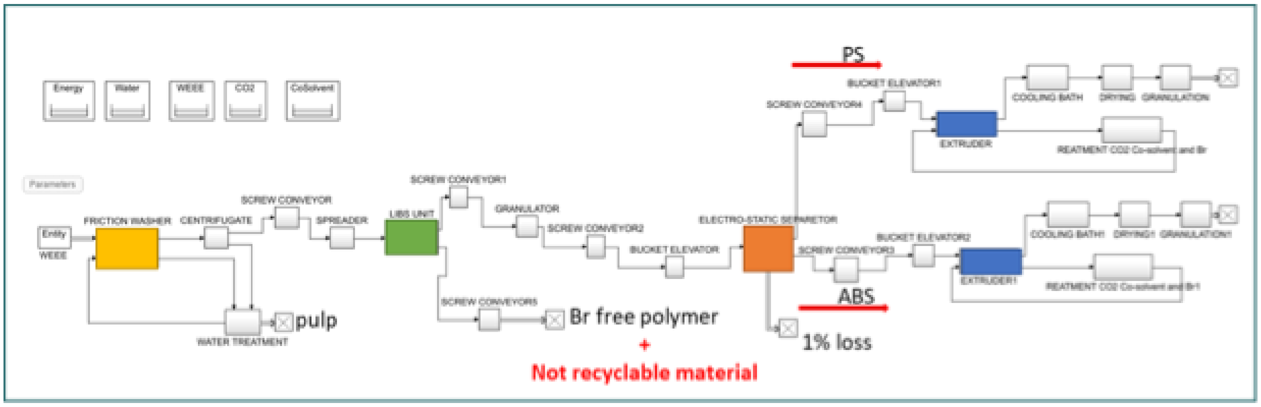

Figure 6 - CREAToR process model

It is important to note that a consistent part of the sink fraction is not recycled, and goes to incineration.

4.2.1 Functional unit

The analysis was conducted for two different functional units:

1. 1 ton of processed WEEE sink fraction;
2. 1 ton of purified polymer produced (ABS/PS).

These scenarios provide a more accurate representation of the specific stages of the CREAToR process and allow for a comprehensive assessment of the environmental and cost performance under different operational conditions.

4.2.2 Geographical boundaries

Since the available data provided by the partners, both from laboratory results and industrial plant data, are related to the Central European region, the European area has been selected as the geographical area for the assessment.

4.2.1 Temporal boundaries

All data has been updated to the years 2022 and the first half of 2023.

4.2.2 Considered scenarios

The life cycle analysis of the CREAToR process was conducted considering four cases, distinguished by the size of the sorting plant and the possibility to recycle the Br-free plastic mix which doesn't need purification. Two plant sizes were considered: the first with a capacity of 750 kg/h and the second with a capacity of 1500 g/h (Table 3).

The considered scenarios are the following:

Table 3: Considered scenarios

SCENARIO	Sorting plant size	Purification plant size	Br-free plastic mix treatment
1	750 kg/h	250 kg/h (ABS) + 250 kg/h (PS)	Disposal via incinerator
2	750 kg/h	250 kg/h (ABS) + 250 kg/h (PS)	Valorisation
3	1.5 ton/h	250 kg/h (ABS) + 250 kg/h (PS)	Disposal via incinerator
4	1.5 ton/h	250 kg/h (ABS) + 250 kg/h (PS)	Valorisation

4.2.3 Assumption and approximation

Several conditions are modelled in the LCA and LCCA systems:

- Considering the collected technical data regarding the sorting phase by CREAToR partners, the brominated fraction extracted by the sink fraction of the waste streams is estimated to consist of around 60% of ABS and 40% of PS.
- Considering that the collected data for the sorting phase is based on WEEE treatment and the purification data is about B&C waste stream treatment, it is assumed that the two scenarios can be combined as one.
- The recycling and purification process for the CO_2 and co-solvent as extractive liquids will be considered in the system even if it is not performed in the CREAToR project. This process is considered necessary for an industrial plant, as reported by the partner ICT.
- The selected allocation method to consider the two sub-products obtained at the end of the sorting process (Br-ABS and Br-PS) is the physical allocation.

One of the main challenges in using a block model to depict the CREAToR technology process is the lack of concrete analytical relations that govern each part of the process and how they are interconnected. Due to the novel nature of the industrial-scale application, certain approximations must be made. These include:

- **Scale factor**: The modelling was carried out using both plant and lab-scale data provided by partners, experts, or literature references extrapolated from similar contexts. However, the real plant's performance may be affected by scale effects that are currently unpredictable. These assumptions could be reviewed and validated only once a pilot plant is in operation. In particular, the process was modelled by combining the two macro phases of the process (sorting and purification) that are currently carried out in plants characterised by very different sizes and TRLs.
- **Continuity of the process**: The CREAToR technology is composed of multiple steps and includes machines with discrete operations and processes that require certain reaction times. Despite this, all the steps and the entire process were considered continuous based on the semi-continuous nature of the plant proposed.
- **Neglecting secondary materials**: The more complex processes of the CREAToR technology are characterised by the presence of other polymers in addition to those considered in this analysis, for which the chemical reactions involved would require a more complex description and modelling, or for which preliminary results have shown that the purification process is not applicable. For these materials, in some cases, there is no reference in literature regarding the possibility of identifying and

separating them from the main flow. For this reason, initially, we are considering only the case in which these materials are not present in the WEEE mix entering the process.

- **Transportation impact**: The chosen approach is the gate-to-gate. By adopting this approach, the findings of WP5 will not be included in the LCA as those results are verified with a different objective – e.g., to determine whether it is beneficial for the partner TREEE to carry out polymer recycling in-house in the future or to outsource the process. The impact of transportation is already considered and integrated with the data of the database used for LCA. This impact is reflected in the material costs included in the LCCA. The database provides the necessary information to estimate the environmental and economic impacts of material transportation, which are then incorporated into the analysis to obtain a comprehensive evaluation of the costs and impacts associated with the system under study.

5 LCA MAIN RESULTS

In this section, the results of the LCA are presented, aiming to assess the environmental performance and cost implications of the CREAToR technology.

The baseline scenario is the one that considers the gate-to-gate boundaries (sorting and purification). This decision has been taken to strictly consider the impact of machinery and resources used.

To evaluate the result, two product systems have been created. The product system "**Purification ABS**" evaluates the impact coming from that process and the amount of the sorting process concerning the physical allocation of 0.60. The same applies to the "**Purification PS"** product system with a weight of 0.40 for allocation.

The following graphs are related to the calculation of environmental impact, in terms of greenhouse gas emissions, considering the scenario with the incineration of waste (Figure 6-9).

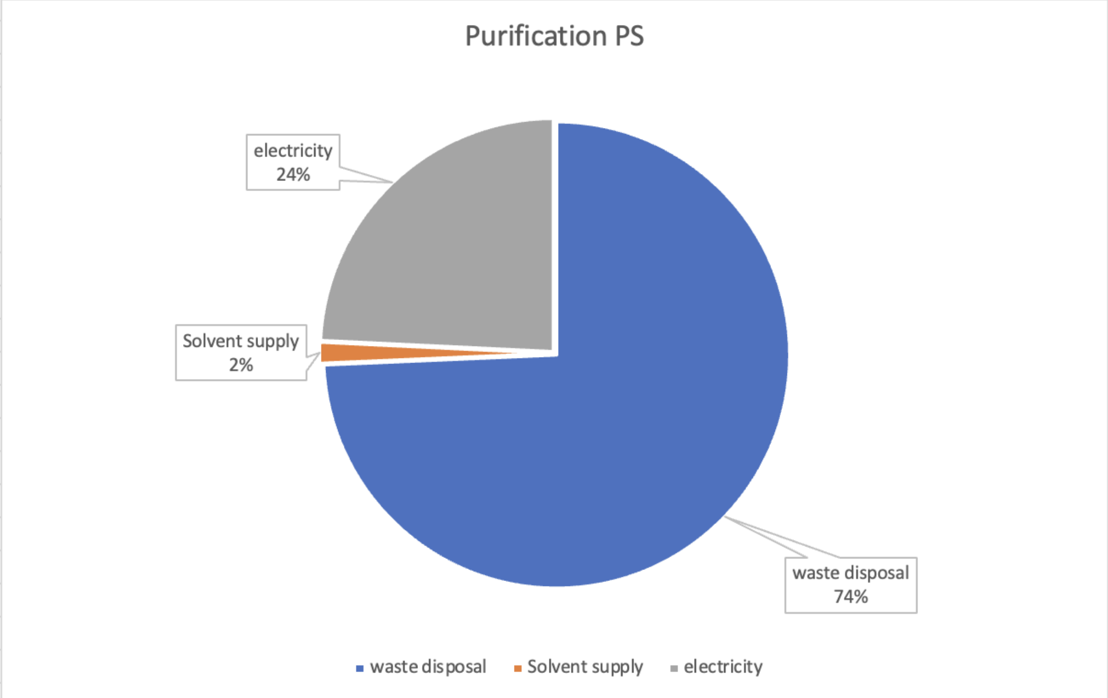

Figure 7 – Flow impact of purification PS process

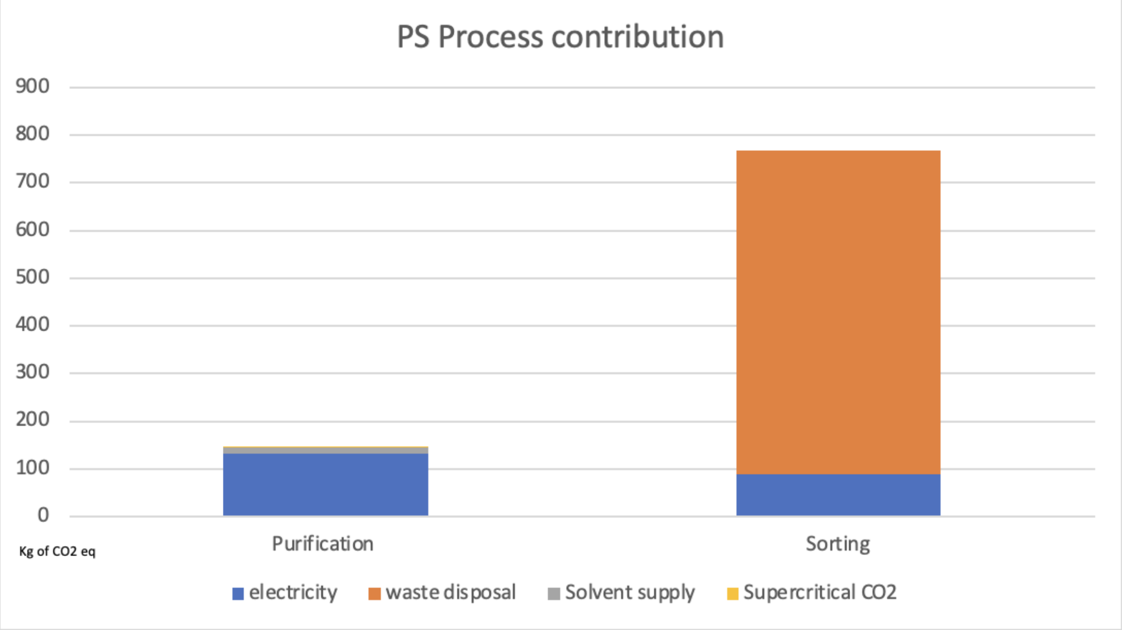

Figure 8 – Contribution divide between sorting and PS purification process

Compared to the whole process the impact of co-solvent and supercritical CO_2 seems small. For PS purification we have 13.21 kg of CO_2 eq on 915 kg of CO_2 tot (co-solvent and supercritical CO_2).

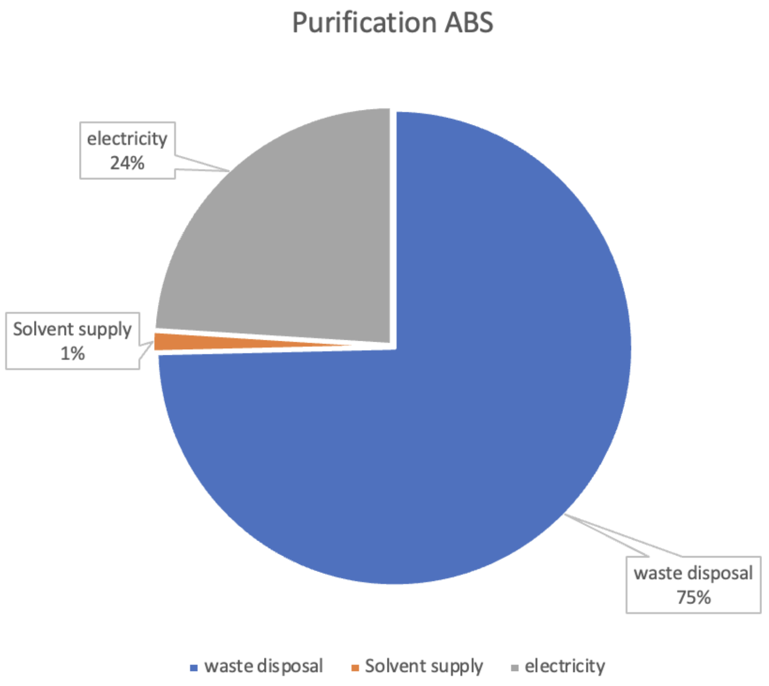

Figure 9 - Flow impact of purification ABS process

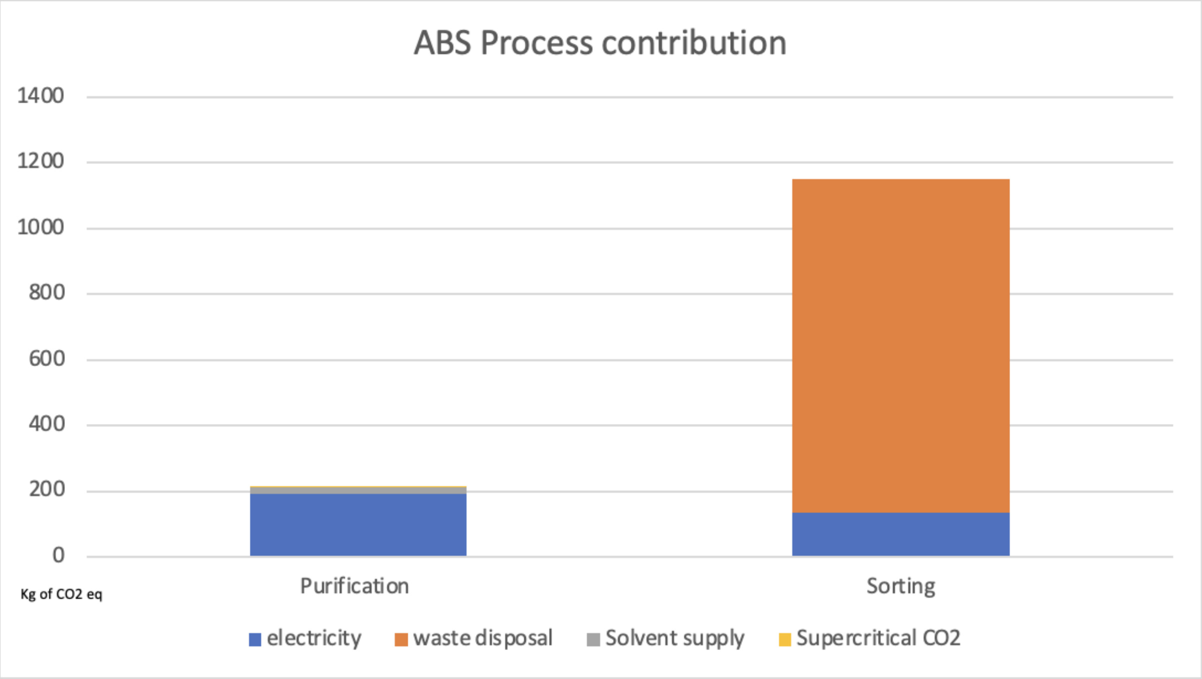

Figure 10 - Contribution divide between sorting and ABS purification process

Compared to the whole process the impact of co-solvent and supercritical CO_2 seems small. For ABS purification we have 23.12 kg of CO_2 eq on 1367 kg of CO_2 tot (co-solvent and supercritical CO_2).

Both evaluations (750 kg and 1500 kg) showed that the treatment of waste is the main issue. The impact coming from the incineration is extremely consistent. The pulp resulting from the first washing treatment, the plastic mix (without PS and ABS) and the mixed material contained in the WEEE input are defined as waste. Considering the waste that goes to incineration means that the highest impact on the whole process comes from the incineration of this materials, shifting the impact from the other flows of the process.

Still, trying to consider the other flows, a relevant aspect is the consumption of electricity coming from fossil sources. The electricity of the sorting process is the only input that differs between the two scenarios, due to the different hourly capacities of the sorting machine considered. The impact is therefore almost the same. This explains why the impact for both PS and ABS slightly differs between the 750 kg and 1500 kg analysis.

Assuming that the whole sink fraction, except for Br-PS and Br-ABS, is going to be incinerated, the environmental impact of the process is therefore extremely high. It is important to note that incineration is not only accountable for the emission of GHG but is also responsible for ozone depletion and the impact on human toxicity. Considering this scenario, the environmental impact is not so different from virgin plastic production process.

A sensitivity analysis has been carried out to investigate the impact if the plastic is recycled instead of been incinerated (Figure 10).

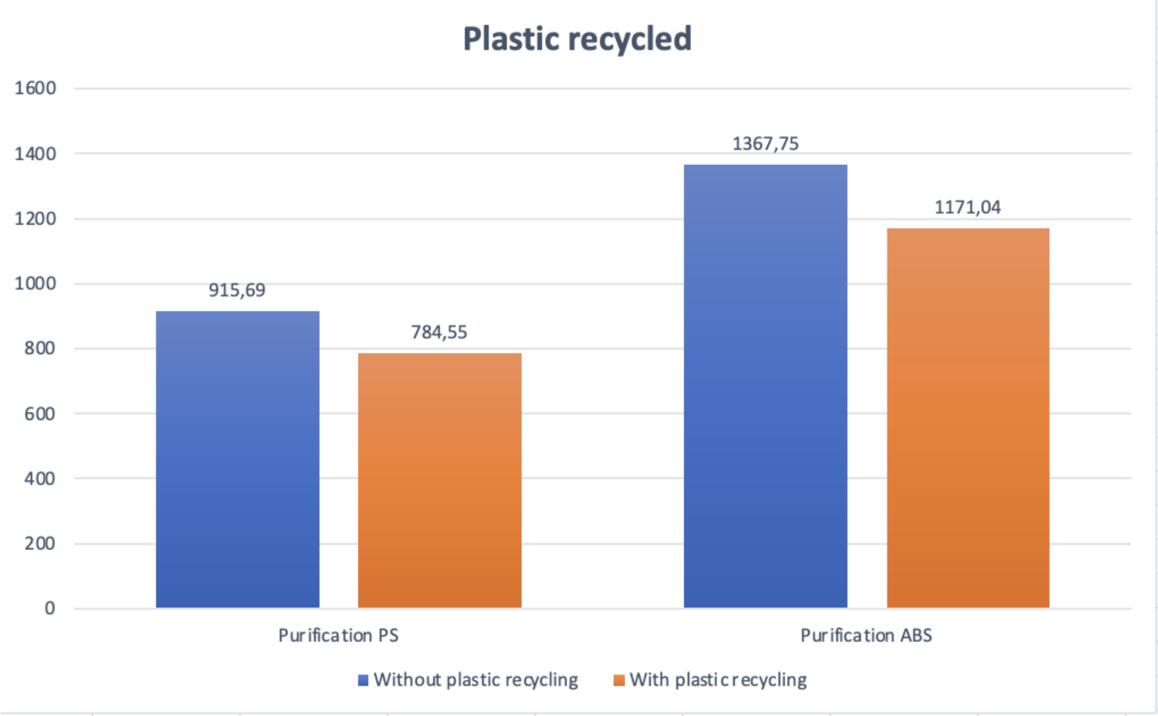

Figure 11 – Comparison between a scenario with plastic recycling and a scenario without plastic recycling for both ABS and PS purification processes

It is clear that reusing a part of the sink stream, especially if it is a plastic (fossil-derived product), can reduce the impact of the whole process. This could be one of the research paths that could be taken into account to improve the technology and consistently reduce its impact.

Furthermore, a comparative analysis with virgin granulated plastic has been performed. This task aims to compare the impact of the traditional scenario of granulated virgin plastic and the innovative scenario of the CREAToR project. It's difficult to find studies and research about the impact of virgin granulated plastic.

One of the sources available is "Sustainability assessments of bio-based polymers" by Troy A. Hottle, Melissa M. Bilec Amy E. Landis. This paper reviews published life cycle assessments (LCAs) and commonly used LCA databases that quantify the environmental sustainability of bio-based polymers, and summarises the range of findings reported within the literature[3].

Although this paper does not conduct a life cycle assessment of the plastic we are interested in, we can take indicative data about the amount of kg of CO_2 eq issued to produce a kg of granulated virgin PS. The data are taken from Ecoinvent v2.2 and the results reported from Ecoinvent represent a cradle-to-granule (i.e. gate) system boundary for the production of 1 kg of granules. Figure 11 below shows the comparative life-cycle environmental impacts from existing databases for petrol-based polymers and biopolymers.

Producing 1 kg of granulated PS generates an impact of 3.5 kg of CO_2 eq, which means 3500 kg of CO_2 eq per 1 tonne of granulated PS. Considering the impact of CREAToR purification PS process (with the incineration of sink fraction and considering the plastic mix as avoided product) we have an amount of 784.55 kg of CO_2 eq per 0.409 of granulated purified PS. If we do the calculation:

$$784{,}55 : 0{,}409 = X : 1$$

$$X = \frac{784{,}55 * 1}{0{,}409} \qquad X = 1919$$

This means that by producing 1 ton of granulated PS with CREAToR's technology we have an impact of 1918 kg of CO_2 eq, while the granulated virgin plastic produces 3500 kg of CO_2 eq per 1 tonne.

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[3] https://www.researchgate.net/publication/272091617_Sustainability_assessments_of_bio-based_polymers

As for ABS, it was more difficult to find the impact of the granulates, but considering all impacts shown in the image above, the medium value is 2.5 kg of CO_2 eq. Therefore, even if we take the medium value (2.5 kg of CO_2 eq) we will have 2500 kg of CO_2 eq per 1 tonne of virgin plastic (Figure 11).

Taking into account the impact of purified ABS from CREAToR and performing the same calculation as above, we will have the following impact:

$1171 : 0{,}592 = X : 1$

$X = \frac{1171 * 1}{0{,}592} \quad X = 1978$

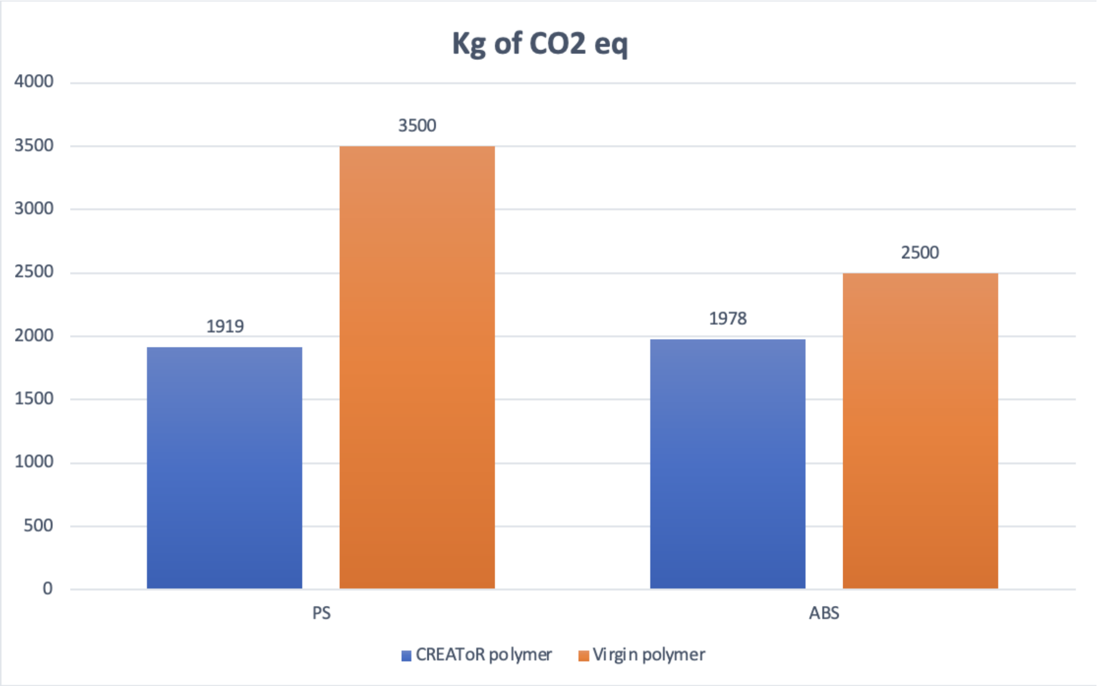

Figure 12 – Comparison between CREAToR polymer and virgin polymer in terms of GHG emissions

6 LCCA MAIN RESULTS

In this section, the results of the LCCA are presented, aiming to assess the economic performance and cost implications of the CREAToR technology in comparison to traditional polymer production methods. The LCCA provides valuable insights into the operational expenditures (OPEX) associated with producing purified granulated polymer using CREAToR's innovative technologies. By contrasting these expenditures with those of the traditional methods that do not incorporate recycling, a comprehensive understanding of the cost-effectiveness and economic viability of CREAToR's technology is obtained. The results of the LCCA offer key indicators and analysis that will guide decision-makers, investors, and stakeholders in the polymer production industry towards sustainable and financially sound choices.

Table 4 reports the total costs evaluated to produce 1 ton of purified polymer for all the considered scenarios.

Table 4 Costs to produce 1 ton of purified polymer.

	Sorting process with 750 kg/h capacity and Br-free plastic mix incineration	**Sorting process with 750 kg/h capacity and Br-free plastic mix valorisation**	**Sorting process with 1.5 ton/h capacity and Br-free plastic mix incineration**	**Sorting process with 1.5 ton/h capacity and Br-free plastic mix valorisation**
Sorting costs	729.18 €/ton of produced polymer	346.27€/ton of produced polymer	385.71€/ton of produced polymer	2.80€/ton of produced polymer
Purification costs	1,161.43€/ton of produced polymer	1,161.43€/ton of produced polymer	1,161.43€/ton of produced polymer	1,161.43€/ton of produced polymer
Total costs	1,890.61€/ton of produced polymer	1,507.70€/ton of produced polymer	1,547.14€/ton of produced polymer	1164.23€/ton of produced polymer

In the case where the Br-free plastic mix fraction is not valorised, the total operational expenditures (OPEX) for producing 1 ton of purified polymer using a 750 kg/h sorting plant amount to €1890.61. The selling price of ABS can range between €1340 and €2680 per ton, while the price of PS can range between €890 and €1790 per ton, depending on the polymer's quality. Considering the proportions of ABS and PS in the sink fraction, the estimated selling price range for the produced purified polymer is between €1156.18 and €2153.57 per ton.

In the case of valorisation of the Br-free plastic mix fraction, the total OPEX would amount to €1507.70 per ton.

In both cases (with and without valorisation of the Br-free plastic mix), the costs of the purification process have the greatest impact on the total. In the first case, they account for approximately 61 % of the total costs, while in the second they account for approximately 77 %.

The use of a larger sorting plant for the sorting process allows for a reduction in certain costs, particularly personnel expenses and fixed costs. In the case where the Br-free plastic mix fraction is not valorised, the total OPEX for producing 1 ton of purified polymer using a 1.5 ton/h sorting plant would amount to €1547.14 per ton. In the case of valorisation of the Br-free plastic mix fraction, the total OPEX would amount to €1164.23 per ton.

In these scenarios as well, the total cost of the purification process remains significant, accounting for 75 % of the total costs in the first case and 99.8 % in the second case.

It is important to consider the range of selling prices for the produced purified polymer, which varies between €1156.18/ton and €2153.57/ton when comparing the total costs.

Table 5 reports the total costs evaluated to produce 1 ton of purified polymer for all the considered scenarios.

Table 5 Costs to recycle 1 ton of WEEE sink fraction.

	Sorting process with 750 kg/h capacity and Br-free plastic mix incineration	Sorting process with 750 kg/h capacity and Br-free plastic mix valorisation	Sorting process with 1.5 ton/h capacity and Br-free plastic mix incineration	Sorting process with 1.5 ton/h capacity and Br-free plastic mix valorisation
Sorting costs	105.99 €/ton of recycled WEEE sink fraction	50.31€/ton of recycled WEEE sink fraction	55.01€/ton of recycled WEEE sink fraction	-0.66€/ton of recycled WEEE sink fraction
Purification costs	168.87€/ton of recycled WEEE sink fraction	168.87€/ton of recycled WEEE sink fraction	168.87€/ton of recycled WEEE sink fraction	168.87€/ton of recycled WEEE sink fraction
Total costs	274.86€/ton of recycled WEEE sink fraction	219.18/€/ton of recycled WEEE sink fraction	223.88€/ton of recycled WEEE sink fraction	168.21€/ton of recycled WEEE sink fraction

The amount of polymer produced from recycling 1 ton of sink fraction is approximately 0.145 tons, which corresponds to a market value ranging from €167.64 to €312.27.

This value can be compared with the total OPEX of the CREAToR technology, which for the scenario with a sorting plant capacity of 750 kg/h amounts to €274.86 in the case where the Br-free plastic mix is sent to the incinerator, and €219.18 in the case where the fraction of Br-free plastic mix is valorised.

In this case, as well, the purification process has the greatest impact on the final cost.
Also, in this case, the use of a larger sorting plant for the sorting process enables a reduction in personnel expenses and fixed costs.In the case of non-valorisation of the Br-free plastic mix fraction, the total OPEX for recycling 1 ton of WEEE sink fraction using a 1.5 ton/h sorting plant would amount to €223.88.
In the case of valorisation of the Br-free plastic mix fraction, the total OPEX would amount to €168.21.
The comparison of total costs should always be made regarding the market value for the produced purified polymer, which can vary between €167.64 and €312.27 for selling prices ranging from €1156.18/ton to €2153.57/ton and an amount of produced polymer of 0.145 tons.

The ultimate goal of the LCCA is to provide useful insights for optimising the economic performance of the entire CREAToR process. It is therefore helpful to analyse the cost breakdown among the various process steps and identify the cost categories that have the greatest impact on the final budget.

In Figure 13 and Figure 14, the costs breakdown by category for the entire CREAToR technology for the production of purified ABS and PS is shown. The breakdowns are presented for each of the considered scenarios. The diagrams do not take into account the effect of multi functionalities, which are represented by costs with negative signs. In all cases, the cost items that have the greatest impact are waste disposal expenses, personnel costs, and material and utility costs.

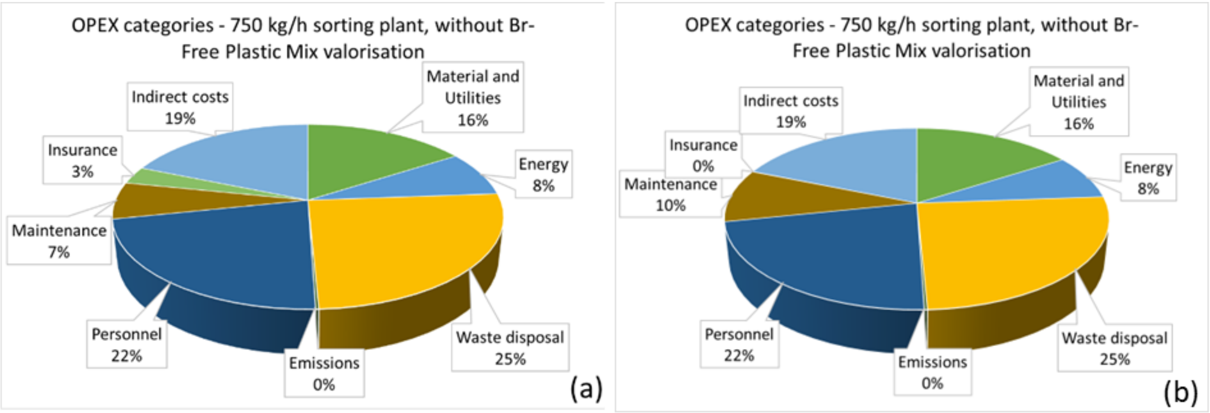

Figure 13 OPEX categories breakdown for the entire CREAToR technology for the 750 kg/h sorting plant.

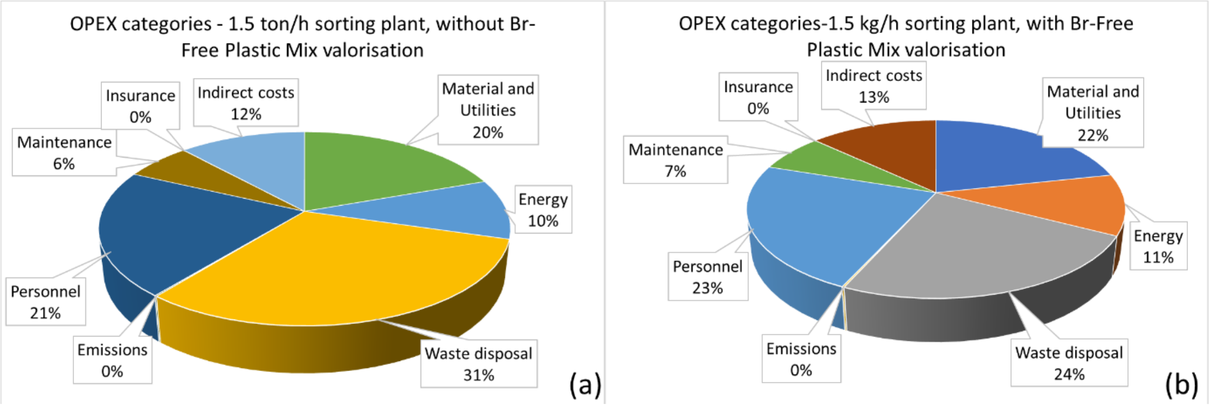

Figure 14 OPEX categories breakdown for the entire CREAToR technology for the 1.5 ton/h sorting plant

The previous paragraphs provided cost estimates for individual functional units, but they did not offer insights into the long-term economic performance of implementing the CREAToR technology. To address this, we evaluated the costs over a year of plant operation, simulating a 24-hour production schedule for 5 days a week, over 48 weeks.

A challenge in estimating annual costs arises from the mismatch between the capacity of the sorting plant and that of the purification plant. The sorting plants considered have capacities of 750 kg/h and 1.5 tons/h, but they can only provide outputs of 75 kg/h and 225 kg/h, respectively. This is significantly lower than the 500 kg/h that the two 250 kg/h sorting plants can process.

To simulate the annual production costs, we accounted for downtime in the purification phase to maintain production times dictated by the bottleneck. Figure 15 and Figure 16 present the findings for the cases of non-valorisation and valorisation of the Br-free plastic mix, respectively.

These results offer valuable insights into the optimal sorting plant size and the potential for valorising the Br-free plastic mix. The optimal scenario occurs when a sorting plant with a capacity of 1.5 tons/hour is chosen, and successful valorisation is achieved. In this case, the balance between expenses and potential revenues remains positive, even under pessimistic polymer selling price scenarios, ranging from €236,946.09/year to €1,527,647.92/year.

Conversely, the worst-case scenario involves a sorting plant with a capacity of 750 kg/h and the inability to valorise the Br-free plastic mix. In this case, selling the purified polymer at the pessimistic price would result in a loss of €440,233.97/year, while achieving the optimistic price would yield a gain of €205,116.94/year.

These findings provide insights into plant sizing and logistics. An alternative solution involves distributing the sorting phase across multiple plants with capacities of 750 kg/h, ensuring a continuous material flow to the 250+250 kg/h sorting plant for purification, eliminating downtime.

However, this solution introduces logistical challenges, such as transportation costs within the gate-to-gate system. Figure 17 presents a revised assessment of annual costs, excluding transportation costs, for the solution with multiple sorting plants. The results show a positive annual balance ranging from €282,694.29 to €3,499,875.48 for the non-valorisation scenario and from €523,141.87 to €3,740,323.05 for the valorisation scenario of the Br-free plastic mix.

Overall, regardless of the Br-free plastic mix valorisation status, the balance between expenses and potential revenues remains consistently positive, highlighting the favourable financial outlook in this specific case.

Figure 15 Annual costs for the entire CREAToR technology for the considered scenarios in the case of Br-free plastic mix incineration.

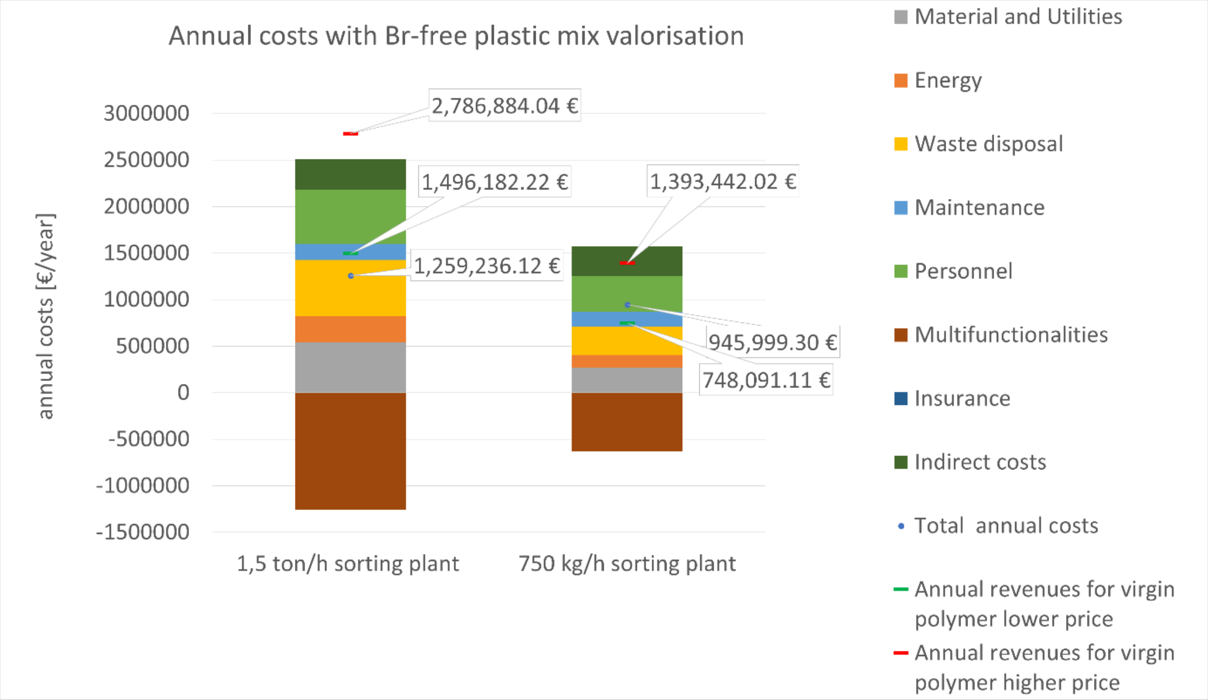

Figure 16 Annual costs for the entire CREAToR technology for the considered scenarios in the case of Br-free plastic mix valorisation.

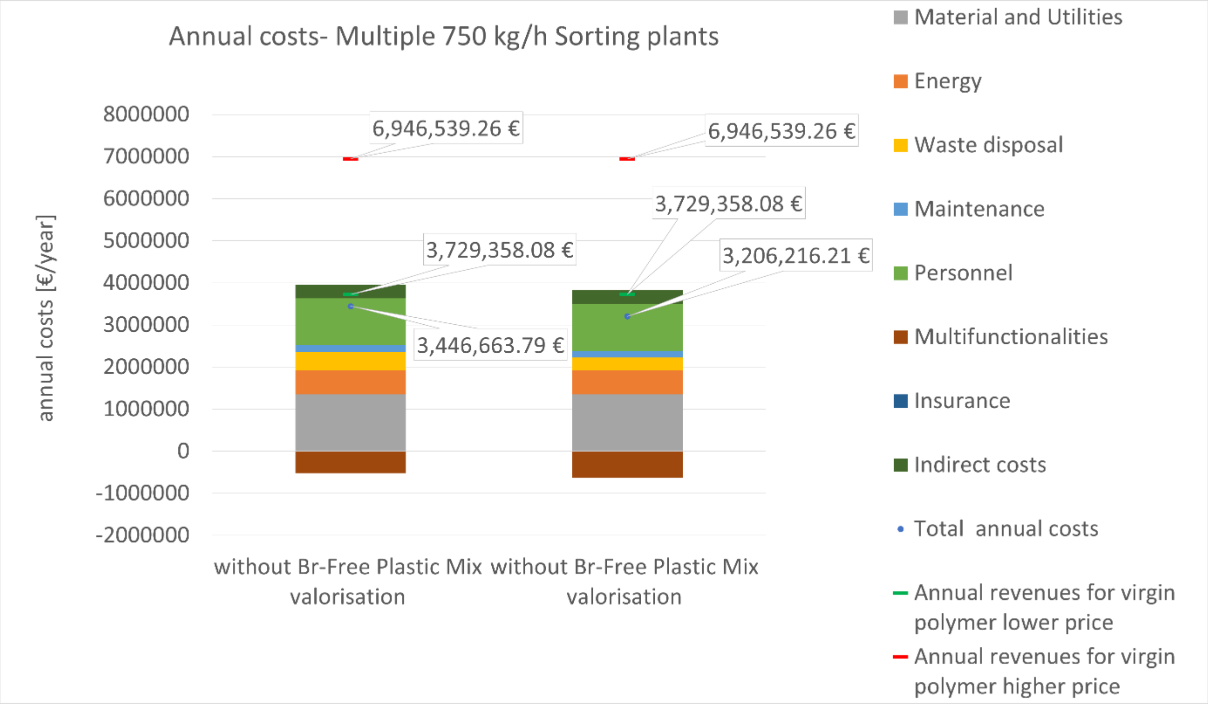

Figure 17 Annual costs for the entire CREAToR technology for the additional scenario involving the use of multiple sorting plants with a capacity of 750 kg/h.

7 CONCLUSIONS

This document aims to publicise the most relevant results of the life cycle assessment (LCA) and life cycle cost assessment (LCCA) analysis of the CREAToR project.

The LCA calculations showed, which are the areas that must be investigated to improve the environmental impact of the whole process, include:

- use of waste materials
- recycling the plastic mix
- use of different sources of electricity
- reuse of CO_2 solvent
- use of different sorting plants of 750 kg.

In particular, for the problem of incineration, a future investigation is recommended to recycle as much material as possible from the initial sink fraction. This would make a significant difference in terms of the environmental impact and also economic revenue.

The last point has been further investigated in a LCCA analysis where the main challenge in estimating the annual costs lies in the mismatch between the sorting plant's capacity and the purification plant's capacity.

The LCCA conducted in this study provides valuable insights into the economic aspects of implementing CREAToR's innovative technologies for plastics recycling. The analysis considered different scenarios, including the valorisation and non-valorisation of the Br-free plastic mix fraction, as well as varying capacities of the sorting plant. The findings highlight the importance of optimising plant sizing and logistics to achieve favourable financial outcomes. The optimal scenario emerges when a sorting plant with a capacity of 1.5 tons/hour is chosen, coupled with the successful valorisation of the Br-free plastic mix. In this case, the balance between expenses and potential revenues remains consistently positive, even under pessimistic polymer selling price scenarios. On the other hand, the worst-case scenario involves a smaller sorting plant capacity and the inability to valorise the Br-free plastic mix, resulting in potential losses. These insights guide decision-makers in the polymer production and recycling industry, highlighting the importance of considering long-term economic performance projections and optimising plant configurations to achieve sustainable and financially viable solutions. The study also emphasises the need for further optimisation and refinement as the technologies are still in the laboratory stage, with ongoing efforts to reduce uncertainties and enhance the accuracy of the cost estimates. Overall, the LCCA serves as a strategic decision-making tool, providing stakeholders with valuable information to support informed choices and drive the adoption of environmentally and economically sustainable practices in the plastics recycling sector.

This deliverable gives a comprehensive overview of the findings and results from the analysis, focusing on both the LCA and the LCCA.