Guidelines for Chemical Recycling LCAs

On behalf of Chemical Recycling Europe

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List of Acronyms

AP-42	Air Pollutant Emissions Factors
CFF	Circular Footprint Formula
CML	Centre of Environmental Science at Leiden
CPA	Circular Plastic Alliance
CRE	Chemical Recycling Europe
EF	Environmental footprint
EoL	End-of-Life
EPD	Environmental product declaration
EU	European UnionGHG Greenhouse Gas
GWP	Global Warming Potential
ILCD	International Cycle Data System
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LHV	Lower Heating Value
PCRs	Product Category Rules
PE	Polyethylene
PEF	Product Environmental Footprint
PET	Polyethylene Terephthalate
PP	Polypropylene
TfS	Together for Sustainability
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
TRL	Technology Readiness Level
VCS	Value Corrected Substitution
WBCSD	World Business Council for Sustainable Development

Glossary

Allocation

"Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems" (ISO 14040:2006, section 3.17)

Background System

"Those processes, where due to the averaging effect across the suppliers, a homogenous market with average (or equivalent, generic data) can be assumed to appropriately represent the respective process … and/or those processes that are operated as part of the system but that are not under direct control or decisive influence of the producer of the good…." (JRC, 2010, pp. 97-98) As a general rule, secondary data are appropriate for the background system, particularly where primary data are difficult to collect.

Chemical Recycling

"Any reprocessing technology that directly affects either the formulation of the polymeric waste or the polymer itself and converts them into chemical substances and/or products whether for the original or other purposes, excluding energy recovery" (CRE, 2019)

Chain of Custody

"Process by which inputs and outputs and associated information are transferred, monitored and controlled as they move through each step in the relevant supply chain" (ISO 22095:2020, section 3.2.1)

Chain of Custody Model

"Approach taken to control inputs and outputs and associated information in a particular chain of custody system…A chain of custody model is typically designed to preserve a set of specified characteristics." (ISO 22095:2020, section 3.1.3)

Chain of Custody System

"Set of measures designed to implement a chain of custody, including documentation of these measures… The purpose of a chain of custody system is to provide credibility that the given material or product has a set of specified characteristics… The information linked to materials or products is transferred, monitored and controlled throughout the entire supply chain or parts of it." (ISO 22095:2020, section 3.1.3)

Closed-loop and Open-loop Allocation of Recycled Material

"An open-loop allocation procedure applies to open-loop product systems where the material is recycled into other product systems and the material undergoes a change to its inherent properties."

"A closed-loop allocation procedure applies to closed-loop product systems. It also applies to open-loop product systems where no changes occur in the inherent properties of the recycled material. In such cases, the need for allocation is avoided since the use of secondary material displaces the use of virgin (primary) materials." (ISO 14044:2006, section 4.3.4.3.3)

Critical Review

"Process intended to ensure consistency between a life cycle assessment and the principles and requirements of the International Standards on life cycle assessment" (ISO 14044:2006, section 3.45).

Foreground System

"Those processes of the system that are specific to it … and/or directly affected by decisions analysed in the study." (JRC, 2010, p. 97) This typically includes first-tier suppliers, the manufacturer itself and any downstream life cycle stages where the manufacturer can exert significant influence. As a general rule, specific (primary) data should be used for the foreground system.

Functional Unit

"Quantified performance of a product system for use as a reference unit" (ISO 14040:2006, section 3.20)

Life Cycle

A view of a product system as "consecutive and interlinked stages … from raw material acquisition or generation from natural resources to final disposal" (ISO 14040:2006, section 3.1). This includes all material and energy inputs as well as emissions to air, land and water.

Life Cycle Assessment (LCA)

"Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO 14040:2006, section 3.2)

Life Cycle Inventory (LCI)

"Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle" (ISO 14040:2006, section 3.3)

Life Cycle Impact Assessment (LCIA)

"Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product" (ISO 14040:2006, section 3.4)

Life Cycle Interpretation

"Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations" (ISO 14040:2006, section 3.5)

Mass Balance Model

"Chain of custody model in which materials or products with a set of specified characteristics are mixed according to defined criteria with materials or products without that set of characteristics…The proportion of the input with specified characteristics might only match the initial proportions on average and will typically vary across different outputs." (ISO 22095:2020, section 3.3.4)

Product System

"Collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product" (ISO 14040:2006, section 3.28)

Specified Characteristic

"Set of product characteristics (3.2.6) and/or production characteristics (3.2.7) that the chain of custody is designed to maintain" e.g., recycled content or biogenic content (ISO 22095:2020, section 3.2.5)

System Boundary

"Set of criteria specifying which unit processes are part of a product system" (ISO 14040:2006, section 3.32)

System Expansion

"Concept of expanding the product system to include additional functions related to the co-products" (ISO 14040:2006, section 3.2.12)

Parties and Roles

Party	Role
CRE: Technical Working Group	Provide advice, guidance, and feedback
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Geoff Smith	WG Member and Advisor
Urvashi Athavale	WG Member and Advisor
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Executive Summary

Chapter 1: Background

Approximately, 32 million metric tons of post-consumer plastic waste was generated in Europe in 2022, and ~27% (7.7 metric tons) of this material was collected and mechanically recycled, while <0.2 metric tons were chemically recycled (PlasticsEurope, 2024). The remainder was incinerated or disposed in landfills. Significant improvements in the circularity of plastics, require further development and implementation of advanced chemical recycling technologies that are capable of recycling polymers and plastic waste that cannot readily be or are not being mechanically recycled. While many life cycle assessments (LCAs) have been performed of chemical recycling technologies to better understand their environmental performance, there is a need for a standard set of guidelines to ensure that LCAs provide consistent and meaningful results that can be used to improve decision-making. The purpose of this document is to review and provide guidance for the critical aspects related to LCAs in the chemical recycling industry. The recommendations in these guidelines are meant to be relatively flexible so that they can be readily applied by LCA practitioners developing chemical recycling LCAs for a variety of applications.

Chapter 2: Introduction to LCA

LCA is a framework for estimating the material and energy inputs and outputs and potential environmental impacts from a product system over its entire life cycle. LCAs are performed in four iterative phases defined by ISO 14044 as Goal & Scope Definition, Inventory Analysis, Impact Assessment, and Interpretation. Defining the goal of the study includes describing the objective, motivation, intended application, and intended audience of the study, while defining the scope includes describing things like the product systems to be assessed, the function and functional units, system boundary, allocation methods, life cycle impact assessment (LCIA) methodologies, and other aspects of the study. In the life cycle inventory (LCI) phase, data and models are developed for all the flows into and out of the unit processes included in the product systems under study. This is followed by the life cycle impact assessment (LCIA), where the flows modelled in the LCI phase are converted into actual environmental burdens. A common example is using 100-year global warming potential (GWP) to combine various greenhouse gas (GHG) emissions based on the warming they cause relative to CO_2 over 100 years. Finally, the interpretation phase holistically evaluates the study, results, and any assumptions or limitations to develop conclusions and recommendations. It should be noted that LCA is inherently iterative, and practitioners may have to return to previous phases or decisions and make adjustments before continuing.

Chapter 3: System Expansion

Since recycling systems are inherently multi-functional in that they treat a waste stream (a service) and produce a product (a good), LCAs of chemical recycling systems must account for this multi-functionality. This is typically done via system expansion, which means that the additional function is also (e.g., waste management or product manufacturing) included in the study. System expansion can be performed using an additive or a subtractive approach. Additive system expansion adds the expanded function to the alternatives that chemical recycling is being compared against, whereas subtractive system expansion subtracts the expanded function from the chemical recycling system. The benefits of the additive system expansion are that it does not provide negative footprint results, which are not meaningful in attributional LCAs. Relative comparisons are also generally more insightful in LCAs, so obscuring their meaning is a substantial downside. Additionally, excluding credits from the chemical recycling alternatives is accepted in environmental product declarations (EPDs) and product environmental footprints (PEFs). However, a potential downside of additive system expansion is that if the chemical recycling system is compared to conventional production without the added burdens from system expansion, then chemical recycling will not look as good as it could comparatively. Therefore, it is beneficial to show results with and without credits.

The primary benefit of the subtractive approach is that the chemical recycling results can standalone without the need to ensure that the additional burdens are included in any comparisons made. This subtractive upstream system expansion approach is also accepted by the TfS guidelines in ”exceptional cases”, while otherwise requiring a “cut-off” approach that excludes these credits (TfS, 2024).

Recommendations

- Clearly describe and justify the choice of status quo waste management alternatives.
- To provide transparency in reports when presenting system expansion results, include a breakdown of the impacts from the chemical recycling process itself from the those associated with the waste management status quo. This allows the credits to be added, subtracted, or excluded completely depending on study requirements.
- If using subtractive system expansion,
    - Clearly explain the source and meaning of any reported negative values.
    - Avoid reporting relative percent differences between alternative and instead focus on the absolute differences between them.
    - Avoid claiming that products produced via chemical recycling have negative environmental burdens; instead focus on absolute changes in impact values when comparing alternatives.

Chapter 4: Functional Units

The specifics of defining the functional unit in a chemical recycling LCA will depend on whether the study takes a waste or product perspective as well as whether it takes an additive or subtractive approach to system expansion. LCAs of chemical recycling that take a waste perspective use the treatment of a set mass of waste of a specified composition. For example, it could be 1 kg of mixed plastic waste (e.g., (Jeswani, et al., 2021) (Schwartz, et al., 2021) (Meys, Kätelhön, & Bardow, 2019) (CE-Delft, 2020)) or 1 metric ton of waste tyres (Banar, 2015).

As discussed in Chapter 3, the choice of functional unit when taking a product perspective, whether for an intermediate chemical, a monomer, a polymer, or an end-use product like film packaging, will depend on whether an additive or subtractive system expansion approach is being employed. If additive system expansion is being used, then two functional units must be defined. The first for the material or product being produced and the second for the associated waste that is being managed to produce the material or product. For example, the Consumer Goods Forum commissioned an LCA of food grade PE/PP film from chemical recycling and used a functional unit of “1 tonne of food grade film (equal mix of polyethylene [PE]/polypropylene [PP]) produced and the corresponding amount of 1.26 tonne mixed plastic waste managed in Europe.” (Sphera, 2022). It is important to note that the mass of 1.26 metric tons provides the amount and type of waste used to produce the 1 metric ton of plastic film. Additionally, for non-comparative declarations (e.g., EPDs), reporting based on a declared unit of (e.g., 1 kg of product) typically defined by an associated PCR is the norm. However, if a subtractive system expansion approach is used, then only one functional unit needs to be defined. For chemical recycling LCAs, this is usually the mass of a product or material that is then compared to conventional means of producing that same mass of product or material if the two are functionally identical. Products of different quality levels can potentially still be compared if they are capable of fulfilling the same function. The comparison will just be based on the function served rather than on a simple mass basis.

Recommendations

- For non-comparative declarations (e.g., EPDs), reporting based on a declared unit of (e.g., 1 kg of product) is acceptable if accompanied by information about the relevant material properties.
- For comparative studies, products need to be compared based on a functional unit, which may differ for different applications.
- Only if the compared materials are functionally equivalent on a mass-basis can a meaningful comparison be carried out on 1:1 mass basis.
- Clearly state the function and functional unit including any significant quantitative and qualitative performance criteria.
    - When taking a waste perspective, this includes the source and type of waste and composition including contamination and impurities.
    - Generally, it is necessary to at least have data on moisture and carbon content for most chemical recycling LCAs for allocation and closing mass and carbon balances.
    - When taking a product perspective, this includes the relevant material properties and other performance characteristics required of the product produced.
- When using additive system expansion, the second functional unit of conventional waste management of an equivalent mass and type of waste as used as a feedstock for chemical recycling needs to be added to the conventional product system.

Chapter 5: System Boundary

When taking a waste perspective, the system boundary will be from cradle-to-grave, even though there are no upstream burdens associated with the waste feedstock. Material flows are tracked from the point of waste generation to the point of recycling or final disposal (Viveros, 2022). When taking a product perspective, there are more available options. The system boundary could be cradle-to-grave or cradle-to-gate with end-of-life (Viveros, 2022) or without end-of-life (Jeswani, et al., 2021). Regardless of the system boundary chosen, the starting point of the analysis must first be defined.

Depending on the source, there may be burdens associated with the feedstock used for chemical recycling. Post-consumer recyclables can be regarded as burden-free because it does not fulfil any appreciable function and there is no demand for it. However, some post-industrial waste streams may be considered co-products that carry some burdens of their production. The Circular Plastics Alliance (CPA) has developed a decision tree (CPA, 2021) to determine if a feedstock is to be considered a waste (no upstream burden) or a co-product (upstream burden via subdivision or allocation).

Even if there is no upstream burden associated with the feedstock, defining the starting point of a chemical recycling LCA is not necessarily simple. There are multiple methodologies that can be followed to determine the appropriate starting point. A primary question is when does a material become a waste, and the answer to the question can change the starting point.

According to the “cut-off method” described by TfS (TfS, 2024), “the impact of preparatory steps and supporting activities such as collection, transportation, sorting, dismantling, or shredding shall be added to the inventory results of the product system producing the secondary product.” The next method that could be used to define the system could be based on simple causality. The argument is that in the status quo case, the waste would still be collected and sorted to remove the high-value plastics from residual mixed plastic waste. Pre-processing, which may include additional sorting, is therefore first step that is only required because the material is to be chemically recycled, and so the system boundary should begin there. Next there is the “reverse cut-off method” proposed by TfS (TfS, 2024) which states that “the impact of preparatory steps and supporting activities such as collection, transportation, sorting, dismantling, or shredding shall be added to the inventory results of the product system generating the waste.” Finally, EN15804+A2 follows a “polluter pays principle”, which is defined as “processes of waste processing shall be assigned to the product system that generates the waste until the end-of-waste state is reached." And they provide a decision-tree for determining when the end-of-waste is reached.

After defining the starting point, it is necessary to define the end point. Many chemical recycling LCAs that take a product perspective use a cradle-to-gate system boundary (Jeswani, et al., 2021), (Quantis, 2020), (Coleman et al., 2020) because the primary purpose is to compare a material produced via chemical recycling to a chemically equivalent product produced via conventional means. In cradle-to-gate product studies, it is still necessary to define the "gate" of the process. If the intention is to make comparisons with conventional products, then the gate must end with the equivalent of a conventional product. This may require extending the gate of the study beyond the gate of the chemical recycler. Placing the gate later in the system allows for a more comprehensive understanding of the product system and for more realistic use and EOL scenarios.

Recommendations

- Non-comparative declarations should, at a minimum, cover the cradle-to-gate stage up to the point of substitution where a virgin material can be substituted (e.g., naphtha, monomers, polymers, or other chemicals).
- Comparative LCA studies should, in principle, be performed over the full life cycle. They may omit life cycle stages beyond the production stage only if the recycled and the virgin materials are functionally equivalent. If the final application of the material is unknown or manifold, include at least the EOL stage and consider exploring the most common applications via scenario analysis.
- If the comparison is carried out against an existing impact profile extracted from an LCA software or published elsewhere, the requirements of ISO 14067, Annex B should be met.
- Use the CPA decision tree (CPA, 2021) to determine if a feedstock is to be considered a waste (no upstream burden) or a co-product (upstream burden via subdivision or allocation).
- For waste feedstocks, have the system boundary begin at waste collection. This is consistent with the starting point defined in the "cut-off method" described by TfS (TfS, 2024).
- Follow the requirements of ISO 14044, clause 4.2.3.3 when excluding any stages, processes, inputs, or outputs.

Chapter 6: Data Quality Requirements

Data is the foundation of all LCAs, therefore it is important to use the best possible data, to perform checks of the data, and to understand the quality and uncertainty associated with the data. The data used to create the inventory model should be as precise, complete, consistent, and representative as possible with regards to the goal and scope of the study under given time and budget constraints. Completeness is judged based on the completeness of the inputs and outputs per unit process and the completeness of the unit processes themselves. The goal is to capture all relevant contributors to the impact categories under study. Identifying unit processes, inputs, or outputs that may be missing requires domain expertise.

Proxies are frequently used in LCAs when no dataset is an exact match for the material or process in question. Geographic proxies are relatively straightforward and represent the situation where data from one geographic region is used to represent another. Technical proxies are more situational and require a greater level of domain expertise to identify appropriate replacements. It is best to look for materials that are produced from similar raw materials and processes. Contribution analysis should be used to check how much the proxy datasets contribute to the results. If the proxy is a relevant or even dominant contributor, then its use may represent a significant limitation of the study and better data may be necessary.

There are a number of ways to review data for suitability for use in a LCA study. Mass, water, substance (e.g., carbon), and energy balances can help identify missing or erroneous data by showing that the data being used defies basic physical constraints on mass and energy conservation.

Recommendations

- Use measurements for direct emissions wherever possible and supplement the measurements with data from emission estimate guidelines (e.g., AP-42, other LCAs, or proxies for completeness).
    - When choosing between multiple reasonable proxies, use a conservative choice for chemical recycling and an optimistic choice for comparative conventional processes to strengthen the conclusions of the study.
    - When selecting geographical proxies, pick regions with as similar a technology mix as possible and update energy production data, if possible.
    - Choices of technical proxies should be based on data for products made of similar materials or from similar processes.
    - Explore the contributions of proxies on the results in contribution analyses and discuss the implications as part of the interpretation.
- As a minimum data check, ensure that mass, water, and C balances are closed to the extent possible and perform a qualitative reasonableness check on the data values (e.g., orders of magnitude all appear realistic).
- Document the quality of the data used relative to its intended purpose.

Chapter 7: Multi-Output Allocation

When a process has multiple co-products, it is necessary to determine how to allocate inputs, emissions, and wastes to each of the co-products. For example, some pyrolysis processes produce product gas, tars, chars, and non-condensable gases. The product gas is typically converted to pyrolysis oil, but the tars and char can also be further processed and beneficially used. In that case, multi-output allocation would be necessary. Prior to allocation, it is necessary to determine which outputs are wastes and which are co-products. This can be done using the CPA decision tree discussed in Chapter 5.

ISO 14044 specifies that when there are multi-output processes, the first step should be to avoid allocation by sub-dividing the process into separate mono-output processes. If sub-division is not possible, the next step is to avoid allocation through system expansion.

If allocation cannot be avoided, then ISO 14044 prefers physical allocation over other forms of allocation, i.e., allocation that reflects the underlying physical relationships between the co-products. A common form of physical allocation is based on mass. However, physical allocation may also be based on energy, carbon content, exergy, protein content, or any other physical properties depending on the co-products in question. Typically, allocation among the products from chemical recycling are allocated by carbon content. The one basic rule of allocation is that the sum of all allocated inventories equals the inventory of the original multi-output process. Steam crackers are a common process where allocation is necessary among multiple outputs, and PlasticsEurope (2017) (PlasticsEurope, 2017) has developed recommendations for steam cracker allocation.

The WBCSD Pathfinder Framework (WBCSD, 2023) (also adopted by TfS, 2022) provides a slightly different decision-tree than ISO 14044 where, if allocation is necessary, it should first be based on approved product category rules or sector specific guidance. If such guidance does not exist and the ratio of economic value of the co-products is greater than 5, then economic allocation should be used. Otherwise, underlying physical relationships should be used if possible, and if that is not possible, then again economic allocation or some alternative allocation should be used.

Recommendations

- Follow the WBCSD Pathfinder (WBCSD, 2023) decision tree for processes with multiple outputs.
- Use PlasticsEurope (2017) (PlasticsEurope, 2017) recommendations for steam cracker allocation.
- Apply different allocation methods to critical processes and discuss how the results affect the conclusions of the study.

Chapter 8: End-of-Life Allocation

The purpose of end-of-life allocation is to address the question of how to assign impacts from virgin production and end-of-life (EOL) recycling processes between the waste-producing and the waste-consuming product system. In the cut-off approach, burdens or credits associated with material from previous or subsequent life cycles are not considered, i.e., are "cut-off". Accordingly, the system boundary ends at the point of waste generation; collection, sorting, pre-treatment, and recycling are again considered part of the waste-consuming product system. This approach provides a strong incentive for using recycled content but provides less of an incentive for end-of-life recycling. It is further unable to distinguish between different forms of EOL recycling or penalize downcycling in any way.

Alternatively, the substitution approach is based on the perspective that material that is recycled into secondary material at end of life is technically able to substitute virgin material. Therefore, a credit is given to account for this substitutability which represents the market-average burden of the substituted virgin material. In its "net scrap" variant, any pre- and post-consumer waste collected for recycling is first used to satisfy the recycled content demand of the cradle-to-gate manufacturing stage. The remaining net scrap is then sent through EOL recycling and receives a credit based on the technical substitutability of the materials. The embodied burden approach is similar to the substitution approach, except that it always credits the same primary inventory that was (or would have been) used in manufacturing to represent the original primary burden embodied in the material regardless of technical substitutability.

Finally, the Circular Footprint Formula (CFF) method lies somewhere between the cut-off and substitution methods. It predefines allocation factors of credits and burdens between the waste-producing and the waste-consuming life cycles and aims to describe market realities that capture both aspects of recycling - the recycled content and recyclability at the end of life. It was developed as part of the Product Environmental Footprint Category Rules Guidance (European Commission, 2017).

Recommendations

- Unless otherwise specified by PCRs or other sector specific guidance, the net-scrap substitution approach can be used a general baseline as it provides incentives to increase both recycled content as well as EOL recycling.
- Apply different EOL allocation methods and discuss how the results affect the conclusions of the study.

Chapter 9: Mass Balance Approach

The mass balance approach is a chain of custody model for transferring and monitoring the flows of input materials with specified characteristics (e.g., recycled or biogenic content) to their related product. ISO 22095 recognizes two implementation methods: the rolling average percentage method (here called the proportional method) and the credit method.

The proportional method, equally applies the average input proportion to all associated outputs. For example, if 25% of the incoming material is from post-consumer waste, and four products are produced, then all four of those products can claim 25% recycled content.

Alternatively, using the credit method, the four products could each claim different amounts of recycled content as long as the total did not exceed 25%. For example, one product could claim 50% recycled content, while another claims 0%. The plastics industry has further broken down the credit method into fuel-exempt and polymers-only approaches. The fuel-exempt approach allows the recycled content to be reattributed among all products and outputs excluding fuel and energy. The polymers-only approach only allows the recycled content to be reattributed between polymer outputs.

Since mass balance is primarily a chain of custody and labeling instrument, there is no direct or obligatory link to LCA calculations as such. However, there is a desire by some in the industry to calculate separate footprints for products labelled “100% virgin/primary” and “100% recycled” in order to help shift demand to the recycled product. None of the relevant standards (ISO 14025 (ISO, 2006), ISO 14044 (ISO, 2006), ISO 14067 (ISO, 2018), ISO 21930 (ISO, 2017)) addresses such a virtual division of a single product flow (with some recycled content) into two separate co-products with 100% virgin and 100% recycled content, respectively. However, there is also no language in these standards that would rule out such a calculation per se.

Jeswani et al. (2019) states that the mass balance approach is only applicable when the final products are completely interchangeable with one another, and when there are no additional differences in processing utilities and auxiliaries (Jeswani, Kruger, Kicherer, Antony, & Azapagic, 2019). However, if this limitation is disregarded, then depending on the specific constellation of carbon intensities and recycled content, the separate calculation of the carbon footprint for the “100% recycled” and the “100% virgin” product may lead to a lower carbon footprint for the “100% recycled” product despite an increase in the absolute total GHG emissions when compared to a production without any recycled content. Therefore, it is important to use caution when discussing LCA results using a mass balance approach. According to ISO 14044, it is important to describe assumptions and their influence on the results transparently to avoid misinterpretation (ISO, 2006). Therefore, when the mass balance approach is used in an LCA, the effect of its use should be discussed as part of the interpretation.

Recommendations

- The total amount of mass balanced products is limited to what can be certified by a generally accepted 3rd party based on the inputs and their specific characteristics.
- If a mass balance approach is used in an LCA,
    - Follow the method outlined in Jeswani et al. (2019) to apply the mass balance approach in product-perspective chemical recycling LCAs (Jeswani, Kruger, Kicherer, Antony, & Azapagic, 2019).
    - Calculate and publish results with and without mass balance
    - Report how adding the recycled materials affects the overall environmental burden of the integrated processes

Chapter 10: Waste Feedstocks

Waste quality and composition are important considerations that typically vary with time by geographic location. Specifically, waste quality and composition may vary seasonally, and it is therefore to use at least a full year of data to account for these variations. Regional variations should be accounted for by using data from the region under study if possible, and from a region that is as similar as possible to the region under study.

The current conventional treatment of waste is important when considering alternatives for waste-perspective LCAs and for system expansion in product-perspective LCAs. Since conventional plastics do not anaerobically biodegrade in landfills, the landfilling of conventional plastics produces relatively negligible amounts of greenhouse gases, while the incineration of conventional plastics leads to substantial fossil CO_2 emissions. Post-consumer waste management varies significantly across Europe. For example, ~55% of disposed municipal solid waste in the EU-27 was incinerated in 2020. However, this value ranged from <1% in Croatia to over 99% in Finland, Sweden, and Switzerland (EuroStat, 2023). Therefore, accurate results require consideration of how waste feedstocks are actually managed in the area under study

Recommendations

- Use at least a year’s worth waste quality and composition data for the geographic reference of the study, or a region as similar as possible.
- Determine how the waste feedstock in question is currently managed in the area under study (e.g., split between landfill, incineration with and without energy recovery, secondary fuel use, etc.) and use that for any comparisons or potential credits.

Chapter 11: Impact Assessment Methods and Indicators

EF 3.1 characterisation factors are considered to be the most robust and up-to-date characterisation factors available for the European context. They are widely used and respected within the LCA community, and are required for Product Environmental Footprint studies and Environmental Product Declarations under EN 15804+A2. Studies including North America can also include TRACI v2.1 to see how the results compare to EF 3.1 (EPA, Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI), 2023). Other regions typically do not have widely agreed upon and up-to-date characterization methods, so using the EF 3.1 characterisation factors is a reasonable starting point, but it may be useful to test additional methods to see how it may change the results.

Selection of impact assessment indicators will affect the data that is required to be collected especially related to direct emissions. Global warming potential and non-renewable primary energy demand should be included because of their relevance to climate change and energy efficiency, both of which are strongly interlinked, of high public and institutional interest, and deemed to be the most pressing environmental issues of our time. Eutrophication, acidification, and photochemical ozone creation potentials should be included because they are closely connected to air, soil, and water quality and capture the environmental burdens associated with commonly regulated emissions such as NO_x, SO_2, volatile organic compounds, and others.

It is important when selecting indicators to review their relevance to the product system being assessed and the goals and scope of the study. The robustness of the indicators should also be considered. For example, EN15804 provides a disclaimer for all included toxicity, abiotic resource depletion, and water deprivation indicators that says they "shall be used with care as the uncertainties on these results are high or as there is limited experienced with the indicator." For example, the precision of the current USEtox™ characterisation factors ix within a factor of 100–1,000 for human health and 10–100 for freshwater ecotoxicity (Rosenbaum, et al., 2008).

Recommendations

- Use the latest EF characterisation factors for the European context and use TRACI in a North American context.
- If regions outside of Europe or North America are included in the study, then EF characterisation factors are a reasonable starting point, but it may be beneficial to test additional LCIA methodologies.
- The choice of specific indicators will depend on the study. However, toxicity, resource depletion, and water deprivation indicators should be used with care due to the potential uncertainty. Their use should be more focused on identifying potentially critical processes and flows.

Chapter 12: Scenario, Sensitivity, and Uncertainty Analysis

Given the inherent uncertainty and variability in the assumptions, data, and models, it is necessary to evaluate how this uncertainty and variability affects the results and conclusions. This is done through scenario, sensitivity, and uncertainty analyses. According to ISO 14044 4.5.1.1, the interpretation of the results requires "a sensitivity check of the significant inputs, outputs and methodological choices in order to understand the uncertainty of the results".

Scenario analyses can be considered a subset of sensitivity analysis, but they are unique enough to discussed separately. Scenario analyses test different potential sets of input values or assumptions to explore and understand discrete alternative cases. While ISO 14044 defines sensitivity analysis as "a procedure to determine how changes in data and methodological choices affect the results of the LCIA" (ISO, 2006), we are using it here to focus on how the results change based on changes in input values. They essentially determine how sensitive the results and conclusions are to such changes. By definition, the results are sensitive to changes in critical inputs and are insensitive to changes to less important inputs. As discussed in

Chapter 3, the most common type of sensitivity analysis is one-at-a-time perturbation analysis. This type of analysis would be useful for variables like energy use, process yields, and biogenic C content. For these (or other inputs), this type of perturbation analysis can be used to calculate “breakeven” points. The breakeven point represents the value for an input where two alternatives are equivalent.

Uncertainty analysis is used to understand how the results may vary based on uncertainty in the models, data, and assumptions. Uncertainty analyses can be qualitative or quantitative. A qualitative uncertainty analysis considers the base results, contribution analysis, scenario analysis, and sensitivity analysis and discusses how key uncertainties may affect the results. If robust analyses have been performed, this may be all that is necessary. However, additional quantitative uncertainty may provide additional insights into the study and may be worth exploring. One type of uncertainty analysis is essentially a scenario analysis where reasonable best- and worst-case values are used for each critical variable and assumption (e.g., energy use, product yield, allocation method). Uncertainty propagation is another way to perform uncertainty analyses. This is most commonly done via Monte Carlo analysis. Monte Carlo analysis requires defining statistical distributions for uncertain parameters and re-running the model a large number of times using randomly selected values for each parameter. It is a powerful tool, but, like all models, the value of the results is limited by the quality of the data.

Recommendations

- Test all critical parameters and assumptions in sensitivity and scenario analyses.
- For comparative studies, perform a quantitative uncertainty analysis, either by defining best and worst case scenarios or by performing a Monte Carlo simulation on the most influential and uncertain parameters
    - If some uncertainties are shared between alternatives, run the analysis on the difference between alternatives to avoid the issue of independent sampling.
- Include sensitivity checks as part of the interpretation
    - LCA is an iterative process. The results may indicate that more data should be collected or more scenario, sensitivity, or uncertainty analyses should be performed.

Chapter 13: Consideration of Emerging Technologies.

Chemical recycling consists of many still developing technologies. When considering such technologies in LCA, it is beneficial to consider how those technologies will perform in the future when they are developed and deployed at full scale. This gives a more accurate comparison to mature technologies such as incineration. One way to attempt to quantify the maturity of a technology is through Technology Readiness Level (TRL). TRL assigns a value to the maturity and performance of new technologies to rank and compare them (Mankins, 2009; Rybicka et al., 2016). LCA of an emerging technology at low TRLs (TRL 2–5) is distinct from traditional LCA since the evaluation precedes the product life cycle. Existing guidelines of LCA (ISO, 2006) are suitable to determine environmental burdens of technologies at TRL 7–9 (Gavankar et al., 2015b; Grubb & Bakshi, 2011; Khanna, Bakshi, & Lee, 2008). If the same methodology is applied to evaluate emerging technologies at TRL (2–5), it may be misleading because of changes in scale and maturity of technology.

Piccinno et al. (2016) developed a framework for scaling up LCAs of chemical processes from laboratory to industrial scale. goes on to suggest industrial scale processes to replace lab-scale processes as well as equations and data for scaling inputs for heating, stirring, homogenizing, grinding, filtration and centrifugation, distillation, and drying, and pumping as well as output products, co-products, wastes, emissions, and heat. The data, equations, and recommendations provide a relative robust framework for scaling up many chemical processes.

The uncertainty in scale-up makes the use of robust sensitivity and uncertainty analyses even more important. These analyses are not only necessary for identifying the critical factors in the technology, but also for better understanding how uncertain technological performance can affect comparisons with existing mature technologies. Since emerging technologies are expected to be deployed at full-scale at some future time, it is useful to include scenarios that attempt to represent those future time periods.

Recommendations

- While there is no simple consensus framework for quantifying how differences in TRL between data and models and the system being represented, larger differences imply greater uncertainty that should be documented and considered in the interpretation of the LCA.
- Transparently document at least qualitative differences between the TRL of the data and what is being modeled when discussing Technological Representativeness in the Interpretation of the LCA.
- The scale-up procedure proposed by Piccinno et al. (2016) can be used to scale most chemical processes. Whatever method is used, it should be documented and justified.
- Develop and test scenarios for the time period when the technology is expected to be operational at full-scale. This could include changing the electricity grid, use of biofuels, as well as waste composition.

Chapter 14: Communication of LCA Results

Effective communication of the results of an LCA can be just as important as the effectively performing the study itself. The most important requirement in ISO 14044 section 5 is that an ISO conformant third-party report must be made available whenever LCA are shared with any third party (i.e., other than the LCA commissioner and practitioner). Results of LCAs may be used internally without a report, but it is necessary to back up third-party communications to provide relevant context and background information. ISO 14044 provides detailed reporting requirements that need to be included in the report for each phase of the LCA so that the audience can effectively understand and evaluate the study and results.

While section 5 of ISO 14044 deals with reporting requirements, section 6 addresses requirements associated with critically reviewing an LCA. ISO/TS 14071 (ISO, 2006) contains additional requirements and guidance on the critical review process and reviewer competencies. A critical review is the only way to ensure that an LCA conforms to ISO 14044, and while it may not be strictly required in all circumstances, it is highly recommended that all LCA reports be reviewed by an independent external expert to add credibility to the report. LCA studies that are intended to be support comparative assertions intended to be released to the public, which includes most LCAs of chemical recycling, are required to be reviewed by an external panel of at least three independent experts that have combined domain and LCA expertise. It should be noted that footprint studies cannot support comparative assertions as they consider only one environmental impact category (ISO, 2017).

Recommendations

- Be as transparent as possible in documenting models, data, and assumptions and their potential effects on the results and conclusions.
- Follow section 5 of ISO 14044 when developing LCA reports.
- All LCA reports should be critically reviewed by least one independent expert.
- Follow section 6 of ISO 14044 and ISO/TS 14071 when performing critical reviews.

1. Background

In 2022, ~32 million metric tons of post-consumer plastic waste was generated in Europe, and ~27% of this material was collected and mechanically recycled, while <0.2 metric tons were chemically recycled (PlasticsEurope, 2024). The remainder was incinerated or disposed in landfills. Conventional mechanical recycling is limited by participation, availability of markets, contamination, and resin purity. Therefore, significant improvements in the circularity of plastics will require further development and implementation advanced chemical recycling technologies that are capable of recycling polymers and plastic waste that cannot readily be or are not being mechanically recycled.

Chemical Recycling Europe (CRE) defines chemical recycling as “any reprocessing technology that directly affects either the formulation of the polymeric waste or the polymer itself and converts them into chemical substances and/or products whether for the original or other purposes, excluding energy recovery” (CRE, 2019), which is the definition be used in this report. This definition is broader but generally consistent with ISO 15270:2008, which defines chemical recycling as “the conversion to monomer or production of new raw materials by changing the chemical structure of plastic waste through cracking, gasification or depolymerization, excluding energy recovery and incineration” (ISO, 2008). The primary technologies used for chemical recycling include pyrolysis, gasification, hydrothermal conversion, solvolysis, and depolymerization.

Given the potential uncertainty in novel recycling methods, it is important to fully understand the potential environmental performance of these technologies compared to conventional product manufacturing and waste management processes. Life cycle assessment (LCA) is a framework for evaluating the resource use, emissions, and potential environmental impacts associated with a product system throughout its entire life cycle from raw material extraction through manufacturing, distribution, use, and end-of-life. LCA has been applied to many chemical recycling applications, and these studies have shown a wide variability in results due to differences in their goal and scope definitions, modeling and allocation methodologies, assumptions, and other choices that must be made when performing LCAs of chemical recycling technologies (Sphera, 2020). A standard set of guidelines is necessary to ensure that LCAs provide consistent and meaningful results that can be used to improve decision-making.

Therefore, the purpose of this document is to review and provide guidance for the critical aspects related to LCAs in the chemical recycling. These critical aspects were identified by CRE and Sphera at the beginning of the project, and this guidance provides recommendations for approaching each of them. The next chapter provides a brief introduction to LCA, and the rest of the chapters discuss specific aspects of chemical recycling LCAs. Each chapter outlines the issue at hand, presents alternatives, and provides recommendations for addressing the issue. The recommendations are relatively flexible so they can be readily applied by practitioners developing chemical recycling LCAs for a variety of applications. These guidelines can then serve as a framework for developing consistent life cycle studies that provide constructive and actionable insights.

As part of creating meaningful LCA guidance, it is important to ensure that the guidance conforms to the appropriate standards. The most critical of these is ISO 14044 (ISO, 2006), which describes the requirements and guidelines for completing LCAs. Depending on the goal and scope of the study, other standards may also be important. For example, ISO 14067 (ISO, 2018) and ISO 14046 (ISO, 2014) cover guidelines for performing carbon and water footprints, respectively. If the study is going to be used as part of environmental product declaration, then conforming to ISO 21930 (ISO, 2017) or EN 15804 (CEN, 2012) are essential. If the LCA is going to be used for comparative marketing purposes in Europe, then ISO 14026 (ISO, 2017) and the proposed EU Green Claims Directive (European Commission, 2023) should be followed, and it may become necessary to follow the European Commission’s Product Environmental Footprint (PEF) (European Commission, 2017) standards. Potential issues with standard conformance will be addressed where relevant.

2. Introduction to LCA

The purpose of this chapter is to provide an overview of LCA including the key relevant issues that will be discussed in the following chapters. LCA is a framework for estimating the material and energy inputs and outputs and potential environmental impacts from a product system over its entire life cycle. In this report, we will be focused on LCAs of products produced from chemical recycling and associated waste treatment systems.

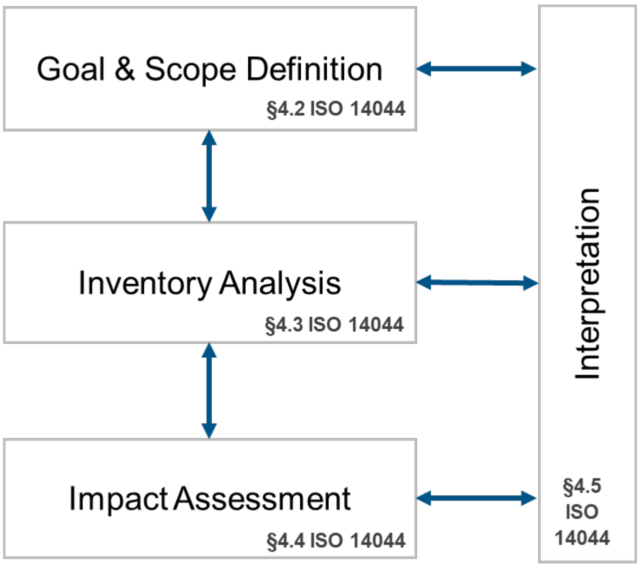


Figure 2-1: LCA phases as defined by ISO 14040 (ISO, 2006).

ISO 14044 defines four phases of LCA as shown in Figure 2-1. Figure 2-1: LCA phases as defined by ISO 14040 (ISO, 2006). LCAs begin by defining the goal and the scope of the analysis. This includes, among others, identifying the functional unit and all the associated processes within the system boundary. The Life Cycle Inventory (LCI) Analysis phase then quantifies all material and energy inputs and outputs for each process. These inputs and outputs are then aggregated to estimate all the resources removed from the environment as well as the emissions to the environment over the entire life cycle. These aggregated resource use and environmental emissions are then used to estimate potential environmental impacts in the Life Cycle Impact Assessment (LCIA) phase. Finally, the results of the analysis are interpreted to develop conclusions, limitations, and recommendations for the study. However, it should be noted that LCA is an iterative process, and it is often necessary to revisit and update previously completed phases based on the findings of a subsequent phase. In the following sections, we will describe each of the phases in more detail including issues that are relevant to chemical recycling LCAs.

2.1. Goal Definition

The first step in an LCA is to define the goal of the study, which includes descriptions of each of the following according to ISO:14044 (ISO, 2006):

- Objectives: What is the purpose of the study?
- Motivation: Reasons for carrying out the study?
- Intended application: What will the study be used for?
- Intended audience: Who will the results of the study be communicated to?
- Comparative assertions: Whether the results are "intended to be used in comparative assertions intended to be disclosed to the public."

For chemical recycling LCAs in particular, it is also during the goal definition where you would determine whether the study should take a waste or product perspective. Chemical recycling has two functions: treating waste and creating a product, and LCAs of chemical recycling can therefore be carried out from either perspective. An LCA taking a waste perspective would compare chemical recycling to other waste management alternatives (e.g., incineration or landfill), while an LCA taking a product perspective would compare the production of a material or product via chemical recycling to conventional means of producing that material or product (Figure 2-2).

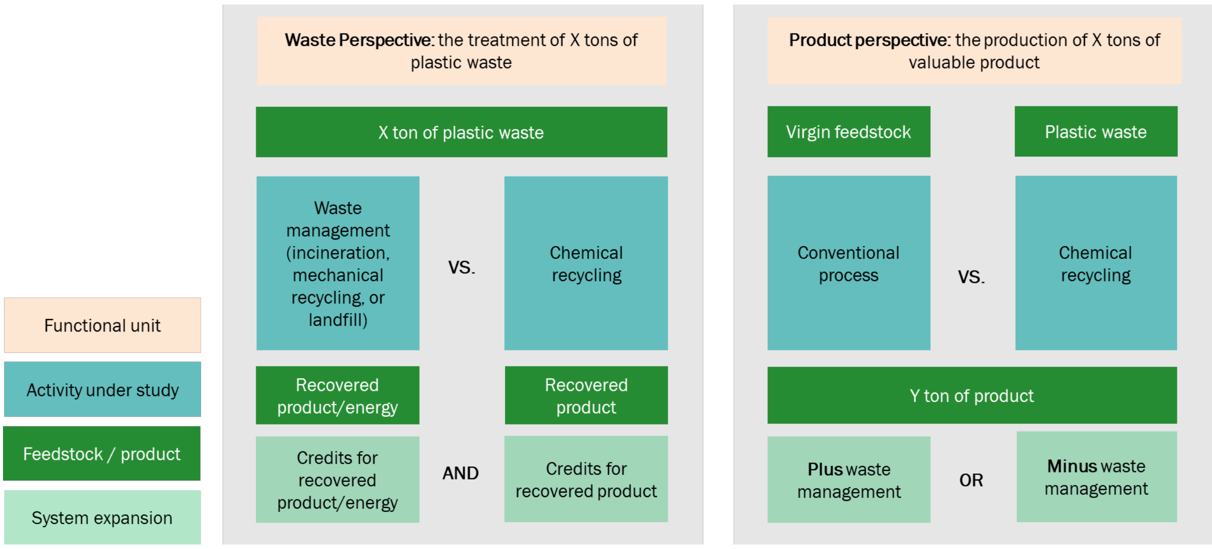


Figure 2-2: Explanation of using a waste or product perspective in an LCA (Sphera, 2020)

Multi-functionality exists in both perspectives and is generally addressed via system expansion. In the waste perspective, recovered products/energies are addressed via substitution of functionally equivalent counterparts from primary sources (e.g., thermal energy from natural gas, virgin monomer/polymer). In the product perspective, multi-functionality is either addressed by adding the conventional waste management function to the conventional product system or by subtracting it from the chemical recycling product system (see chapter 3 for details).

2.2. Scope Definition

After defining the goal of the study, the scope is defined next. The most critical aspects of the scope definition include defining and describing the product systems to be compared, the function of those systems, the resulting functional unit to be used as a quantitative basis of comparison, and the system boundary.

2.2.1. Product systems

The first step of defining the scope of the study is to define the product systems that are under consideration. This typically includes a brief description of the products including key performance characteristics. Images of the products or stylized process diagrams may be used to give the reader a better understanding of the products or systems being compared.

Note that ISO 14040 defines a "product" to be a good or a service, as such, both waste management (service) and production of a material (good) are eligible product systems as outlined above.

2.2.2. Functions and functional unit

After the product systems have been described, the function and functional unit must be defined. Example functions for chemical recycling LCAs include the management of mixed plastic waste and/or the production of a recycled polymer or other chemical. The functional unit then provides a quantitative basis of comparison for the functions described. The functional unit always includes a magnitude and unit. There should also be a description of any other critical performance characteristics (e.g., food grade for plastic film). Specifying the duration may also be necessary if the product systems have different lifetimes (e.g., a single use bottle versus a reusable bottle).

Therefore, a functional unit for a chemical recycling LCA taking a waste perspective may be the treatment of 1 metric ton of mixed plastic waste with a specified composition. An LCA taking a product perspective might have a functional unit of the production of 1 metric ton of food grade PE film or 330 ml food grade beverage containers capable of carrying 1,000 L of water over two years. The latter functional unit could potentially be used to compare chemically recycled polyethylene terephthalate (PET) bottles to conventional reusable bottles or other portable beverage packaging. The functional unit is then used to develop the reference flows for each product system that represent the materials and energies required to provide the functional unit. In non-comparative LCAs (e.g., EPDs) a declared unit may be used that is the same as the reference flow. The correct declared unit to use will be specified in the product category rules (PCR).

When a system has multiple functions, such as treating waste and producing a product, then it is possible to have multiple functional units to account for these multiple functions. This approach of using multiple functional units is required when using system expansion via addition, which is be further discussed in Chapter 4, while issues specific to functional units of chemical recycling studies are further explored in Chapter 5.

2.2.3. System boundary

Defining the system boundary is the next step in the scope definition. The system boundary determines the processes that will be included in the study, and it should be consistent with the goal of the study. The system boundary is often illustrated using a process flow diagram that clearly illustrates the major processes or life cycle phases within the system boundary. For LCAs with a product perspective, there are two primary types of system boundaries: cradle-to-gate and cradle-to-grave. In these instances, the term “cradle” refers to raw material extraction, the term “gate” refers to the production gate of a facility, and the term “grave” refers to end-of-life treatment, recycling, and final disposal.

A cradle-to-grave LCA includes every stage of a product’s life cycle from raw material extraction, manufacturing, distribution, use, and end-of-life, while a cradle-to-gate LCA ends once the product is manufactured and packaged (at shipping gate). It should be noted that, in principle, LCAs are meant to be cradle-to-grave, and the omission of life cycle stages “is only permitted if it does not significantly change the overall conclusions of the study” (ISO 14044, Section 4.2.3.3.1) (ISO, 2006). If the omission of the distribution, use, and/or end-of-life stages cannot be justified, then the study should be called a “cradle-to-gate study” rather than a “life cycle assessment” (see also ISO 14040, section 3.2, and Annex A, section A.1.2). It is also common to see cradle-to-gate LCAs that include EoL and only exclude the use stage. LCAs with a waste perspective do not easily fit into either of these types of system boundaries. So, phrases like “bin-to-grave” or “gate-to-grave” are often used to describe those studies. However, they can also be seen as cradle-to-grave studies where the waste input is free of upstream burdens.

As part of developing the system boundary, it is necessary to define the temporal, technological, and geographical coverage of the study. Depending on the system under study, the time horizon (e.g., the time over which impacts are considered) may be an important part of the temporal coverage. It should be noted, that when defining the scope of the study, these definitions are meant to describe the intended coverage based on the goal of the study. How well the study actually represents the intended coverage should be evaluated in a data quality assessment during the Interpretation phase.

Issues specific to the system boundary of chemical recycling LCAs will be explored in Chapter 5.

2.2.4. Attributional versus Consequential LCA

When defining the scope of the study, one can choose between two forms of LCA: attributional and consequential. Attributional is the original and more common form of LCA. This type of LCA attributes a certain share of the global impacts to a defined functional unit. These global impacts are assumed to be a static snapshot in time, and processes interact strictly via physical flows (e.g., mass or energy). For example, one could compare the environmental impacts associated chemical recycling to those of waste incineration by attributing impacts to a functional unit of the treatment of 1,000 kg of mixed plastic waste using an attributional approach.

Alternatively, consequential LCA assesses how global impacts may change due to a marginal change in the supply or demand of the functional unit. This form of LCA looks at the consequences of choices between alternatives, and processes may interact via cause-effect relationships. Understanding these causal relationships requires quantitative analysis of how markets will react to changes (e.g., econometric models, system dynamics, partial or general equilibrium models). For example, one could evaluate the case where there is a new market of PET bottles produced from chemical recycling and compare that to the case where no such market exists. The study would need to include predictions of the supply and demand of other products would change due to the existence of this new market. Consequential LCAs therefore require significantly more time, data, and modeling effort than similar attributional LCAs and introduce additional uncertainties in the process. Therefore, attributional LCA should be default type of LCA performed.

2.2.5. Allocation

Multi-output allocation

Many production processes produce more than one product (e.g., waste sorting, pyrolysis, and steam cracking). When this occurs, it is necessary to partition the inputs and outputs of the process to each of these products. In these situations, ISO 14044 first recommends avoiding allocation by either system expansion or dividing the original process into single product sub-processes. If allocation cannot be avoided, then allocation should preferentially be based on physical relationships between the inputs, outputs, and products (e.g., mass, energy content, C content). Carbon content is the typically the ideal choice for chemical recycling outputs, but it is useful to test at least two methods to see how they may affect the results and conclusions. Allocation based on other relationships may also be used (e.g., economic value). Allocating based on economic value places more of the burdens of production and the more valuable products based on the idea that they are more responsible for emissions because the revenue they provide is a bigger driver of the activity.

Multi-functional allocation

Multi-functional allocation is closely related to multi-output allocation. The main difference is that while multi-output allocation deals with two or more physical goods (i.e., mass or energy product flows), a multi-functional process or product system can provide multiple functions in the form of one or more physical goods and one or more services. For LCA studies of recycling technologies, in particular, this means that the service of waste management (function #1) is combined with the production of a physical secondary product (function #2). Since neither subdivision nor co-product allocation are possible for such a combination, system expansion is the most common way to address this situation (see chapter 3 for further details).

EOL allocation

Another important type of allocation is deciding how burdens and credits associated with recycling or energy recovery at end-of-life should be handled.

One can distinguish two main approaches to accounting for end-of-life recycling and recycled content.

- Cut-off approach (also known as 100:0 or recycled content approach) – burdens or credits associated with material from previous or subsequent life cycles are not considered i.e., are “cut off”. Therefore, waste input to the production process is free of upstream virgin material burdens but, equally, no credit is received for material available for recycling at end of life. This approach rewards the use of recycled content but does not reward end of life recycling.

- Substitution approach (also known as 0:100 or end of life approach) – this approach is based on the perspective that material that is recycled into secondary material at end of life is technically able to substitute virgin material. Hence, a credit is given to account for this substitutability which represents the market-average burden of the substituted virgin material. To avoid double counting the benefits of recycled content, waste materials collected for recycling in EoL are first used to satisfy the recycled content demand of the manufacturing phase before being sent to recycling and crediting in EoL. This 'net scrap' approach rewards both end of life recycling as well as the use of recycled content. In open-loop recycling situations where the recycled material substitutes a different material, the substituted material burden is credited. Down- and upcycling can be factored in by using substitution rates smaller or larger 100%.

Alternatively, the Circular Footprint Formula (CFF) method developed as part of the Product Environmental Footprint Category Rules Guidance (European Commission, 2017) defines an allocation between the cut-off and substitution approaches with the aim of describing market realities to accurately balance credits and burdens associated with end-of-life recycling and the use of recycled content.

2.2.6. Other Considerations

In addition to the previously discussed items, ISO 14044, Section 4.2.3.1 also requires that the following items be "considered and clearly described":

- LCIA methodology and types of impacts – what impact categories are included?
- Interpretation to be used – how will the results be interpreted?
- Assumptions and limitations – what assumptions have been made and how may they or other issues limit the applicability of the study?
- Data and data quality requirements – what data is required and of what quality?
- Type and format of the report – what form of report is to be produced?
- Type of critical review, if any; briefly describe the critical review process, if any

2.3. Inventory Analysis

The inventory analysis phase is where the inputs and outputs (e.g., materials, emissions, energy) from every process within the system boundary are quantified and documented. Data collection and modeling occur during the inventory analysis, and it therefore typically consumes more time and resources than the other LCA phases. The LCI should be consistent with the defined goal and scope, and a well-defined goal and scope can make the LCI phase easier by providing clear guidance on what needs to be done when collecting data and developing models. A critical aspect of the LCI is data collection, the requirements of which will vary for the defined foreground and background system.

2.3.1. Foreground and background system

LCI models can conceptually be divided into a foreground and a background system. The foreground system represents the primary focus of the study. These are often the processes directly under operational/financial control of the study commissioner, and they should additionally consider processes that are specific to the product system under study. For example, waste collection and sorting, pyrolysis, and pyrolysis oil processing to provide a recycled alternative to naphtha would be part of the foreground system in many chemical recycling LCAs. Alternatively, the background system represents the necessary processes and flows of materials in the rest of the technosphere not represented by the foreground system. In chemical recycling LCAs, this could be the necessary raw material, fuel, and energy inputs into the system to process the waste into pyrolysis. Therefore, the study commissioner typically has a level of control over the foreground system that they do not have for the background system.

2.3.2. Data Collection

A substantial part of the time and effort of the inventory analysis is spent in data collection. Ideally, primary data that is measured or estimated by the study commissioner or process operator is used for the foreground system. Primary data collection is often informed by qualitative descriptions and flowcharts for product production and quantitative measurements or estimates of the inputs and outputs of material, energy, water, and emissions. Collecting this primary data requires input from domain experts. Secondary data from LCI databases, LCA reports, or peer-reviewed literature is typically used for the background system.

2.4. Impact Assessment

2.4.1. Impact Assessment Procedure

Life cycle impact assessment (LCIA) uses the results of the LCI to calculate the potential environmental impacts associated with the functional unit. It consists of three required elements and three optional elements as shown in Table 2-1. However, besides selecting the methodology and impacts to use during the scope definition, classification and characterization are generally completed by existing LCA software and databases without much user input. Additional choices can be made with regard to normalization, grouping, and weighting to improve interpretation and understanding of the results. It should be noted that weighting is prohibited in comparative LCAs intended to be released to the public by ISO 14044. Additionally, LCIA results are relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

Table 2-1: Required and optional elements of LCIA

Required Elements	
Selection	Select the impact categories, category indicators and characterization models
Classification	Assign the LCI results to impact categories
Characterization	Calculate the category indicator results
Optional Elements	
Normalization	Calculate the relative magnitude of the impact relative to a reference
Grouping	Sort or rank impacts (e.g., by location or severity)
Weighting	Use value-choices to convert and possibly aggregate impact results (e.g., monetary damage)

2.4.2. Impact Assessment Frameworks and Categories

There are numerous impact assessment frameworks with pre-defined characterization factors that are implemented in LCA software including e.g. Environmental Footprint v3.1 (EF 3.1), CML, ReCiPe and TRACI v2.2 (JRC, 2010)The different frameworks are applicable to different regions, include different impact categories, and may use different calculation methodologies and units. The EF methodology was originally based on the ILCD recommended methods (Hauschild M, 2011), but several have since been modified and updated by the European Commission as part of the on-going development of the Product Environmental Footprint initiative. EF 3.1 characterisation factors are considered to be the most robust and up-to-date available for the European context, are widely used and respected within the LCA community, and are required for Product Environmental Footprint studies and Environmental Product Declarations under EN 15804+A2.Table 2-2 provides a description of common impact categories and example methods used to evaluate them for the European context. TRACI 2.2 is recommended for North America as it is the only impact assessment methodology framework that incorporates US average conditions to establish characterization factors. For impact categories where TRACI characterization factors are not available (e.g., water footprinting) or where they are not considered to be the most current (e.g., global warming potential), the methods described in Table 2-2 may be used.

There is ongoing research related to impacts associated with microplastic pollution, however, there is still significant uncertainty in these methods, and finding or developing the necessary inventory data is difficult (Maga, et al., 2022) (Schwarts, et al., 2024) (Pellengahr F, 2025).

Table 2-2: Impact category descriptions

Impact Category	Description	Unit	Reference
Climate change (global warming potential)	A measure of greenhouse gas emissions, such as CO_2 and methane. These emissions are causing an increase in the absorption of radiation emitted by the earth, increasing the natural greenhouse effect. This may in turn have adverse impacts on ecosystem health, human health and material welfare.	kg CO_2 equivalent (eq.)	(IPCC, 2013)
Acidification Potential	A measure of emissions that cause acidifying effects to the environment. The acidification potential is a measure of a molecule's capacity to increase the hydrogen ion (H^+) concentration in the presence of water, thus decreasing the pH value. Potential effects include fish mortality, forest decline and the deterioration of building materials.	moles H^+ eq.	(Seppälä J., 2006; Posch, 2008)
Eutrophication (terrestrial [T], freshwater [F], marine [M])	Eutrophication covers all potential impacts of excessively high levels of macronutrients, the most important of which nitrogen (N) and phosphorus (P). Nutrient enrichment may cause an undesirable shift in species composition and elevated biomass production in both aquatic and terrestrial ecosystems. In aquatic ecosystems increased biomass production may lead to depressed oxygen levels, because of the additional consumption of oxygen in biomass decomposition.	T: moles N eq. F: kg P eq. M: kg N eq.	(Seppälä J., 2006; Posch, 2008; Struijs, 2009)
Ozone Depletion	A measure of air emissions that contribute to the depletion of the stratospheric ozone layer. Depletion of the ozone leads to higher levels of UVB ultraviolet rays reaching the earth's surface with detrimental effects on humans and plants.	kg CFC-11 eq.	(Guinée, et al., 2002)
Photochemical Ozone Formation	A measure of emissions of precursors that contribute to ground level smog formation (mainly ozone O_3), produced by the reaction of volatile organic compounds and carbon monoxide in the presence of nitrogen oxides under the influence of UV light. Ground level ozone may be injurious to human health and ecosystems and may also damage crops.	kg C_2H_4 eq.	(Van Zelm R., 441-453)
Resource use, minerals and metals	The consumption of non-renewable resources leads to a decrease in the future availability of the functions supplied by these resources. Depletion of mineral resources and non-renewable energy resources are reported separately. Depletion of mineral resources is assessed based on ultimate reserves.	kg Sb eq.	(Guinée, et al., 2002)

Impact Category	Description	Unit	Reference
Resource use, energy carriers	A measure of the total amount of non-renewable primary energy extracted from the earth. Resource use is expressed in energy demand from non-renewable resources including both fossil sources (e.g. petroleum, natural gas, etc.) and uranium for nuclear fuel. Efficiencies in energy conversion (e.g. power, heat, steam, etc.) are taken into account.	MJ eq. (net calorific value)	(Guinée, et al., 2002; van Oers, de Koning, Guinée, & Huppes, 2002)
Respiratory inorganics	Particulate matter emissions and secondary aerosols formed in the atmosphere from NOx, NH3 and SO2 emissions contribute to human health impacts in the form of respiratory disease and related effects.	Disease incidence	(Fantke, 2016)
Human toxicity/ Eco-toxicity	A measure of toxic emissions which are directly harmful to the health of humans and other species.	Comparative toxic units (CTU_h, CTU_e)	(Rosenbaum, et al., 2008)
Water Use	An assessment of water scarcity accounting for the net intake and release of fresh water across the life of the product system considering the availability of water in different regions.	Litres of water eq.	(Boulay, 2017)

2.5. Scenario, Sensitivity, and Uncertainty Analysis

After first LCIA results are calculated, it is useful to conduct additional analyses to better understand how key assumptions and uncertainty in data and models may affect the results and conclusions. Comparative LCAs intending to be released to public are required to include “an analysis of results for sensitivity and uncertainty” according to ISO 14044, Section 4.4.5 and 5.3.1.

2.5.1. Scenario Analyses

Scenario analyses are used to assess the effects of sets of discrete values or alternatives on the results, i.e., scenarios can differ from each other in more than one way. Scenario analyses can be used to explore how different situations or methodological choices affect the results and conclusions. For example, one could only change the electricity grid mix or the choice of allocation methodology, or one could change multiple parameters and choices at the same time to represent a specific situation.

2.5.2. Sensitivity Analyses

Sensitivity analyses effectively attempt to assess how robust the results and conclusions are to changes in critical parameter values. The most commonly used method of sensitivity analysis is one-at-a-time perturbation analyses, where the results are recalculated as a parameter is varied from some minimum to maximum value. These results can then be plotted and/or used to calculate a sensitivity ratio, which is the ratio of the percent change in the result to the percent change in the parameter. If the relationship between the parameter and results is linear, then the sensitivity ratio is a constant value. However, if the relationship is nonlinear, then the sensitivity ratio will be a function of the parameter. If there are parameters that are known act together non-linearly (e.g., they are multiplied or divided by one another), then two-at-a-time perturbation analyses can be employed and the results shown on contour plots.

2.5.3. Uncertainty Analyses

The purpose of uncertainty analysis is to understand how uncertainty in the models, data, and assumptions may affects the results and the robustness of the conclusions. This can consist of quantitative uncertainty propagation such Monte Carlo analysis. Monte Carlo analysis requires additional information on the parameters used in the model. Monte Carlo analysis requires statistical distributions for each of the parameters, while interval analysis simply requires minimum and maximum values. Monte Carlo analysis then reruns the calculations using random values selected from the provided statistical distributions of the parameters to develop distributions of the result values. One way to implement an interval analysis is to develop best and worst case scenarios for each alternative product system and then calculate the results for each scenario. I

2.6. Interpretation

There are three primary elements of the interpretation phase of LCA:

- Identify significant issues
- Evaluate completeness, sensitivity, and consistency
- Provide conclusions, limitations, and recommendations

Identifying significant issues essentially consists of reviewing the LCI and LCIA results to determine those that are most important to the defined goal and scope. For example, this could include comparisons of the GWP or other impact assessment results for each of the alternatives as well as the key contributing factors to those results. Evaluating the completeness, sensitivity, and consistency begins with determining whether all the necessary information needed for the interpretation are available. The sensitivity check assesses the robustness of the results based on how they may be affected by uncertainties in data, models, and assumptions, and it is informed by the scenario, sensitivity, and uncertainty analyses. Finally, conclusions, limitations, and recommendations are developed based on a holistic evaluation of the previous elements of the interpretation and the previous phases of the LCA.

2.7. Reporting and Critical Review

According to ISO 14044, clause 5.2, if the results of an LCA are to be communicated to a third party, a third-party report must be prepared. The report should completely and accurately document how the study was performed as well as its results and conclusions, as specified by the reporting requirements in ISO 14044, clause 5.2. The report should document the study in sufficient detail to readily facilitate comprehension of all the trade-offs and complexities involved in the LCA.

Additionally, if the LCA is meant to support comparative assertions to be disclosed to the public, then a critical review by a panel of at least three independent experts must be performed. Non-comparative LCAs do not require a critical review. However, an independent critical review by one of more experts is the only mechanism to independently confirm the conformity of the study with the ISO 14044 standard, and therefore performing a critical review improves the credibility of any LCA study.

2.8. Capabilities and Limitations

LCA is a powerful tool for assessing the potential environmental impacts of product systems, and it can be used to identify potential "hot spots" and areas for improvement. The holistic nature of LCAs also helps to avoid burden-shifting and identify unintended negative consequences of decisions. However, LCA is not a one-size-fits-all tool for quantitative assessment of environmental sustainability, and there are critical limitations. For instance, LCA cannot

- assess all relevant environmental issues;
- predict actual or precise environmental impacts;
- predict the exceeding of thresholds, safety margins, or risks; or
- predict market responses to changes in production or consumption.

Therefore, LCA must be combined with additional knowledge, tools, and analyses to overcome these limitations when necessary.

3. System Expansion

All mechanical and chemical recycling systems have multiple functions: treating a waste stream and producing a product. These multiple functions must therefore be properly accounted for when defining the functional unit(s) and system boundary for the LCA. There are two methods for handling this system expansion: addition and subtraction as shown in Figure 3-1.

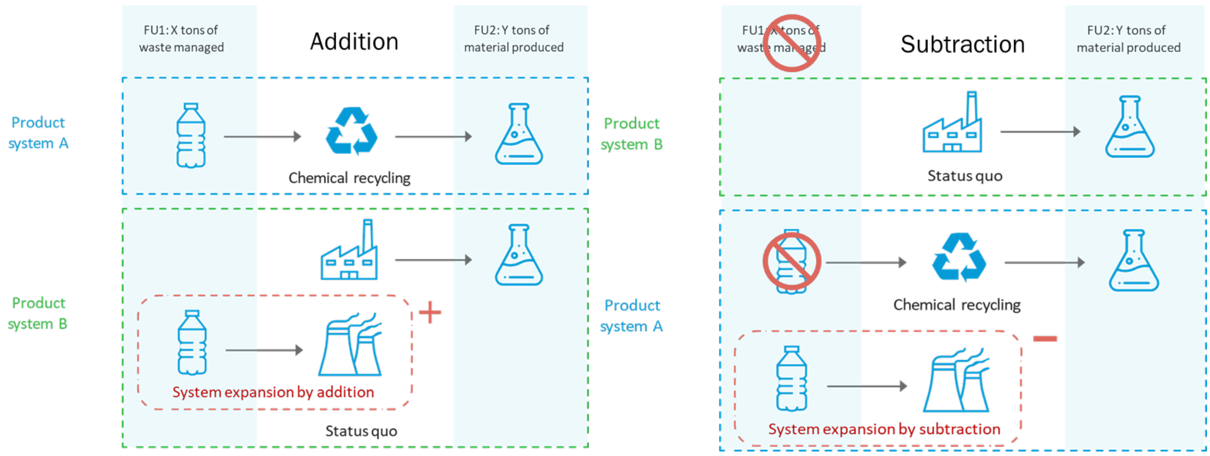


Figure 3-1: Comparison of system expansion by addition and subtraction from a product perspective, adapted from Koffler et al. (2021).

3.1. Additive and Subtractive System Expansion

When using an additive approach to system expansion, two functions and functional units are defined. The first function is the production of a material or product, and the associated functional unit is, for example, 1 metric ton of food grade PET granulate. The additional functional unit would therefore be the amount of waste managed to produce that 1 metric ton of PET. The chemical recycling process inherently provides both functions, but the treatment of the associated waste would need to be added to the conventional alternative for producing PET. This is the approach recommended by Sphera (Sphera, 2021).

When using a subtractive approach to system expansion, only one function and functional unit is defined. This function is the production of a material or product, and a functional unit could be, for example, 1 metric ton of food grade PET granulate. The treatment of waste is handled by subtracting the inventory associated with conventional waste management from the chemical recycling alternative. The conventional system is then modeled as-is with no further consideration of alternative waste management. While a “cut-off” approach that excludes these credits is the first choice for EoL allocation according to the TfS guidelines, they do accept the use of “upstream system expansion” in exceptional cases that fulfill the following criteria (TfS, 2024):

- Showing a societal benefit in form of overall reduced GHG emissions in comparison to relevant other available treatment methods.
- Being a new technology with high likelihood of improvement of efficiencies after commercial scale up.
- Ensuring the use of regularly updated data according to the TfS guideline.
- Market for the alternative waste treatments is known, the requirements shall be clearly defined.
- ISO compliant substitution approach is applied, the exact use of the waste is known.

- Substitution shall only be applied if the alternative treatment directly replaces the final disposal, and the process is therefore reduced through provision of the co-product.
- Data about the impact of the alternative production process needs to be obtained to calculate the PCF of the alternative product and compare it to the system under study.
- A clear description of the process for selecting the final EoL option substituted by chemical recycling shall be documented.

However, the default approach by TfS is “cut-off”, where such credits would not be applied at all (TfS, 2024). Therefore, it is useful to present results in such a way that the credits can be applied or excluded as necessary.

3.2. Pros and Cons of Each Type of System Expansion

Table 3-1 summarizes the pros and cons of each approach. The primary benefit of the additive approach is that it cannot lead to net-negative LCIA results which are not very meaningful in attributional LCAs unless, for example, there are negative emissions a.k.a. permanent removals of CO_2 from the atmosphere. LCAs with net-negative results due to this sort of system expansion are often met with criticism (Zero Waste Europe, 2020) (Keller, Voss, & Lee, 2022) because the results are primarily the outcome of an accounting choice which aims at calculating the difference between a product system with and without chemical recycling rather than the absolute footprint of chemical recycling.

Table 3-1: Pros and cons of additive and subtractive system expansion

	Addition	Subtraction
Pros	✓ No negative footprint results ✓ More meaningful relative comparisons ✓ Accepted for EPDs and PEFs	✓ Mono-functional, so results can “stand alone” ✓ Results can be directly compared to the conventional product by itself ✓ Communication is easier ✓ Accepted by TfS in “exceptional cases”
Cons	× Multi-functional, so possibly more difficult to communicate × Misleading when compared to just the conventional product by itself	× Negative footprint results are possible × Less meaningful relative comparisons × Not accepted for EPDs or PEFs

The primary benefit of the subtractive approach is that the results of the recycled material can be directly compared to the results for conventional material production. When using an additive approach, the conventional waste management always needs to be added to the conventional material production, which makes comparisons and communication of results less straightforward. On the other hand, additive system expansion ensures that relative comparisons to the conventional product system are more meaningful. As can be seen from Figure 3-2, the percentage difference between product system A (here: chemical recycling) vs. the additive product system B+C (here: conventional material production B plus conventional waste management C) is -50%. If one instead subtracted C from A, the percentage reduction would increase to -67% and can, in the event of net-negative results for A-B, even exceed -100%. Since these relative comparisons are less meaningful, it is best to avoid them where possible. However, in LCAs generally, relative comparisons are more meaningful. It is much easier to interpret a 34% reduction in climate change impact than it is to interpret a reduction of 0.56 kg CO_2 eq. So, removing obscuring the meaning of relative comparisons is a substantial downside to the use of subtractive system expansion. However, reporting relative comparisons of total burdens excluding credits is still useful and can potentially help overcome this limitation.

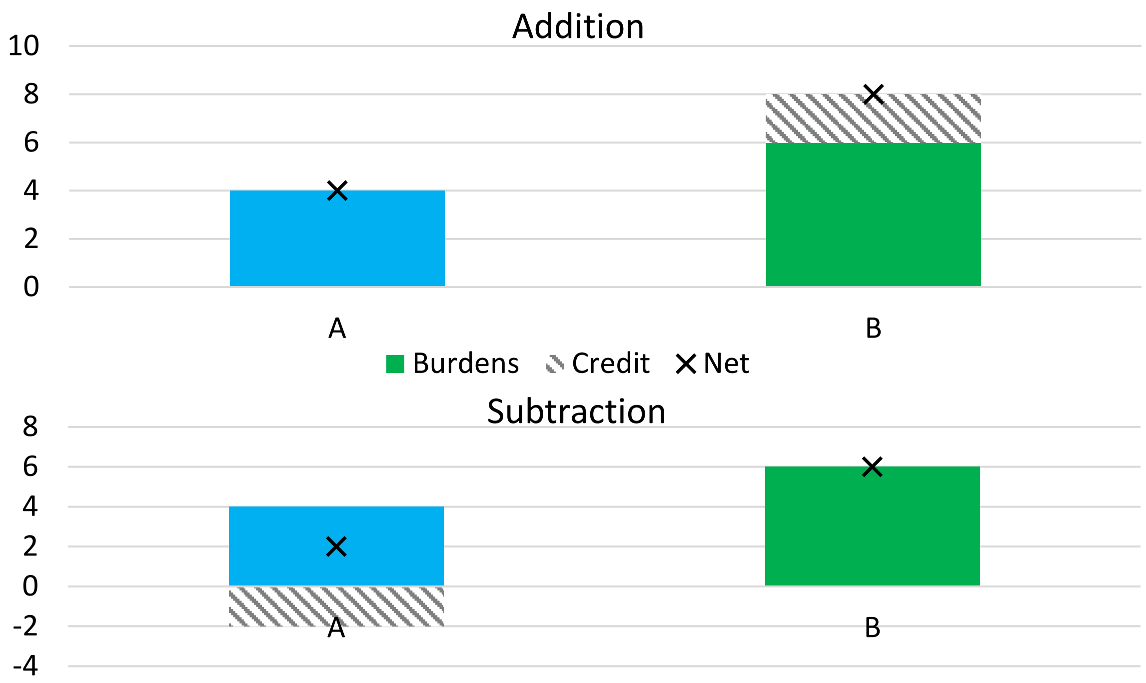


Figure 3-2: Exemplary difference between additive and subtractive system expansion

Accordingly, LCAs using subtractive credits are currently not accepted for Type III Environmental Declarations in accordance with ISO 14025 (ISO, 2006) or Product Environmental Footprints (PEFs) (Damiani, 2022). However, even though such declarations are inherently non-comparative, there is a risk that an EPD, LCA, or PCF of a chemically recycled product will be compared to its conventional counterpart without considering the additional waste management function. This risk could be mitigated by including the results of a complete comparison in the Additional Environmental Information section of an EPD while providing a link to the comparative third-party report as required by ISO 14044, clause 5.2 (ISO, 2006).

3.3. Recommendations

- Clearly describe and justify the choice of status quo waste management alternatives.
- To provide transparency in reports when presenting system expansion results, include a breakdown of the impacts from the chemical recycling process itself from the those associated with the waste management status quo. This allows the credits to be added, subtracted, or excluded completely depending on study requirements.
- If using subtractive system expansion,
    - Clearly explain the source and meaning of any reported negative values.
    - Avoid reporting relative percent differences between alternatives and instead focus on the absolute differences between them.
    - Avoid claiming that products produced via chemical recycling have negative environmental burdens; instead focus on absolute changes in impact values when comparing alternatives.

4. Functional Units

As described in chapter 2, the functional unit quantifies the relevant performance of product systems and provides the quantitative basis of comparison in the form of reference flows. It is important that all the selected alternatives can be assessed using the same functional unit. The specifics of defining the functional unit in a chemical recycling LCA will depend on whether the study takes a waste or product perspective as well as whether it takes an additive or subtractive approach to system expansion. While most chemical recycling LCAs will choose one of these perspectives, there can be situations where using both perspectives could provide additional insights (Keller, Voss, & Lee, 2022).

4.1. Waste Perspective

LCAs of chemical recycling that take a waste perspective use the treatment of a set mass of waste of a specified composition including impurities/contamination. For example, it could be 1 kg of mixed plastic waste (e.g., (Jeswani, et al., 2021), (Schwartz, et al., 2021), (Meys, Kätelhön, & Bardow, 2019), and (CE-Delft, 2020)) or 1 metric ton of waste tyres (Banar, 2015). The most critical part of the defining the functional unit for waste perspective LCAs is to clearly state the source and composition of the waste because alternative technologies that treat other waste streams may not be comparable. Consistent specifications on waste composition are essential to have comparable systems.

4.2. Product Perspective

As discussed in Chapter 3, the choice of functional unit when taking a product perspective, whether for an intermediate chemical, a monomer, a polymer, or an end-use product like film packaging, will depend on whether an additive or subtractive system expansion approach is being employed. If additive system expansion is being used, then two functional units must be defined. The first for the material or product being produced and the second for the associated waste that is being managed to produce the material or product. For example, the Consumer Goods Forum commissioned an LCA of food grade PE/PP film from chemical recycling and used a functional unit of "1 tonne of food grade film (equal mix of polyethylene [PE]/polypropylene [PP]) produced and the corresponding amount of 1.26 tonne mixed plastic waste managed in Europe." (Sphera, 2022). It is important to note that the mass of 1.26 metric tons provides the amount and type of waste used to produce the 1 metric ton of plastic film. Additionally, for non-comparative declarations (e.g., EPDs), reporting based on a declared unit of (e.g., 1 kg of product) typically defined by an associated PCR is the norm.

However, if a subtractive system expansion approach is used, then only one functional unit needs to be defined. For chemical recycling LCAs, this is usually the mass of a product or material that is then compared to conventional means of producing that same mass of product or material if the two are functionally identical. For example, the functional unit defined by Jeswani et al. (2021) when using a product perspective is the production of 1 metric ton of low-density polyethylene granulate of virgin-grade quality (Jeswani, et al., 2021). Note that they clearly state the level of quality required for the material.

Products of different quality levels can potentially still be compared if they are capable of fulfilling the same function. The comparison will just be based on the function served rather than on a simple mass basis. For example, it may be possible to use more plastic of lower strength for a packaging application to provide the same functional quality as a plastic with higher strength. However, in this case the functional unit would be based on the packaging application, and the reference flows for the two different plastics would be different. Finally, for non-comparative declarations (e.g., EPDs), reporting based on a declared unit of (e.g., 1 kg of product) typically defined by an associated PCR is the accepted norm and should be accompanied by specified information on the material properties and performance.

4.3. Recommendations

- For non-comparative declarations (e.g., EPDs), reporting based on a declared unit of (e.g., 1 kg of product) is acceptable if accompanied by information about the relevant material properties.
- For comparative studies, products need to be compared based on a functional unit, which may differ for different applications.
- Only if the compared materials are functionally equivalent on a mass-basis can a meaningful comparison be carried out on 1:1 mass basis.
- Clearly state the function and functional unit including any significant quantitative and qualitative performance criteria.
    - When taking a waste perspective, this includes the source and type of waste and composition including contamination and impurities.
    - Generally, it is necessary to at least have data on moisture and carbon content for most chemical recycling LCAs for allocation and closing mass and carbon balances.
    - When taking a product perspective, this includes the relevant material properties and other performance characteristics required of the product produced.
- When using additive system expansion, the second functional unit of conventional waste management of an equivalent mass and type of waste as used as a feedstock for chemical recycling needs to be added to the conventional product system.

5. System Boundary

After we have chosen our perspective, method of system expansion, and functional unit, it is necessary to further define the system boundary. When taking a waste perspective, the system boundary will be from cradle-to-grave, even though there are no upstream burdens associated with the waste feedstock. Material flows are tracked from the point of waste generation to the point of recycling or final disposal (Viveros, 2022) When taking a product perspective, there are more available options. The system boundary could be cradle-to-grave or cradle-to-gate with end-of-life (Viveros, 2022) or without end-of-life (Jeswani, et al., 2021). As part of defining the system boundary, it is also necessary to define the temporal, technological, and geographical coverage of the study. Regardless of the system boundary chosen, the starting point of the analysis must be defined.

5.1. Upstream Burden of Feedstock

Depending on the source, there may be burdens associated with the feedstock used for chemical recycling. Post-consumer recyclables can be regarded as burden-free because it does not fulfil any appreciable function and there is no demand for it. However, some post-industrial waste streams may be considered co-products that carry some burdens of their production. In many LCAs, the distinction between waste and co-products is based on revenue (i.e., materials that are sold are co-products). However, this is not the only distinction that is possible. For example, the European Commission's (EC) Circular Plastic Alliance proposed a decision tree in 2021 for distinguishing waste from co-products based on the European Waste Directive (CPA, 2021). Accordingly, a product is a material that is deliberately produced, while a co-product must

1. have a use that is certain;
2. be directly usable without further processing;
3. be produced as an integral part of the production process; and
4. have a lawful use.

If any of the above conditions is not met, then the material is to be considered a waste. Accordingly, it would enter the system burden-free. A co-product, on the other hand, would have to carry some share of its production burden. In such cases, allocation is used to determine what share of the burden should be apportioned to each product/co-product. Methods for such multi-output allocation are further discussed in Chapter 7.

5.2. Defining the Starting Point

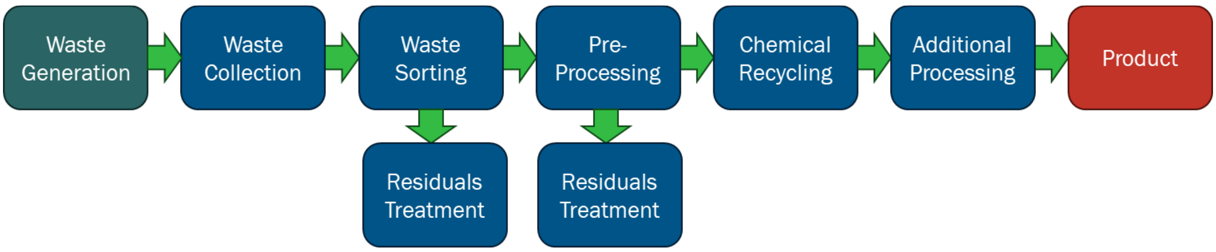


Figure 5-1: A simplified process flow diagram for cradle-to-gate LCAs of chemically recycled products

Even if there is no upstream burden associated with the feedstock, defining the starting point of a chemical recycling LCA is not necessarily simple. There are multiple methodologies that can be followed to determine the appropriate starting point. A primary question is when does a material become a waste, and the answer to the question can change the starting point.

According to the “cut-off method” described by TfS (TfS, 2024), “the impact of preparatory steps and supporting activities such as collection, transportation, sorting, dismantling, or shredding shall be added to the inventory results of the product system producing the secondary product.” This means that the system boundary would begin with waste collection and would include all sorting and pre-processing. This is the most comprehensive system boundary, and it is frequently used (Jeswani, et al., 2021). Waste collection and sorting can contribute up to ~10% of total GWP, so they are non-negligible aspects of the system.

The next method that could be used to define the system could be based on simple causality. The argument is that in the status quo case, the waste would still be collected and sorted to remove the high-value plastics from residual mixed plastic waste. Pre-processing, which may include additional sorting, is therefore first step that is only required because the material is to be chemically recycled, and so the system boundary should begin there.

Next there is the “reverse cut-off method” proposed by TfS (TfS, 2024) which states that “the impact of preparatory steps and supporting activities such as collection, transportation, sorting, dismantling, or shredding shall be added to the inventory results of the product system generating the waste.” For most systems, this would lead to a system boundary that begins with chemical recycling. However, this may depend on the specific steps that are included in pre-processing. Physical pre-processing like “sorting, dismantling, or shredding” would be excluded from the system boundary, but other types of thermo-chemical pre-processing (e.g., hydrothermal de-chlorination, torrefaction, and melting.) could be included in the system boundary.

Finally, EN15804+A2 follows a “polluter pays principle”, which is defined as “processes of waste processing shall be assigned to the product system that generates the waste until the end-of-waste state is reached.” And they provide a decision-tree for determining when the end-of-waste is reached. The decision tree asks four questions to determine where the end-of-waste is reached:

1. Is the recovered material commonly used for specific purposes?
2. Does a market or demand exist for the recovered material (e.g., does it have positive economic value)?
3. Does the recovered material fulfil the technical requirements for the specific purposes and meet existing regulatory standards?
4. Does the use of the recovered material fulfil the limit values for Substances of Very High Concern (SVHC)?

If the answer to all four questions is “Yes”, then the end-of-waste has been reached. Under this definition, pretreatment would not be included in the system boundary because no market or demand exists for mixed plastic waste.

5.3. Defining the End Point

After defining the starting point, it is necessary to define the end point. There are multiple potential end points, and the appropriate choice will depend on the goals of the project. Many chemical recycling LCAs that take a product perspective use a cradle-to-gate system boundary (Jeswani, et al., 2021), (Quantis, 2020), (Coleman et al., 2020) because the primary purpose is to compare a material produced via chemical recycling to a chemically equivalent product produced via conventional means. Since the primary purpose is the comparison and the products are equivalent, the use and end-of-life stages are excluded because they are the same for both materials. However, product LCAs are cradle-to-grave in principle, and according to ISO 14044, clause 4.2.3.3.1, “the deletion of life cycle stages, processes, inputs or outputs is only permitted if it does not significantly change the overall conclusions of the study.” (ISO, 2006) This means life cycle stages being “the same” is not automatically sufficient reason to exclude them.

When making direct comparisons between equivalent products, then the exclusion of the use and end-of-life stages will not change the rankings and absolute differences in the results. However, such exclusions can change relative comparisons and the identified "hot spots" in the system. Additionally, including end-of-life makes it possible to consider the circularity of the products (e.g., chemically recycling mixed plastic waste once and then sending it to landfill or incineration does not do much to help circularity).

The above ISO requirement can be met by simply making sure that the conclusions do not exceed the cradle-to-gate system boundary (e.g., by combining any comparative claim with a "from cradle to gate" qualifier). However, it may still be perceived as misleading if an inflated percentage difference between recycled and primary material is only achieved because of the exclusion of life cycle stages with equal but significant contributions. As such, the omission of any life cycle stages should be clearly stated and appropriately justified.

In cradle-to-gate product studies, it is still necessary to define the "gate" of the process. If the intention is to make comparisons with conventional products, then the gate must end with the equivalent of a conventional product. This may require extending the gate of the study beyond the gate of the chemical recycler. For example, if a chemical recycler produces pyrolysis oil that is then sold for further processing, it is not possible to directly compare raw pyrolysis oil to any conventional product. Therefore, it would be necessary to include a hydrotreatment process to refine the pyrolysis oil into a product that can be compared to fossil naphtha. This would represent the earliest potential gate in the system, but the gate could be moved further downstream to the production of monomers, polymers, or even end-use products. This choice would depend on the goal of the project. Placing the gate later in the system allows for a more comprehensive understanding of the product system and for more realistic use and EOL scenarios.

5.4. Recommendations

- Non-comparative declarations should, at a minimum, cover the cradle-to-gate stage up to the point of substitution where a virgin material can be substituted (e.g., naphtha, monomers, polymers, or other chemicals).
- Comparative LCA studies should, in principle, be performed over the full life cycle. They may omit life cycle stages beyond the production stage only if the recycled and the virgin materials are functionally equivalent. If the final application of the material is unknown or manifold, include at least the EOL stage and consider exploring the most common applications via scenario analysis.
- If the comparison is carried out against an existing impact profile extracted from an LCA software or published elsewhere, the requirements of ISO 14067, Annex B should be met.
- Use the CPA decision tree (CPA, 2021) to determine if a feedstock is to be considered a waste (no upstream burden) or a co-product (upstream burden via subdivision or allocation).
- For waste feedstocks, have the system boundary begin at waste collection. This is consistent with the starting point defined in the "cut-off method" described by TfS (TfS, 2024).
- Follow the requirements of ISO 14044, clause 4.2.3.3 when excluding any stages, processes, inputs, or outputs.

6. Data Estimates, Requirements, and Checks

Data is the foundation of all LCAs, therefore it is important to use the best possible data, to perform checks of the data, and to understand the quality of the data used. The data used to create the inventory model should be as precise, complete, consistent, and representative as possible with regards to the goal and scope of the study under given time and budget constraints.

6.1. Completeness of Data Collection

A critical goal of the data collection process is completeness. Completeness is judged based on the completeness of the inputs and outputs per unit process and the completeness of the unit processes themselves. The goal is to capture all relevant contributors to the impact categories under study. When data is collected it should therefore be checked for completeness. Identifying unit processes, inputs, or outputs that may be missing requires domain expertise.

6.2. Direct Emissions

One area where it can be difficult to get complete data is from direct emissions. Generating data for direct emissions can pose a unique challenge based on the data availability and type. Often emissions are not directly measured, or it may only be known that the emissions are below regulatory thresholds. However, this is not the same as having zero emissions. When directly measured emissions data are available, it is frequently in the form of concentrations or volumetric flowrates that need to be converted to mass relative to the functional for the purpose of the LCA. Despite the limitations, these direct measurements are the best available data and should be used when possible. They can then be supplemented from other sources as necessary for completeness. Estimates can be made using mass balances, stoichiometry, and process simulation models, while additional data sources include emissions estimate guidelines (e.g., US EPA's AP-42, (EPA, 2023)), other LCAs of similar process, or data on the combustion of a similar fuel as a proxy.

6.3. Proxies

Proxies are frequently used in LCAs when no dataset is an exact match for the material or process in question. Geographic proxies are relatively straightforward and represent the situation where data from one geographic region is used to represent another. In these situations, it is useful to pick geographical regions that are as similar as possible to one another in terms of their production technology pathways. If possible, adjust the electricity and possible other energy inputs (e.g., fuels) to the appropriate region as that can mitigate some of the difference between production alternatives in different regions, especially if the environmental burden is dominated by electricity consumption. The actual effects of using geographical proxies on the results and conclusions can be difficult to evaluate since it depends on the specific data being represented and the similarities and differences between the region represented in the data and the region of interest in the study.

Technical proxies are more situational and require a greater level of domain expertise to identify appropriate replacements. It is best to look for materials that are produced from similar raw materials and processes. For many chemicals, it may be possible to find data for precursor chemicals, and these often make suitable proxies. In comparative LCAs, if choosing between multiple reasonable proxies, choose the one with relatively high environmental burdens for the chemical recycling alternative and choose the one with relatively low environmental burdens for the conventional benchmark. Such a conservative approach to proxy selection ensures that any potential bias is in the favor of the conventional alternatives and will strengthen the conclusions and helps to avoid accusations of bias or greenwashing.

Contribution analysis should be used to check how much the proxy datasets contribute to the results. If the proxy is a relevant or even dominant contributor, then its use may represent a significant limitation of the study and better data may be necessary. Regardless of importance, the implications of using proxies should be discussed in the Data Quality Assessment section of the LCA report.

6.4. Data Quality Requirements

ISO 14044, section 4.2.3.6.2 defines the aspects of data quality that should be addressed in the scope definition and evaluated as part of the interpretation (Table 6-1). Addressing each of these aspects is required for LCAs intended to be used in public comparative assertions. Therefore, it is important to document the quality of the data used relative the system under study.

Table 6-1: Data quality requirements according to ISO 14044

Required elements	What does it represent?
Completeness	The fraction of flows and processes included in the system
Consistency	How uniformly methodologies, assumptions, and choices were applied across the study
Geographical Coverage	The geographical area data and models should represent
Precision	The variability of the data values
Representativeness	How well the data reflects the actual system of interest in terms of geography, time period, and technology
Reproducibility	The extent to which the information provided on the study would allow a third party to reproduce the reported results
Technological Coverage	The specific technologies or mix of technologies data and models should represent
Temporal Coverage	The age of the collected data and the time period over which the data should be collected
Uncertainty of the Information	How well the data, models, and assumptions used in the study correspond with the actual system.

6.5. Data Checks

There are a number of ways to review data for suitability for use in a LCA study. Mass, water, substance (e.g., carbon), and energy balances can help identify missing or erroneous data by showing that the data being used defies basic physical constraints on mass and energy conservation. In certain cases, stoichiometry can be similarly used to determine that the chemical inputs and outputs are balanced and reasonable. Finally, benchmarking can be used to compare supplied data to datasets for similar processes to see if the results are similar. If the results are substantially different, that may indicate an error.

6.6. Recommendations

- Use measurements for direct emissions wherever possible and supplement the measurements with data from emission estimate guidelines (e.g., AP-42, other LCAs, or proxies for completeness).
    - When choosing between multiple reasonable proxies, use a conservative choice for chemical recycling and an optimistic choice for conventional production to strengthen the conclusions of the study.
    - When selecting geographical proxies, pick regions with as similar a technology mix as possible and update energy production data, if possible.
    - Choices of technical proxies should be based on data for products made of similar materials or from similar processes.
    - Explore the contributions of proxies on the results in contribution analyses and discuss the implications as part of the interpretation.
- As a minimum data check, ensure that mass, water, and C balances are closed to the extent possible and perform a qualitative reasonableness check on the data values (e.g., orders of magnitude all appear realistic).
- Document the quality of the data used relative to its intended purpose.

7. Multi-Output Allocation

When a process has multiple co-products, it is necessary to determine how to allocate inputs, emissions, and wastes to each of the co-products. For example, some pyrolysis processes produce product gas, tars, chars, and non-condensable gases. The product gas is typically converted to pyrolysis oil, but the tars and char can also be further processed and beneficially used. In that case, multi-output allocation would be necessary. A necessary first step prior to allocation is to determine which outputs are wastes and which outputs are co-products.

7.1. Avoiding Allocation

ISO 14044 specifies that when there are multi-output processes, the first step should be to avoid allocation by sub-dividing the process into separate mono-output processes.

If sub-division is not possible, the next step is to avoid allocation through system expansion. System expansion via substitution results in a mono-functional inventory by providing a substitution credit for co-products using average or generic datasets of the substituted material produced in a different process route. For example, if carbon black is recovered from pyrolysis char, then a substitution credit for carbon black produced in the predominant furnace black process may be applied.

There are drawbacks to this form of system expansion, though. First, every system expansion adds inventory data that are foreign to the product system under study. Second, while the substitution credit eliminates the additional co-products from the inventory, it doesn't result in a "realistic" emission profile for the product under study. All it does is subtract inventories from each other with no claim that the result represents a process that could exist like that in reality. Third, choosing different inventories to subtract will lead to different results for the product under study, and the selection of the "right" inventory to subtract can be debated at length. This includes the question whether the inventory used for substitution can or cannot be an allocated multi-output processes itself. Since system expansion aims to "avoid allocation", using an inventory for substitution that itself was created via allocation doesn't avoid allocation at all but simply relocates it from the foreground process to a background process. Lastly, it is not uncommon that this type of subtraction leads to net-negative results in one or more impact categories, which are not meaningful in an attributional LCA where the goal is to calculate the absolute environmental footprint of the product. As such, multi-output allocation my be preferable to system expansion in many situations even if ISO 14044 generally prefers system expansion over allocation.

7.2. Methods of Allocation

ISO 14044 prefers physical allocation over other forms of allocation, i.e., allocation that reflects the underlying physical relationships between the co-products. A common form of physical allocation is based on mass, and the most common other form of allocation is by revenue. However, physical allocation may also be based on energy, carbon content, exergy, protein content, or any other physical properties depending on the co-products in question. Typically, allocation among the products from chemical recycling are allocated by carbon content. However, if one or more co-products do not contain any carbon, for example, then allocation by carbon content would not appear sensible.

Mass allocation effectively results in all co-products having the same environmental footprint per unit of mass. Similarly, economic allocation results in all co-products having the same environmental footprint per unit of revenue, which means high-value co-products are assigned a higher environmental footprint per unit of mass than lower-value ones. Allocation based on energy content and carbon content are often used for processes that produce fuels or hydrocarbons, respectively.

It is not always obvious which allocation key is the most appropriate, so the choice of the "right" allocation key can be debated just as much as the choice of the right inventory for substitution when applying system expansion. ISO 14044 therefore requires that different allocation approaches are tested in scenario analysis if more than one appears reasonable.

The one basic rule of allocation is that the sum of all allocated inventories equals the inventory of the original multi-output process. Note that just like for system expansion, there is no claim here that the allocated inventories are realistic ones. In fact, only mass allocation will preserve mass balances; but even then the ratios of inputs and outputs do not necessarily amount to a unit process that could ever exist in reality. As such, mixed forms of allocation have gained popularity in more recent years, where the inputs and outputs are not all allocated using the same simplistic ratio of [(co-product contribution)/(total output)], but are rather allocated based on stoichiometry, thermodynamics, or other causal relationships to arrive at more realistic inventories for each co-product. For example, stoichiometric allocation attempts to represent physical reality based on chemical transformations i.e., the flow of molecules during chemical reactions.

7.3. WBCSD Pathfinder Framework on Allocation

ISO 14044 specifies that allocation, if necessary, should be first based on actual physical relationships between the co-products and the input/outputs (e.g., mass, energy content, or C content), and if that is not possible, allocation by other relationships can be used (e.g., revenue). However, the WBCSD Pathfinder Framework (WBCSD, 2023) (also adopted by TfS, 2022) provides a slightly different decision-tree (Figure 7-1) where, if allocation is necessary, it should first be based on approved product category rules or sector specific guidance. If such guidance does not exist and the ratio of economic value of the co-products is greater than 5, then economic allocation should be used. Otherwise, underlying physical relationships should be used if possible, and if that is not possible, then again economic allocation or some alternative allocation should be used. When allocating by revenue, it is a best practice to use at least a years worth of data.

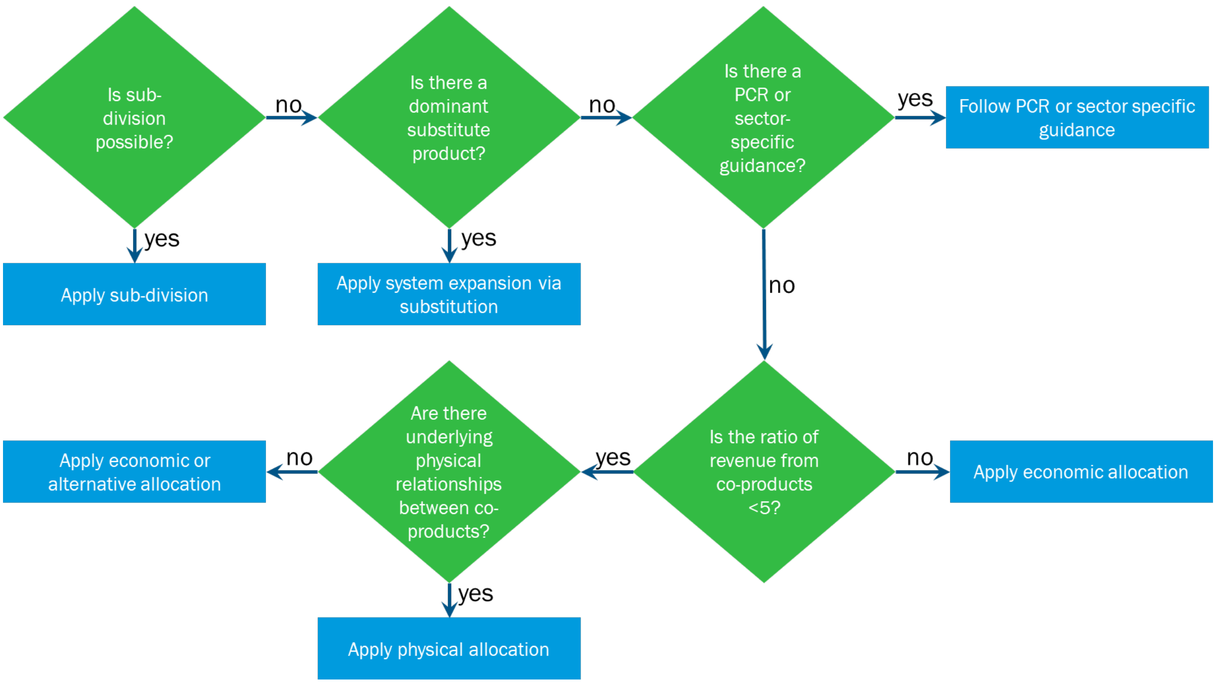


Figure 7-1: Decision-tree for handling multi-output processes.

The decision-tree provides pragmatic guidance to resolve the multi-output problem. However, besides the arbitrary nature of any revenue threshold value, the Pathfinder Framework may be interpreted to at least deviate from if not conflict with the ISO 14044 allocation hierarchy by preferring revenue allocation over physical allocation if the threshold is met whereas ISO 14044 does not mention such thresholds. However, as this is done similarly in other contexts (ULE, 2022), the associated communication risk is low. It should therefore be noted that multiple allocation methodologies or factors should be tested as part of the scenario analysis to determine how they may affect the conclusions.

7.4. Steam Cracker Allocation

In plastics production, steam cracking is used to produce monomers and other chemicals from hydrocarbon feedstocks (e.g., refined pyrolysis oil or naphtha). Given the large number of potential products from a single process, allocation is necessary to assign burdens to each product. (PlasticsEurope, 2019) eco-profiles program requires the use of the PlasticsEurope (2017) (PlasticsEurope, 2017) allocation methodology, which defined eight “main products” from the steam cracker:

- Ethylene
- Propylene
- Benzene*
- Butadiene*
- Hydrogen
- Toluene*
- Xylene*
- Butenes

*if separated, otherwise the mixture is an additional product

All other products are considered “additional products”. They further recommend that feedstock burdens be allocated by mass to all products, but that the energy demand and emissions be allocated by mass only to the main products. The additional products do not receive any burdens from energy use or direct emissions.

7.5. Recommendations

-
- Follow the WBCSD Pathfinder (WBCSD, 2023) decision tree for processes with multiple outputs.
- Use PlasticsEurope (2017) (PlasticsEurope, 2017) recommendations for steam cracker allocation.
- Apply different allocation methods to critical processes and discuss how the results affect the conclusions of the study.

8. End-of-Life Allocation

The purpose of end-of-life allocation is to address the question of how to assign impacts from virgin production and EOL recycling processes between the waste-producing and the waste-consuming product system. Material recycling and energy recovery represent a multi-functionality issue (i.e., waste treatment and production of a secondary product) similar to the multi-output issue. The goal is to meaningfully allocate the burdens as well as the benefits of recycling and energy recovery between product systems. This chapter focuses on end-of-life allocation for material recovery, but a consistent methodology should also be used for energy recovered during end-of-life. Figure 9-1 shows the main approaches used for end-of-life allocation.

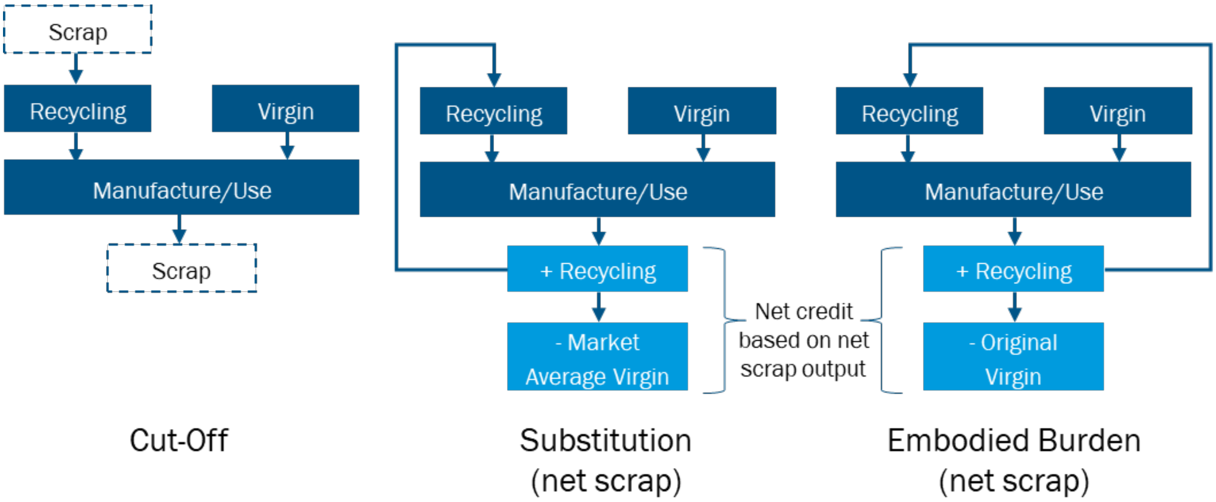


Figure 8-1: Schematic representation of the cut-off, substitution, and embodied burden approaches.

8.1. Cut-off

Burdens or credits associated with material from previous or subsequent life cycles are not considered, i.e., are "cut-off". Therefore, any recyclable input to the production process is free of any upstream virgin material burdens; only waste collection, sorting, and pre-treatment are included as upstream burden of the recycling process. Accordingly, the system boundary ends at the point of waste generation; collection, sorting, pre-treatment, and recycling are again considered part of the waste-consuming product system. This approach provides a strong incentive for using recycled content but provides less of an incentive for end-of-life recycling. It is further unable to distinguish between different forms of EOL recycling or penalize downcycling in any way.

8.2. Substitution

This approach is based on the perspective that material that is recycled into secondary material at end of life is technically able to substitute virgin material (Figure 9-1). Hence, a credit is given to account for this substitutability which represents the market-average burden of the substituted virgin material. In its "net scrap" variant, any pre- and post-consumer waste collected for recycling is first used to satisfy the recycled content demand of the cradle-to-gate manufacturing stage. The remaining net scrap is then sent through EOL recycling and receives a credit based on the technical substitutability of the materials.

Note that there is no general consensus on the substitution factors for different materials, and a 1:1 substitution ratio is often used as a default. Whatever substitution ratio is used, it should be justified and documented.

The net scrap calculation is advantageous as it avoids assigning an upstream burden to the incoming recyclable material, which would have to be the difference between 100% virgin and 100% secondary material (e.g., the Circular Footprint Formula [CFF]). As such, the cradle-to-gate results are identical to the cut-off approach described above and provide the same incentive to maximize the recycled content. However, it further provides an incentive for high-quality EOL recycling as it assigns a credit for the recovered secondary material and is able to account for up- and downcycling by applying substitution rates larger or smaller 1:1.

8.3. Embodied Burden

The concept of "embodied" environmental burdens is widely used in life cycle assessment and footprinting literature to describe the cradle-to-gate burdens of a material but has only recently been applied to EOL allocation (Koffler & Finkbeiner, 2017). The embodied burden approach is very similar to the substitution approach, except that it always credits the same primary inventory that was (or would have been) used in manufacturing to represent the original primary burden embodied in the material regardless of technical substitutability (Figure 9-1). As such, it is not concerned with the substitutability of the secondary material, be it in closed or open loop situations, but only with the fact that the secondary material takes its "embodied burdens" with it into the next product system. This is akin to a relay race where the embodied burden gets passed on from product system to product system until the material is no longer recycled. The product system that sends the material to landfill or incineration will then have to assume the embodied burdens permanently.

Since technical substitutability can be unknown as the exact composition of the recycled material can be unknown to the material/product producer, the benefit of this approach is that the product system providing the waste for recycling can hand off the original primary burden of virgin production on a 1:1 basis regardless of the technical substitutability. In addition, up- or downcycling can still be factored in by crediting (and therefore passing on) the primary material burden for less than 100% of the recycled material.

This approach may be difficult to apply to materials that have been in the technosphere for long periods of time (e.g., from materials used in buildings or infrastructure to copper first refined in the Bronze Age) because it will be difficult to find datasets that accurately represent the original burden of production. However, it is generally the case in LCA that one uses current inventory data to represent past or future activities, so the issue is not unique to this EOL allocation approach.

8.4. Value-Corrected Substitution

Value-corrected substitution (VCS) as proposed by (Koffler & Florin 2013) uses the ratio of the price of a specific waste material to the price of corresponding virgin material to estimate the degree of downcycling. As such, the value correction represents the hypothetical effort to reinstate virgin material quality from a specific waste material, but it can also be applied to upcycling where the waste material has a higher value than the virgin material.[1] This method can therefore differentiate various types of post-industrial and post-consumer waste based on historical scrap price data. The biggest difference to the substitution and embodied burden approach described above is that the system boundary is located at the point where recyclables

[1] For example, (Koffler & Florin 2013) found that the scrap class of aluminum nodules had a higher value than 99.9% primary aluminum ingot as it represents a special alloy used for high voltage power lines.

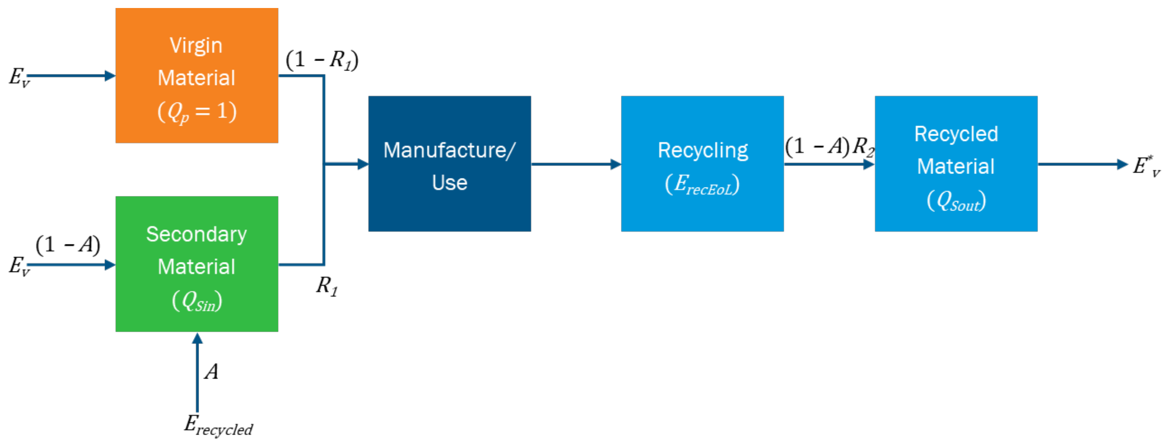
in question enter the recycling process. The waste material is then credited directly with virgin material using the price ratio between the two.

VCS can also be combined with a net scrap calculation to preserve the cradle-to-gate results of the cut-off and the net scrap substitution approach described above, as long as price differences between recycled content consumed in manufacturing and recyclables generated in manufacturing or collected in EOL are factored into this calculation. The application of this approach hinges on the availability of price data for both the specific scrap type (e.g., from www.scrapindex.com) and the virgin material for the same time period and the same reference region. It is advised to use multi-year data to establish price ratios so that price fluctuations are averaged out.

8.5. Circular Footprint Formula

The Circular Footprint Formula (CFF) method predefines allocation factors of credits and burdens between the waste-producing and the waste-consuming life cycles and aims to describe market realities that capture both aspects of recycling - the recycled content and recyclability at the end of life. It was developed as part of the Product Environmental Footprint Category Rules Guidance (European Commission, 2017). Figure 8-2 shows a schematic representation of the CFF for material recovery. The full formula has additional terms for energy recovery a disposal at end of life.

The A factor is critical and varies between 0.2 and 0.8. Lower values are for materials with higher demand than supply of recyclable materials and therefore the formula focuses on recyclability at end-of-life (i.e., it's closer to substitution), while higher values are for materials with high supply and low demand, and the formula focuses on the recycled content (i.e., it's closer to cut-off). Default values for the variables in the formula for different materials are provided in Annex C (European Commission, 2020).



$$CFF_{matl} = (1 - R_1)E_v + R_1\left(A\,E_{recycled} + (1 - A)E_v\frac{Q_{Sin}}{Q_p}\right) + (1 - A)\,R_2\left(E_{recEoL} - E_v^*\frac{Q_{Sout}}{Q_p}\right)$$

A	Allocation factor for burdens & credits between supplier & user of recycled materials	R_1	Proportion of recycled material content
E_v	Emissions from virgin production	R_2	Proportion of material that is recycled at end-of-life
$E_{recycled}$	Emissions from recycled material production	Q_p	Quality of virgin material ($Q_p = 1$)
E_{recEoL}	Emissions from recycling at end-of-life	Q_{Sin}	Quality of incoming recycled material
E^*_v	Emissions from substituted virgin material	Q_{Sout}	Quality of recycled material at end-of-life

Figure 8-2: Schematic representation of the CFF for materials recovery.

There are several potential downsides to the CFF. It is relatively complicated to use, which could increase the likelihood of errors. More fundamentally, it also artificially reduces the maximum achievable recycling credit to 80%. The CFF also uses (1 – A) and Qs/Qp to capture the market situation of supply versus demand, but they are correlated with each other, which shifts the results in favour of recycled content over end-of-life recycling. Additionally, while this report focuses on material recycling, it should be noted that the equivalent factor to A for recovered energy is B and is set to zero, which allows waste-to-energy full benefits of energy recovery that are not achievable when using the CFF for material recovery. Energy recovery also lacks a Qs/Qp factor, which may further favour energy recovery over material recovery.

8.6. Recommendations

- Unless otherwise specified by PCRs or other sector specific guidance, the net-scrap substitution approach can be used as a general baseline as it provides incentives to increase both recycled content as well as EOL recycling.
- Apply different EOL allocation methods and discuss how the results affect the conclusions of the study.

9. Mass Balance Approach

The products of chemically recycling are often mixed with conventional petrochemicals as part of the integrated production of final products using existing infrastructure. Therefore, there is a need for a methodology to estimate the fraction of such products that should be considered as made from 100% recycled feedstock to meet existing demand. To understand how the mass balance approach handles this issue, it is first necessary to understand chain of custody models in general.

9.1. Chain of Custody Models

ISO 22095:2020 (ISO 2020) defines five chain of custody frameworks that aim to transfer, monitor, and control the inputs, outputs and other associated information as they move through each step in the supply chain (Figure 9-1). Typical examples include use of bio-feedstocks, use of recycled feedstocks, and use of sustainably managed agriculture/forestry products.

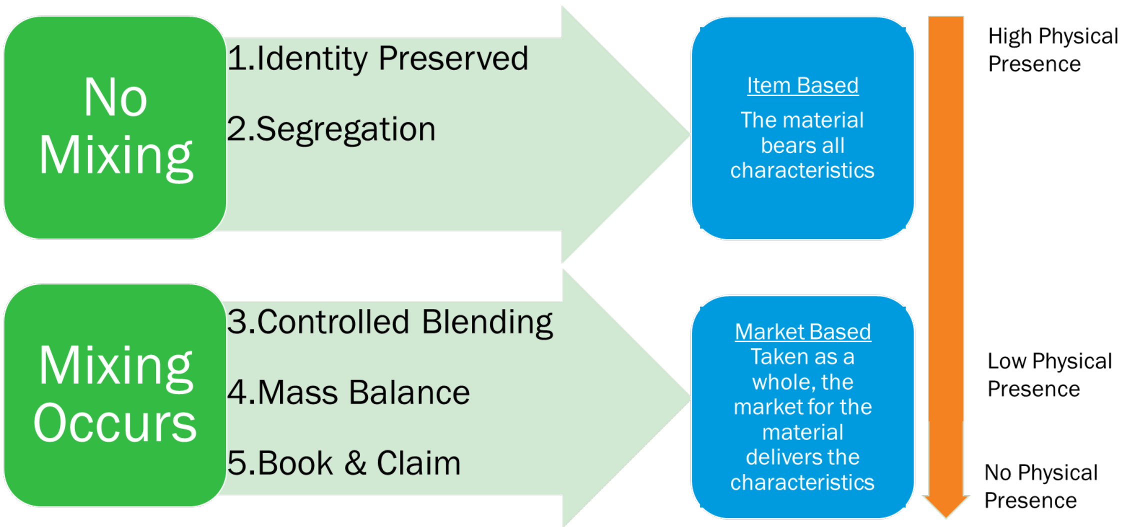


Figure 9-1: The five chain of custody models identified by ISO 22095 (ISO, 2020).

Identity preserved and segregation both work by keeping materials physically separated throughout the value chain to preserve their characteristics. Identity preserved works by using a single source of material, while segregation allows for inputs with equivalent characteristics from multiple sources to be processed together. Alternatively, the other models allow for physical mixing. Controlled blending does so by using a known and constant proportion of inputs with the specified characteristic, and therefore all outputs contain a verifiable proportion of the specified characteristic. For example, a paper mill may always use 25% post-consumer recycled pulp in a certain product. The mass balance approach goes a step further and allows materials with different characteristics to be mixed at different ratios, but the proportion of the input with the specified characteristic matches the initial proportions on average and will typically vary across different outputs. ISO 22095 recognizes two implementation methods: the rolling average percentage method (here called the proportional method) and credit method that will be discussed further in the following sections. Finally, the book and claim model is not directly connected to the physical flow of materials. Instead, credits are issued based on the amount of material with the specified characteristic that is produced. These credits are then sold and traded independently of the material itself. The credits must be reliably controlled to avoid double-counting, and they thus ensure that for each purchase for which a claim is made, materials with the specified characteristic have been produced.

9.2. Mass Balance Approach

The concept of "mass balance" as described in (Jeswani, Kruger, Kicherer, Antony, & Azapagic, 2019) is applied for the chemically recycled product (through the steam cracker). Even though the concept is described for biomass balance (BMB) products (substitution of fossil feedstock with bio-naphtha and/or bio-methane), the same concept can be applied to chemically recycled products, where, for example, pyrolysis oil substitutes conventional fossil feedstock. Figure 9-2 shows a simplified diagram of how the allocation of the recycled share of products is estimated using the mass balance approach when mixed feedstocks are used in integrated production processes.

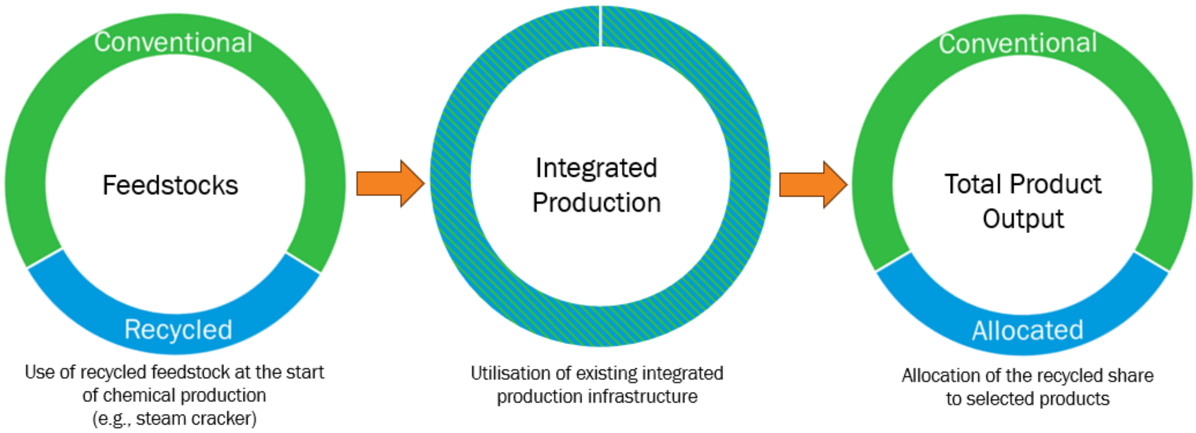


Figure 9-2: Schematic representation of the mass balance approach for recycled product. Adapted from Jeswani et al. (2019).

It must be noted that according to Jeswani et al. (2019) the mass balance approach is only applicable when the final conventional and bio-/recycled products are completely interchangeable with one another, and when there are no additional differences in processing utilities and auxiliaries. This can be an important limitation to consider because incorporating larger amounts of recycled content could at some point require changes to the processing utilities and auxiliaries. Adhering to this limitation could significantly limit the potential for increases in recycled content due to necessary processing changes as recycled content increases. Despite this limitation, there are numerous existing programs and schemes that utilize or recommend the mass balance or the similar energy balance approach for biofuels, bioenergy, and biomaterials [66][10][15].

As stated in the previous section, ISO 22095 identifies two methods to implement a mass balance approach: the proportional method and the credit method (Figure 9-3). It should be stated that these methods are only distinguishable when there are multiple co-product outputs. The proportional method equally applies the average input proportion to all associated outputs. For example, if 25% (25 metric tons out of 100 metric tons) of the incoming material is from post-consumer waste, and four products are produced, then all four of those products can claim 25% recycled content. Alternatively, using the credit method, the four products could each claim different amounts of recycled content as long as the total did not exceed 25kg, assuming there are negligible losses from inputs to products. For example, one product could claim 50% recycled content, while another claims 0%. However, there has been opposition to the use of the credit method from groups like Beyond Plastics, an organization that generally opposes chemical recycling, on the basis that is does not provide customers with an accurate accounting of the recycled content in the individual products they are purchasing (Bell, 2023). The choice of implementation could have substantial effects when estimating the impacts associated with a given product.

The plastics industry has further broken down the credit method into fuel-exempt and polymers-only approaches. The fuel-exempt approach allows the recycled content to be reattributed among all products and outputs excluding fuel and energy. The polymers-only approach only allows the recycled content to be reattributed between polymer outputs. The differences between the rolling average and the two credit methods are shown in Figure 9-3.

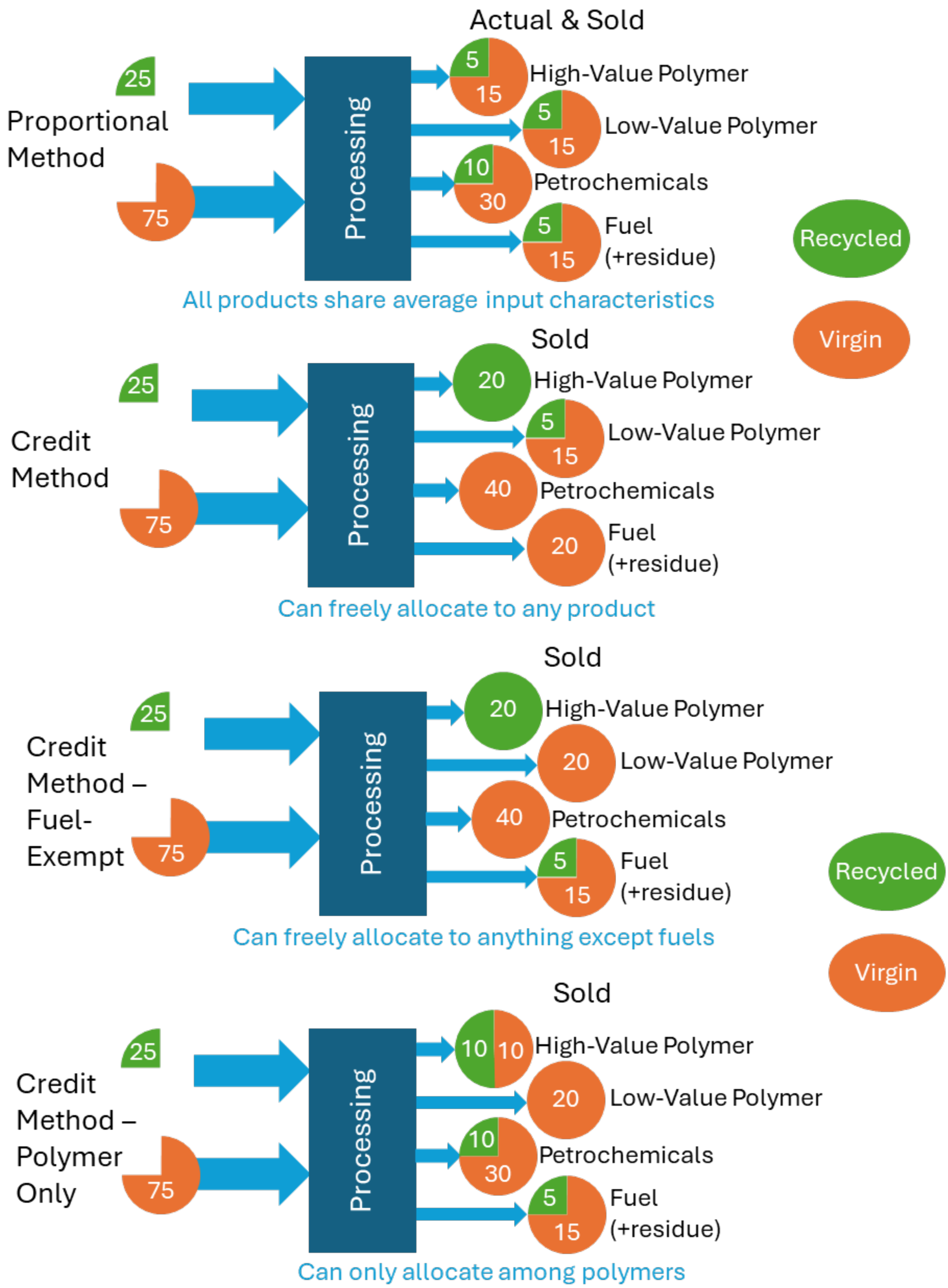


Figure 9-3: Depiction of potential recycled content allocation using different mass balance approaches.

In October of 2023, twenty plastic industry associations including CRE wrote and open letter to the European Commission arguing that the use of the fuel-use exempt mass balance approach is necessary for European countries to meet their 50% plastic recycling target in 2025 (Packaging Europe, 2023). Additionally, organizations such as the American Chemistry Council (American Chemistry Council, 2021) and Plastics Europe (Plastics Europe, 2020) have made public statements in support of the mass balance approach.

9.3. CRE Position

CRE has taken an official position on the mass balance approach (CRE, 2021) that states that it:

- is a proven chain of custody approach used in many areas bringing innovations to the market such as fair-trade practices in the food industry and the adoption of "green energy" where a similar Energy-Balance approach enables its flow through the same grid as for fossil energy and the significant development of the industry,
- is essential in meeting recycling targets for plastics in Europe,
- brings transparency and audited traceability process.

Additionally, CRE believes that the Fuel Exempt method described in section 9.2 is the most preferable.

9.4. Definition of Chemical Value

When virgin feedstocks are completely interchangeable with chemically recycled feedstocks, the mass balance approach just consists of a straightforward substitution on a mass basis. However, in certain circumstances there are differences between the virgin feedstock and the chemically recycled feedstock that is replacing it (e.g., C content, energy content). In these cases, there is a need to adjust the equivalent quantity of recycled feedstock. Jeswani et al. recommended using the lower heating value (LHV) as the metric of chemical value for these purposes (Jeswani, et al., 2021). LHV is recommended because these feedstocks are typically also used as energy sources and the LHV is readily available across feedstocks. When using LHV to define chemical values, it is important that the total energy content substituted does not exceed the amount of energy available. However, properties other than LHV could be used. The most likely alternative to LHV is C content because it is also readily available and provides a reasonable proxy for the "value" of hydrocarbons. However, it is important to ensure that the amount of carbon substituted does not exceed the amount of carbon available.

9.5. Conformance with Standards

There is currently no ISO standard on the mass balance approach. However, an ISO working group under TC 308 – Chain of Custody began work on ISO 13662 on Mass Balance — Requirements and Guidelines in 2023, with publication likely no sooner then 2025 (ISO, 2025). According to ISO 14044, it is important to describe assumptions and their influence on the results transparently to avoid misinterpretation (ISO, 2006). Therefore, when the mass balance approach is used in an LCA, the effect of its use should be discussed as part of the interpretation. This should include a calculation of average results without mass balance to confirm that results with mass balance add up to the same total again.

There are additional questions about whether a mass balance approach can be used in EPDs. While most program operators have not offered an official position on the use of the mass balance approach, ECO Platform, announced in 2023 that "Mass Balance Approaches shall not be used in any ECO EPD." This restriction affects EPDs from their 21 participating program operators (ECO Platform, 2023).

9.6. Mass balance in LCA

Since mass balance is primarily a chain of custody and labeling instrument, there is no direct or obligatory link to LCA calculations as such. However, there is a desire by some in the industry to calculate separate footprints for products labelled “100% virgin/primary” and “100% recycled” in order to help shift demand to the recycled product. Note that none of the relevant standards (ISO 14025 (ISO, 2006), ISO 14044 (ISO, 2006), ISO 14067 (ISO, 2018), ISO 21930 (ISO, 2017)) addresses such a virtual division of a single product flow (with some recycled content) into two separate co-products with 100% virgin and 100% recycled content, respectively. However, there is also no language in these standards that would rule out such a calculation per se.

Nevertheless, a more practical problem may arise in cases where the environmental burden of the combined processing of virgin and recycled feedstock increases as a result of adding the recycled feedstock (e.g., through an increase in energy consumption or a decrease in yield). It should be noted that such a situation violates the requirement stated by Jeswani et al. that the mass balance approach is only applicable when the final products are functionally equivalent with one another, and when there are no additional differences in processing utilities and auxiliaries (Jeswani, Kruger, Kicherer, Antony, & Azapagic, 2019). If this limitation is disregarded, then depending on the specific constellation of carbon intensities and recycled content, the separate calculation of, e.g., the carbon footprint for the “100% recycled” and the “100% virgin” product may lead to a lower carbon footprint for the “100% recycled” product despite an increase in the absolute total GHG emissions when compared to a production without any recycled content. In this case, a virtual subdivision could be used to allocate the increase in emissions to the recycled product. Situations like this are why it is important to transparently report the total emissions, and to provide calculations with and without the mass balance approach.

9.7. Recommendations

- The mass balance approach can be a valuable and meaningful way to report recycled content in products produced through integrated production processes.
- The total amount of mass balanced products is limited to what can be certified by a generally accepted 3rd party based on the inputs and their specific characteristics.
- If a mass balance approach is used in an LCA,
    - Follow the method outlined in Jeswani et al. (2019) to apply the mass balance approach in product-perspective chemical recycling LCAs.
    - Calculate and publish results with and without mass balance
    - Report how adding the recycled materials affects the overall environmental burden of the integrated processes

10. Waste Feedstocks

Mixed post-consumer plastic waste is a common feedstock for chemical recycling, however, it is not the only possible feedstock. For example, some processes use separate polyethylene film, while others convert waste tyres into new products. The choice of feedstock can have a significant impact on the results of the LCA. Chemical recycling is meant to compliment mechanical recycling and therefore utilize waste feedstocks that are not suitable for mechanical recycling. Saputra (Lase et al., 2023) estimated in their most optimistic case that complimentary mechanical and chemical recycling could potentially improve the plastic recycling rate to 73 to 80% in Europe. 41% to 46% of this recycling comes from mechanical recycling, and the remainder from plastic-to-plastic (15% to 38%) or plastic-to-chemicals (19% to 35%) recycling. To achieve these recycling rates, attention must be paid to the waste feedstocks used in chemical recycling and how they affect LCA results.

10.1. Variations in Waste Quality and Composition

Waste quality and composition are important considerations that typically vary with time by geographic location. Specifically, waste quality and composition may vary seasonally, and it is therefore to use at least a full year of data to account for these variations. Regional variations should be accounted for by using data from the region under study if possible, and from a region that is as similar as possible to the region under study. This may not necessarily the closest possible region because other considerations may be more important (e.g., urban vs. rural, socio-economic level, and mix of residential, commercial, and industry). Relatively recent municipal solid waste composition data is available for most EU-27 countries (EuroStat, 2023). However, the level of detail may not be uniform and the included categories may vary as waste stream compositions have not been standardized. Therefore, when using geographical proxy data, it is useful to compare data that is available to the desired region to the region represented in the data and narrow the use of proxies where possible. For example, the region under study may have data on generation of plastic waste and its disposition, but the data is not broken down by region. In this case, that data could potentially be supplemented by the resin composition data from another similar region without having to replace all the feedstock data. Having or estimating values for moisture and carbon content is also typically necessary in most chemical recycling systems.

If running future scenarios, it may be necessary to develop or use projections of changes in waste composition. If the future scenario is relatively soon (e.g., 2030), then projections from current trends can be used. If the future scenario is later in the future, additional assumptions may need to be made about how the waste composition will change. One change to consider is increases in the mix of bioplastics among conventional plastics. Companies may also move away from plastic packaging to other materials (e.g., paper), or may use more plastics that are easier to mechanically recycle (e.g., high density polyethylene and PET).

10.2. Conventional Waste Management

The current conventional treatment of waste is important when considering alternatives for waste-perspective LCAs and for system expansion in product-perspective LCAs. Since conventional plastics do not anaerobically biodegrade in landfills, the landfilling of conventional plastics produces relatively negligible amounts of greenhouse gases, while the incineration of conventional plastics leads to substantial fossil CO_2 emissions. Post-consumer waste management varies significantly across Europe. For example, ~55% of disposed municipal solid waste in the EU-27 was incinerated in 2020. However, this value ranged from <1% in Croatia to over 99% in Finland, Sweden, and Switzerland (EuroStat, 2023). This does not even consider the fact that solid waste is typically managed in relatively local areas, so it may not be meaningful to use mixes of large regions (e.g., the EU or large countries) to estimate how the waste in a specific area is managed. Given the importance of conventional waste management, it is necessary to understand to the extent possible how the relevant waste feedstocks are actually managed in the area under study.

10.3. Recommendations

- Use at least a year's worth waste quality and composition data for the geographic reference of the study, or a region as similar as possible.
- Determine how the waste feedstock in question is currently managed in the area under study (e.g., split between landfill, incineration with and without energy recovery, secondary fuel use, etc.) and use that for any comparisons or potential credits.

11. Impact Assessment Methods and Indicators

11.1. Methods

Various impact assessment methodologies are applicable for use in the European context including e.g. Environmental Footprint v3.1 (EF 3.1), CML, and ReCiPe (JRC, 2010). The EF methodology was originally based on the ILCD recommended methods (Hauschild M, 2011), but several have since been modified and updated by the European Commission as part of the on-going development of the Product Environmental Footprint initiative. EF 3.1 characterisation factors are considered to be the most robust and up-to-date available for the European context, are widely used and respected within the LCA community, and are required for Product Environmental Footprint studies and Environmental Product Declarations under EN 15804+A2. When performing studies that include regions outside of Europe, then it may be useful to also consider additional impact methods to see if the results change significantly. For example, studies including North America can also include TRACI v2.2 to see how the results compare to EF 3.1 (EPA, Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI), 2023). Other regions typically do not have widely agreed upon and up-to-date characterization methods, so using the EF 3.1 characterisation factors is a reasonable starting point, but it may be useful to test additional methods to see how it may change the results.

11.2. Selecting Indicators

Selection of impact assessment indicators will affect the data that is required to be collected especially related to direct emissions. Global warming potential and non-renewable primary energy demand should be included because of their relevance to climate change and energy efficiency, both of which are strongly interlinked, of high public and institutional interest, and deemed to be the most pressing environmental issues of our time. Eutrophication, acidification, and photochemical ozone creation potentials should be included because they are closely connected to air, soil, and water quality and capture the environmental burdens associated with commonly regulated emissions such as NO_x, SO_2, volatile organic compounds, and others.

Water consumption, i.e., the anthropogenic removal of water from its watershed through shipment, evaporation, or evapotranspiration, as well as the Water Scarcity Footprint (WSF), have high political relevance as the UN estimates that roughly a billion people on the planet do not have access to improved drinking water, which entails a variety of problems around ecosystem quality, health, and nutrition.

It is important when selecting indicators to review their relevance to the product system being assessed and the goals and scope of the study. As long as there are no ozone depleting substances emitted in the foreground system, then ozone depletion potential is unlikely to especially relevant to most chemical recycling studies. The *Montreal Protocol on Substances that Deplete the Ozone Layer* was implemented in 1989 with the aim of phasing out emissions of ozone depleting gases. With a few exceptions, use of CFCs, the most harmful chemicals has been eliminated, while complete phase out of less active HCFCs will be achieved by 2030. However, it is a mature indicator and can be included for completeness.

It is also important to review the robustness of the indicators. For example, EN15804 provides a disclaimer for all included toxicity, abiotic resource depletion, and water deprivation indicators that says they “shall be used with care as the uncertainties on these results are high or as there is limited experienced with the indicator." For example, the precision of the current USEtox™ characterisation factors ix within a factor of 100–1,000 for human health and 10–100 for freshwater ecotoxicity (Rosenbaum, et al., 2008). However, these more uncertain indicators may still be useful in helping to identify the processes and flows that contribute the most to their associated impact categories.

Similarly, there is ongoing research related to impacts associated with microplastic pollution, however, there is still significant uncertainty in these methods, and finding or developing the necessary inventory data is difficult (Maga, et al., 2022) (Schwarts, et al., 2024) (Pellengahr F, 2025).

11.3. Recommendations

- Use the latest EF characterisation factors for the European context and use TRAIC in a North American context.
- If regions outside of Europe or North America are included in the study, then EF characterisation factors are a reasonable starting point, but it may be beneficial to test additional LCIA methodologies.
- The choice of specific indicators will depend on the study. However, toxicity, resource depletion, and water deprivation indicators should be used with care due to the potential uncertainty. Their use should be more focused on identifying potentially critical processes and flows.

12. Scenario, Sensitivity, and Uncertainty Analysis

Given the inherent uncertainty and variability in the assumptions, data, and models, it is necessary to evaluate how this uncertainty and variability affects the results and conclusions. This is done through scenario, sensitivity, and uncertainty analyses. According to ISO 14044 4.5.1.1, the interpretation of the results requires "a sensitivity check of the significant inputs, outputs and methodological choices in order to understand the uncertainty of the results". The purpose of the sensitivity check is to evaluate the robustness of the results and conclusions by identifying how they are "affected by uncertainties in the data, allocation methods or calculation of category indicator results, etc." The sensitivity check must consider any scenario, sensitivity, or uncertainty analyses that were performed. Sensitivity and uncertainty analyses are required for comparative LCAs intended to be disclosed to the public, which includes most chemical recycling LCAs.

As discussed in previous sections, there are several key assumptions and parameters that are worth exploring in scenario, sensitivity, and uncertainty analyses:

- Electricity grid mixes (e.g., effect or renewable or future grid mixes)
- Energy use
- Process yields
- Biogenic C content (potentially increasing with time)
- Allocation methods
- Methods of conventional waste treatment (e.g., landfill versus incineration)
- LCIA methods, if including regions outside of Europe
- Existence and types of credits

12.1. Scenario Analysis

Scenario analyses can be considered a subset of sensitivity analysis, but they are unique enough to discussed separately. Scenario analyses test different potential sets of input values or assumptions to explore and understand discrete alternative cases. For example, additional scenarios could be developed to test alternative electricity grid mixes (e.g., renewable or future). Scenarios could also be developed to test other LCIA methods or different types of credits (or no credits). Assessing additional scenarios is a good way to better. Assessing additional scenarios is useful for "what if?" testing to determine how the results and conclusions may change under different circumstances. The results of scenario analyses are usually presented by comparing them to the baseline results. The intent is to show how each scenario may affect the initial results.

12.2. Sensitivity Analysis

While ISO 14044 defines sensitivity analysis as "a procedure to determine how changes in data and methodological choices affect the results of the LCIA" (ISO, 2006), we are using it here to focus on how the results change based on changes in input values. They essentially determine how sensitive the results and conclusions are to such changes. By definition, the results are sensitive to changes in critical inputs and are insensitive to changes to less important inputs. As discussed in Chapter 3, the most common type of sensitivity analysis is one-at-a-time perturbation analysis. This type of analysis would be useful for variables like energy use, process yields, and biogenic C content. For these (or other inputs), this type of perturbation analysis can be used to calculate “breakeven” points. The breakeven point represents the value for an input where two alternatives are equivalent. This is illustrated in Figure 12-1. If the breakeven point is outside of the range of likely values, then it can be claimed that the results are robust with regard to that input value. However, if the breakeven point is a likely value for the input in question, then that indicates that the results are sensitive to this specific input value. This can be a final conclusion, or more data could be collected to narrow the potential range of the input value.

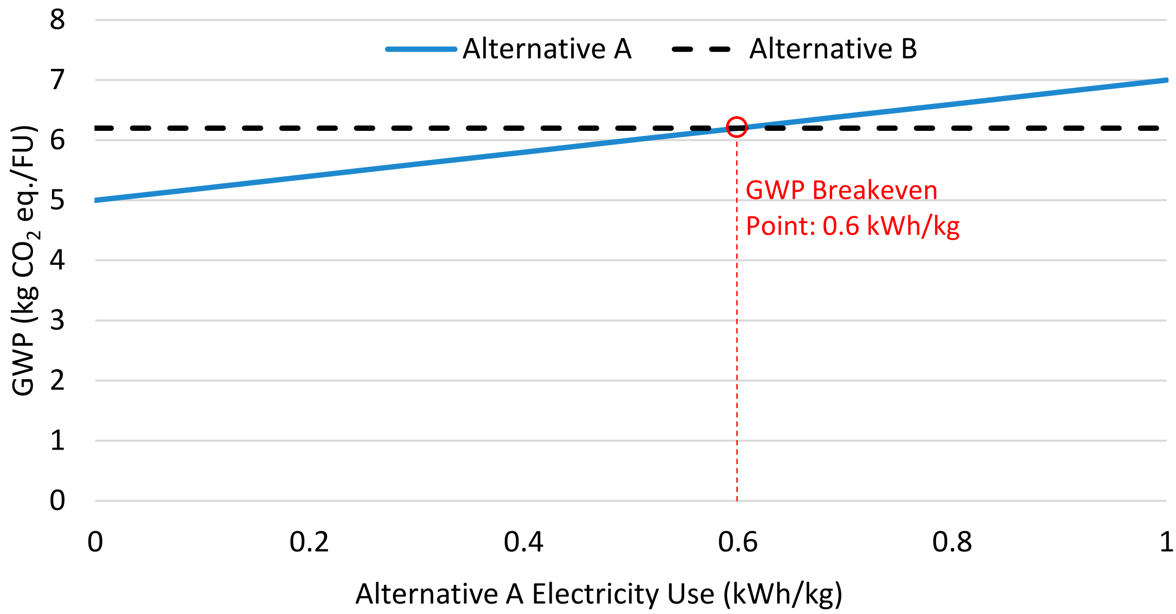


Figure 12-1: Illustration of a breakeven point in sensitivity analysis.

12.3. Uncertainty Analysis

Uncertainty analysis is used to understand how the results may vary based on uncertainty in the models, data, and assumptions. Uncertainty analyses can be qualitative or quantitative. A qualitative uncertainty analysis considers the base results, contribution analysis, scenario analysis, and sensitivity analysis and discusses how key uncertainties may affect the results. If robust analyses have been performed, this may be all that is necessary. However, additional quantitative uncertainty may provide additional insights into the study and may be worth exploring. One type of uncertainty analysis is essentially a scenario analysis where reasonable best- and worst-case values are used for each critical variable and assumption (e.g., energy use, product yield, allocation method). If an alternative’s worst case is better than the best case for another alternative, then that is strong evidence that the alternative is actually better than the other. However, if there is overlap, then there is some remaining uncertainty as to which alternative may be better than the other.

As discussed in Chapter 3, uncertainty propagation is another way to perform uncertainty analyses. This is most commonly done via Monte Carlo analysis. Monte Carlo analysis requires defining statistical distributions for uncertain parameters and re-running the model a large number of times using randomly selected values for each parameter. It is a powerful tool, but, like all models, the value of the results is limited by the quality of the data. If meaningful statistical distributions cannot be developed for each of the critical parameters, then the output distributions will be less meaningful. However, if all that is known is reasonable ranges of parameters, then uniform and/or triangular distributions can be used for all parameters to provide an estimate of the potential variation in performance. It should be noted, that Monte Carlo analyses are most useful when used on the difference between two alternatives. This is because there may be variables that appear in multiple alternatives that will affect them both in similar ways (e.g., electricity GWP intensity). By running the analysis on the difference between two alternatives, the Monte Carlo results then provide information on under what circumstances the base results change. This is illustrated in Figure 12-2.

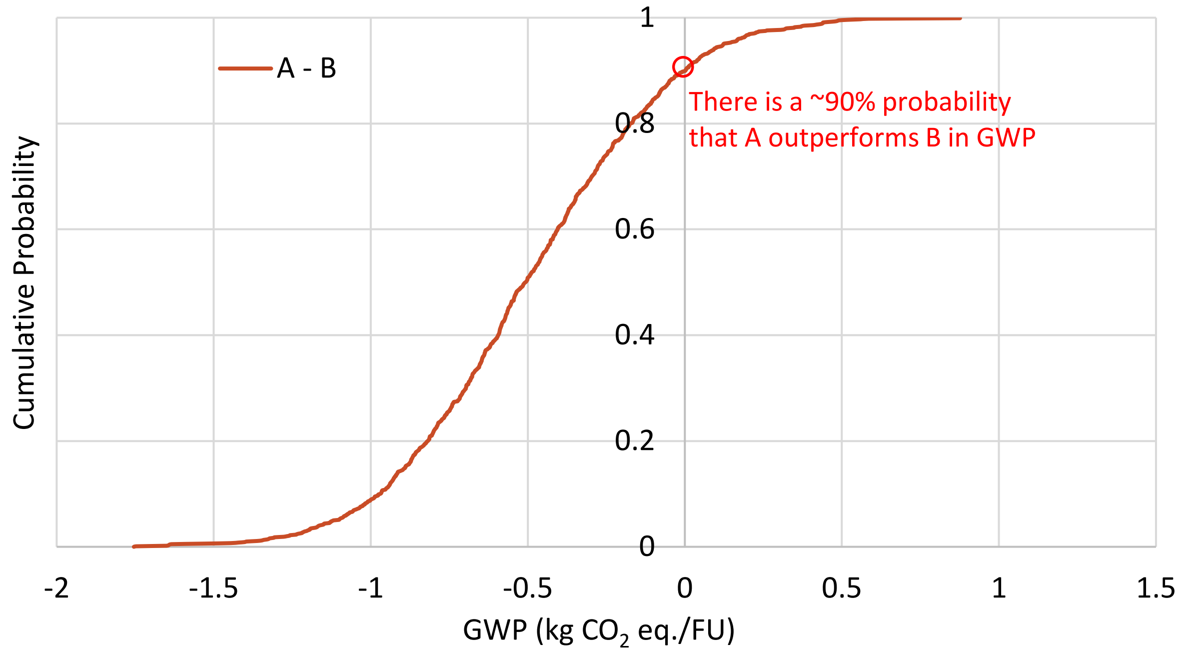


Figure 12-2: Illustration of Monte Carlo results for the GWP difference between two alternatives

When testing the difference between alternatives, the results indicate the probability that one alternative outperforms another in any given impact category. Correlations can also be calculated between the difference in each impact category and the input values to determine which inputs are most critical to the difference.

12.4. Recommendations

- Test all critical parameters and assumptions in sensitivity and scenario analyses
- For comparative studies, perform a quantitative uncertainty analysis, either by defining best and worst case scenarios or by performing a Monte Carlo simulation on the most influential and uncertain parameters
    - If some uncertainties are shared between alternatives, run the analysis on the difference between alternatives to avoid the issue of independent sampling
- Include checks as part of the interpretation
    - This is an iterative process. The results may indicate that more data should be collected or more scenario, sensitivity, or uncertainty analyses should be performed.

13. Consideration of New and Developing Technologies

Chemical recycling consists of many still developing technologies. When considering such technologies in LCA, it is beneficial to consider how those technologies will perform in the future when they are developed and deployed at full scale. This gives a more accurate comparison to mature technologies such as incineration. One way to attempt to quantify the maturity of a technology is through Technology Readiness Level (TRL).

13.1. Technology Readiness Level

TRL assigns a value to the maturity and performance of new technologies to rank and compare them (Table 13-1) (Mankins, 2009; Rybicka et al., 2016). Within three to five years, many projects reach TRL 1-5 and then stagnate at that level after the influx of public funds declines. A large-scale transformation of the CR with sufficient capacity will take 20 to 30 years. Funding should continue after TRL 5 is reached (Crippa et al., 2019) because technologies with low environmental impact and high maturity are needed in the short term (Schwarz et al., 2021, p. 340). If a specific project achieves a high TRL, this is not necessarily transferable to other projects of the same technology (Solis & Silveira, 2020).

LCA of an emerging technology at low TRLs (TRL 2–5) is distinct from traditional LCA since the evaluation precedes the product life cycle. For product LCA, data valid for specific place, situation, or state can generate useful results. Whereas LCA of technology evaluates general technology where potential impacts under many different and more general circumstances will generate results of greater utility, but also entailing greater uncertainty (Sanden, Jonasson, Karlstrom, & Tillman, 2005). Existing guidelines of LCA (ISO, 2006) are suitable to determine environmental burdens of technologies at TRL 7–9 (Gavankar et al., 2015b; Grubb & Bakshi, 2011; Khanna, Bakshi, & Lee, 2008). If the same methodology is applied to evaluate emerging technologies at TRL (2–5), it may be misleading because of changes in scale and maturity of technology. Therefore, LCA of emerging technologies requires methodological advances in the current LCA framework.

Table 13-1: Description of the nine levels of technology readiness.[a]

Category	TRL	Descriptions
Laboratory Scale	1	Observation and description of the basic principle.
	2	Formulation of the technology concept or application
	3	Characteristic proof of concept
Pilot Scale	4	Validation of components and/or subsystems in a laboratory environment
	5	Component/subsystem validation in deployment environment
	6	System validation in deployment environment
Commercial Scale	7	Demonstration of a similar system at full scale in deployment environment
	8	System completion and qualification through testing and demonstration
	9	Operation of the system over the full range of expected conditions

a. Adapted from Mankins, 2009; Moni et al., 2020; Rybicka et al., 2016

13.2. Handling Emerging Technologies

Moni et al. (2020) reviewed the application of LCA at low TRLs (2-5). In these cases, the available data are from lab or pilot scale, so the data needs to be supplemented with assumptions regarding scale-up to better represent the eventual environmental scaling. Lab scale data may overestimate actual potential environmental impacts due to unrealized process yield and efficiency gains that will exist at full scale. Piccinno et al. (2016) developed a framework for scaling up LCAs of chemical processes from laboratory to industrial scale. An overview of the procedure is shown in Figure 13-1. Piccinno et al. (2016) goes on to suggest industrial scale processes to replace lab-scale processes as well as equations and data for scaling inputs for heating, stirring, homogenizing, grinding, filtration and centrifugation, distillation, and drying, and pumping as well as output products, co-products, wastes, emissions, and heat. The data, equations, and recommendations provide a relative robust framework for scaling up many chemical processes. However, assumptions will need to be made, and there is inherent uncertainty in scaling of laboratory data to industrial-scale.

Figure 13-1: Scale-up procedure for LCAs of chemical processes.

The uncertainty in scale-up makes the use of robust sensitivity and uncertainty analyses even more important. These analyses are not only necessary for identifying the critical factors in the technology, but also for better understanding how uncertain technological performance can affect comparisons with existing mature technologies. Since emerging technologies are expected to be deployed at full-scale at some future time, it is useful to include scenarios that attempt to represent those future time periods. Such scenarios could use future projections of the electricity grid, use of biofuels, as well as waste composition to better represent the time when the technology will be fully operational.

13.3. Recommendations

- While there is no simple consensus framework for quantifying how differences in TRL between data and models and the system being represented, larger differences imply greater uncertainty that should be documented and considered in the interpretation of the LCA.
- Transparently document at least qualitative differences between the TRL of the data and what is being modeled when discussing Technological Representativeness in the Interpretation of the LCA.
- The scale-up procedure proposed by Piccinno et al. (2016) can be used to scale most chemical processes. Whatever method is used, it should be documented and justified.
- Develop and test scenarios for the time period when the technology is expected to be operational at full-scale. This could include changing the electricity grid, use of biofuels, as well as waste composition.

14. Communicating LCA results

Effective communication of the results of an LCA can be just as important as the effectively performing the study itself. If the results of the best possible LCA study are ineffectively communicated, then the audience may be left confused or even misled. Fortunately, there are existing standards and directives that can be followed to help ensure that LCAs are communicated transparently and effectively.

14.1. ISO Standards

Section 5 of ISO 14044 is dedicated to documenting and reporting LCA studies (ISO, 2006). ISO 14026 is the standard for communicating environmental footprints (ISO, 2017), and ISO 14025 is the relevant standard for Type III Environmental Declarations (EPDs) (ISO, 2006). However, since LCAs provide the foundation for environmental footprints and EPDs, it is necessary to start with ISO 14044. The most important requirement in ISO 14044 is that an ISO conformant third-party report must be made available whenever LCA are shared with any third party (i.e., other than the LCA commissioner and practitioner). However, confidential data may be placed in a separate annex that should be critically reviewed but does not need to be made available to other third parties in accordance with ISO 14044 and ISO/TS 14071.

Results of LCAs may be used internally without a report, but it is necessary to back up third-party communications to provide relevant context and background information. ISO 14044 provides detailed reporting requirements that need to be included in the report for each phase of the LCA so that the audience can effectively understand and evaluate the study and results.

14.2. Critical Review

While section 5 of ISO 14044 deals with reporting requirements, section 6 addresses requirements associated with critically reviewing an LCA. ISO/TS 14071 (ISO, 2006) contains additional requirements and guidance on the critical review process and reviewer competencies. The critical review process ensures that:

- the LCA was carried out in manner consistent with ISO 14040 and ISO 14044;
- the LCA was carried out in a scientifically and technically valid manner;
- the data used are consistent with the goal of the LCA;
- the interpretation is consistent with the identified limitations and the goal of the LCA; and
- the LCA report is consistent and transparent.

The first deliverable from the critical review is the critical review statement that conclusively documents the review process, the reviewer(s) conclusions and recommendations, and an unambiguous statement whether the LCA is in conformance with ISO 14044. The second and final deliverable from the critical review.is the critical review report that includes the detailed comments from the reviewer(s) and the responses of the practitioner.

A critical review is the only way to ensure that an LCA conforms to ISO 14044, and while it may not be strictly required in all circumstances, it is highly recommended that all LCA reports be reviewed by an independent external expert to add credibility to the report. LCA studies that are intended to be support comparative assertions intended to be released to the public[2], which includes most LCAs of chemical recycling, are required to be reviewed by an external panel of at least three independent experts that have combined domain and LCA expertise. When selecting a panel to critically review an LCA it is typically beneficial for at least one member to have domain expertise in chemical engineering (Keller, Voss, & Lee, 2022). Environmental footprint studies (e.g., carbon footprints) and Type III Environmental Product Declarations (EPD) have their own requirements for external assurance. Figure 14-1 shows the required as well as the recommended forms to maximize credibility in the marketplace.

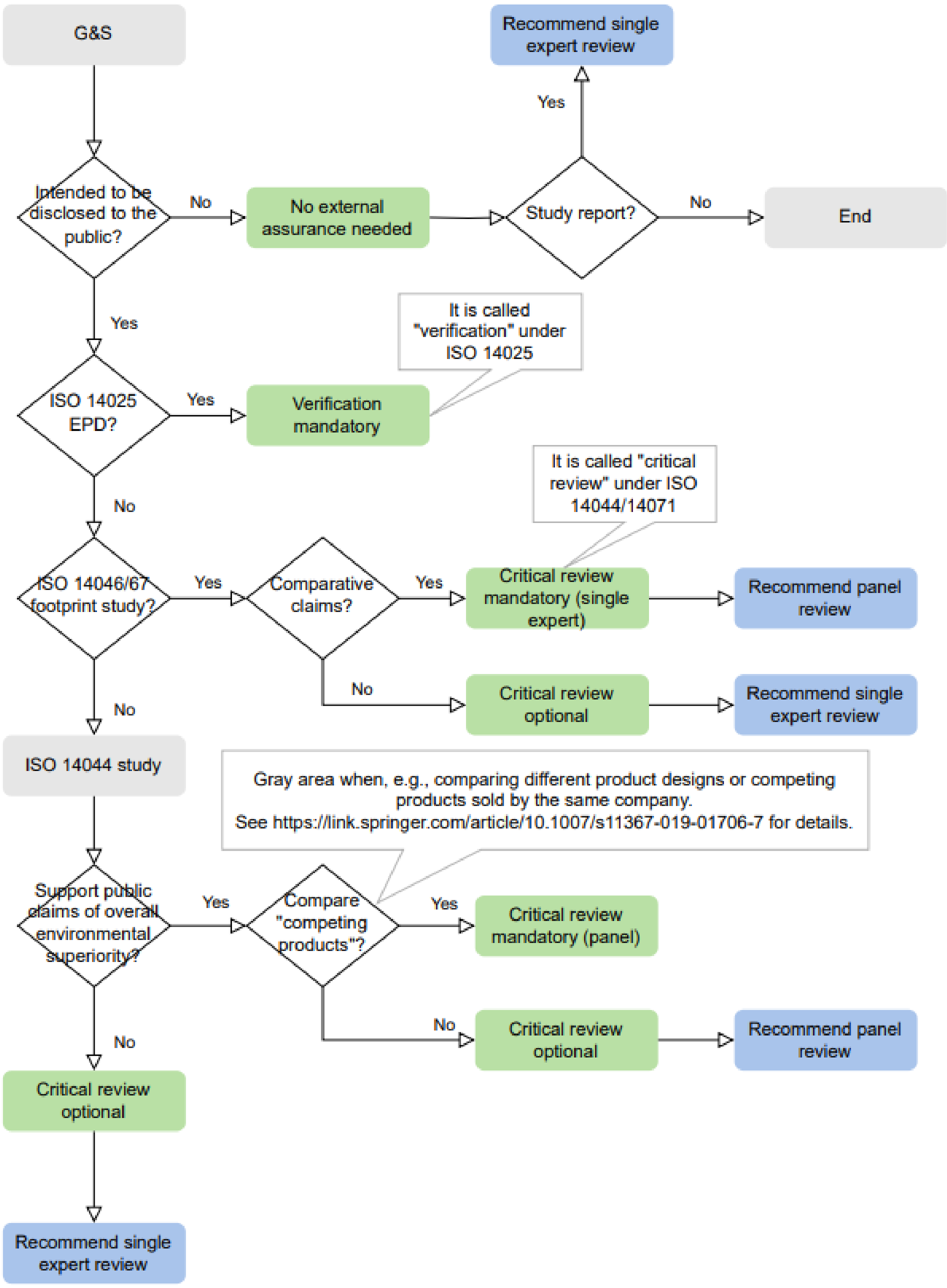


Figure 14-1: Decision tree for critical review of LCA communications

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[2] ISO 14044:2006, clause 3.6 defines comparative assertions as “environmental claim regarding the superiority or equivalence of on product over a competing product that performs the same function”. Footprint studies cannot support comparative assertions as they consider only one environmental aspect.

14.3. EU Green Claim Directive

In March 2023, the European Commission released a Proposal for a Directive on green claims (European Commission, 2023). The proposed directive aims to ensure that consumers "receive reliable, comparable and verifiable information to enable them to make more sustainable decisions and to reduce the risk of 'green washing'." The foundation of the directive is that environmental claims will need to be externally verified and substantiated using LCA. It prohibits the use of phrases like "net zero", "carbon neutral" and "eco-friendly" from all marketing and packaging unless the claims have been verified and substantiated. This means that having a critically reviewed LCA or carbon footprint study will be necessary to support environmental marketing claims.

14.4. Negative Carbon Emissions

An issue that must be specifically addressed is the reporting of negative carbon emissions. It can be risky to report negative carbon emissions in an attributional LCA if carbon has not actually been permanently removed from the atmosphere. The most common way this occurs in LCAs of chemical recycling is through the use of subtractive upstream system expansion (Chapter 4). The avoided emissions can be larger than emission burdens from chemical recycling leading to net-negative emissions. However, these negative results quantify a change in emissions from status quo to a situation where the waste is diverted from conventional waste management to chemical recycling. As such, it represents a form of consequential modeling rather than an attributional "footprint" study, which is why such subtractive system expansion is not currently allowed in environmental footprints or EPDs.

14.5. Recommendations

- Be as transparent as possible in documenting models, data, and assumptions and their potential effects on the results and conclusions.
- Follow section 5 of ISO 14044 when developing LCA reports.
- All LCA reports should be critically reviewed by least one independent expert.
- Follow section 6 of ISO 14044 and ISO/TS 14071 when performing critical reviews.

References

Allacker et al. (2014). Allocation solutions for secondary material production and end of life recovery. *Institute for Environment and Sustainability*, 1-12.

American Chemistry Council. (2021, December). *Principles for the Advanced Recycling of Plastics Using a Mass Balance Approach.* Retrieved from American Chemistry Council Web Site: https://www.americanchemistry.com/content/download/9931/file/Principles-for-the-Advanced-Recycling-of-Plastics-Using-a-Mass-Balance-Approach.pdf

Arena, & Ardolino. (2022). Technical and environmental performances of alternative treatments for challenging plastics waste . *Resources, Conservation & Recycling*.

Armenise et al. (2021). Plastic waste recycling via pyrolysis: A bibliometric survey and literature review . *Journal of Analytical and Applied Pyrolysis* .

Banar, M. (2015). Life cycle assessment of waste tire pyrolysis. *Fresenius Environmental Bulletin, 24*(4), 1215-1226.

Bare, J. (2012). *Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) - Software Name and Version Number: TRACI version 2.1 - User's Manual.* Washington, D.C.: U.S. EPA.

Bell, L. (2023). *Chemical Recycling: A Dangerous Deception.* Beyond Plastics and International Pollutants Elimination Network (IPEN).

Boulay, A.-M. J. (2017). The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE). *The International Journal of Life Cycle Assessment*.

Broeren et al. (2022). *Monitoring chemical recycling: How to include chemical recycling in plastic recycling monitoring?* CE Delft.

BSI. (2012). *PAS 2050-1:2012: Assessment of life cycle greenhouse gas emissions from horticultural products.* London: British Standards Institute.

Catena-X. (2024). *Catena-X Product Carbon Footprint Rulebook.* Retrieved February 11, 2025, from https://www.carbon-transparency.org/resources/catena-x-product-carbon-footprint-rulebook

CE-Delft. (2020). *Exploration chemical recycling – Extended summary: What is the potential contribution of chemical recycling to Dutch climate policy?* Delft: CE Delft.

CEN. (2012). *CEN - EN 15804, Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products.* Brussels: European Committee for Standardization.

CGF. (2022). *Chemical Recycling in a Circular Economy for Plastics: A Vision and Principles Paper.* The Consumer Goods Forum.

Cherubini et al. (2018). Uncertainty in LCA case study due to allocation approaches and life cycle. *The International Journal of Life Cycle Assessment*, 2055-2070.

Coleman et al. (2020). *LCA carbon footprint summary report for Eastman carbon renewal technology.* Kingsport: Eastman Chemical Company.

Collias et al. (2021). *Introduction—Circular Economy of Polymers and Recycling Technologies.*

CPA. (2021). *Guidance on Waste Definitions.* European Commission.

CRE. (2019). *Definition*. Retrieved from Chemical Recyclying Europe: https://www.chemicalrecyclingeurope.eu/copy-of-about-chemical-recycling-1

CRE. (2021, Novemeber 11). *Mass-Balance for chemical recycling is essential for achieving higher recycling rates, incorporating recycling content and reducing dependency on crude oil.* Retrieved from https://www.chemicalrecyclingeurope.eu: https://www.chemicalrecyclingeurope.eu/_files/ugd/aecacb_7bcc3ab42b0b4361b62cac7957c9cb69.pdf

Crippa et al. (2019). *A circular economy for plastics – Insights from research and innovation to inform policy and funding decisions.* European Commission.

Damiani, M. F. (2022). *Understanding Product Environmental Footprint and Organisation Environmental Footprint methods.* Luxembourg: Publications Office of the European Union. doi:https://dx.doi.org/10.2760/11564

ECO Platform. (2023, December). *ECO Platform Public Statement on the use of the Mass Balance Approach .* Retrieved from Statements: ECO Platform Web Site: https://www.eco-platform.org/files/download/statements/ECO_2023.12.12_revised-Statement_MBA%2BGOOs.pdf

Ekvall et al. (2020). *Modeling recycling in Life Cycle Assessment.* Swedish Environmental Research Institute.

Environment, D.-G. f. (2023). *Proposal for a Directive on Green Claims.* European Commission.

EPA. (2012). *Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) – User's Manual.* Washington, D.C.: U.S. EPA.

EPA. (2023). *AP-42: Compilation of Air Emissions Factors.* United States Environmental Protection Agency.

EPA. (2023). *Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI).* Retrieved from United States Environmental Protection Act: https://www.epa.gov/chemical-research/tool-reduction-and-assessment-chemicals-and-other-environmental-impacts-traci

European Commission. (2017). *Product Environmental Footprint Category Rules Guidance v6.3.* Brussels.

European Commission. (2021). *Recommendations on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations.*

European Commission. (2023). *DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on substantiation and communication of explicit environmental claims (Green Claims Directive).* Brussels: European Commission.

EuroStat. (2023). *Municipal waste by waste management operations*. Retrieved from Eurostat Data Browser: https://ec.europa.eu/eurostat/databrowser/view/ENV_WASMUN/default/bar?lang=en&category=env.env_was.env_wasst

Fantke, P. E. (2016). Health Impacts of Fine Particulate Matter. In U.-S. L. Initiative, *Global Guidance for Life Cycle Impact Assessment Indicators Volume 1.* UNEP.

Frischknecht. (2010). LCI modelling approaches applied on recycling of materials in view of environmental sustainability, risk perception and eco-efficiency. *International Journal for Life Cycle Assessment*, 666-671.

Graedel, T., & Reck, B. (2015). Six Years of Criticality Assessments - What Have We Learned So Far? *Journal of Industrial Ecology*. doi:10.1111/jiec.12305

Greenhouse Gas Protocol. (2013). *Product Life Cycle Accounting and Reporting Standard.* Retrieved February 11, 2025, from https://ghgprotocol.org/product-standard#supporting-documents

Guinee et al. (2004). Economic Allocation: Examples and Derived Decision Tree. *Institute of Environmental Sciences*.

Guinée, J. B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., . . . Huijbregts, M. (2002). *Handbook on life cycle assessment. Operational guide to the ISO standards.* Dordrecht: Kluwer.

Hauschild M, G. M. (2011). *Recommendations for Life Cycle Impact Assessment in the European context - based on existing environmental impact assessment models and factors.* Luxembourg: European Commission.

Hauschild M, G. M. (2011). *Recommendations for Life Cycle Impact Assessment in the European context - based on existing environmental impact assessment models and factors.* JRC.

Hermansson et al. (2022). Allocation in recycling of composites - the case of life cycle assessment. *The International Journal of Life Cycle Assessment*, 419-432.

ICCA. (2021). *Life Cycle Assessment of circular systems - Guide & case studies.* International Council of Chemical Associations.

Imren et al. (2023). *Ineos Styrolution Comparative LCA Report.* Sphera.

IPCC. (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories - Volume 4 - Agriculture, Forestry and Other Land Use.* Geneva, Switzerland: IPCC.

IPCC. (2013). *Climate Change 2013: The Physical Science Basis.* Geneva, Switzerland: IPCC.

ISO. (2006). *ISO 14025:2006, Environmental labels and declarations — Type III environmental declarations — Principles and procedures.* ISO.

ISO. (2006). *ISO 14040: Environmental management – Life cycle assessment – Principles and framework.* Geneva: International Organization for Standardization.

ISO. (2006). *ISO 14044: Environmental management – Life cycle assessment – Requirements and guidelines.* Geneva: International Organization for Standardization.

ISO. (2008). *ISO 15270:2008, Plastics — Guidelines for the recovery and recycling of plastics waste.* ISO standard.

ISO. (2014). *ISO 14046:2014, Environmental management — Water footprint — Principles, requirements and guidelines.* Geneva: International Organization for Standardization.

ISO. (2017). *ISO 14026:2017, Environmental labels and declarations — Principles, requirements and guidelines for communication of footprint information.* Geneva: International Organization for Standardization.

ISO. (2017). *ISO 21930:2017, Sustainability in buildings and civil engineering works — Core rules for environmental product declarations of construction products and services.* Geneva: International Organization for Standardization.

ISO. (2018). *ISO 14067:2018, Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification.* Geneva: International Organization for Standardization.

ISO. (2025). *ISO/WD 13662, Chain of Custody — Mass Balance — Requirements and guidelines.* ISO standard.

Jeswani, H. K., Kruger, C., Kicherer, A., Antony, F., & Azapagic, A. (2019). A methodology for integrating the biomass balance approach into life cycle assessment with an application in the chemicals sector. *Science of The Total Environment, 687*, 380-391. doi:https://doi.org/10.1016/j.scitotenv.2019.06.088

Jeswani, H. K., Kruger, C., Russ, M., Horlacher, M., Antony, F., Hann, S., & Azapagic, A. (2021). Life cycle environmental impacts of chemical recycling via pyrolysis of- mixed plastic waste in comparison with mechanical recycling and energy recovery. *Science of The Total Environment, 769*. doi:https://doi.org/10.1016/j.scitotenv.2020.144483

Jeswani, H., Krüger, C., Russ, M., Horlacher, M., Antony, F., Hann, S., & Azapagic, A. (2021). Life cycle environmental impacts of chemical recycling via pyrolysis of mixed plastic waste in comparison with mechanical recycling and energy recovery. *Science of the Total Environment, 769*. doi:https://doi.org/10.1016/j.scitotenv.2020.14448

JRC. (2010). *ILCD Handbook: General guide for Life Cycle Assessment – Detailed guidance. EUR 24708 EN* (1st ed.). Luxembourg: Joint Research Centre.

JRC. (2023). *Environmental and economic assessment of plastic waste recycling: A comparison of mechanical, physical, chemical recycling and energy recovery of plastic waste.* Joint Research Centre .

Karg, J. (2022). Analyse kritischer Modellierungsaspekte und praktische Umsetzung einer Ökobilanz des chemischen Recyclings von Kunststoffen.

Keller, F., Voss, R., & Lee, R. (2022). *Overcoming Challenges of Life Cycle Assessment (LCA) & Techno-Economic Assessment (TEA) for Chemical Recycling.* Institute of Energy Process Engineering and Chemical Recycling.

Koffler et al. (2021). *Life Cycle Assessment of Chemical Recycling - First steps towards harmonization.* Sphera.

Koffler et al. (2021). *Life Cycle Assessment of Chemical Recycling - First steps towards harmonization.* Sphera.

Koffler, C., & Finkbeiner, M. (2017). Are we still keeping it “real”? Proposing a revised paradigm for recycling credits in attributional life cycle assessment. *The International Journal of Life Cycle Assessment*, 181-190.

Koffler, C., & Florin, J. (2013). Tackling the Downcycling Issue—A Revised Approach to Value-Corrected Substitution in Life Cycle Assessment of Aluminum (VCS 2.0). *Sustainability*, 4546-4560.

Lase et al. (2023). How much can chemical recycling contribute to plastic waste recycling in Europe? An assessment using material flow analysis modeling. *Resources, Conservation & Recyclying*, 28-60.

Maga, D., Galafton, C., Blomer, J., Thonemann, N., Ozdamar, A., & Bertling, J. (2022). Methodology to address potential impacts of plastic emissions in life cycle assessment. *The International Journal of Life Cycle Assessment, 27*, 469-491. doi:https://doi.org/10.1007/s11367-022-02040-1

Mankins, J. (2009). Technology readiness assessments: A retrospective. *Acta Astronautica*, 1216-1223.

Meys, R., Kätelhön, A., & Bardow, A. (2019). Towards sustainable elastomers from CO2: life cycle assessment of carbon capture and utilization for rubbers. *Green Chemistry, 21*(12), 3334-3342. doi:https://doi.org/10.1039/C9GC00267G

Mol, & Oosterveer. (2015). Certification of Markets, Markets of Certificates: Tracing Sustainability in Global Agro-Food Value Chains. *Sustainability*, 12258-12278.

Moni et al. (2020). Life cycle assessment of emerging technologies: A review. *Journal of Industrial Ecology*, 52-63.

Nassar, N., Barr, R., Browning, M., Diao, Z., Friedlander, E., Harper, E., . . . Graedel, T. (2012). Criticality of the Geological Copper Family. *Environmental Science & Technology*, 1071-1078.

Nicholson et al. (2022). The Critical Role of Process Analysis in Chemical Recycling and Upcycling of Waste Plastics. *Annual Review of Chemical and Biomolecular*, 9-30.

Packaging Europe. (2023, October 17). *Mass balance fuel-use exempt necessary to scale up chemical recycling, says plastics supply chain*. Retrieved from News: Packaging Europe:

https://packagingeurope.com/news/mass-balance-fuel-use-exempt-necessary-to-scale-up-chemical-recycling-says-plastics-supply-chain/10471.article

Pellengahr F, C.-P. E.-M. (2025). Modeling marine microplastic emissions in Life Cycle Assessment: characterization factors for biodegradable polymers and their application in a textile case study. *Frontiers in Toxicology, 7*. doi:https://doi.org/10.3389/ftox.2025.1494220

Pfister, S., Koehler, A., & Hellweg, S. (2009). Assessing the Environmental Impacts of Freshwater Consumption in LCA. *Environ. Sci. Technol., 43(11)*, 4098–4104.

Piccinno et al. (2016). From laboratory to industrial scale: a scale-up framework for chemical processes in life cycle assessment studies. *Journal of Cleaner Production*, 1085-1097.

Plastics Europe. (2020, January). *Mass Balance Approach to Accelerate the Use of Renewable Feedstocks in Chemical Processes.* Retrieved from Plastics Europe Web Site: https://plasticseurope.org/wp-content/uploads/2021/10/20100129-View-Paper-Mass-Balance-Approach-Renewable-Feedstocks.pdf

PlasticsEurope. (2017). *Recommendation on Steam Cracker allocation.* PlasticsEurope.

PlasticsEurope. (2019). *Eco-profiles program and methodology.* PlasticsEurope.

PlasticsEurope. (2024). *The Circular Economy for Plastics: A European Analysis.* Retrieved February 11, 2025, from PlasticsEurope: https://plasticseurope.org/knowledge-hub/the-circular-economy-for-plastics-a-european-analysis-2024/

Posch, M. S. (2008). The role of atmospheric dispersion models and ecosystem sensitivity in the determination of characterisation factors for acidifying and eutrophying emissions in LCIA. *International Journal of Life Cycle Assessment, 13*, 477-486.

Quantis. (2020). *Life Cycle Assessment Of Plastic Energy Technology For The Chemical Recycling Of Mixed Plastic Waste.* Quantis.

Rosenbaum, R. K., Bachmann, T. M., Swirsky Gold, L., Huijbregts, M., Jolliet, O., Juraske, R., . . . Hauschild, M. Z. (2008). USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. *Int J Life Cycle Assess, 13(7)*, 532–546.

Russ et al. (2020). *Evaluation of pyrolysis with LCA - 3 case studies.* Sphera.

Rybicka et al. (2015). Technology readiness level assessment of composites recycling technologies. *Journal of Cleaner Production*, 1001-1012.

Saputra Lase et al. (2023). How much can chemical recycling contribute to plastic waste recycling in Europe? An assessment using flow material analysis modeling. *Resources, Conservation & Recycling*.

Schrijvers et al. (2016). Developing a systematic framework for consistent allocation in LCA. *International Journal for Life Cycle Assessment*, 976-993.

Schwarts, A. E., Herlaar, S., Cohen, Q. M., Quik, J. T., Golkaram, M., Urbanus, J. H., . . . Huijbregts, M. A. (2024). Microplastic aquatic impacts included in Life Cycle Assessment. *Resources, Conservation and Recycling, 209*(October 2024), 1077-1087. doi:https://doi.org/10.1016/j.resconrec.2024.107787

Schwartz, A. E., Ligthart, T. N., Godoi Bizarro, D., De Wild, P., Vreugdenhil, B., & van Harmelen, T. (2021). Plastic recycling in a circular economy; determining environmental performance through an LCA matrix model approach. *Waste Management, 121*, 331–342. doi:https://doi.org/10.1016/j.wasman.2020.12.020

Schwarz et al. (2021). Plastic recycling in a circular economy; determining environmental performance through an LCA matrix model approach. *Waste Management*, 331-342.

Seppälä J., P. M. (2006). Country-dependent Characterisation Factors for Acidification and Terrestrial Eutrophication Based on Accumulated Exceedance as an Impact Category Indicato. *International Journal of Life Cycle Assessment, 11*(6), 403-416.

Solvis, & Silviera. (2020). Technologies for chemical recycling of household plastics – A technical review and TRL assessment. *Waste Management*, 128-138.

Sphera. (2020). *Evaluation of pyrolysis with LCA - 3 Case Studies.* BASF. Retrieved April 11, 2025, from https://www.basf.com/dam/basf/www/global/documents/en/sustainability/we-drive-sustainable-solutions/circular-economy/selected-down_load/BASF_ChemCycling_LCA_Study.pdf

Sphera. (2025). *Search Life Cycle Assessment Datasets*. Retrieved April 11, 2025, from Sphera: https://lcadatabase.sphera.com/

Staaij et al. (2012). *Analysis of the operation of the mass balance system and alternatives: Final report.* European Commission.

Struijs, J. B. (2009). *Aquatic Eutrophication. Chapter 6 in: ReCiPe 2008 A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Report I: Characterisation factors, first edition. .*

Tabrizi et al. (2021). *Recycled content in plastics: the mass balance approach.* RethinkPlasticAlliance.

TfS. (2024). *The Product Carbon Footprint Guideline for the Chemical Industry v3.0.* Together for Sustainability. Retrieved April 11, 2025, from https://www.tfs-initiative.com/app/uploads/2024/12/TfS-PCF-Guidelines-2024.pdf

Ügdüler et al. (2020). Challenges and opportunities of solvent-based additive extraction methods for plastic recycling. *Waste Management*, 148-182.

ULE. (2022). *Product Category Rules for Building Related Products and Services, Part A: Life Cycle Assessment Calculation Rules and Report Requirements.* UL Standards & Engagement.

van Oers, L., de Koning, A., Guinée, J. B., & Huppes, G. (2002). *Abiotic resource depletion in LCA.* The Hague: Ministry of Transport, Public Works and Water Management.

Van Zelm R., H. M. (441-453). European characterisation factors for human health. *Atmospheric Environment, 42*.

Viveros, A. (2022). *Life Cycle Assessment of Food Grade Film.* Sphera.

WBCSD. (2023). *Pathfinder Framework: Guidance for the Accounting and Exchange of Product Life Cycle Emissions.*

WRI. (2011). *GHG Protocol Product Life Cycle Accounting and Reporting Standard.* Washington D.C.: World Resource Institute.

Zampori, L., & Pant, R. (2019). *Suggestions for updating the Product Environmental Footprint (PEF) method.* European Commission.

Zero Waste Europe. (2020). *Die Umweltauswirkungen des chemischen Recyclings von Kunststoffen: Zehn Kritikpunkte an vorliegenden Ökobilanzen.* Retrieved from https://www.nabu.de/imperia/md/content/nabude/abfallpolitik/201218_die_umweltauswirkungen_des_chemischen_recyclings_von_kunststoffen_final.pdf