Avoiding greenhouse gas emissions

The essential role of chemicals

Life Cycle Assessment of circular systems

Guide & case studies

International Council of Chemical Associations

The International Council of Chemical Associations (ICCA) is committed to playing a key role in the systemic transition to circular economy as a key component of sustainability.

Disclaimer
The case studies included in this report illustrate the application of elements of Life Cycle Assessment (LCA) approaches, in the context of calculating the potential impacts for climate and greenhouse gas (GHG) emissions. The use of the case studies is illustrative only, and does not constitute an endorsement by the International Council of Chemical Associations (ICCA) for any particular product, process, supplier or vendor.

Preamble

The International Council of Chemical Associations (ICCA) is committed to playing a key role in the systemic transition to circular economy as a key component of sustainability.

From the design phase of products to their end-of-life, the chemical industry can offer innovative solutions to the benefit of the sector itself and throughout the value chain, encouraging and supporting downstream industries to become more circular.

As the association of the global chemical industry, ICCA supports the acceleration of the transition towards a more sustainable future thereby taking into account the following principles for a circular economy:

- Environmental and social sustainability need to be assessed when developing circular, viable business solutions.
- The full life cycle of products and processes should be taken into consideration to assess the benefits of innovative solutions
- Increased cooperation among value chain partners will be sought.

This document complements a series of studies by ICCA and its members companies, including a range of case studies and methodological documents, highlighting the importance of Life Cycle Assessments (LCA), especially when it comes to quantifying and reporting on the chemical industry's own footprint (scope 1 emissions), and the enabling role of its products in lowering CO_2 emissions in value chains.

The global chemical industry is committed to ensure that LCA methodology can handle the specifics of circular solutions in a robust way, enabling the comparison of circular solutions with their conventional counterparts. Circular systems enabled by the chemical industry are presented to illustrate how LCA methodologies are used to quantify overall emissions, as well as other impact categories (e.g. water, land, air).

This document explains the importance of using a LCA methodology to characterize the environmental benefits of circular systems, with a focus on greenhouse gases (GHG). This study by the consultant Quantis also underlines the need indeed to ensure that circular systems are beneficial overall, also regarding resource savings, environmental impacts, and societal benefits.

We hope this document will benefit decision makers to better understand LCA studies and use their results to select technologies and projects, and/or to orient policies and strategies.

M. Mensink,
ICCA Council Secretary

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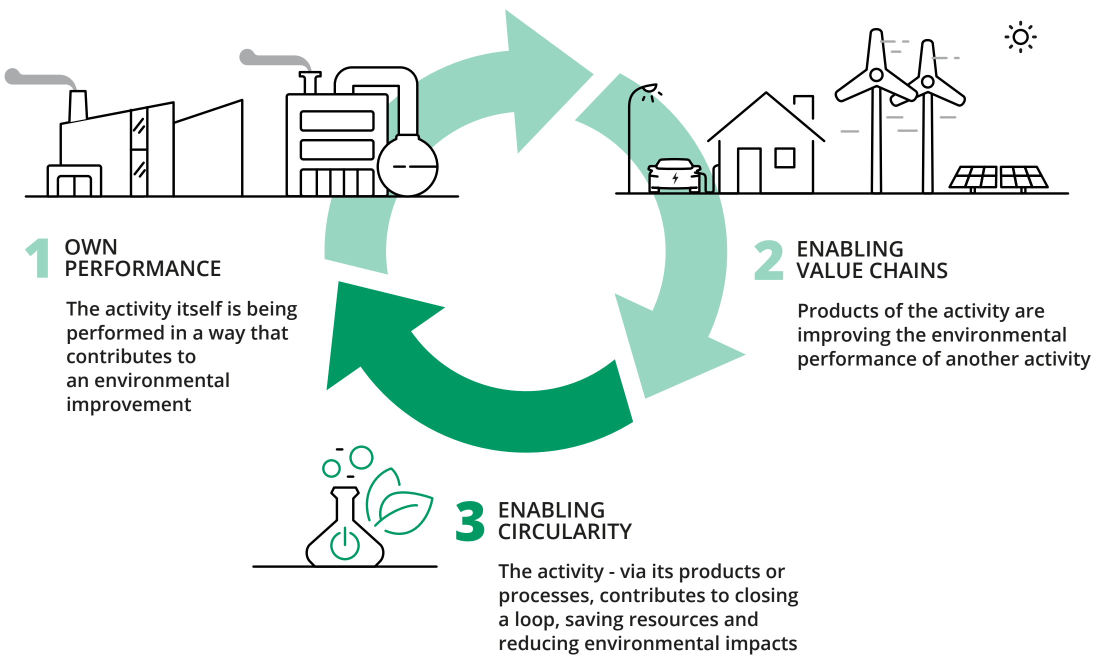
Executive summary

The International Council of Chemical Associations (ICCA) is committed to playing a key role in supporting a circular economy as a key component of sustainability, whereby resources and materials are continuously cycled to eliminate waste while creating value for all. That is the reason ICCA, with the support of the consultant Quantis, has been working on several studies on Life Cycle Assessment which we consider an integral part of going circular.



Environmental impact and progress need to be viewed in a holistic way:
(1) from an industry's own emissions perspective,
(2) for the emissions it enables to avoid in the value chain, and
(3) for circular solutions it takes part in.

The environmental Life Cycle Assessment (LCA) is a widely accepted methodology to quantify the environmental impacts of a product or a technology. It is a holistic approach, covering the entire value chain of a given product and a wide set of environmental issues. Robust data, transparency of the analysis and comparability of results ensure the relevance of LCA as the go-to tool for decision-makers aiming to assess sustainable solutions (aligned with ISO standards).

By focusing on a single environmental issue – climate change – it is possible to understand how LCA methodology can be used to assess circular solutions, ensuring that comparisons between circular and linear solutions are as fair as possible.

This document addresses the key fundamentals when looking at LCA results for circular solutions:

- **The assessment should consider all services provided by each solution** being compared to ensure a fair comparison - especially important for circular solutions that often deliver several services at the same time, such as managing waste and producing new raw materials.

- **Accounting for variations in the type of feedstock and the quality of the output products** delivered by the two solutions enables LCA to make relevant comparisons and not to over- or under-sell one of them. Ultimately, it should aim to be material or technology neutral, wherever possible, especially when the material or technology has no significant impact on the final assessment.

- **Assessing each solution over a long timeframe** may help in accounting for any later environmental impacts such as delayed emissions occurring after temporary carbon storage.

- LCAs have the potential to reflect the environmental benefits and burdens of a solution as a whole. Avoided emissions due to increased circularity most often result from efforts by multiple partners. **Attributing changes in emissions to the complete value chain**, without subdividing between partners, gives a full picture of the benefits of circular solutions. Further methodology development and industry alignment will be required.

- If benefits must be split, or allocated, to enable an individual stakeholder to quantify their own contribution, **allocation approaches should be transparent, fair and justified**.

- As circular solutions develop, LCA results may also reflect **changes in context-dependent elements**, such as the local energy mix,process efficiency, or disposal/end uses options. Such changes may strongly impact the environmental performance of emerging circular solutions, and, to some extent, of conventional solutions as well.

- Future availability of **low-carbon energy** can be taken into account in LCA, especially for circular solutions that save resources but are energy-intensive. However, it must be transparent with the appropriate technology and economic feasibility assessment.

- LCA can also cope with **changes in the availability of recovered waste or by-products**, which may ultimately impact the environmental performance of the system.

- **Novel circular solutions will themselves continue to evolve** as technologies mature and recovery schemes are more widely implemented. Such elements should and can be taken into account in LCA calculations.

Overall, this report shows how LCA methodology can handle the specificities of circular solutions, enabling the comparison of circular solutions with their conventional counterparts. Future developments in LCA can further strengthen the central role it has to play in decision-making: a wider scope in terms of the environmental impacts considered, increasing availability of process-specific data, and a wider adoption of common approaches. This will further increase the robustness of LCA in evaluating circular solutions and their capacity to reduce the impacts of human activities on the environment.

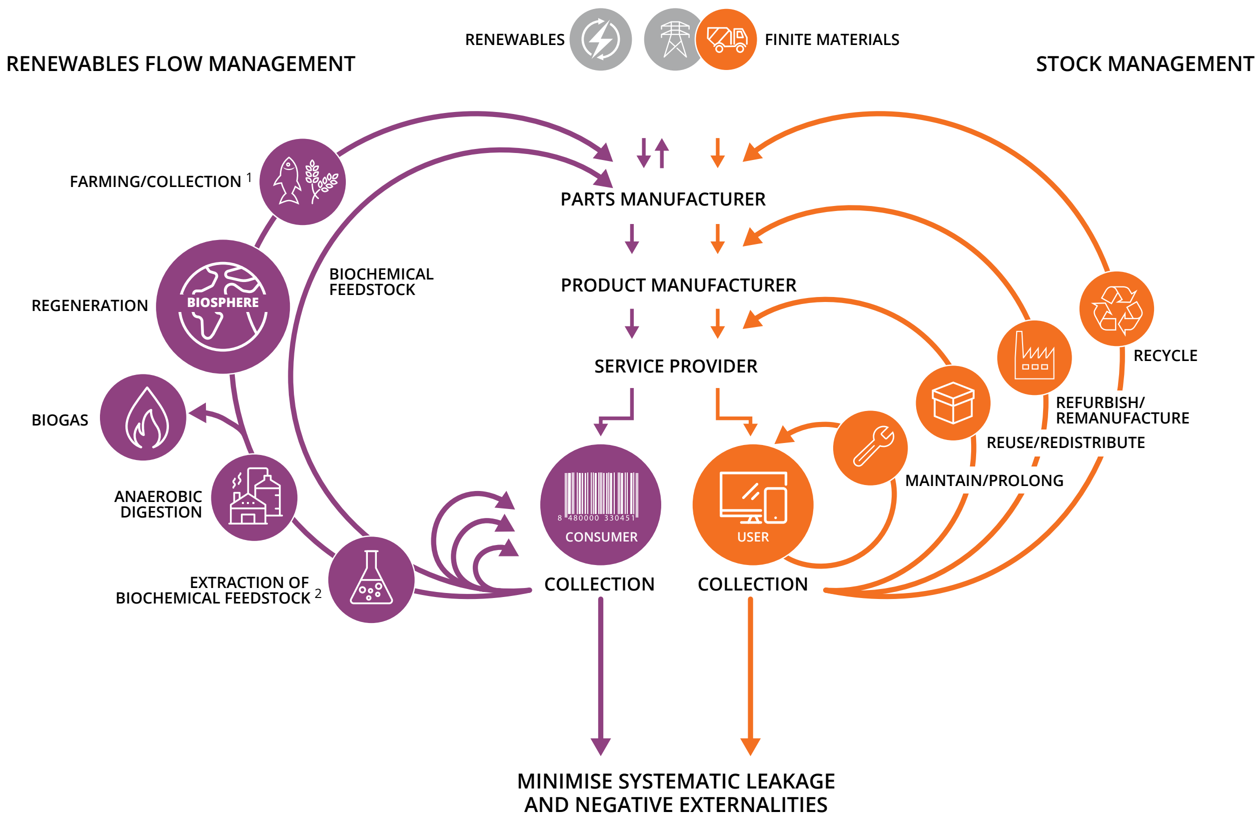
Part 1

Life Cycle Assessment of circular systems: Setting the scene

Introduction

The advent of circularity

Long-term value creation requires new systems that make less use of materials and energy, and enable the restoration of natural capital. In this respect, circular systems can offer attractive alternatives that businesses are already exploring today. The circular economy is one that is "restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value through cycles"[1]. Such circular systems often seek to decouple economic development from finite resource consumption.



1. Hunting and fishing
2. Can take both post-harvest and post-consumer waste as an input

Circular economy - the broader view: the circular economy aims to keep products, components and materials at their highest utility and value for longer times

Role of the chemical industry in circular systems

The chemical industry has a key role to play in circularity. With its capacity to transform molecules, it has the potential to contribute to circular systems in several ways. Recent research points to two main approaches the industry takes in order to transform to a more circular, sustainable model: (1) developing technology and business models to circulate molecules, and (2) enabling the circular economy in downstream industries **[2]**.

Progress towards a circular economy relies on reusing, repurposing, recycling and recovery of value locked in materials traditionally viewed as waste. Initiatives by the chemical industry to foster circular systems in value chains, beyond their own fences, are countless, many of them already at industrial scale, and even a larger number in the development phase. These new technologies are real solutions to the challenges of:

- **Optimization of material use**
  - Optimizing energy consumption through the use of advanced catalysts and synthesis.
  - Recycling material losses or post-consumer waste in order to produce new materials **[3]**. This has led the chemical industry to recycle polymers from used car parts to make new ones, plastic bottles into phones, or hard to recycle mixed plastic waste to produce high-quality secondary plastic.
  - Reusing materials already present in the system, thus avoiding the production of new materials. Examples include solvent recovery or catalyzer reuse.
  - Chemically treating, purifying and separating waste materials to enable subsequent recycling. Examples include cleaning metals or packaging, and bleaching waste paper products.
- **Utilization of alternative feedstock**
  - Using waste as feedstock (e.g. production of Polyhydroxyalkanoate, a building block of certain bio-plastics).
  - Using bio-based feedstock to develop renewable materials (e.g. cellulosic bioethanol production from wheat/barley straw, chemically-mediated recovery of cellulose from lignin to make bioethanol or production of succinic acid from yeast).
  - Capturing carbon for re-use as feedstock through CCU (Carbon Capture and Usage) technologies. For example, CO_2 recovered from exhaust gases can be used to produce methanol, a key raw material with many applications.

Circularity as an accelerator to climate change mitigation

Chemicals are essential to greenhouse gase (GHG) and energy savings throughout the value chain and society. This comes in addition to what the industries dependent on chemicals can deliver towards carbon neutrality regarding their own process efficiency in terms of GHG emissions. Integration of such enabling roles in policy is gaining pace. In Europe, for example, the framework of the European Union's (EU) Green Deal recognizes that "an economic activity shall be considered to contribute substantially to climate change mitigation" by directly enabling other activities **[4]**.

New circular technologies can bring additional environmental benefits on the product efficiency side, because using fewer primary resources also has the potential to reduce waste volumes and emissions to the environment. One way to look at the benefit of circular systems is through the lens of climate change. Increasing circularity of products, materials and molecules can be one of the approaches to climate change mitigation, because reusing materials allows to conserve the embodied energy and other valuable resources used to manufacture the virgin products.

Reduction of GHG emissions across the value chain, from manufacturing to consumption

Efficient **use of resources**

Regenerative **carbon technology solutions** (natural or CCS)

Three links between circular economy and climate change (adapted from Ellen McArthur Foundation, 2019) [5]

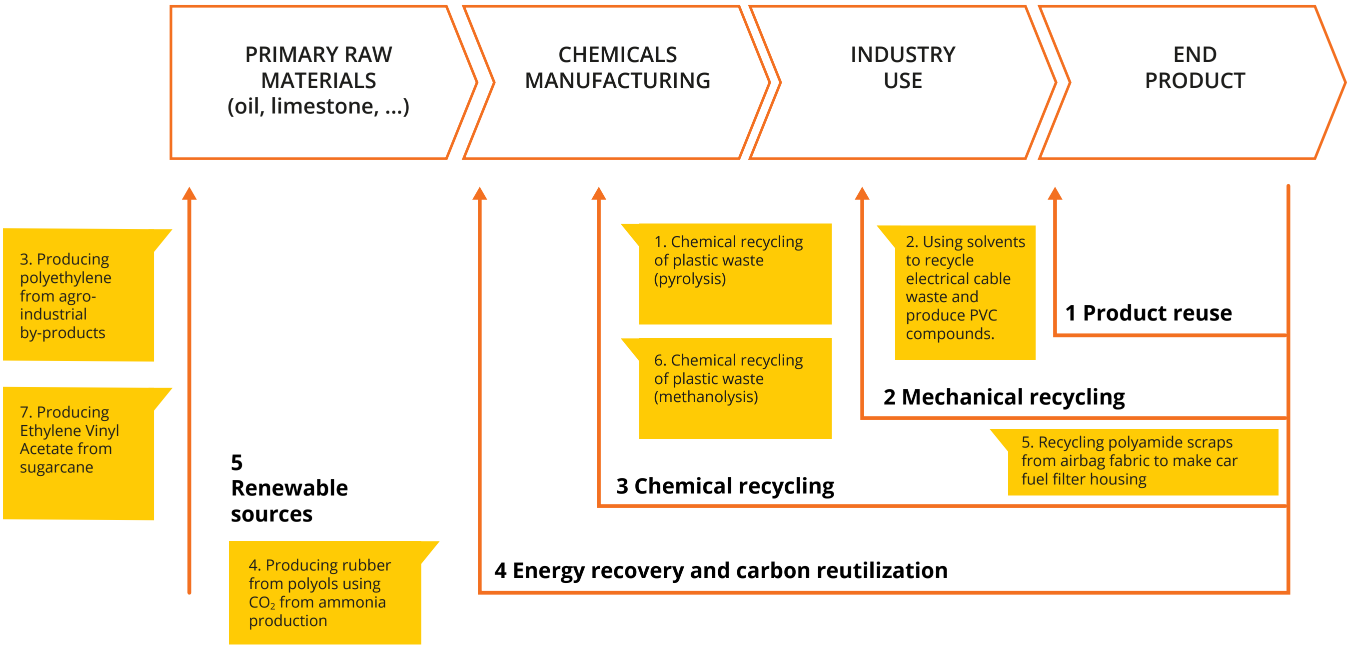
Circular systems in this document

The present document focuses on the accounting of environmental impacts and benefits generated by circular systems. A variety of case studies are briefly presented, each illustrating specific methodological approaches requiring attention in the case of circular systems. They also illustrate the diversity of circular systems and the potential for loops at many steps in the value chain. How questions posed by carbon accounting are solved in the presented examples is potentially valid for all environmental impacts, not just climate change:

1. Chemical recycling of mixed plastic waste by pyrolysis in order to produce virgin-grade polyethylene.
2. Using solvents to mechanically recycle electrical cable waste in order to produce PVC compounds.
3. Producing polyethylene from by-products of agro-industrial processes (waste animal fats from the meat industry and palm oil fatty acids from palm oil refining)
4. Producing rubber from polyols based on CO_2 captured from an ammonia production plant.
5. Recycling polyamide from airbag fabric scraps to make automobile fuel filter housing.
6. Chemical recycling of mixed plastic waste by reforming in order to produce syngas which is further used to produce a variety of plastic resins, fibers and acetyl chemical products.
7. Producing Ethylene Vinyl Acetate from sugarcane.

Measuring environmental impact through Life Cycle Assessment

The environmental Life Cycle Assessment (LCA) is a widely accepted methodology that evaluates and quantifies the environmental impacts of a product. Its holistic nature, which covers the entire value chain of a given product and a wide set of environmental issues, has made it the go-to tool for decision-makers aiming to develop sustainable solutions or looking for an effective communication tool.



The circular cases presented in this document illustrate the diversity of circular systems, with loops at various steps in the value chains

Life Cycle Assessment: How does it work?

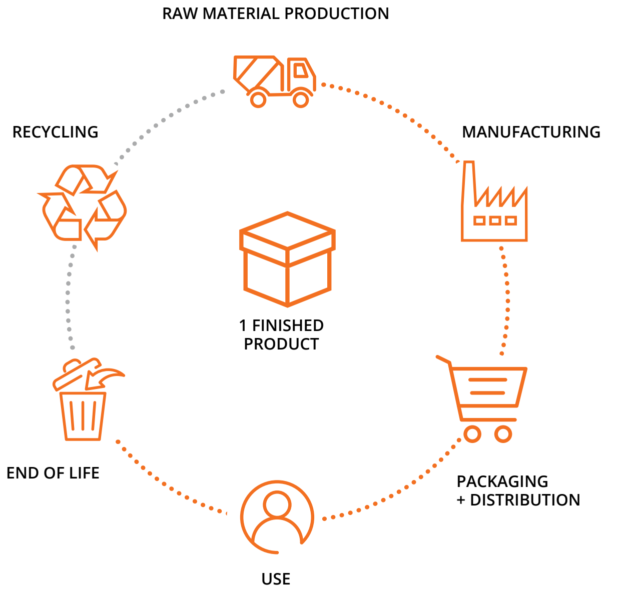
As companies and public authorities seek to ensure that their actions (purchases, investments, processes) are as sustainable as possible, it is necessary to rely on robust metrics to assess the performance of different solutions. The environmental Life Cycle Assessment (LCA) is a widely accepted methodology that evaluates and quantifies the environmental impacts of a product (e.g. climate change, water consumption) across a full product life cycle. It takes into account the consumption of resources (including energy) as well as emissions released to air, water, and soil. Environmental impacts are assessed throughout the life cycle of the product or the performed service, from the extraction of the raw materials necessary for its production all the way to its end-of-life, which LCA practitioners call from "cradle" to "grave".

The approach used to perform LCA is standardized by ISO 14040 and 14044, which detail the key iterative steps to ensure the quality and robustness of any assessment. More information is provided in ICCA's executive guide on "How to Know If and When it's Time to Commission a Life Cycle Assessment" **[6]**.

Overall, all practitioners must follow 4 steps:

- **Define the goal & scope** of the study. The goal includes intended audience and applications. Scope definition ensures that the scope of activities and the unit of comparison lead to a fair comparison between systems and reflects correctly the systems' functions and services to society. The process is iterative and each step provides feedback for other steps of the assessment process.
- **Build the inventory** of emissions throughout all life cycle steps by quantifying the extraction and consumption of resources including energy (i.e. process inputs), as well as products, co-products and waste, and emissions released to air, water, and soil (i.e. process outputs). This step often requires combining data collected from primary sources with existing databases and credible assumptions.
  Data quality is paramount to guarantee the quality of any LCA and should be carefully considered when reading or carrying out this type of assessment.
- **Assess the contribution** of the system to different potential environmental impacts by using a Life Cycle Impact Assessment (LCIA) methodology. Impacts cover issues related to human health (e.g. toxicity, air pollution), biodiversity (e.g. ecotoxicity, land use), resource depletion (mineral and fossil) as well as more general challenges (e.g. climate change, water depletion).
- **Interpret the results** in order to provide a general overview of the main challenges faced by the assessed solution and detail key levers to improve the overall performance of the solution being examined.

LIFE CYCLE OF A PRODUCT



A. INVENTORY OF EMISSIONS (LIFE CYCLE INVENTORY)

Building the inventory of emissions throughout all life cycle steps by quantifying the extraction and consumption of resources as well as co-products, waste and emissions

B. LIFE CYCLE IMPACT ASSESSMENT

The potential environmental impacts are obtained by calculation that "transform" emissions and uses from the inventory into their effects on the environment. The" impact categories" include climate change, human and eco-toxicity, ionizing radiation, and resource base deterioration (e.g. water, non-renewable primary energy resources, land).

The key role of LCA in decision-making

LCA are used to assess the environmental impacts that can be attributed to products and services. As such, LCA results help further improve processes, support policy by showcasing the most efficient solutions, and provide a solid ground for comparison between solutions delivering the same service.

LCA assessments of non-circular and circular systems give companies a better understanding of the main drivers behind the environmental footprint of their products. They are useful to communicate credibly about the environmental performance of any product, and to engage suppliers and customers.
LCA can also guide eco-design efforts of a product: it can be used to assess the benefit of potential design changes, such as substituting a material or ingredient, incorporating more recycled content, or altering packaging. Furthermore, if a more sustainable product is designed, the product footprint results can be used to communicate credibly on the improvements, preventing the risk of greenwashing while enhancing transparency and comparability. A report published by the ICCA and the World Business Council of Sustainable Development (WBCSD) provides guidance on how to use LCA to measure, manage and communicate avoided emissions in systems involving chemical products **[7]**.

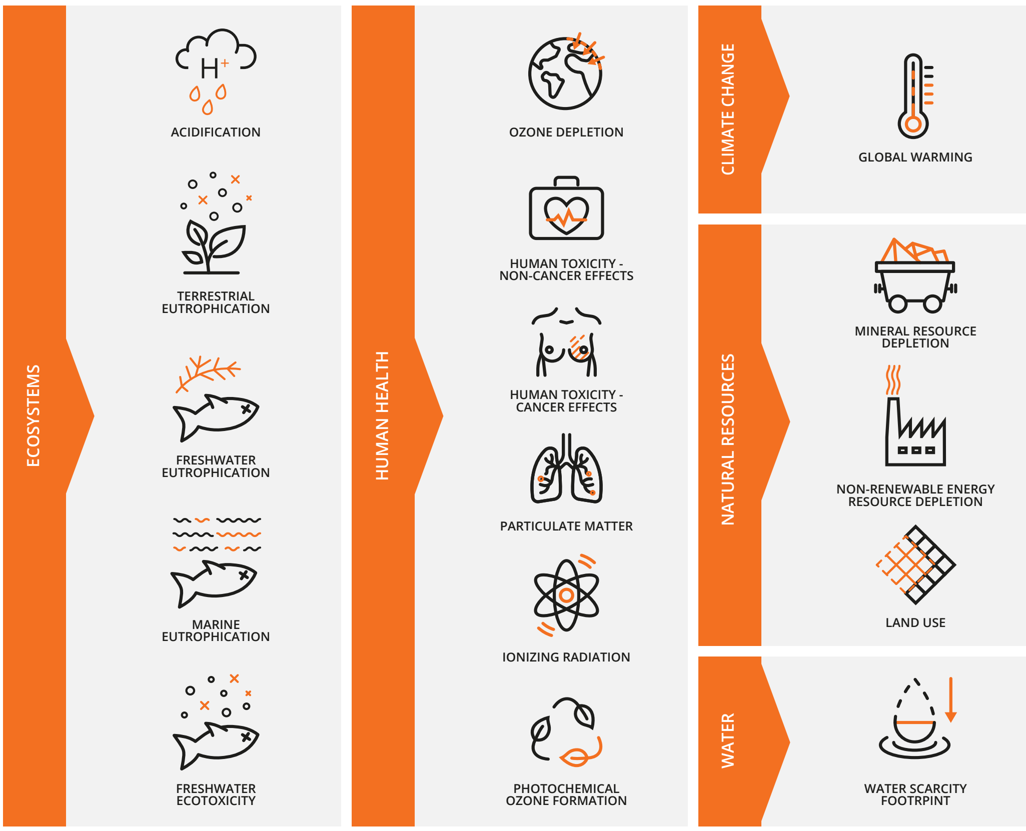
LCA is also gaining visibility in climate policies, since it is the preferred methodology to quantify the overall carbon balance of a system. All of these aspects have made LCA the go-to tool for decision-makers looking to choose solutions based on science.

LCA TIP: **Life Cycle Assessments are most often "attributional"**

LCA are usually "attributional". They focus on the life cycle impacts that can be "attributed" to the product and compared to those of another product. Sometimes, it is necessary to instead take a "consequential" approach, which integrates the consequences of adopting the product/service. For example, a consequential LCA of a carpooling service takes into consideration the fact that it causes a change in the market translating to a variation of traveling behaviors, with an overall increase of travelers and a switch to car pooling from other modes of transportation.

The importance of considering all impacts

Every LCA can provide insight into key environmental challenges associated with a product or service, even if the assessment focuses on a single impact category. A multicriteria approach is however recommended to unlock the full potential of LCA, and to check for possible trade-offs with other environmental impacts, for example when assessing solutions aimed at reducing GHG emissions via low-carbon solutions.



Tip: Using LCA, it is possible to assess a large number of environmental and human health issues in a holistic manner. Environmental impact categories commonly used include impacts on ecosystems (e.g. acidification, eutrophication), impacts on human health (e.g. particulate matter emissions, ozone depletion), the use of natural resources (e.g. mineral resource depletion, land use) and transversal issues (e.g. climate change)

An example often highlighted is that of biofuels. While these can effectively reduce the greenhouse gas (GHG) emissions related to energy generation and use, the resulting demand for more agricultural inputs can lead to additional environmental burden for other environmental impact categories. Thus, a multicriteria approach is needed to fully understand the impacts on the environment and to take the appropriate countermeasures to avoid trade-offs.

LCA in the context of circularity

The fundamental principles of LCA apply as easily to circular systems as they do to linear ones: What can be measured, system definition, and in general most methodological approaches keep valid for circular systems. Also, as for linear systems, the GHG emission avoidance enabled by a circular system is equal to the difference between the emissions from the circular system and a reference system over a defined period of time. However, LCA has also been adapted in order to better account for the specificities of circular systems ensuring that comparisons between circular systems and linear ones are as fair as possible.

Benefits of applying LCA to circular solutions

In the context of climate change, research on circular systems is quickly gaining momentum in industry, academia and policy, leading to a vast number of promising technologies, for example in the fields of CO_2-derived chemicals, chemical recycling, fuels and minerals. LCA and techno-economic assessment (TEA), another assessment methodology that ensures the overall economic viability of a technology, are two essential methodologies for substantiating those technologies and guiding research and development towards commercialization [8].

LCA can be used to compare circular solutions to conventional ones in order to assess the environmental benefits associated with circularity. Because LCA provides a global overview of complex circular systems, it facilitates value chain discussions between stakeholders and helps decision makers identify the key success factors of a circular economy.

From linearity to circularity: what to keep in mind

LCA was developed with linear systems in mind, which is reflected in the nomenclature often used to describe the systems under assessment ("cradle-to-gate" or "cradle-to-grave"). In circular systems, as the mindset is circular ("from cradle to cradle"), the limit between processes which should or shouldn't be included in the assessment is less clear. Furthermore, several other characteristics of circular systems require special attention in LCA, such as the fact that they often provide multiple services (which makes it hard to compare to conventional solutions) or still under development (which hides the full potential of a technology). This mindset has led to some struggles by practitioners to apply LCA to circular systems, raising questions such as:

- How can a circular solution be compared to its traditional counterpart if they do not provide exactly the same service to society?
- How can the benefit of delaying emissions from occurring (for example by avoiding incineration of fossil-based materials which leads to carbon storage in the technosphere) be taken into consideration?
- If a circular system generates a product of interest but also other co-products, how much of the environmental burden should be attributed to the product of interest?
- When a product is recycled, should the environmental impact of recycling be attributed to the new product or the initial product? Should the new product receive credit for avoiding the use of virgin material?
- Can energy-intensive circular solutions use low-carbon energy to reduce their environmental footprint?
- How can LCA take into consideration the effect that changes in feedstock availability and cost could have on existing or innovative processes (e.g. energy consumption increases related to the use of less pure resources)?
- How can expected future increases in efficiency be taken into consideration in an LCA of a circular technology which is not yet at maturity?
- What are the key methodological or data-driven adaptations that are necessary to reinforce LCA and make it easily applicable to circular systems?

LCA has evolved to take into account these circularity questions with significant work underway to refine the use of LCA methodologies in the case of circular systems. Part 2 of this document addresses each of the above topics and aims to give an overview of the work carried out to answer the four main questions raised by LCA and circularity:

1. **What** is the basis for comparison?
2. **Who** claims the benefits and burdens of circular systems?
3. **When** should changes in the context be accounted for?
4. **How** can the LCA methodologies of circular solutions be further reinforced?

Part 2

What, who, when and how?

LCA is a useful tool to assess the environmental performance of a circular solution in comparison with a conventional counterpart. But to produce relevant results, the comparison must be fair. So it all starts with defining what should be the good basis of comparison. At the same time, life cycle avoided emissions almost always arise from efforts by multiple partners along a value chain, particularly for circular systems. So the question arises: Who bears the environmental burdens and who should claim the benefits of circular solutions? And when to account for changes in the context, as LCA results may be context-dependent: Results will vary depending for instance, on the energy-mix of the country where the circular system is operated. Emerging circular solutions are also particularly likely to be affected by changes as they develop into more mature solutions in the future.

What is the basis of comparison between circular and conventional systems?

Several elements must be kept in mind regarding the goal and scope of the study. For one, it is important that both systems under comparison provide the same function. Because circular solutions provide multiple services to society, they require adaptation of the scope of the study to ensure that all functions are taken into consideration. Furthermore, if the two solutions do not use the same feedstock (e.g. one waste management technology can only take in a subset of the materials taken in by the second technology), this difference should be accounted for in LCA. Quality variations in the output products of both solutions are also important to address.

Another element of a study's goal and scope is the timeframe of emissions considered. Emissions related to the solution under study are quantified over a given period of time, thus including delayed emissions (e.g. those occurring during the product's use phase, or at its end-of-life). Emissions occurring after this period are not accounted for, meaning that any carbon that has not been reemitted is considered permanently stored. The definition of this period's duration can have a significant impact on results.

Taking into account feedstock characteristics, multiple services and the context

Choosing the right unit of comparison between two systems

In order to compare two systems, it is necessary that they are both providing the same function. For example, it makes little sense to compare 1 kg of recycled plastic to 1 kg of recycled glass since, for an application such as making a milk bottle, the amount needed of each material varies. The two solutions must be compared on the basis of the same delivered service(s) – in this case, containing 1 liter of milk.

For this reason, every comparative LCA defines a common unitary service unit for the two systems under study, called the "functional unit". In the above example, the functional unit would be "contain and deliver 1 liter of milk from the milk processing plant to the consumer household". This common unit enables comparison between two different manufacturing technologies, or two different sources of raw material.

The choice of functional unit depends on the goal of the assessment and the subsequent comparison. Is the objective to compare manufacturing processes (e.g. production of fuels from CCU vs from a conventional source) or waste management technologies (e.g. chemical recycling vs incineration of mixed plastic waste)? Different study objectives lead to different ways of defining the functional unit **[9]**.

- In a LCA of the same product manufactured in two different ways (delivering products with the same chemical structure, composition, or characteristics), the functional unit will simply be a unit of manufactured product, reflecting the characteristics of the product. For example, in an LCA of chemically recycled PET (polyethylene terephthalate), the functional unit would be 1 kg of PET (virgin-grade). This means environmental impacts will be quantified for 1 kg of PET (virgin-grade).
- For different products or processes producing similar services: the common functional unit should reflect the service provided. For example, in an LCA of a chemical recycling process using mixed plastic waste as feedstock, the functional unit would be "managing 1 ton of mixed plastic waste".

Very often, circular solutions provide more than one service. In the BASF case study (see page 19), for example, chemical recycling of plastic provides two services: it is useful to manage plastic waste, but it also generates raw materials to make new polymers. To assess these two functions jointly in LCA, the functional unit needs to include both services, such as "producing 1 kg of recycled PET **and** managing X kg of plastic waste". This approach, in which the multiple functions of the system are all included in a single LCA, is called system expansion. It is frequently applied in LCA involving multifunctional solutions. Its advantages and disadvantages as well as potential alternative approaches are presented in the next section and in section "*Allocation between two consecutive product life cycles*" (page 29).

All you need to know on how to choose the right basis of comparison when assessing a circular system

Choosing a common unit of comparison between two systems: the “Functional Unit”

To properly compare two systems with an LCA, they must provide the same services to society. Therefore, comparative LCA studies are based on a common unitary service. For example, if the aim of the study is to compare two waste management technologies, the common unitary service is “manage 1 ton of waste”. In LCA, this unitary service unit is called the “functional unit”. When defining the functional unit in an LCA, it is important to consider all services provided by the solutions under study. This is particularly relevant for circular solutions which often provide multiple services.

Comparing circular systems with different feedstocks, multiple services different contexts…

In comparative LCA involving circular systems, there are three situations requiring particular attention to ensure a fair comparison between the systems under study:

- **When one or both of the systems is multifunctional,** i.e. it provides more than one service to society. For example, chemical recycling is a way of handling plastic waste and producing raw materials for new polymers. In LCA, multifunctionality is dealt with through "system expansion", to ensure that the two compared systems deliver the same services.
- **When the two systems do not utilize the same feedstock.** This situation occurs when comparing two waste management technologies such as, for example, plastics pyrolysis and depolymerization which do not handle the same types of plastic waste. In LCA, comparability between the two technologies is made possible by applying system expansion. In this example, the expanded system includes the alternative end-of-life process (e.g. incineration) for the remaining plastics that cannot be recycled.
- **When the two systems produce materials of varying quality.** For example, chemical recycling may produce virgin-grade recycled plastic, whereas mechanical recycling may produce plastic of lesser quality which cannot be used for all applications. Quality variations are reflected in LCA results when the comparison between two systems is based on product functionality (e.g. low-quality recycled products are needed in larger amounts, as they can be used fewer times). Another approach is to apply a quality factor to the results.

Delayed carbon emissions: accounting for the full value of circular solutions

Many circular solutions avoid immediate emissions when carbon is only temporarily stored in a new product, such as plastic. Over the life cycle of these products, carbon that was initially recycled and stored is reemitted into the atmosphere. These “delayed” emissions are accounted for in LCA.

The value of such circular solutions lies not just in temporary carbon storage, but in the fact that they avoid the use of a conventional virgin raw material (e.g. recycled plastic replaces virgin plastic). Thus, the true value of circular solutions is appreciated through a comparison with their conventional alternatives.

Permanent storage of carbon

Many circular solutions lead to carbon storage within a product, such as a fuel or plastic. Temporary carbon storage leads to delayed emissions, which are accounted for in LCA. In LCA, carbon is considered permanently stored if it has not been reemitted within a certain timeframe, often 100 years.

Biogenic feedstocks

Carbon of biogenic origin is taken up from the atmosphere, bounded in plants and after incineration of bio-based products as end-of-life treatment released to the atmosphere. From a life cycle perspective this is carbon neutral and omitted from carbon accounting, while cradle-to-gate LCA often calculate the reduction of the carbon footprint due to the amount of CO_2 bounded in the bio-based product (as additional information).

The value of such biobased solutions lies not just in temporary carbon storage, but more importantly in the fact that they avoid the use of a conventional virgin raw material. Thus, the true value of bio-based solutions is appreciated through a comparison with their conventional alternatives relying on non-biogenic raw materials.

Comparability: do the two solutions provide the same service?

Three main aspects require specific attention in comparative LCA of circular solutions:

- The multi-functionality of the systems under comparison
- The feedstocks used by each assessed technology
- The variability of material quality between the compared solutions

Managing multi-functionality

Circular solutions are often multifunctional, providing more than one service to society. For example, they provide the service of managing waste or CO_2 emissions, while also generating recycled products reducing the demand for virgin materials. Without including all of these services in the study perimeter, it is impossible to account for any beneficial offsets, leading to unfair comparisons.

For example, an LCA comparing the environmental performance of chemically recycled vs fossil-based PET might use as a common functional unit "producing 1 kg of PET". However, chemical recycling also ensures that a given amount of plastic waste is managed and leaves the waste stream. In order to fully understand the environmental implications of both solutions, the service of managing waste should also be included in the study, hence in the functional unit (ex. "Produce 1 kg of PET **and** manage X kg of plastic waste").

LCA TIP: **System expansion**

In system expansion, the study boundaries are no longer limited to the single product or process of interest, but are expanded to include additional services (e.g. managing waste) in order to build two comparable scenarios. For example, to compare landfilling of plastic waste to chemical recycling, the landfilling scenario should also include the production of virgin plastic to compensate for the amount of recycled plastic which would have been produced in the chemical recycling scenario.

The two comparison scenarios are then defined as follows:

- Scenario A: Produce 1 kg of recycled PET **and** manage X kg of plastic through chemical recycling.
- Scenario B: Produce 1 kg of virgin PET **and** manage X kg of plastic through conventional waste management technologies (e.g. incineration and landfilling).

The scenarios are illustrated in figure 1.

In this example, chemically recycled PET and virgin PET were made comparable by applying the method of system expansion to build two comparison scenarios. System expansion is particularly useful in comparative LCA of circular solutions as they are often multifunctional[1].

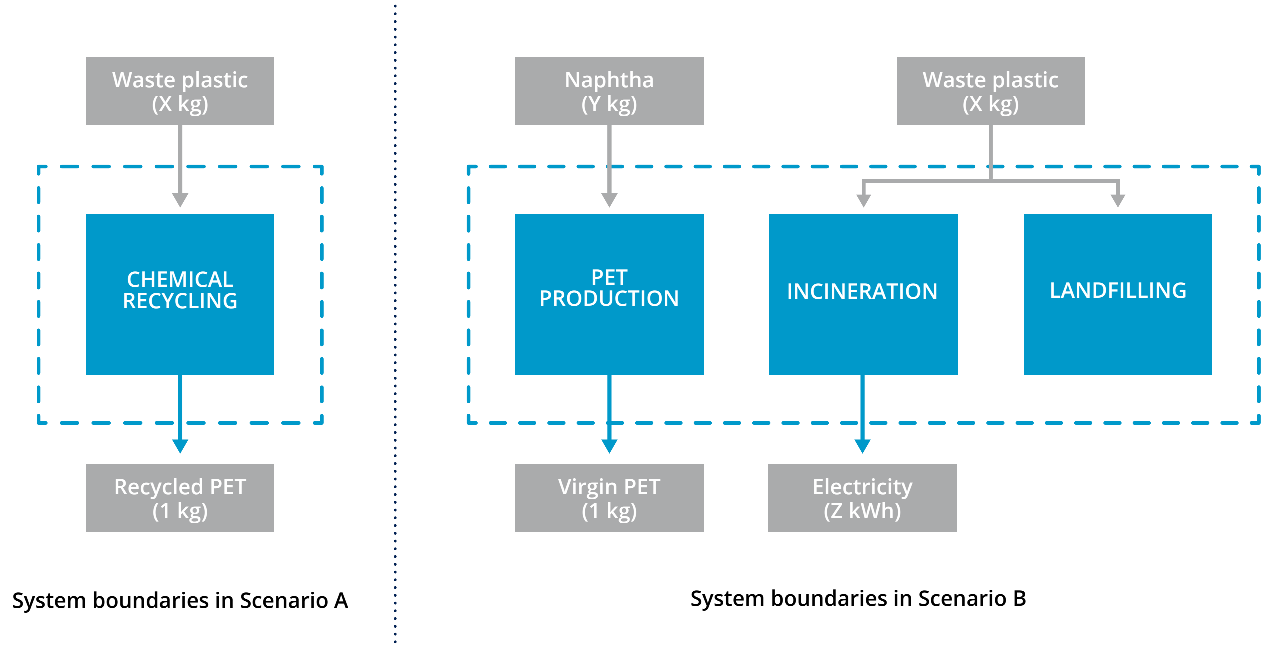


Figure 1: System boundaries in two scenarios for production of PET. Scenario A produces 1 kg of recycled PET. Scenario B produces 1 kg of virgin PET,

1. This approach provides a full comparison of circular systems, however it does not allocate the environmental benefits or burdens of a given process between the different stakeholders or life cycles being assessed. In the case of PET chemical recycling, the share of environmental burdens allotted to the producer of waste versus those allotted to the user of the recycled material are not discussed. Other approaches have been suggested if the goal of the study needs such an allocation; these are discussed in section "***Allocation between two consecutive product life cycles***" (page 29).

Assessing a multifunctional solution from different angles:

Evaluation of pyrolysis with LCA - 3 studies

This study assesses the environmental performance of plastics chemically recycled with the ChemCycling™ technology. This technology provides two services: plastic waste management, and production of new virgin-grade plastics. In this case, to assess the ChemCycling™ technology according to the multiple functions it provides, the authors chose to carry out three separate LCA each taking a different perspective and each with their own functional unit:

- **The waste perspective**: Comparison of pyrolysis (ChemCycling ™) and incineration to treat 1 ton of mixed plastic waste
- **The material perspective**: Comparison of manufacturing 1 ton of plastics based on pyrolysis oil and 1 ton of conventional plastics from primary fossil resources (naphtha)
- **The plastics quality perspective**: Comparison of three end-of-life options: chemical recycling and mechanical recycling, which produce secondary plastics of different qualities, and incineration. Results of this assessment are not shown as they draw on concepts that are presented later in section *"Role of the chemical industry in circular systems"* (page 9).

These perspectives take into account the fact that ChemCycling™ (1) manages plastic end-of-life, (2) replaces fossil-based plastics, and (3) produces virgin-grade recycled plastic unlike mechanical recycling. The two first assessment angles, i.e. the waste and material perspectives, are typical in LCA of recycling solutions.

From the **waste perspective**, pyrolysis via ChemCycling™ is compared as a waste management technology to incineration with energy recovery. The functional unit is therefore defined as the “management of 1 ton mixed plastic waste”.

LCA results, shown on figure 2, indicate that pyrolysis of mixed plastic waste emits 50% less CO_2 than incineration.

From the **material perspective**, plastics produced with ChemCycling™ pyrolysis oil are compared to plastics produced with naphtha from crude oil. The functional unit is the “production of 1 ton of LDPE”.

LCA results, shown on figure 3, indicate that CO_2 emissions are saved when manufacturing plastics is based on pyrolysis oil instead of naphtha. It should be noted, however, that the lower emissions in the case of ChemCycling™ result from displacing the incineration of the mixed plastic waste used as a resource in ChemCycling™.

Waste perspective

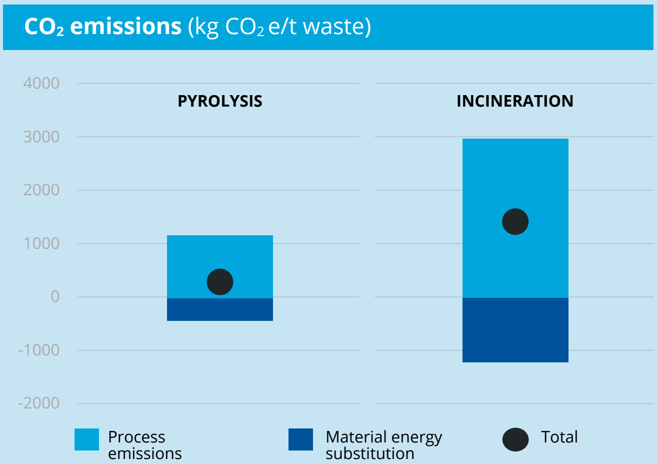


Figure 2: Pyrolysis of 1 ton mixed plastic waste emits 50% less CO_2 than incineration with energy recuperation. Each process generates emissions (in light green) but also leads to material / energy substitution. Pyrolysis is credited for producing pyrolysis oil which substitutes naphtha. Incineration is credited for producing electricity and thermal energy.

Material perspective

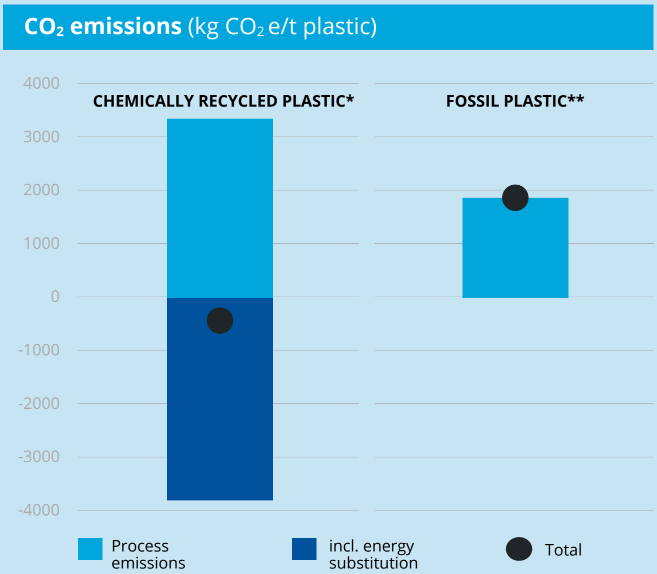


Figure 3: Conventional production of 1 ton low density polyethylene (LDPE) versus 1 ton LDPE from pyrolysis. For the production of 1 ton LDPE via pyrolysis the overall CO_2 emissions are negative. Chemically recycled plastic is credited for displaced incineration emissions, which would have occurred in the reference scenario.

www.basf.com
More on study: https://on.basf.com/3fWai2N

Considering feedstock variability

System expansion is also useful to compare two waste management technologies which use **different feedstock** and thus, do not provide exactly the same service to society.

Consider two plastic waste management technologies with varying capabilities: a chemical recycling technology (technology A), which handles a large variety of plastic waste, and a mechanical recycling technology (technology B), which takes in only a fraction of suitable plastic waste as feedstock. Technology B does not provide the same service to society as technology A, as it does not handle certain types of plastic which are effectively recycled by technology A. To compare A and B on a fair basis, they must take in the same mix of input materials, combining additional technologies if necessary.

In this case, if technology A can recycle 100% of the input mixed plastic waste, technology B may only recycle 75% of the input. Thus, to fulfill the same functional unit ("Managing 1 ton of mixed plastic waste"), the two solutions should be defined as follows[2]:

- Solution A: chemically recycle 1 ton of mixed plastic waste
- Solution B: mechanically recycle 0.75 ton of mixed plastic waste **and** handle 0.25 ton of non-mechanically recyclable plastics

In this example, comparability between chemical and mechanical recycling is ensured by expanding the system boundaries beyond the recycling process in itself, adding the additional environmental burden of dealing with non-recyclable waste in solution B.

Considering quality variations

Another important element to consider in comparative LCA is **product quality**. Many circular solutions generate products of lesser quality than their virgin counterparts. Mechanical recycling, for example, can lead to degradation of quality because the material structure has been altered (e.g. polymer chains get shorter) or because contaminants accumulate. As a result, mechanically recycled plastics may have to be complemented with virgin material, or they may be of insufficient quality for certain applications.

There are two solutions to address product quality differences in LCA studies:

- **Variations in quality can be accounted for by comparing the products based on their usage**. Take a fictional example of an LCA focusing on milk bottles. Bottle A, a glass bottle, can be used 100 times. Bottle B, a plastic bottle, is of lesser quality and can only be used once. The functional unit will be defined as "containing 1l of milk and delivering it to customers 100 times". For this function to be fulfilled, only one bottle A is necessary against 100 bottles B. Thus, differences in quality are accounted for by defining the functional unit based on the usage of the bottle (i.e. a bottle used X times), rather than just on the object itself (i.e. a bottle).
- **A "quality factor" can also be used to account for quality differences between products**. This approach is useful when the usage of the products is not well defined (e.g. recycled plastic material used for a variety of applications). The Circular Footprint Formula, developed by the European Union's Joint Research Center (JRC), allocates burdens and benefits of circular solutions between life cycles (see section *"Allocation between two consecutive product life cycles"* (page 29) for more information). It includes quality ratios, accounting for the quality of both ingoing and outgoing recycled materials. Quality ratios can be based on economic aspects (price ratio of secondary compared to primary materials), or on physical aspects if more relevant. Expert judgement is necessary to ensure that these ratios are applied consistently and lead to a fair comparison.

The timeframe of emissions: accounting for carbon flows

Accounting for delayed carbon flows

Many circular solutions lead to the storage of carbon within a product, therefore preventing its immediate release in the atmosphere. For example, CO_2 released by a power plant can be captured and bound into ethanol fuel through, reducing greenhouse gas (GHG) emissions from the power plant. Another example of carbon recovery and storage is the production of recycled polymers from post-consumer plastics which would otherwise have been incinerated. While incineration generates GHG emissions, recycling plastic avoids these carbon emissions and uses the recovered carbon to make new polymers, binding the carbon in a product.

In both examples, the technologies involved result in a net reduction of immediate GHG emissions. Over time, though, the carbon stored in the products is usually bound to be reemitted soon enough: the ethanol fuel will be combusted, and the plastic product will be discarded and possibly incinerated. In the end, GHG emissions still occur and are only delayed until the products' end-of-life.

However, the circular systems mentioned (i.e. plastic recycling or CCU) generate products which replace another conventional product - in this case, fossil-based plastic or fuel. Thus, the value of circular solutions lies in the emissions avoided by replacing these conventional products. This benefit can be quantified in LCA if circular solutions are compared to equivalent conventional alternatives.

In the example of a CCU-based fuel, the correct comparison between two equivalent systems is shown in figure 6 on page 22. The conventional system consists of the CO_2-emitting factory to which is added a conventional fuel, which also emits CO_2 and other GHG at its end-of-life. In the CCU system, CO_2 is emitted upon burning of the CCU-based fuel. Some emissions also occur during the process itself. LCA serves to accurately assess the environmental performance of the two systems, so long as the assessment compares two equivalent systems and takes into account all emissions involved.

2. In this example, for simplicity, it is considered that both scenarios lead to the same amount of recycled plastic being produced.

Ensuring comparability through system expansion: case study by Inovyn

(Vinyloop) PVC Recovery Options: Environmental and Economic System Analysis

This LCA study assesses four waste management technologies which handle mixed cable waste, with a specific focus on the PVC fraction. The four PVC waste management technologies considered are implemented in similar countries of Northwestern Europe (Denmark, Germany). They are as follows:

- MVR Hamburg: Waste incineration with energy and metal recovery
- Stigsnaes: Feedstock recycling through a pyrolysis process
- Watech: Feedstock recycling through a process of hydrolysis then pyrolysis
- Vinyloop: Mechanical recycling through the Vinyloop process using solvents

Landfilling is chosen as the reference option.

While the technologies listed above provide the same service in terms of PVC waste management, each of them generates different output products, such as recovered metals and electricity (MVR Hamburg), sodium chloride and metal scrap (Stigsnaes), coke and metal scrap (Watech), or regenerated PVC compounds (Vinyloop).

To enable comparison of these four technologies, system expansion was applied by:

- Listing the output products of each technology
- Defining an overall set of products containing all output products listed
- Extending each technology system by adding the conventional production route for the output products that are not produced by this technology

The resulting solutions are illustrated in figure 4.

Thus, the environmental impact of each technology under study is complemented with the impact of generating the products which are not an output of this technology, but which are generated by the other options. This additional burden represents the "environmental opportunity cost" of choosing one particular option, meaning the additional services that are necessary to complement this technology if it is chosen over the others.

The results of the comparative LCA, which are presented in figure 5, clearly demonstrate the importance of system expansion.

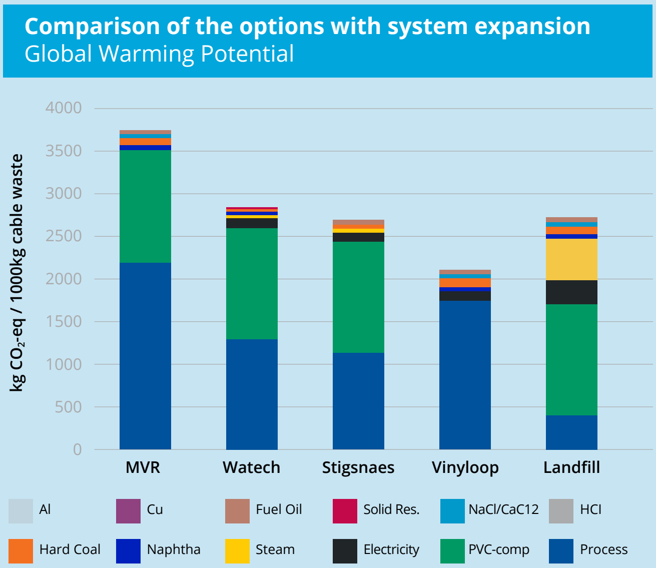


Figure 5: Environmental impact in terms of climate change for five PVC waste management technologies. For each technology, the impact of the process itself is shown in dark blue. LCA results indicate that the Vinyloop process has a relatively high Global Warming Potential and is only second to incineration in terms of impact. However, it generates a PVC compound, thus avoiding the step of PVC compounding which has a high environmental impact. Through system expansion, the study shows that Vinyloop is the best option of the five from a climate change perspective.

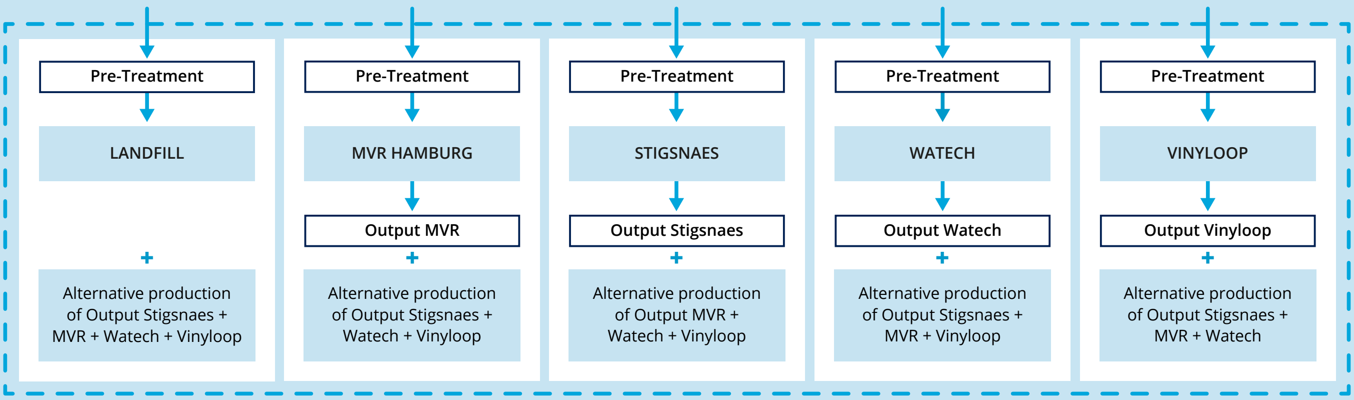


Figure 4: After system expansion, each system includes the output products of the technology under study as well as the other products which are not generated with this technology. For example, the output of the Stigsnaes technology is sodium chloride, an oil fraction, solid residue, polyethylene and metal scrap. However, Stigsnaes does not produce electricity, coke or PVC compounds, which are some of the output products of the other technologies (MVR, Watech and Vinyloop). Expanding the Stigsnaes system entails adding the alternative production of these products to the system.

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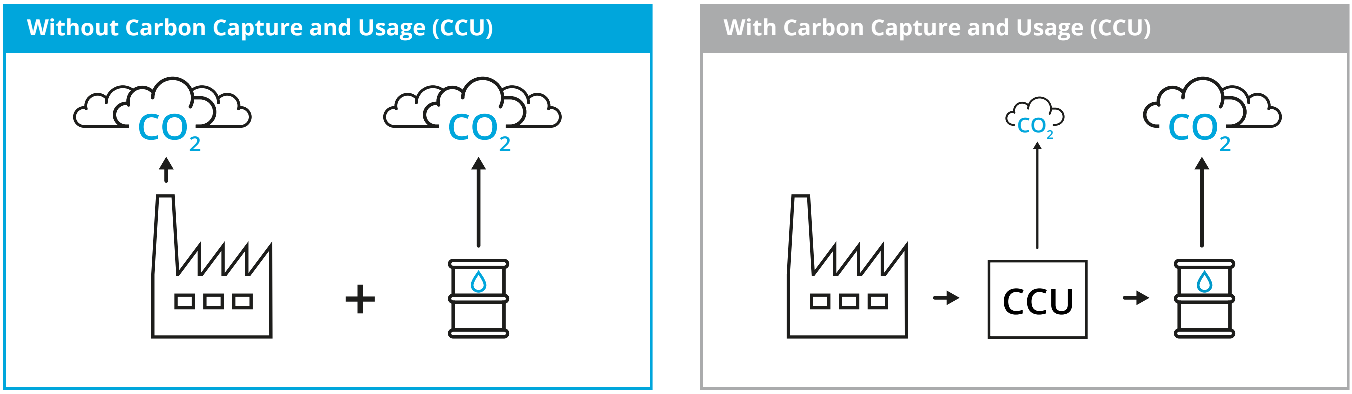

Figure 6: With CCU, CO_2 emitted from a power plant is captured and avoided. It is then bound into a fuel, which will generate GHG emissions when the fuel is combusted. The CCU system is equivalent to a conventional system in which power plant emissions occur directly, and a conventional fuel emits carbon upon combustion as well.

When is carbon storage considered permanent?

Circular solutions such as CCU or plastic recycling avoid emissions to the atmosphere by recovering carbon that is then stored in the products they generate. After these products have been used, the stored carbon is often released back into the atmosphere - CCU-based fuel is burned and a recycled plastic is incinerated. These emissions are accounted for in LCA. Section *"Accounting for delayed carbon flows"* (page 20) covers the topic of delayed emissions and why circular solutions are valuable even if the carbon they store is rapidly reemitted into the atmosphere.

Stored carbon may be released again within a few months to years. However, some products may store carbon for a much longer time period. One commonly cited example is construction: wooden buildings or CO_2-based insulation foam will likely remain in use for a long period after their initial production, not reaching their end-of-life until several decades later.

If carbon emissions do not occur within a certain number of years, this carbon is usually considered as permanently stored. In LCA, it is important to define the point at which carbon is considered as permanently stored. All emissions occurring within this timeframe must be accounted for, and any emissions which might occur later are discounted. The choice of timeframe depends on the objectives of the study. Two approaches, corresponding to two different timeframes, are detailed below.

The 100-year timeframe approach:

LCA usually considers emissions within a 100 year timeframe, including delayed emissions to give a correct picture of all carbon flows absorbed or emitted during a product's life cycle. Any emissions occurring within this time period must be accounted for. Any carbon that has not been emitted after 100 years is considered as permanently stored.

To illustrate, consider two recycling solutions that store the same amount of carbon but in two different products: process 1 generates ethanol and process 2 a plastic polymer for the construction sector. For simplicity, consider that both products are identical in all other aspects, such as electricity use. Both products initially store the same amount of carbon via recycling and ensure the same net reduction of carbon emissions. However, the two products will not have the same fate. In process 1, the carbon stored in ethanol molecules will be reemitted entirely as CO_2 upon combustion. In process 2, the plastic polymer may remain in the building for longer than 100 years. The long-term effects of both recycling solutions differ and should be accounted for differently.

As demonstrated in this example, a comparison between solutions that lead to delayed emissions must cover the entire life cycle of both products ("cradle-to-grave" approach), to ensure that delayed emissions are accounted for and quantified within a 100-year time frame. At the least, the effect of delayed emissions should be mentioned in order to provide decision-makers with a full understanding of the environmental implications.

The forward-looking approach

As climate change is likely to be an even more significant issue in 100 years, some LCA practitioners take a forward-looking approach of extending the timeframe of emissions beyond 100 years. Recent sources recommend that all emissions from a process should be accounted for if they occur within 500 years **[10]** or even 10.000 years **[11]**. For example, some argue that, in the case of CCU, the standard 100-year time period could incentivize medium-term carbon storage solutions, which would lead to emissions at a time when climate change will still be a critical issue for society.

This approach is interesting in the case of CCU as it helps distinguish between solutions that are "quick fixes", and others which offer a solution in the longer term. However, shorter-term solutions are also valuable and should not be discounted. Because CO_2 has a cumulative effect on global warming, storage of any duration is beneficial. The question of temporary carbon storage is particularly relevant in LCA studies involving biogenic carbon. Because the biogenic carbon cycle is a fast cycle (i.e. carbon cycles between plants and the atmosphere quickly), it does not have the same impact on climate change as carbon from fossil sources. For this reason, biogenic carbon is considered separately in LCA (see the following section).

Why (temporary) biogenic carbon storage matters: case study by SABIC

Renewable Polyethylene based on Hydrotreated Vegetable Oil, from waste animal fats or vegetable oil.

The study quantifies the environmental impact of polyethylene produced using hydrotreated vegetable oil (HVO) diesel as a feedstock for steam cracking. HVO is produced from hydrotreating of waste animal fats, a by-product of meat processing, or from hydrotreating of palm oil fatty acids, a by-product of palm oil production.

The carbon that is captured in the final product, i.e. polyethylene, is of biogenic origin rather than fossil origin. This distinction is important in carbon accountancy. In the case of biogenic carbon, CO_2 is removed from the atmosphere. For example, the carbon composing palm oil fatty acids, and ultimately incorporated in the polyethylene, initially comes from the air. In the case of fossil-based polyethylene, on the other hand, there is a net transfer of carbon from fossil storage (crude oil) to the atmosphere at incineration. Figure 7 illustrates the difference between the two systems.

This case study therefore follows accounting guidelines specifically defined for carbon of biogenic origin.

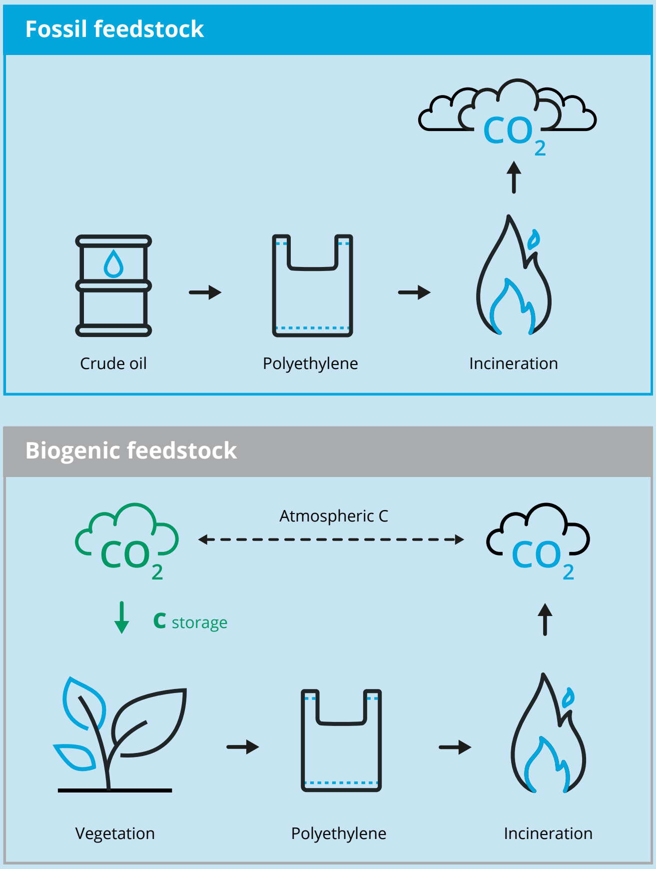

Figure 7: Polyethylene made from fossil feedstock leads to net CO_2 emissions to the atmosphere at the product's end-of-life, when it is incinerated. When biogenic feedstock is used instead, such as palm oil fatty acids, CO_2 emitted upon incineration is considered as taken up again by vegetation.

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More on study: https://bit.ly/39UyQ8I

The specific question of biogenic carbon

General carbon accounting guidelines, such as those of the International Panel on Climate Change (IPCC) **[12]**, and more specific LCA guidelines, such as those of the JRC **[10]**, state that biogenic CO_2 emissions should be omitted from carbon accounting since these emissions are part of the natural cycles on Earth. There is one exception to this general rule, which concerns the small portion of carbon emitted in the form of methane. Indeed, methane contributes twice to climate change, first as methane, and second once it has oxidized into CO_2. Because CO_2 will be captured again by vegetation, this second contribution should be discounted. However, the first contribution must be modelled and accounted for in LCA. For example, in an LCA of a circular solution involving the burning of biofuels, all CO_2 emissions can be discounted, but methane emissions must be accounted for as biogenic methane.

Some LCA practitioners may choose to model biogenic CO_2 flows as well, even though they are not accounted for in the final total. The JRC, for example, recommends that all biogenic carbon flows be modelled, with the impact of biogenic CO_2 being considered as null. The final result is no different than if biogenic CO_2 flows were not modelled at all, however this gives a better picture of overall carbon flows.

While this default approach is widely accepted and used in LCA, it poses two issues that have led to other approaches being developed. First, as shown on figure 8, biogenic carbon has a mitigating effect when it is captured, and a reinforcing effect on climate change when it is released in the atmosphere **[13]**. So, while the overall climate effect of using biogenic carbon along this cycle is neutral, the effect is not neutral at a given point in time. Second, biogenic carbon may be embedded in permanent products. This carbon storage is not accounted for if biogenic carbon is omitted from the LCA.

Growing awareness of the importance of temporary carbon storage has led to the development of a new dynamic approach that takes into account these issues **[14]**. While traditional LCA gives an aggregated "snapshot" of emissions without consideration of the time of emissions, dynamic LCA provides a consistent assessment of the impact, through time, of all GHG emissions (positive) and carbon sequestration (negative). For results to be reliable, the timing of every emission must be accounted for in order to quantify temporary storage. So, dynamic LCA is complicated to carry out and it currently remains experimental. However, if it is more widely implemented, it will prove to be a valuable approach for policy makers to gain a better understanding of temporary storage.

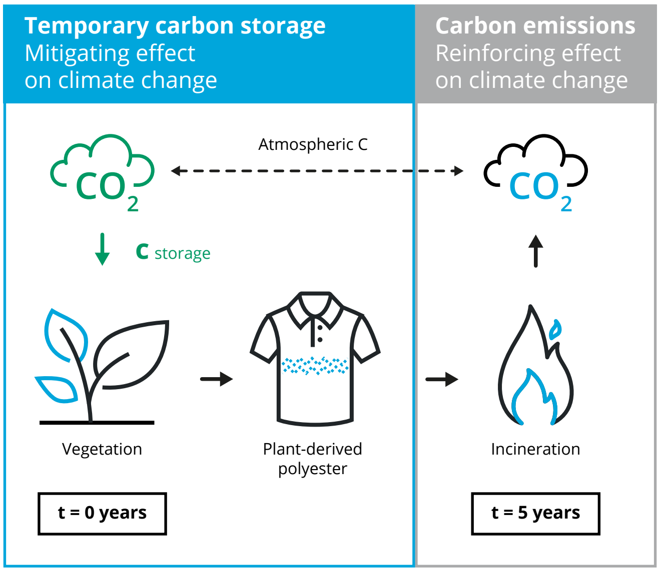

Figure 8: Temporary carbon storage: biogenic carbon has a mitigating effect on climate change when it is captured. This effect ends when it is released in the atmosphere.

Who bears the environmental burdens or claims the benefits of circular solutions?

Life cycle avoided emissions almost always arise from efforts by multiple partners along a value chain, particularly for circular systems. Making a system more circular involves multiple changes along the value chain, including raw material suppliers, material manufacturers such as chemical companies, material processors, part-assemblers and users of the technology. So, changes in overall emissions – and in avoided emissions enabled by circular systems – belong to all the players in the system.

For this reason, avoided emissions shall belong to the complete value chain without subdividing between partners. This gives a full picture of environmental benefits which is useful for policy-makers, who need to appreciate the overall benefits and burdens of circular solutions to decide whether to support their development or not.

If necessary, avoided emissions enabled by circular systems as compared to the reference system may then be split, or allocated, along the process and the actors involved. This enables an individual stakeholder to quantify their own impact, avoiding double counting, and act on these emissions. It is especially important for circular solutions where stakeholders have a different leverage on the environmental benefits and burdens of the system as a whole.

Some circular solutions aim to make use of a co-product of an existing process. The process is thus multifunctional and its environmental impacts must be shared between the co-products. Other circular solutions aim to use a material that has reached its end-of-life for its initial application for a new product cycle. The environmental benefits and burdens associated with this circular solution should be appropriately shared between the two consecutive product systems.

Allocation between the co-products of a multifunctional system

Many circular solutions are developed with the aim of turning a co-product of an existing process into a valuable product. In this case, the circular solution is part of a broader, multifunctional system which provides a main product as well as a secondary product obtained through the circular solution.
For example, in the case of ethanol production from sugarcane bagasse, the bagasse is a co-product of an existing system that aims primarily to produce sugar. The environmental impact of sugarcane cultivation must be shared between the main product - sugar - and the co-product - sugarcane bagasse (see figure 9, page 27).

To enable evaluation of the circular solution's environmental performance itself, the burdens and benefits of the system as a whole must be shared between the main product and the secondary "circular" product. In LCA, this is referred to as "solving multi-functionality" **[15]**. Multi-functionality is an issue that is not specific to circular solutions and has been discussed extensively in LCA literature, providing recommended approaches.

Standards and guidelines give the following methods to handle multi-functionality, listed in order of recommendation by ISO 14044 **[8]**:

1 System expansion
2 Substitution
3 Allocation using underlying physical relationship
4 Allocation using another relationship

1. System expansion, to embrace all co-products in a single system

In system expansion, the idea is to assess a system as a whole, considering all the co-products (or functions) it provides, instead of focusing solely on the co-product of interest. The system boundaries are expanded to include the other functions of the product system, and the functional unit is modified to include these additional function(s). The reference system that is used for comparison must deliver equivalent functions. The approach is illustrated by the figure 9 (on page 27).

In the previously-cited example of ethanol production from sugarcane bagasse, the system expansion approach consists in carrying out an LCA of the entire sugar production system, which jointly produces sugar and ethanol. The reference system of comparison is a combination of the two separate systems that are necessary to produce the two products conventionally (e.g. sugar and ethanol). It should be noted that this approach does not yield product-specific results, meaning that the environmental footprint of ethanol alone is not determined.

All you need to know on allocating burdens and benefits

"Allocation" is the answer

There are several approaches to allocate burdens and benefits between co-products of a multi-functional system (e.g. a system producing sugar and ethanol from sugarcane bagasse). They are listed in order of preference according to standards and guidelines:

- In **system expansion**, the system is assessed as a whole (e.g. the system producing both sugar and ethanol), and is compared to a reference system comprising all of the functions of the circular solution (e.g. conventional production of sugar to which is added conventional production of ethanol). This approach avoids potential allocation bias, but does not yield product-specific results. It is generally recommended unless product-specific results are necessary.
- In **substitution**, the circular solution receives credit for the production of the non-relevant pre-exiting co-product (e.g. sugar). This approach gives product-specific results, meaning that the impact of the co-product produced by the circular solution alone can be determined. However, the results can be difficult to interpret.
- With the approach of **allocation using a physical relationship**, impacts of the multi-functional system are shared between co-products based on an underlying physical basis (e.g. respective mass or energy content). This approach is appropriate when the two co-products are of the same physical nature (e.g. two monomers produced by a chemical recycling process).
- The approach of **economic allocation** is appropriate when the co-products are of a different nature. The impacts of the multi-functional process are shared between co-products based on their respective economic values. This approach yields product-specific results, though they are subject to change due to price fluctuations of the co-products. Overall, economic allocation reflects the market balance between offer and demand for co-products.

Should the recovered waste itself take benefit of avoided emissions enabled by its recycling?

Many circular solutions aim to use a material that has reached its end-of-life for a new product cycle. They are associated with environmental benefits (i.e. they avoid extracting virgin material) and environmental burdens (i.e. the recycling process generates its own environmental impacts). So, who is accountable for the environmental burdens (emissions) or benefits (credits) of using waste to produce secondary raw materials? The answer depends on the approach that is chosen for end-of-life allocation. This choice can help encourage either the collection and recycling of waste or the use of these secondary raw materials depending on the market need and should therefore depend on the market needs.

Closed-loop systems: a straightforward allocation

Closed-loop systems are a particular example of recycling where a product that has reached its end-of-life is recycled into the same product, with identical properties. The same actors are involved in generating recyclable materials at end-of-life and incorporating these in new products. In such systems, the allocation approach is simplified in that all benefits accrue to the sole stakeholder who both utilizes and generates the recyclable material. In practice, these benefits are directly accounted for by reducing the amount of initial virgin material needed as input in the first product cycle.

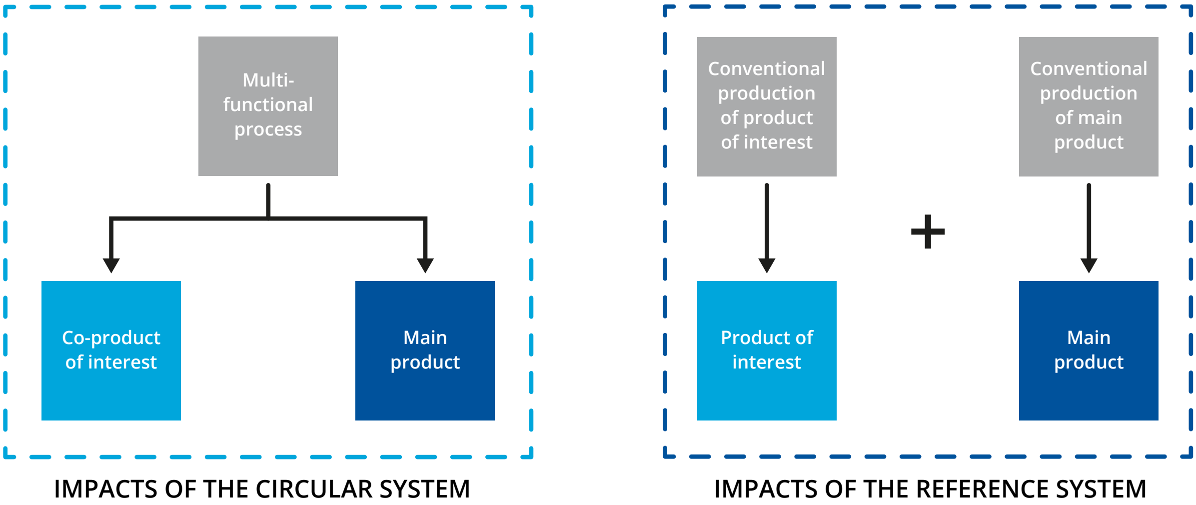

Figure 9: System expansion: The system is expanded and assessed as a whole, including both the co-product of interest (e.g. ethanol) and the main product (e.g. sugar). The reference system is a combination of the conventional production systems for the product of interest (e.g. ethanol) and the main product (e.g. sugar).

2. Substitution, when the output of a circular process substitutes another

Unlike system expansion, substitution does not include additional functions in the assessment. Rather, as shown in figure 10, the circular solution receives credit for the production of the main product (e.g. sugar), representing the environmental burdens avoided by substituting conventional production.

In the example of ethanol production from sugarcane bagasse, the substitution approach implies first to assess the entire system, which produces sugar and ethanol, then to subtract the impact of conventional sugar production. This approach yields a product-specific result: the environmental footprint of ethanol is quantified separately from that of sugar.

Mathematically, substitution is equivalent to system expansion. However, the results and their interpretation differ between both approaches. For example, substitution can lead to negative results (e.g. negative emissions), which gives a false impression that the system is taking up CO_2 and reducing the amount in the atmosphere. Furthermore, credits from substitution may vary significantly depending on the "conventional" production chosen as a reference. As such, practitioners should be mindful about this choice by selecting the most likely solution to be replaced and by considering different scenarios through sensitivity assessments.[3] Thus, results obtained through the substitution approach must be interpreted carefully, bearing in mind how they were obtained.

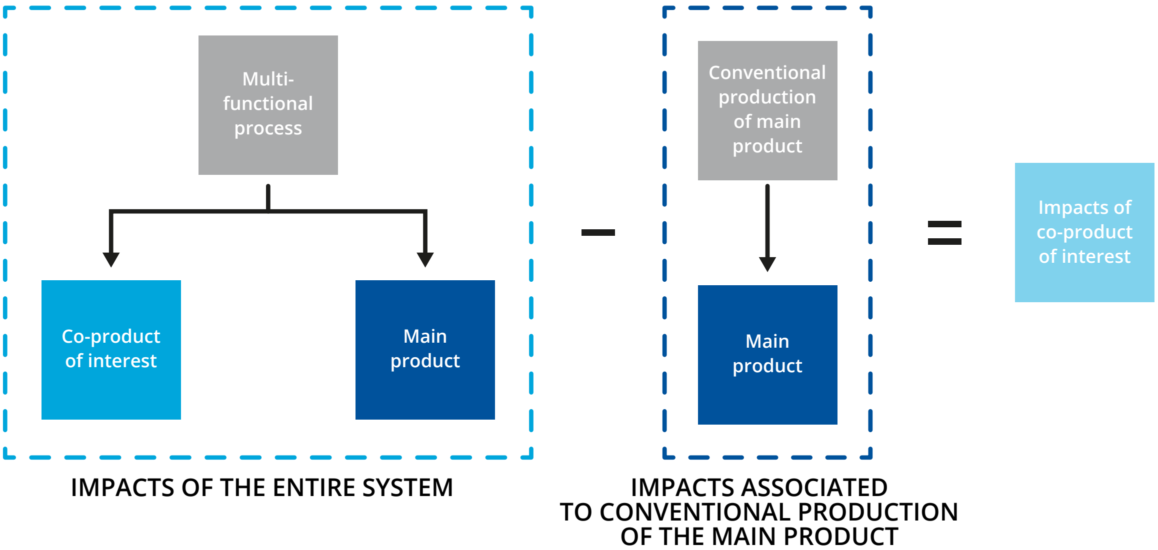

Figure 10: Substitution: The production of the main product (e.g. sugar) is avoided, and the circular solution is credited for the avoided emissions. The result is product-specific: it corresponds to the impact associated solely to the co-product of interest.

3. The method for choosing the reference conventional production can be aligned with approach used to define the baseline scenario for the calculation of avoided emissions, as described in the ICCA guidelines on avoided emissions reporting **[6]**.

Allocation between co-products: case study by RWTH Aachen University

Towards sustainable elastomers from CO_2: Life Cycle Assessment of carbon capture and utilization for rubbers [16]

The question of allocation between co-products is addressed in this LCA of rubbers incorporating CO_2 captured from an ammonia production plant, using the Cardyon® technology developed by Covestro for polyol synthesis. The study compares the environmental impacts of CO_2-based rubber with conventional rubbers which it can substitute, for global warming and several other impact categories.

The system considered in this study is multi-functional: it produces ammonia, CO_2-based rubber, and energy at end-of-life when the rubber is incinerated. According to ISO and other guidelines specific to CCU, system expansion is applied to cope with multi-functionality. The expanded system considered in this LCA therefore provides three functions:

- To produce 1 kg of CO_2-based rubber
- To produce 0.185 kg of ammonia (amount necessary for the co-production of CO_2 when manufacturing a CO_2-based rubber with 30 wt% of CO_2 incorporated in the rubber)
- To incinerate 1 kg of CO_2-based rubber for producing energy.

The conventional system that serves as a comparison fulfills the same function and is the sum of the production of 1kg of conventional rubber, including its incineration at end-of-life for energy generation, and the production of 0.185 kg of ammonia without CO_2 capture.

LCA results indicate that greenhouse gas (GHG) emissions are lower for the CO_2-based system, as shown in figure 11. These reductions result from the overall system and are not product-specific. To obtain results for CO_2-based rubber alone, the authors performed a sensitivity analysis, aiming to estimate which portion of the environmental savings can be allocated to rubber.

To highlight the impact of allocation approaches on product-specific results, two possibilities are considered. First, a worst-case allocation attributes all impacts to CO_2-based rubber, without considering the co-production of ammonia. Second, the best-case allocation uses the substitution approach to introduce a credit for ammonia production.

Figure 12 shows the results of the sensitivity analysis. With the worst-case allocation, emissions due to the production of 1 kg of CO_2-based rubber amount to 4.83 $kgCO_2eq$. In the best-case allocation scenario, emissions amount to 4.57 $kgCO_2eq$. Overall, the sensitivity analysis demonstrates that no matter the choice of allocation method, CO_2-based rubbers have a lesser impact on climate change than their conventional counterparts, due to the fact that they have different ingredients and processing routes and that they emit less CO_2 during their incineration for energy production.

CO_2-based rubber compared to conventional HNBR (hydrogenated nitrile butadiene rubber)

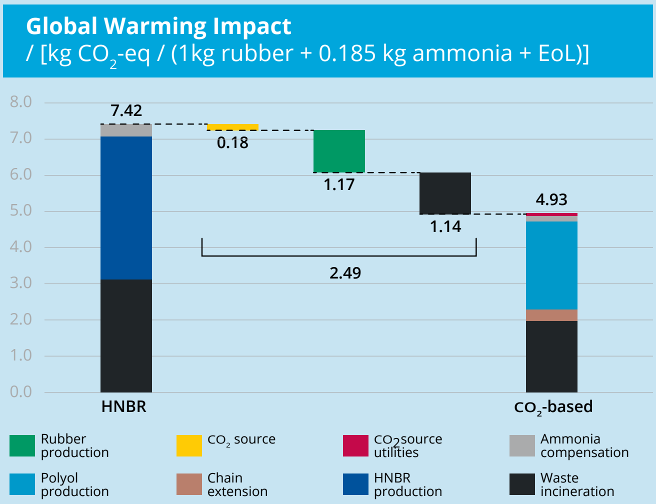

Figure 11: results obtained for CO_2-based rubber compared to one type of conventional rubber, hydrogenated nitrile butadiene rubber (HNBR). The reduction results partly from (1) the capture of CO_2 emitted during ammonia production and its storage in CO_2-based rubber. However, the main reductions stem from (2) changes in the rubber production itself (CO_2-based rubber uses different components), and (3) reduced emissions at incineration (CO_2-based rubber contains less carbon than HNBR, which means that the impact of incineration for energy production is lower).

CO_2-based rubber compared to various conventional rubbers

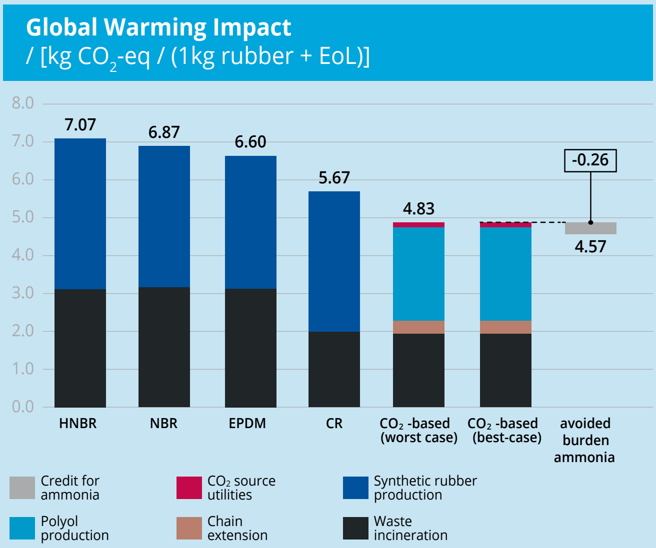

Figure 12: Product specific global warming impacts are shown in kg CO_2-equivalents per 1 kg of rubber and the end-of-life treatment of 1 kg rubber. The following conventional rubbers are shown: HNBR, nitrile butadiene rubber (NBR), ethylene propylene diene monomer rubber (EPDM), chloroprene rubber (CR). For CO_2-based rubbers, environmental impacts were obtained for (i) a worst-case scenario (100% of environmental impacts allocated to the CO_2-based rubbers) and (ii) a best-case scenario (credit for ammonia). The CO_2 source utilities include CO_2 compression and CO_2 transport.

LCA study performed and published by RWTH Aachen University , R. Meys, A. Kätelhön, A. Bardow: Green Chem., 2019, 21, 3334-3342.

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3. Allocation based on a physical ratio to distribute the environmental burdens
An alternative to system expansion and substitution is the allocation of environmental impacts of the multi-functional process between co-products or functions. This distribution can be based on a ratio of mass or energy content between the co-products.

Taking the same example of co-production of sugar and ethanol from sugarcane (see page 25), mass or energy allocations can be applied to allocate the impacts of sugarcane production between sugar and bagasse. Mass allocation entails evaluating, for a defined quantity of sugarcane entering the refinery, the weight ratio between the amount of sugar and bagasse produced. For energy allocation, it is the calorific power ratio between sugar and bagasse which will be used to distribute the environmental burdens of sugarcane production between the two co-products.

In this example, however, as is often the case for circular solutions, the co-products are of different physical natures, uses and values: sugar is used for food and bagasse for energy. Thus, while it is possible to base allocation on a physical ratio as described above, this approach makes little sense, and other alternatives should be explored.

Allocation using a physical relationship remains appropriate when the co-products are of the same physical nature (e.g. monomers). In the example of a fictional chemical recycling process regenerating EVA (ethylene vinyl acetate) into ethylene and vinyl-acetate monomers, the ratio between the molecular mass of both monomers can be used to allocate the burdens and benefits of the chemical process.

4. Allocation using another underlying relationship
If a physical ratio is not appropriate, another underlying relationship can be used. The environmental impacts of the multi-functional process are then distributed among its co-products or functions according to adequate attributes of these co-products or functions. Very often, economic value is chosen as the common attribute: the largest portion of the impact is attributed to the co-product or function with the greatest economic value.

Economic allocation can strongly influence the attribution of benefits for circular solutions. Such solutions often use co-products with little economic value, which, as a result of economic allocation, bear only a small portion of the impact of their production. In fact, in many cases, their economic value is so little that they are simply considered burdenless, meaning that the impact of their production is considered to be null.

In the previously cited example of ethanol production from sugarcane bagasse, the market value of the main product (e.g. sugar) is much higher than that of the co-product of interest (e.g. bagasse) which was traditionally considered as unusable waste. Thus, according to economic allocation, only a small share of the impact of sugarcane production must be attributed to bagasse, and consequently to ethanol production.

Economic allocation is a valuable approach as it yields product-specific results which reflect the low or high market demand for co-products that are otherwise considered as waste. However, a change in demand may occur if, for example, the circular solution (e.g. ethanol production from sugarcane bagasse) becomes widely implemented, driving up the demand for the co-product. In this case, previous LCA results based on economic allocation would be outdated and should be revised. This is discussed further in section ***"Variations of feedstock availability and cost"*** (page 38).

Allocation between two consecutive product life cycles

Many circular solutions aim to reuse a material that has reached its end-of-life in a new product cycle. There are two types of recycling patterns:

- Open-loop recycling, in which material from one product cycle is recycled into another product. Examples include mechanical recycling of PET plastic bottles to make polyester fabric.
- Closed-loop recycling, in which material from a product cycle is recycled into the same product. One example is chemical recycling of PET plastic bottles into new PET bottles.

In both cases, recycling can be beneficial because it avoids the consumption of virgin materials. For example, when waste PET is recycled into polyester clothing, the recycling process itself has an impact on the environment, but at the same time it avoids the environmental cos of producing virgin PET. The environmental benefit of avoided virgin material use and the burden associated with the recycling process must be shared between the first product cycle (e.g. plastic bottles) and the second (e.g. polyester clothing).

Several methods to distribute impacts between life cycles
There are several methods to distribute impacts between life cycles, each yielding different results. They are applicable to both open-loop and closed-loop situations, although a simplified approach may be taken for closed-loop recycling because it involves a single system (i.e. the producer of PET bottle waste would also be the consumer of recycled PET in such a scenario). All approaches provide valuable results and choosing one or the other mainly depends on the economical and policy drivers for the end-of-life process.

Choosing an allocation approach: case study by DOMO Chemicals

Comparative Life Cycle Assessment of two polyamide 66-based engineering plastic formulations, one with a primary resin base, and the other with a high-quality recycled resin base (Technyl® 4earth®).

Figure 13: Recovery of high-quality polyamide from the scraps resulting from coated disks used to manufacture car airbags

This LCA study focuses on the Move 4earth® technology owned by DOMO Chemicals which makes it possible to obtain a high-quality recycled polyamide 6.6 from airbag fabric scrap cuttings. This production scrap consists of polyamide 6.6 woven yarn, with a silicone coating that ensures the performance characteristics for the airbags to function safely.

By using an innovative separation technique to remove this coating, the Move 4earth® process enables the recovery of a very high quality polyamide 6.6 polymer, which can then be used as a matrix for the Technyl® 4earth® high-performance recycled polyamide. The LCA study examines the environmental performance of this process to produce recycled polyamide for the manufacture of a thermal engine automobile fuel filter housing, in comparison with its virgin equivalent. The LCA results show that recycled polyamide via the Move 4earth® separation process reduces greenhouse gas (GHG) emissions by 32% compared to virgin primary polyamide.

The comparison is based on the “cradle-to-grave” life cycles of the two versions, with identical specifications of the fuel filter housing (safety margin coefficient, life span, ...).

What proportion of environmental impacts should be allocated to the fabric scraps?

One important question addressed in the study is that of allocation. The environmental impacts of the manufacturing of the primary product (the coated polyamide 6.6) must be appropriately allocated between the airbag discs and the fabric cuttings.

The sensitivity analysis considers three possible allocation approaches:

1. **The Main approach: cut-off**. The impact of virgin fabric production is entirely allocated to the airbag fabric disc. No burden is allocated to the fabric scrap. This is the approach considered most appropriate in the study.
2. **Option 1: economic allocation**. The impact of virgin fabric production is allocated between the airbag discs and the scrap cuttings based on their respective economic values.
3. **Option 2: economic allocation of impacts from both the fabric production AND recycling steps**. The reasoning is that recycling the fabric scrap requires removal of the coating that is necessary for the airbags. As this removal step bears environmental impacts as well, it may be justified to attribute them partly to the airbag discs themselves. This approach takes a broader “system” perspective: it allocates the overall system impacts to both final products, i.e. airbags discs and recycled polyamide.

   Note: allocation based on mass is not appropriate in this case. The fabric scraps would bear the same impact per unit of mass as the airbag fabric, which is higher than that of primary polyamide as it includes processes such as spinning, sizing and weaving. These processes are needed to produce airbag fabric but are not necessary for recycled polyamide. Thus, it would not be fair for recycled polyamide to carry those burdens according to mass allocation.

In the main approach, the fabric scraps are considered as waste that is recycled. As explained above in section *"The general allocation approaches for both open-loop or closed-loop systems"* (page 32), cut-off is commonly used in situations where the offer for waste is high while the demand is low. This is slightly different from the examples cited in section *"Allocation between two consecutive product life cycles"* (page 29), in that the fabric cuttings are “new scrap” (the fabric was not previously used).

Nevertheless, this "new scrap" can justifiably be considered as waste rather than a co-product since the Move 4earth® recycling technology was developed well after the airbag fabrication process, integrating all of the constraints due to this existing process without modifying it. Thus, the cut-off approach is appropriate and, in fact, it is the approach followed in the study.

In option 1, the fabric scrap is considered as a co-product of airbag fabric discs rather than as waste. The impacts of fabric production must be shared between the two co-products of the operation of disc cutting based on their respective economic values. As explained in section *"Allocation between the co-products of a multifunctional system"* (page 25), allocation can be carried out either based on a physical relationship (e.g. mass) or based on relative economic values. In this case, the latter option appears justified due to the high value difference between those two co-products. It must be kept in mind that this approach is subject to potential market price variations.

Option 2 is similar to option 1 except that the two co-products considered are the airbag fabric discs and the recycled polyamide (rather than the fabric scraps). This approach considers that the step in which the coating is removed from the polyamide is part of the overall process, encompassing disc cutting and scrap recycling into secondary polyamide 6.6. It reflects the fact that this step of the recycling process is necessary due to the composition of the airbag fabric, which is coated for safety reasons. With this approach, part of the impact of recycling is attributed to the airbag disc itself. Again, allocation is based on relative economic values of the airbag fabric disc and secondary polyamide 6.6, for the same reason as in option 1.

Allocation assumptions influence the calculated environmental benefit of Technyl 4earth

Results show that recycled polyamide 6.6 obtained with the Move 4earth® process is less impactful than primary polyamide 6.6, for all considered impacts and whatever the allocation approach, from cut-off (the main approach) to economic allocation (options 1 and 2).

Figure 14 illustrates results for the climate change impact category. When the cut-off approach is replaced by economic allocation (option 1), the calculated climate impact is slightly higher. Indeed, fabric scraps currently have a low but non-zero economic value on the market. A proportionate share of the burden of polyamide production is allocated to the fabric scraps, as opposed to the cut-off approach in which they are burdenless.

On the other hand, in option 2 in which both the burden of fabric production AND that of recycling are shared between airbag discs and scrap, the calculated climate change impacts decrease compared to option 1. This means that, when the burden of scrap recycling is shared between the scrap itself and the airbag discs, the overall environmental impact of the recycled product is reduced.

Comparing different allocation approaches

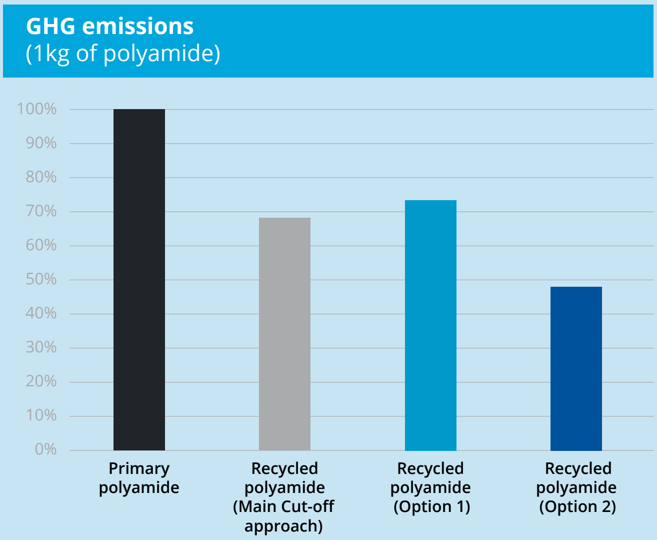

Figure 14: Results of the sensitivity analysis regarding the choice of method for allocating impacts of primary polyamide fabric production between airbag discs (the primary product) and fabric scraps which are recycled using the Move 4earth® technology. The main option is the cut-off approach. The 1st alternative option is an economic allocation between airbag discs and fabric scraps. The 2d alternative option is an economic allocation of the burdens of the fabric AND of recycled, between airbag discs and recycled polyamide.

Justify the allocation

In this case study, the cut-off allocation approach is justified by the fact that the scrap had no economic value before the Move 4earth® process was developed. Furthermore, allocation option 2 suggests even larger avoided emissions, and stems from the idea that the airbag must now bear part of the new environmental costs of reprocessing the scraps. This becomes justified as recycling is increasingly recognized as an integral part of any product system.

This option illustrates how impact allocation decisions depend on the history of the recycling process and how it is seen as coupled or decoupled from the manufacturing of the "primary" product (i.e. the airbag fabric disks).

It is important to note that the degree of interdependence between the primary use and the reuse has a great impact on environmental burden sharing, opening the door for discussions about the economic and environmental value of the recycled product. Furthermore, the economic value of the scrap may increase in time with the increasing demand for this recyclable material, until eventually reaching a stable equilibrium.

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The general allocation approaches for both open-loop or closed-loop systems

How benefits and impacts are allocated to successive life cycles is intimately linked to the development of recycling schemes in the market, as it influences and is influenced by market offer and demand. Take the example of a circular solution that produces polyester fabric from mechanically recycled PET bottles. In a sense, the waste PET used as a raw material is "free" of the environmental burdens of the initial raw materials extraction and transformation. However, this waste PET has to be transformed from plastic bottles into new processable material. So, who is accountable for the environmental burdens (emissions) or benefits (credits) of using waste plastic bottles to produce recycled PET? The answer depends on the approach that is chosen for end-of-life allocation, a choice that can be based on the balance between offer and demand for recyclable materials.

- If the offer of recyclable materials (e.g. waste PET) is higher than the demand, it makes sense to favor increased use of recycled materials in products. In this case, the allocation approach should attribute the benefits of recycling to those that **make use** of recycled materials (e.g. the producer of polyester from recycled PET bottles).
- If the demand for recyclable materials is higher than the offer (e.g. waste aluminium), the rationale is to favor the recovery at the primary product's end-of-life. Here, the preferred allocation approach will attribute the benefits of recycling to those that **generate** recyclable materials (e.g. the aluminium can producer).

These two perspectives have led to the definition of three main approaches to allocating burdens and benefits between life cycles, as depicted in figure 15 **[17]**:

3 ways to share environmental impacts between the primary and the recycled product

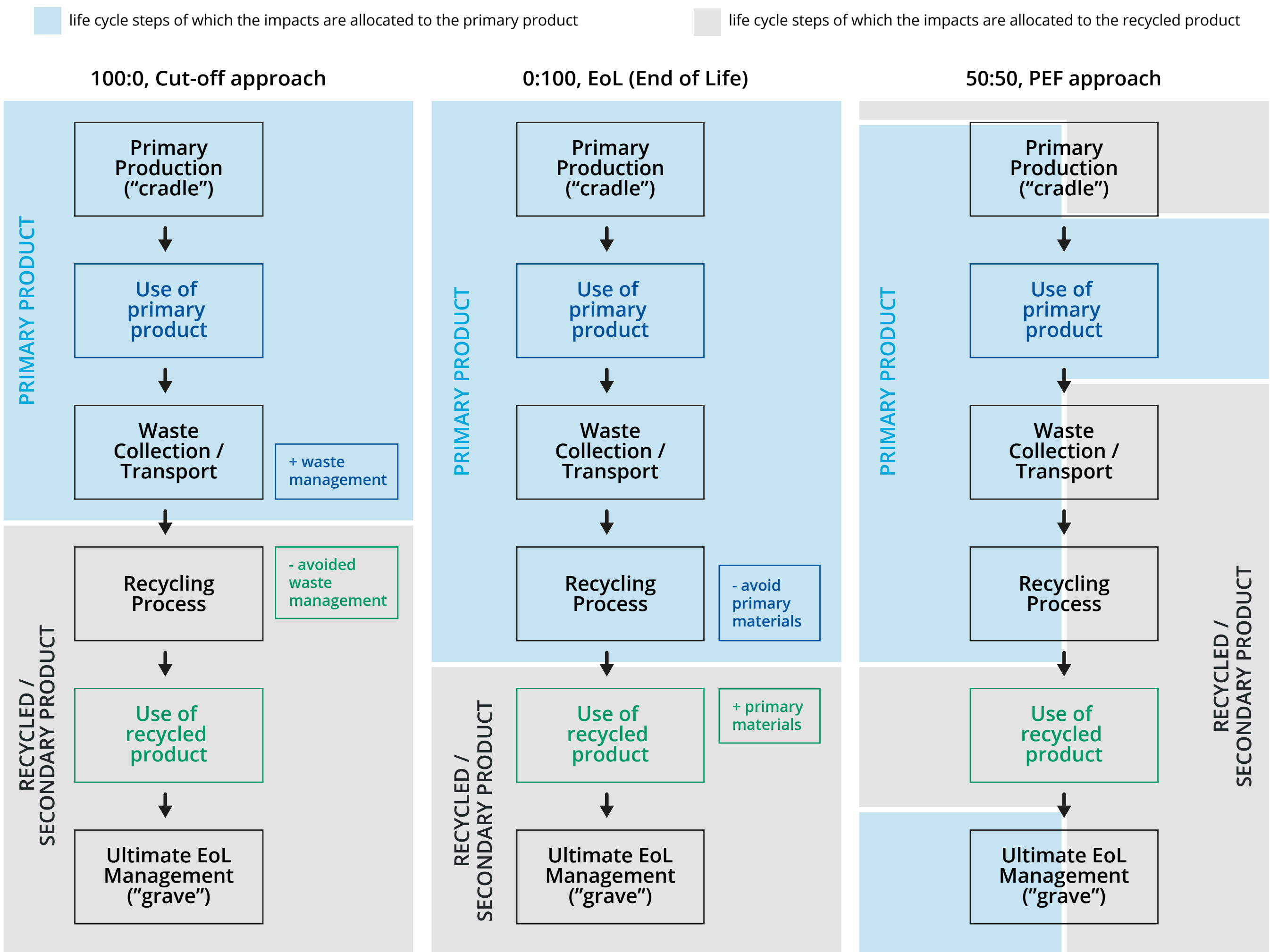

Figure 15: Main approaches to allocate impacts and benefits in LCA between first and next cycles. The 100:0 approach, or cut-off approach, is preferred in situations where demand for the waste material is low compared to the offer. This approach considers that the recycling process uses a burden-free feedstock. The 0:100 approach, or EoL recycling approach, is preferred when the demand for waste material is higher than the offer. This approach attributes all of the benefits of recycling to the primary product system, which generates recycled materials at end-of-life. The second life cycle (in grey) incurs the burden of using a recycled/secondary product instead of burdenless waste. The 50:50, or PEF (Product Environment Footprint) approach, share the impacts and benefits between the primary and secondary product cycles. Adapted from [17].

- The **100:0 approach**, or cut-off approach, is preferred in situations where the demand for waste material is low compared to the offer. This approach considers that the secondary product system (i.e. the circular solution) should not incur an environmental cost for the feedstock which is considered as free of environmental burdens. Thus, the circular solution receives all of the benefits of recycling, whereas none of these benefits are credited to the product system which generated waste materials for recycling. This approach is easy to apply and understand because it naturally follows the technical and business boundaries. In the example of waste PET bottles recycled into polyester clothing, the circular system receives flakes of waste PET from the primary product system. This feedstock is considered burdenless, meaning that the PET flakes have zero associated environmental impacts when they enter the circular system. The primary product system does not receive any credit for generating reusable material, and it is allocated the impact of the flake-generating process.
- The **0:100 approach**, or EoL recycling approach, is preferred when the demand for waste material is higher than the offer. This approach attributes all benefits of recycling to the primary product system, which generates the recycled waste. These benefits are attributed in the form of an environmental credit for having avoided future production of virgin material. The circular solution, which turns the recycled materials into a new product, receives none of the benefits of recycling and incurs the same environmental burden as if it were using virgin materials.
  If this approach were applied to the example of waste PET bottles recycled into polyester clothing, the primary product system (i.e. PET bottles) would receive an environmental credit equal to the amount of virgin PET production that is avoided due to the use of the recycled product. The secondary product cycle, which uses the recycled PET, would incur the same environmental burdens as if it were virgin PET.

Both approaches are simple to apply. They are convenient for situations in which the market balance between offer and demand for recycled materials is well known, where the choice is obvious between promoting recycled content in products or recovery at end-of-life. However, when that is not the case, an intermediate approach is necessary to share the benefits and burdens of recycling equitably between the life cycle that produces waste and the life cycle that consumes it.

- In the **50:50 approach**, benefits of recycling are shared equally between the primary and the secondary product cycles. The primary product system receives half of the credit for generating recycled material, and the secondary product system incurs only half of the burden for the material it uses.
- Variations on this approach further adjust the sharing of benefits to more precisely reflect market realities. **The Circular Footprint Formula** (CFF)[4] for example, which was developed as part of the European Commission's Product Environmental Footprint initiative, includes an "A factor" representing the market balance between offer and demand for recyclable materials **[18]**. In PEF studies, a low A factor (e.g. A = 0.2) is recommended when the offer is low and demand is high. Meanwhile a high A factor (e.g. A = 0.8) is recommended when the offer is high but the demand is low[5]. The CFF also includes quality ratios to address the issue of downcycling, in which the secondary product is of lesser quality than the primary product. These quality ratios are often based on economic aspects (price ratio of secondary compared to primary materials), or on physical aspects if more relevant.

By sharing the benefits of recycling between Life cycles, intermediate approaches offer a balance between promoting recycling and including recycled material in new products. This is especially appropriate for circular solutions for which the market situation is not clear-cut, in which case it is best to favor the entire recycling process rather than a single actor.

The specific case of closed-loop systems

In closed-loop systems, a product that has reached its end-of-life is recycled into the same product, with identical properties. Examples include chemical recycling of PET bottles into new bottles of identical quality, or recycling of aluminium cans into new aluminium cans. In these examples, the production of the primary product uses a portion of recycled material, which is generated again during recycling at end-of-life and then included in an identical secondary product, and so on.

4. The Circular Footprint Formula was developed as part of the European Commission's Product Environmental Footprint initiative, with the aim of standardizing the calculation of environmental burdens and benefits within the production and end-of-life of materials. It is used to model the recycled content of products and the end-of-life of materials, through landfill, incineration and recycling.
5. The A factor allocates burdens and benefits between supplier and user of recycled materials. It is added to the CFF formula to enable reflecting the market realities of user demand and supplier offer of materials. When the A factor is low, meaning that the demand for recycled material is higher than the offer, the impacts and credits of the process are mostly given to the life cycle that produces the material (e.g., metals). On the opposite end of the spectrum, when the recycled material is highly available but demand is low (e.g. EoL tyres), the impacts and credits are mostly allocated to the user of the recycled material. In the case of plastics, the market is considered balanced and a value of 0.5 is recommended by the European Commission.

In such closed-loop systems, the allocation approaches mentioned in section *"The general allocation approaches for both open-loop or closed-loop systems"* (page 32) remain applicable but are not necessary. Because the recyclable material (e.g. PET pellets) is both utilized and generated by the same product system, there is no need to share the burdens and benefits of recycling between multiple stakeholders. In practice, this is done by directly accounting for the reduced amount of virgin material needed as input. The burdens of recycling, which involves collecting waste PET and transforming it into pellets, can be accounted for at end-of-life.

Figure 16 presents a closed-loop system in which a product utilizes a portion of recyclable material (R_1) and, at end-of-life, generates more recyclable material (R_2). In the simplest version of a closed-loop system, $R_1 = R_2$ and the recyclable material stays continuously within the system. The burdens of recycling (Erecycled) are included. The benefits of reusing secondary material are accounted for by reducing the amount of virgin material necessary in the product cycle ($1-R_1$), and thus of the associated burdens (EV).

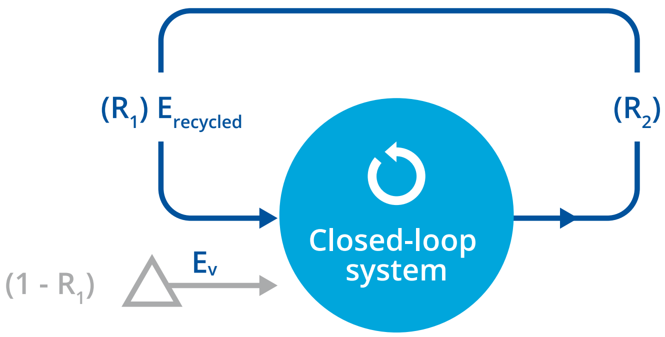

Figure 16: Schematic representation of a closed-loop system in which a product utilizes a portion of recyclable material (R_1) and, at end-of-life, generates more recyclable material (R_2). The benefits of reusing secondary material are accounted for by reducing the amount of virgin material necessary in the product cycle ($1-R_1$). Source: Quantis (ScoreLCA document).

LCA TIP: **Carbon accounting with a Mass Balance chain-of-custody model**

Another allocation question arises when a plant produces an end product from a mix of recycled and non-recycled feedstock. Take the example of chemical recycling technologies which, unlike mechanical recycling, generate virgin-grade feedstock which is then used to produce plastic. Producing this plastic would require prohibitively large infrastructure investments if they were to be operated separately from conventional plastic production. For this reason, the chemical recycling technology is simply plugged in to the existing chemical infrastructure.

Because recycled feedstock is mixed with virgin feedstock, it is not possible to analyze the recycled content in the final plastic, as all products stem from a portion of recycled material, but it is possible to track the physical relation of the feedstock and the final product. ISO 22095 further describes the requirements for a mass balance chain-of-custody model.

With mass balance accounting, the recycled feedstock is allocated to different end products according to a set of rules **[19]**. These products may then claim and market the content as "recycled" or "circular".

From the point of view of the plastics manufacturer, recycled plastics enter the plant as just another raw material, are blended with other raw materials to produce a variety of products, and the amount of products considered as "recycled" or "circular" that leave the manufacturing plant is equal to the amount entering it. **From the point of view of the consumer, one part of the products is marketed as "recycled" or "circular" and the rest is not. "Recycled" or "circular" products may be sold at a premium price to fund the recycling process.**

Allocating environmental benefits when the final product stems from a mix of recycled and non-recycled feedstocks: case study by Eastman Chemical

Carbon footprint of Eastman's carbon renewal technology, producing syngas from a variety of mixed plastic waste instead of coal: the "mass balance" accounting approach

This LCA nicely illustrates what to do when a mix of recycled and non-recycled feedstocks generates a unique (intermediate) product. The study compares Eastman's carbon renewal technology (CRT), a commercial molecular recycling technology for mixed waste plastic generating synthesis gas ("syngas"), compared against the conventional production of the same syngas. Syngas, composed of carbon monoxide and hydrogen, is used as a "building block" to produce new plastic resins, fibers and chemical products.

Examples of suitable waste feedstocks for CRT recycling include post-consumer polyester carpet fiber, pre-consumer cross-linked polyethylene scrap, and post-industrial cellulose acetate plastic scrap. As none of these materials are suitable for conventional recycling, they are typically disposed of in landfills. By breaking them down to the molecular level, CRT enables the valorization of these wastes into syngas which is further converted into new plastic materials, with no compromise in quality.

The CRT recycling process, a "reforming" technology, takes place in existing Eastman manufacturing systems producing syngas from coal. CRT allows mixed plastic waste to replace an equivalent amount of coal as a feedstock for syngas production. The mix of plastic feedstock reflects a range of actual sources recycled in 2020. The analysis focuses on the carbon footprint, comparing the production of 1 kilogram of syngas produced via the two different routes. Climate impacts are allocated according to two approaches:

1. **Cut-off approach for the recycled feedstock: waste plastic is attributed zero environmental impacts**
   The waste plastic feedstock is considered burdenless. This cut-off approach is selected because of the low economic value of the considered waste plastics and of the diversity of feedstocks and final products: CRT recycles a diverse mix of waste plastics into a set of plastics and fibers.

2. **Mass balance for the produced syngas: part of it is considered as recycled**
   Capitalizing on existing installations, Eastman's CRT recycling process occurs in operations already producing syngas from coal. Relying on existing world-scale manufacturing installations avoids the large and inefficient investments that construction of an independent segregated process would require.

The syngas product is an indistinguishable mix of hydrogen and carbon monoxide obtained by reforming mixed feedstock containing recycled plastics and coal. A specific quantity of syngas is allocated as containing recycled content based on the quantity of waste plastic feedstock that is input into the reforming process. This is the "mass balance approach" and, at Eastman, is certified under ISCC PLUS. The same mathematical attribution is also used when calculating the carbon footprint of CRT syngas on the one hand and of conventional syngas on the other hand. The CRT syngas with allocated recycled content is used downstream to produce plastics and fibers with recycled content under the mass balance approach. Figure 17 compares the carbon footprint of syngas based on coal to that of CRT syngas.

CRT recycling leads to a 20% reduction in greenhouse gas (GHG) emissions, taking into account transportation and pre-processing of the waste materials. The reduction grows to 50% when waste feedstocks are considered as stemming from the most advantaged plastics sources within a 500-mile radius from the CRT site.

The actual carbon footprint of the mix of coal-based and CRT-based syngas lies between the two values on figure 17. Mass balance demonstrates the value of further developing CRT, by showing the maximum reductions that could be obtained with this technology.

Comparison in carbon footprint
Global warming potential (kg CO_2/kg syngas)

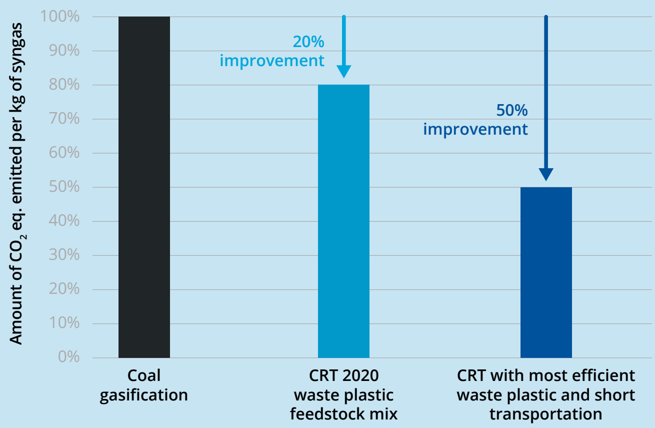

Figure 17: Carbon footprint for syngas from coal compared to recycled feedstocks. These feedstocks correspond to a range of actual waste sources (in light blue) or to a more advantageous scenario in terms of type and location of plastic waste (in dark blue).

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When to account for changes in the context?

Comparative LCA are used to determine which of two solutions is best from an environmental standpoint. LCA results are however context-dependent, meaning that results would be different if, for instance, the solution were implemented in a country with a different energy mix leading to a lower carbon impact. Emerging circular solutions are particularly likely to be affected by changes in the context as they develop to become mature solutions in the future.

Some key contextual elements to consider are:

- **Green energy**: the environmental impact of energy is lower when it comes from a renewable source. Energy-intensive circular solutions will greatly benefit from cleaner energy and the availability of low-carbon energy is expected to greatly increase in the future, as is the demand.
- **Feedstock availability and cost**: many circular solutions make use of recovered resources that are currently abundant and readily available, such as plastic waste. The development of such solutions leading to a rise in demand, the access to this feedstock may be subject to increasing competition.
- **Emerging technologies**: circular solutions are often based on novel technology clusters that are not yet mature. LCA can be adapted to cope with missing data and potential efficiency improvements of emerging technologies.

In LCA, potential future developments such as those mentioned above are clearly mentioned in the study, as an acknowledgement that environmental impacts may evolve over the years. Some studies go further than a simple mention and carry out sensitivity analyses to study the effect of context variations on LCA results.

Evolving supply of green energy

For the LCA of a process using electricity or heat, the energy source(s) influence the associated emissions. Thus, the energy mix may have a noticeable effect on the environmental impacts of the circular system. Energy from renewable sources in particular (e.g. renewable electricity or biogas), hereafter referred to as “green energy”, has a much lower climate impact than most traditional energy sources such as coal or natural gas.

Most often, LCA studies base calculations on the energy mix of the country in which the technology is implemented, which may contain a percentage of green energy. In the specific case of a process using exclusively green energy, the energy mix may be defined as “100% renewable energy” (more on this in section *"How do circular solutions benefit from green energy supply"* (page 38)).

Because the climate impact of green energy is low, increasing availability of green energy may shift LCA results to justify solutions that are energy-intensive. This shift is expected to continue, as many countries have committed to reduce overall greenhouse gas (GHG) emissions by increasing the percentage of green energy in the overall energy mix. At the same time, the demand for green energy is likely to greatly increase in the coming years as entire economies aim to become carbon neutral.

Future availability and demand for green energy are important to consider in LCA of circular solutions. Indeed, they are often based on novel technologies which could take several years before becoming fully implemented and operational, by when the energy mix will have evolved. This leads to a first question on how such potential evolutions can be integrated into LCA, to best orient decision-making.

It also leads to a second question concerning the attribution of emission reductions linked to decarbonizing energy: when a process is based on green energy instead of fossil energy, can it claim emission reductions if it does not actively participate in generating this green energy?

Future availability of green energy can modify the environmental benefits of circular solutions

Prospective LCA of circular solutions is helpful to decide whether to further support their development. The innovative technologies and partnerships involved are expected to continue evolving until they are fully mature and implemented. By that time, the energy mix will potentially include a much larger part of green energy, generating fewer emissions.

While a greener energy mix benefits both circular and non-circular solutions, emission reductions are proportionally larger for solutions requiring large amounts of energy. In CCU, for example, CO_2 can be activated with hydrogen, which itself is energetically costly to produce. If the environmental impact of energy is reduced, so is the impact of hydrogen production and thus of the CCU technology.

As the share of green energy increases in the national mix, reducing its environmental impacts, it also reduces the environmental credits of energy-producing solutions such as incineration. For example, when comparing incineration and chemical recycling as two end-of-life scenarios for plastic, incineration is credited for heat and electricity recuperation. The credit corresponds to avoided impacts of conventional production of heat and electricity, i.e. from the national mix. As the impact of the national mix is reduced, so is the credit attributed to incineration, favoring chemical recycling for plastic end-of-life.

All you need to know on changes in the context

Future availability of green energy can modify the environmental benefits of circular solutions

Circular solutions are often assessed for their environmental performance at an early stage in their development, meaning they may not be fully implemented until several years later. For this reason, comparative LCA of such solutions must examine scenarios of varying green energy availability in the future. For energy-intensive circular solutions, the impact may be large. Often, this potential effect is examined via a sensitivity analysis.

Does a project purchasing green energy create an increase in supply?

At a global level, the development of green energy sources reduces the climate impact of overall energy consumption. However, a system purchasing green energy does not generally lead to an increase in its supply. Thus, LCA of green energy-powered processes often use the national energy mix in the calculations, except if it can be shown that the process in question is directly responsible for the generation of the green energy it uses.

Abundance or scarcity of recovered feedstocks can change in time and influence allocation

Many circular solutions make use of resources that are abundant and have little to no economic value (e.g. by-products of existing processes, or end-of-life waste material). Further development and implementation of these solutions may increase demand for the secondary feedstock they use, which will thus gradually become less abundant and more expensive. As the market for these resources reaches a new equilibrium, allocation approaches must be adapted to reflect this new balance.

Secondary feedstock scarcity: considering longer term scenarios

As the abundant recovered resources which provide the basis for circular solutions become scarce, they also become harder to collect. Circular solutions may thus become less profitable, both economically and environmentally. This can be considered in carbon accounting by using scenarios, or should be addressed at least qualitatively in the interpretation of results.

Future improvement of circular technologies can be simulated or estimated

LCA of novel circular solutions reflect their current level of maturity and environmental efficiency. On the other hand, their conventional counterparts are often fully mature technologies already widely implemented and benefiting from (environmental) economies of scale. Increases in process efficiency of the circular solution is an important topic to consider. To produce a fair comparative assessment, improvement of circular solutions can be simulated or estimated to evaluate their future performance.

New or innovative circular solutions: pay attention to data gaps

LCA methodology relies on a mix of average and process specific data depending on the availability and criticality of these data. Whenever specific data is missing, surrogate data obtained from LCA databases, from the literature or from simulations are used. Data gaps can be particularly frequent when assessing new or innovative technologies such as circular solutions. In such cases (e.g. missing data on the energy consumption of the recycling process or the yield of the process) conclusions should be drawn carefully.

In practice, changes in the energy mix are examined as a "sensitivity analysis". Some **[8]** recommend performing a scenario analysis in which several paths are explored to consider the transition of the energy mix, from a status-quo scenario to a fully decarbonized scenario. Another approach is to fully replace the energy mix with a renewable source in the calculations. Both approaches may not accurately forecast the energy mix transition, but provide valuable insights into the degree to which the assessed solution is influenced by a green energy transition.

How do circular solutions benefit from green energy supply

Green energy improves the environmental performance of energy-consuming processes. Circular solutions, which can be energy intensive but use less fossil feedstock, are favored by increasingly available green energy.

While, at a global level, it is clear that the development of green energy leads to fewer emissions from the energy sector, there remains some discussion on how to distribute these emission reductions between certified green energy consumers and those that simply use the national energy mix.

One option is to fully attribute the lower emissions related to green energy to the process which makes use of it. For example, if a chemical recycling process uses 100 kWh of conventional energy, switching to renewable energy leads to a reduction in the process's energy-related emissions. Such an approach is often used as a sensitivity analysis: LCA of a process is first carried out considering a conventional source of energy, which is then replaced with a renewable source in a sensitivity study. The magnitude of the calculated emissions reduction gives an indication of how dependent the process is on green energy to be more environmentally performant.

Purchasing 100% green energy to power a process does not however increase the overall supply unless a renewable power plant was built specifically for this reason. Rather, it is just diverting green energy from another customer. For this reason, it is often recommended to use the national energy mix in an LCA of a green energy-powered process.

For example, the EU recommendations for LCA for CCU state that "in line with consequential modelling it is thus not acceptable within LCA to allow any additional power consumers including CCU plants to claim renewable electricity from previously existing renewable power installations". Only in the particular case where green energy is produced specifically for the process under assessment, either on site or through a Power Purchase Agreement, then LCA may consider 100% green electricity. Other standards and norms however, including ISO 14067 for product carbon footprinting, support the use of green energy in LCA in a wider range of situations[6]. Thus, when reading an LCA report, it is important to bear in mind the chosen approach for green energy accounting.

6. See ISO 14067, 14021 and 14026 for further guidance.

It should be noted that, if the objective of the LCA is to compare a circular solution to a conventional equivalent, it is important that the two solutions use the same source of energy to compare them fairly. Indeed, if one solution is considered to be powered with renewable energy, whereas the other uses conventional energy, LCA results will be biased in favor of the first solution. For the comparison to be fair, LCA should consider that both solutions use the same source of energy (e.g. the national electricity grid) in order to truly reflect the comparative environmental performances of both.

Variations of feedstock availability and cost

Abundance or scarcity of recovered feedstocks influence allocation decisions

Many circular solutions make use of resources that are abundant and have little to no monetary value, which are generated as co-products of an existing system (e.g. waste animal fats from meat processing) or as end-of-life product waste (e.g. plastic waste). Because there are few applications for these resources, they are cheap, abundant and, in fact, are a burden to dispose of. These characteristics are currently driving the development of circular solutions.

As these circular technologies evolve toward maturity or new solutions are developed, they will use increasing amounts of the abundant resources mentioned above. Thus, over time, the balance between offer and demand will change, as well as costs. The opposite may also happen, when a scarcely recovered feedstock becomes more abundant as recovery schemes develop. In LCA, these market effects influence results via the allocation decisions.

This is for example true for co-products of a multifunctional system, where burdens and benefits are often allocated based on the relative economic value of the co-products. This approach is called economic allocation and is detailed in section ***"Allocation between the co-products of a multifunctional system"*** (page 25). Take the example of ethanol produced from sugarcane bagasse, a by-product of sugar production. Bagasse has generally been considered as waste with little economic value. Sugar, on the other hand, is a highly valuable product. For this reason, economic allocation of the impacts of sugarcane cultivation attributes most of those impacts to sugar, and very little to bagasse. If the demand for bagasse increases (for the production of ethanol or any other use), so does the economic value of bagasse. This would lead to a shift in allocation in which a larger part of the impacts of sugarcane production must be attributed to bagasse.

Evolving sources of energy: case study by Braskem

LCA of Green and Fossil Ethylene Vinyl Acetate

This LCA evaluates the environmental impacts of bio-based Ethylene Vinyl Acetate (EVA) ("Green EVA") compared to its conventional, fossil-based production route ("Fossil EVA"), for a range of environmental impacts. EVA is a widely-used polymer-based material made from ethylene and vinyl acetate. This LCA exemplifies how the question of green energy can be addressed in LCA calculations.

In the "Green EVA" scenario, ethylene comes from sugarcane while vinyl acetate is fossil-based. In the "Fossil EVA" scenario, both ethylene and vinyl acetate are obtained from petroleum. The study is a cradle-to-gate assessment, i.e. it does not include the use phase and end-of-life as these phases are identical for Green EVA and Fossil EVA.

The Green EVA solution generates electricity

In the Green EVA scenario, sugarcane is processed into ethanol, and remaining biomass is burned to produce electricity. The Green EVA system is therefore multifunctional, producing ethanol and electricity as a by-product. Multifunctionality is handled via substitution, a variant of system expansion (see section *"Allocation between the co-products of a multifunctional system"* (page 25)).

The Green EVA scenario receives a credit for substituting 1.5 kWh of electricity - the amount generated by burning biomass residues - from a conventional source. The study assumes that bioelectricity replaces electricity from a thermo-electric power plant powered by natural gas implanted in Brazil, the country in which the study is carried out. While this assumption is realistic for now, as bioelectricity will preferably replace thermal sources, the authors acknowledge that the national electricity mix is undergoing strong changes and that thermal electricity may not be representative in the long run (in Brazil, the grid mix is in already made up in large part of hydroelectricity). For this reason, the authors carried out a **sensitivity analysis** on the conventional electricity source substituted in the Green EVA scenario.

In this analysis, the Fossil EVA scenario remains the same. The Green EVA scenario, however, is modified so that the surplus electricity from bagasse burning substitutes the average grid mix instead of 100% thermal electricity. Results are shown in figure 18.

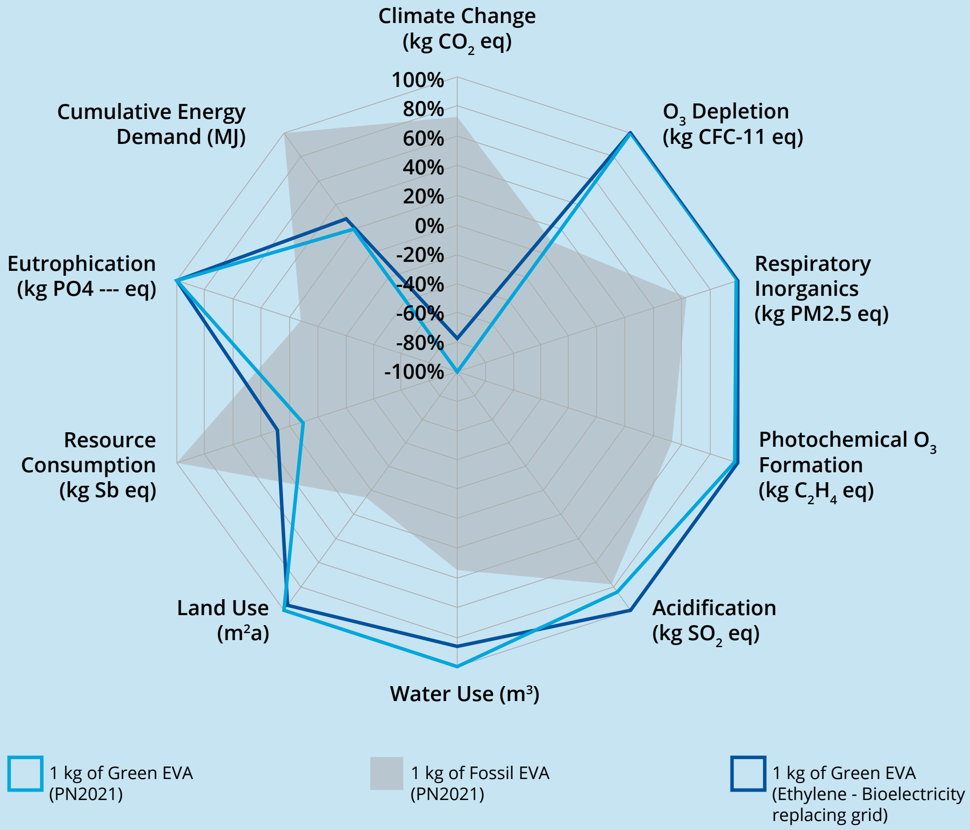


Figure 18: Sensitivity analysis for the replacement of electricity grid mix by the surplus electricity from bagasse burning. The reference scenario, Fossil EVA, remains the same (in grey). The original Green EVA scenario is shown in light blue. The sensitivity analysis, with results shown in dark blue, corresponds to Green EVA production in which surplus electricity from bagasse burning substitutes the average grid mix instead of 100% thermal electricity. Regarding the Climate Change indicator[7], the Fossil EVA scenario has the largest impact. The sensitivity analysis (in dark blue) leads to a slight increase in emissions compared to the original Green EVA scenario (in light blue). This reflects the fact that, if surplus electricity from Green EVA substitutes the average grid mix, the benefit for the climate is lower than if substituting thermal electricity.

7. Ten indicators of environmental impact were included in the study. They show that, while Green EVA presents a clear advantage from a climate standpoint, it is more impactful than the conventional alternative for other environmental issues.

www.braskem.com
More on bio-based ethanol: https://bit.ly/39Z6bPH

Market effects can also affect allocation decisions in the case of waste material generated at product end of life. Indeed, the environmental impact of recycling must be shared between two life cycles: that of the product that is generating the waste, and that of the recycled product that is generated from this waste. There are several approaches to allocating between life cycles, which are detailed in section ***"Allocation between two consecutive product life cycles"*** (page 29). One commonly used approach, the Circular Footprint Formula (CFF), illustrates how the balance between offer and demand for the waste material can affect allocation. In the CFF, the "A factor" is set depending on the market situation. It is closer to 0 when there is high demand for the waste material, as is the case for many metals, and closer to 1 when the demand is low, such as for textiles. As the resources used by a circular solution become less readily available, the A factor must be set closer to 0 to reflect the new balance between offer and demand.

Diminishing economic and environmental returns

As the abundant resources which provide the basis for circular solutions become scarce, they may also become harder to collect. Circular solutions usually start by using feedstock that is easy to obtain, such as large streams of non-mixed industrial plastic waste or CO_2 emissions from ammonia production. As the easily accessible resources are increasingly utilized, other sources may be considered even if less abundant or harder to access. This includes Municipal Solid Waste with decreasing fractions of plastic, or atmospheric CO_2 that is much less concentrated than CO_2 from industrial exhaust.

According to the phenomenon of diminishing economic returns, circular solutions become less economically viable as the resources they are based on become harder and more expensive to obtain. This also holds true from an environmental perspective: while collecting waste PET from a fruit packing house does not require much transportation, sorting or treatment, recovering PET (polyethylene terephthalate) from mixed Municipal Solid Waste is a more complex process both logistically and technically. As the need for transportation, sorting and treatment increases, so does the environmental impact of the circular solution as a whole.

Thus, a balance should be found between maximizing product circularity and the environmental impacts it induces. The optimal degree of recycling is difficult to determine before the equilibrium is reached naturally. The question remains important and can be addressed at least qualitatively in LCA studies.

Emerging circular technologies

Circular solutions are based on novel technologies enabling the (re)use of resources which were not usable previously. Their environmental performance must often be assessed at an early stage of their development, to determine whether it is worthwhile to continue investing in the solution as a replacement for an existing alternative. In particular, LCA can help with the early detection of "environmental hotspots" which could further be improved through additional research and development.

Prospective LCA can guide decision-making, however it requires paying special attention to:

- **Data availability**: for technologies at pilot stage, there can be missing data regarding one or several parts of the process. Such data gaps must be bridged.
- **Future technological improvements**: as technologies evolve from pilot stage to maturity, they become more efficient and their environmental performance can improve. LCA studies must take this into consideration to ensure that a fair comparison with the reference technologies, which may also evolve in time.

Why scarce data is an issue

LCA methodology should rely on process-specific data regarding inputs of water, energy and raw materials in order to ensure the overall robustness of the approach. When some of this data is not yet available for the components of the circular system, LCA relies on surrogate data to fill the gaps. This surrogate data can be obtained from LCA databases, from the literature or it can be estimated based on national economic data in Input-Output tables. Another approach that is often chosen is process simulation, for example to compute energy-related emissions, instead of real process-specific data.

Surrogate data delivers conclusions that are therefore less representative of the specific process under study. It is a particularly relevant issue for novel circular solutions at pilot stage, for which process-specific data is often lacking. In these cases, it is recommended to fill data gaps in order to preserve the quality of the LCA analysis.

For example, the EU Guidelines for LCA of Carbon Capture and Utilization state that data gaps can be filled with an appropriate proxy, and recommend a subsequent "relevance check" in which both a "best case" and a "worst case" assumption are tested.

Nevertheless, reliance on surrogate data should be limited to a minimum. Section ***"Promoting data availability"*** (page 42) addresses the importance of increasing data availability to reinforce carbon LCA.

Considering potential technological improvements

LCA is a powerful tool to evaluate the environmental impacts of emerging solutions. However, such emerging technologies (and their environmental footprint) are likely to continue evolving as a result of continued research and potential economies of scale. On the other hand, their conventional counterparts are fully mature technologies already widely implemented and benefiting from such (environmental) economies of scale.

To produce a fair comparison between an emerging circular solution and its conventional counterpart, the assessment must take into consideration the scale-up of circular processes until full maturity. Several approaches are available to model current pilot-scale technologies at maturity.

For example, the United States' Department of Energy (US DOE) classifies technologies according to their level of maturity, ranging from lab-level research to commercial scale, and describes the LCA expectations at each level, from a screening-level LCA allowing for approximations, to a project-level LCA reflecting real-world conditions **[20]**.

Likewise, in a report on comparative LCA of alternative feedstock for plastics production, the European Commission's JRC states that "companies and industries generally go through a learning curve, meaning that their efficiency and productivity increase as their experience (i.e. cumulative production) increases." This learning curve can be accounted for through process simulation, generating data representative of a more advanced process; by using existing data from a similar, mature process; or by applying "learning rates", reflecting improvements experienced in similar processes.

These approaches are each associated with some uncertainty as they are either based on estimations and simulations, or they produce an assessment that does not correspond exactly to the considered technology. Furthermore, they are not always applied consistently across LCA studies.

Many LCA practitioners choose not to include potential technological improvements in the calculations, but rather to address them in the interpretation of results, an important section of every LCA detailing the main challenges faced by the assessed solution and the key levers to improve its overall performance.

How to reinforce LCA?

LCA produces a holistic and unequivocal environmental profile that enables the comparison of circular solutions with their conventional counterparts. General LCA methodology is applicable to circular solutions just like their conventional counterparts. Nonetheless, further developments can continue to increase its relevance.

LCA studies including other impact categories (e.g. land use or water consumption) will provide additional insights relevant for decision-making between circular and conventional systems. Improved data availability for emerging circular solutions will also increase the robustness of comparative assessments. Lastly, the definition of common standards in LCA and the development of a good understanding of the methodology are both important to align future work in the field.

Considering all relevant environmental impacts: land use, toxicity, water consumption, …

LCA assessments are increasingly used to quantify the expected benefits of a circular solution on climate change. Other environmental impacts including land use, toxicity or water consumption should also be assessed in order to provide a holistic assessment of environmental impacts. This document and the case studies presented put the focus on climate change, but the approaches described in the previous chapters are also relevant for multi-criteria studies.

A multi-criteria approach is recommended to identify potential trade-offs between impact categories. For circular solutions aiming to re-circulate carbon inside new products, carbon emissions are reduced but other impacts may increase as a result.

One example is that of biofuels. While these can effectively reduce the greenhouse gas (GHG) emissions related to energy generation and use, the resulting demand for more agricultural inputs can lead to additional burdens in terms of toxicity or land use. This holds true for other bio-based products, such as olefins from renewable sources like wood or maize **[21]**. LCA shows that, while GHG emissions are greatly reduced compared to conventional olefin production, the acidification potential can increase significantly due to agricultural feedstock production. Other impact categories are just as important to consider as climate change, and tradeoffs such as in the production of bio-based olefins must be identified. This is useful to provide the best guidance for decision-making and, when possible, develop countermeasures to these tradeoffs.

Promoting data availability

LCA assessments preferably rely on process-specific environmental data in order to calculate the overall environmental impacts of circular systems. Data completeness and quality ensure that the assessment is robust. However, missing data is a common issue in LCA and particularly for circular solutions still at pilot-scale, for which little data is available. ***"Emerging circular technologies"*** (page 40) further discusses these data gaps and the methods by which they can be handled in LCA to increase the precision of the results.

Ultimately, although LCA provides useful insights even when data is incomplete, its value lies in the solid and accurate results it can yield when the assessment is based on relevant data. Thus, promoting data availability in all sectors, including the chemical industry, is key to further enhance the value of LCA. This is achieved by developing collaborative databases with a network of member companies in which stakeholders share data to further advance LCA research in the field. Another approach is to carry out specific LCA that are made publicly available to enrich the debate.

Common standards in LCA define the way forward

Every LCA relies on a set of methodological decisions regarding the aspects discussed in the previous chapters, such as allocation or accounting for the use of green energy. LCA practitioners must examine the various options available and make the best choice according to the context of the study, and be explicit about them.

Many guidelines and standards have been developed to assist LCA practitioners in their decision making, and to ensure consistency in the results obtained across different studies. These guidelines often stem from initiatives a specific industry sectors to guide LCA practitioners, such as CCU technologies **[8] [10]**, or those written by the World Steel Association for the steel industry **[22]**. Cross-industry work, such as the PEF (Product Environmental Footprint) of the European Commission, is also important to harmonize such sector-specific guidelines.

Basing methodological decisions on existing guidelines and standards leads to results that are comparable with other solutions, providing far more value in terms of decision-making support. The consistency with which these standards are applied and the quality of data are two key elements that reinforce LCA and strengthen its role as the essential tool for environmental assessments.

All you need to know on how to make LCA more robust

Multi-impact LCA are key

The environmental impacts - and potential benefits - of circular solutions extend beyond climate change. Other impacts, such as land use, toxicity or water consumption, are also important to consider. As for non-circular systems, multi-impact LCA can help identify tradeoffs between the different environmental impacts, providing guidance for decision-making and to potentially develop countermeasures to these tradeoffs. All methodological considerations addressed in the previous chapters for greenhouse gases (GHG) are also relevant for other environmental impacts.

Promoting data availability for new circular processes

LCA assessments preferably rely on process-specific data for critical parts of the assessed process. This reinforces credibility and overall quality. Thus, increasing availability of process-specific data for emerging circular systems will be key. This is often achieved by developing collaborative databases between stakeholders of a same sector, or by making process-specific LCA data publicly available for use in other studies in the future. As these data become publicly available, existing LCA studies should be reviewed to ensure that the conclusions are still valid in light of this new information.

Common standards in LCA of circular systems define the way forward

Every LCA relies on a series of methodological assumptions, such as allocation choices or accounting for the use of green energy. While LCA is a mature methodological field, additional guidelines on aspects linked to circularity are continuously published, to guide methodological choices and enable comparability across studies. The development of these standards will continue to enhance consistency across studies. It is crucial that standards be well understood, well received and come with the appropriate tools to be used correctly and consistently in the field.

About ICCA

The International Council of Chemical Associations (ICCA) is the worldwide voice of the chemical industry, representing chemical manufacturers and producers all over the world.

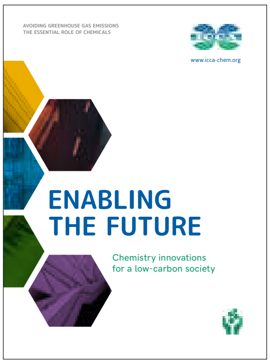
Responding to the need for a global presence, ICCA was created in 1989 to coordinate the work of chemical companies and associations on issues and programs of international interest. It comprises trade associations and companies involved in all aspects of the chemical industry.

ICCA is a chemical industry sector with a turnover of more than 3,600 billion euros. ICCA members (incl. observers & Responsible Care members) account for more than 90 percent of global chemical sales. ICCA promotes and co-ordinates Responsible Care® and other voluntary chemical industry initiatives.

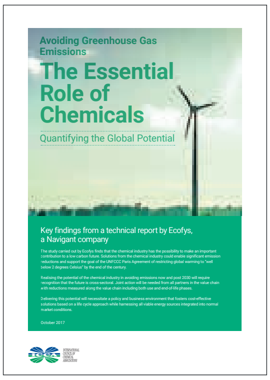
ICCA has a central role in the exchange of information within the international industry, and in the development of position statements on matters of policy. It is also the main channel of communication between the industry and various international organizations that are concerned with health, environment and trade-related issues, including the United Nations Environment Programme (UNEP), the World Trade Organization (WTO) and the Organisation for Economic Co-operation & Development (OECD).

Related ICCA documents

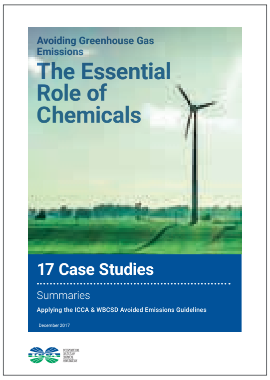
This document on **LIFE CYCLE ASSESSMENTS APPLIED TO CIRCULAR SYSTEMS** is the latest of a series of studies on the quantification, with a life cycle perspective, of greenhouse gas (GHG) emissions savings enabled by products of the chemical industry:



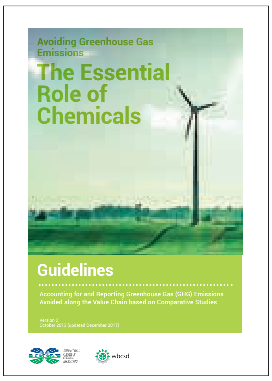
ENABLING THE FUTURE: CHEMISTRY INNOVATIONS FOR A LOW-CARBON SOCIETY (2019): Commissioned to KPMG and fors, the study reveals that 450 generic technologies are enablers of GHG savings, of which 137 are highly feasible. The 17 innovative solutions featured in the report could develop emission reductions of about 5-10 Gigaton by 2050 – which is about one quarter of the total world emissions today. These solutions will require robust transformation of entire sectors, such as power generation and storage, industry and production, mobility and transportation, nutrition and agriculture, and building and housing.



AVOIDING GREENHOUSE GAS EMISSIONS: THE ESSENTIAL ROLE OF CHEMICALS. QUANTIFYING THE GLOBAL POTENTIAL (2017): Commissioned to Ecofys, the report illustrates how efficient processes and chemical industry solutions can contribute to GHG savings. ICCA estimates that by 2030, light materials for transportation, efficient buildings and lighting, electric cars, wind and solar power and improved tires, at global scale, have the potential to avoid 2.5 Gigatons of GHG emissions globally every year.



AVOIDING GREENHOUSE GAS EMISSIONS: THE ESSENTIAL ROLE OF CHEMICALS - 17 CASE STUDIES (2017): Commissioned to Quantis, this report assembles 17 examples of Life Cycle Assessment case studies. The purpose is twofold: to motivate all stakeholders to discuss climate change using robust studies, taking the full life cycles into account, and to encourage all chemical companies to generate high quality assessments.



AVOIDING GREENHOUSE GAS EMISSIONS: THE ESSENTIAL ROLE OF CHEMICALS – GUIDELINES (UPDATED IN 2017): Prepared jointly with the World Business Council for Sustainable Development (WBCSD) the guidelines define how to measure avoided GHG emissions via LCA methodologies applied to entire value chains.

The case studies

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